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The Use of Recycled Plastic in Asphalt Pavements: Feasibility Study

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16. Abstract

The plastics industry has been actively exploring new end-market opportunities for the more than 35 million tons of waste plastics generated annually. The use of recycled WP in asphalt presents an opportunity to improve pavement performance while reducing the growing amount of WP being landfilled or released into the environment. However, the use of WP in asphalt mixtures poses challenges due to variations in plastic composition and the presence of non-plastic contaminants. The absence of standardized procedures has resulted in inconsistent integration methods and unclear roles of WP within asphalt concrete (AC) mixtures. Therefore, the goal of this multiphase study is to evaluate the feasibility of using recycled plastics in asphalt mixtures. This Phase 1 study focused on the dry process, assessing the differences on the physical and chemical characteristics of various WPs, checking the effects of different laboratory mixing protocol to produce WP-modified mixtures, and investigating bonding mechanisms at the binder–aggregate interface when WP was added to pre-heated aggregates. Performance-based parameters from the Hamburg Wheel Tracking Test (HWTT) and the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) were compared. Results showed that WP-modified mixtures produced with higher aggregate pre-heating temperatures exhibited enhanced rutting and moisture-damage resistance while maintaining short-term cracking resistance compared to a reference (no WP) mix. When comparing two different types of WP (LDPE and PP), both improved moisture-damage resistance, with LDPE demonstrating superior performance. Bonding tests revealed that aggregates coated with WP exhibited reduced water wettability and increased binder–aggregate bonding strength. At the end, the practical implementation of a WP-modified mixture was further evaluated in a field project. A Nebraska Superpave Recycled Mixture (SPR) using 25% RAP incorporating 1% post-consumer LDPE was produced at an asphalt plant and used in a local paving project in South Sioux City, Nebraska. Comparisons between laboratory- and plant-produced mixtures confirmed the feasibility of producing WP-modified mixtures and the validity of the mixing procedure adopted in the lab, with similar performance tests results. Overall, the mixtures exhibited improved rutting and moisture resistance while maintaining short-term cracking resistance. Future work will focus on the long-term performance evaluation and field monitoring of WP-modified mixtures, as well as assessing their recyclability potential.

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Chapter 1 Introduction

The lack of sustainable alternatives to minimize the deposition and accumulation of mismanaged waste plastics (WPs) in the environment is a growing concern [1]. According to Ritchie et al. [2] , the amount of plastic generated globally has doubled in the last two decades, accounting for 460 million tons in 2019. During that year, less than 10% of all plastic generated was recycled, while 19% was incinerated, 49% was disposed of in landfills, and the remaining was considered mismanaged WPs, including all waste burned in open pits, dumped into the ocean, or disposed of in dumpsites.

In the United States, over 35 million tons of WP were generated in 2018, with a low recycling rate of 8.7%. In that case, 75% of all WP generated were disposed in landfills [3]. Since the rate of recycling for WPs is quite low, and the paving industry has a history of utilizing waste products in their road surfaces, the use of those materials in paving applications could serve as a more sustainable solution to help manage plastic waste and reduce the necessity of virgin materials for road surface construction. As a paving material, the WPs can be used as a binder modifier [4–6] , an aggregate [4,7], a mixture modifier [4], or a combination of these [4,8].

Several research efforts are currently underway at the time of writing this report to establish the feasibility of WP addition into asphalt mixtures, showing improvements in the HMA's indirect tensile strength [9,10], resistance to rutting [9–11], moisture damage [8], and fatigue cracking. Despite the promising results in terms of mechanical performance gain presented by previous studies on the topic, there are still many knowledge gaps that need to be addressed for optimized use of WPs in the hot mix asphalt (HMA), such as possible WP particle size limitations, WP integration methods for a respective type, percentage of WP that needs to be added, pre-heating temperature of aggregates, or even the order in which the materials are added

within the mixture [12].

In general, there are two methods to incorporate WPs into the HMA. In the dry method, the WP is added directly to the aggregates as an aggregate replacement or an additive, acting as a reinforcement material in the mix. In the wet method, WP is added directly into the binder, aiming to produce a polymer-modified asphalt (PMA). In this case, the WP acts as a binder modifier [7,8,13–16]. In general, both methods can lead to WP-modified mixes with improved performance according to some parameters verified in the literature, such as Marshall stability, stiffness, indirect tensile strength, rutting, and retained stability [7,8,16–18]. When compared to the wet process, the dry method can represent a more suitable alternative for incorporating a larger quantity of WPs into the asphalt mixture and reducing the release of microplastics into the environment, since the plastic aggregates are situated deeper within the pavement structure instead of being concentrated towards the surface layer [19,20]. Despite the benefits, key knowledge gaps have been identified, including the lack of a consistent procedure applicable across studies, a feasibility assessment for scaling laboratory-based procedures to field applications, and laboratory evaluations utilizing advanced performance-based tests as suggested in the Balance Mix Design (BMD) approaches.

1.1 Research Significance

The focus of this study is to evaluate the feasibility and potential implementation of WP into the HMA via the dry method. The dry method allows for a larger quantity of WP to be incorporated into HMA, which can be relevant for reducing the amount of mismanaged WP released into the environment. However, as mentioned before, there is no standard procedure for adding WP through the dry process due to many variables (order of material's addition, mixing and compaction temperatures, type and shape of WP particles, and many others) which can influence the final mix design [4].

Considering the characteristics of WPs, factors that play a major role in the dry addition procedure include the WPs' specific gravity, melting point, size, and shape. For that reason, different mixing approaches have been proposed to incorporate WP into HMA through the dry processes, which vary mainly according to the necessity of pre-heating aggregates, mixing temperatures, and the instant WP should be added during the mixing procedure. Therefore, there is a knowledge gap that needs to be addressed.

Also, other recycled materials, such as Reclaimed Asphalt pavement (RAP), have been widely used in the U.S as a cost-effective and environmentally friendly alternative to replace virgin materials in asphalt mixtures [21]. According to the National Asphalt Pavement Association [22], the national average use of RAP is around 21%, while in Nebraska, all NDOT-approved asphalt mixtures currently include RAP contents ranging from 20% to 45%, with ongoing efforts to increase that amount up to 65% [23–26]. Overall, RAP-mixes tend to have enhanced rutting resistance, but higher cracking potential due to the presence of aged binder [21]. In that sense, there are also rising concerns about how WP addition might perform in highly recycled systems, due to the increased stiffness [12].

Moreover, a feasibility assessment for scaling laboratory-based procedures to field applications, and laboratory evaluations utilizing advanced performance tests as suggested in the Balance Mix Design (BMD) approaches, is critical to implement this innovation in pavement projects.

Therefore, to properly examine the feasibility and potential implementation of WPs into asphalt mixtures, it is crucial to understand how and why each approach is utilized and their respective outcomes, alongside evaluating the performance of the different mixing procedures and WP types, and the effects of different pre-heating temperatures [27]. Additionally, it is

important to evaluate the combined effects of waste products (e.g., RAP and WP) on the HMA performance considering current performance tests to assess cracking and rutting resistance, which are the most common types of distress in pavements, as well as the evaluation of key small-scale binder-aggregate adhesion mechanisms that might lead to improved performance to further advance the use of sustainable materials.

1.2 Research Objectives

The ultimate goal of this multi-phase study is to evaluate the feasibility of using recycled plastics in asphalt pavements by considering the effect of recycled plastics on the rutting, cracking, and moisture damage resistance of asphalt mixtures. The aims of Phase 1 of this study are to:

- Identify waste plastics sources in Nebraska and select a few of them based on their physicochemical properties that are considered important for use in asphalt mixtures through the dry process.
- Develop a laboratory procedure for introducing selected waste plastics that can mimic the production of recycled plastic modified mixtures at asphalt plants.
- Evaluate the performance of plastic modified asphalt mixtures prepared with various sources and types of waste plastics in the laboratory. The focus of this objective is on developing a mix design for plastic modified mixtures based on performance-based parameters.
- Investigate the effects of WP on binder-aggregate adhesion based on the thermodynamic properties of the aggregate surface and binder-aggregate bond strength.
- Verify the feasibility of incorporating WPs in Nebraska Superpave Recycled Mixtures (SPR), checking the lab-produced mixture's performance parameters as well as the feasibility of implementation of the mixture in a large-scale field project.

1.3 Organization of the Report

This report is organized into five chapters. The first chapter consists of an introduction to the project, the research objectives, and the organization of the study. Chapter 2 provides a literature review on the types of WP used in paving applications and the incorporation methods

utilized by different authors. Chapter 3 provides a brief overview of research methodology, focusing on the materials, mixing protocol developed, experimental methods, and field construction feasibility. Chapter 4 presents laboratory test results, accompanied by statistical analyses to determine the effects of WP addition on performance-based parameters, bonding strength, and scalability of the tested solution. Chapter 5 summarizes the major findings of the study and proposes recommendations for future research.

Chapter 2 Literature Review

2.1 Waste Plastic Generation

The high generation and deposition of waste plastics (WPs) in the environment represent a growing worldwide concern [1]. It is estimated that from 1950 until 2015, the global cumulative WP generation accounted for 6300 million tons, with 12% being incinerated and less than 9% being recycled (Figure 2.1). Currently, around 60% of all WPs generated globally are discarded in landfills or the natural environment [28].

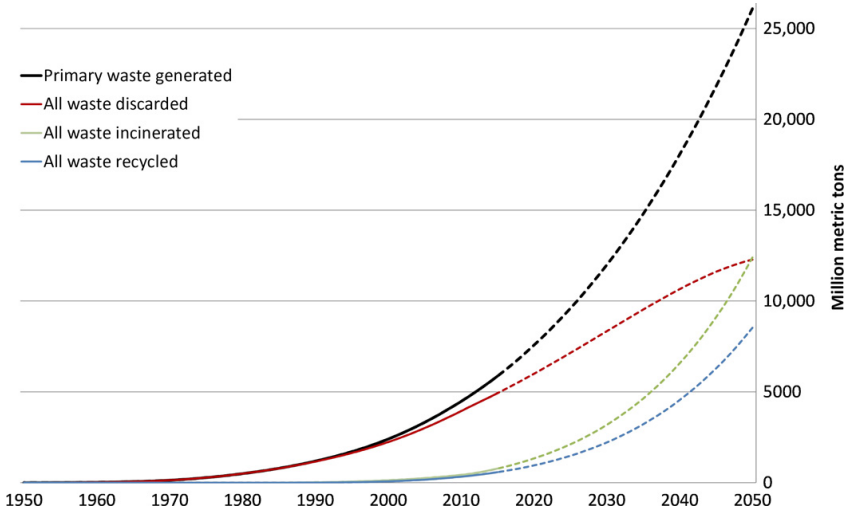

Figure 2.1 Cumulative plastic waste generation and disposal (in million metric tons) from 1950 to 2015 [28].

According to Ritchie et al. [2], the amount of plastic generated globally has doubled in the last two decades, accounting for 460 million tons in 2019. During that year, less than 10% of all plastic generated was recycled, while 19% was incinerated, and 49% disposed in landfills. The remaining 22% represented the amount of mismanaged WP (MWP), including all waste burned in open pits, dumped into the ocean, and disposed of in dumpsites. Figure 2.2 shows the distribution of mismanaged WPs in the world in 2019. China and India were identified as the

biggest producers of MWP, with over 12 million tons. Brazil and a part of Africa (i.e., Nigeria, the Democratic Republic of Congo, Egypt, and Tanzania) accounted for 1 to 3 million tons each [2].

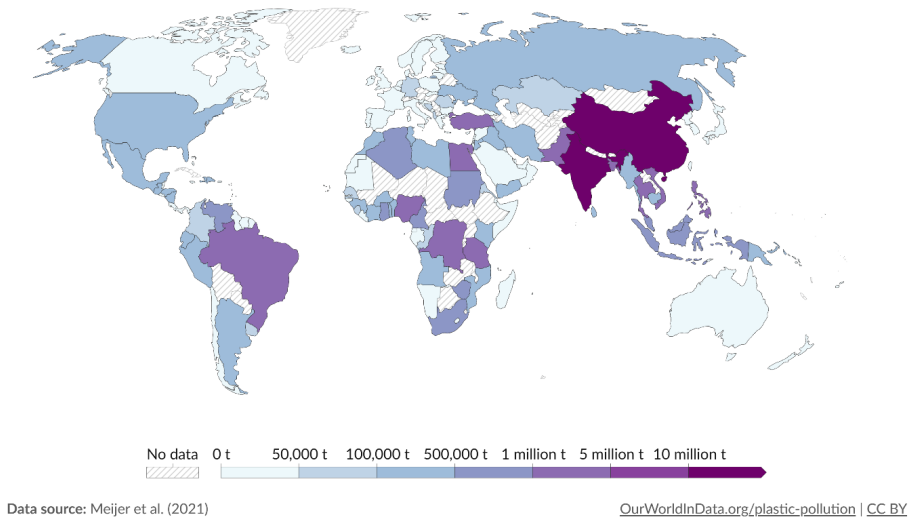

Figure 2.2 Mismanaged plastic waste in 2019 [2].

Although fewer MWPs were generated in the United States (approximately 267,569 tons), plastic waste comprises a significant portion of all Municipal Solid Waste (MSW) generated in the country. According to the American Chemistry Council, in 2018, over 35 million tons of WP were produced in the U.S., accounting for 12.2% of all MSW generated in that year. With a low recycling rate, only 8.7% of all plastic generated in the country was recycled, while 27 million tons of WP were discarded in landfills, totaling 75% in 2018 alone, which represented 18.5% of all MSW landfilled in that year [2,3].

Regarding the recycled plastics, they are categorized into seven types, as shown in Table 2.1. The recycling numbers are called a “resin identification code,” and their numbers, 1 to 7, differentiate the types of plastic it is made from. One of the potential applications identified is as

an HMA constituent material for the surface layer of asphalt pavements, with PET, HDPE, and LDPE being the most explored [29].

Table 2.1 Plastic Recycling Numbers and Identification Codes [22].

Recycling No.	Symbol	Abbreviation	Polymer Name	Uses Once Recycled
1		PETE or PET	Polyethylene terephthalate	Polyester fibers, thermoformed sheet, strapping and soft drink bottles.
2		HDPE	High-density polyethylene	Bottles, grocery bags, recycled bins, agriculture pipe, base cups, car stops, playground equipment and plastic lamber.
3		PVC or V	Polyvinyl chloride	Plastic, fencing and nonfood bottles.
4		LDPE	Low-density polyethylene	Plastic bags, six-pack rings, various containers, dispensing bottles, wash bottles, tubing and various molded laboratory equipment.
5		PP	Polypropylene	Auto parts, industrial fibers, food containers and dishware.
6		PS	Polystyrene	Desk accessories, cafeteria trays, toys, videocassettes and cases, and insulation board and other expanded polystyrene products (e.g., Styrofoam).
7		Other	Acrylic, butadiene styrene, fiberglass, nylon, polycarbonate, etc.	

2.2 Use of WP As an Alternative Paving Material

Recently, the world's population has placed a much larger focus on world climate, pollution, and ways to control the CO_2 excess through reducing, reusing, and recycling. The recycling of waste materials and reducing the carbon footprint of manufactured products through the conservation of energy and reduction in the use of raw materials has become a primary focus. The asphalt pavement industry has a long history of using recycled materials in asphalt mixtures to achieve engineering, economic, or environmental benefits [21]. Besides reclaimed asphalt

pavement (RAP) being recycled at a rate of approximately 94 percent, other recycled materials such as recycled asphalt shingles (RAS), recycled tire rubber (RTR), waste engine oils, steel slag, and recycled glass have been and will continue to be used in some markets or applications [30].

In late 2016, media reports began suggesting the use of recycled plastics in asphalt as an opportunity to improve the performance of asphalt pavements while eliminating the growing amount of waste plastics being landfilled or polluting the environment [21]. The plastics industry has been actively exploring new end market opportunities for the over 30 million tons of waste plastics generated every year [21,30]. One of the potential applications identified is asphalt pavements; however, the use of recycled plastics in asphalt can be challenging due to variations in composition and the presence of non-plastic contaminants. To ensure the quality of asphalt mixtures containing recycled plastics, requirements are needed to specify the key properties of these materials and how they should be used to improve the overall pavement life cycle benefits while protecting the environment [21].

WPs recommended for paving applications are mostly thermoplastic types. Their chemical structure allows them to melt when heated and solidify when cooled. Thermoplastics include polyethylene terephthalate (PET), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), acrylonitrile butadiene styrene (ABS), and polyethylene (PE). PE is further classified into high-density polyethylene (HDPE) and low-density polyethylene (LDPE) based on the differences in crystallinity and branching in their polymer chain, leading to differences in the material's density [31]. Regarding the use of WPs for HMA applications, PET, HDPE, LDPE, and PP are the most explored, with PP being the most generated WP in the U.S. Municipal Solid Waste (MSW), followed by PE [4,14].

Figure 2.3 Examples of waste thermoplastics [14].

WP can either be considered post-industrial or post-consumer waste. Post-industrial waste, also known as pre-consumer waste, is generated during the manufacturing phase of a plastic product and is usually cleaner and less contaminated. Post-consumer waste, which is generated by end-users, such as households, can present a higher risk of contamination, either by other types of plastics or elements, such as paper and cloth [32,33].

Considering the studies on plastic-modified mixes, Figure 2.4 illustrates the temporal evolution of publications on asphalt mixtures with WP, categorized by the incorporation method used. The numbers in the middle section of each bar represent the number of publications according to the procedure used. The dry procedure accounts for 36.13% of all publications, while the wet procedure accounts for 45.38%. The remaining publications were either a literature review on the use of WP in asphalt mixtures (10.08%), a methodology that tested both wet and dry methods (1.68%), a different type of incorporation method under the “other” category (i.e.,

semi-wet, WP dissolved in tall oil pitch before mixing with the binder, Pyrolysis wax WP added to the binder) (5.04%), and a methodology not specified by the author (1.68%).

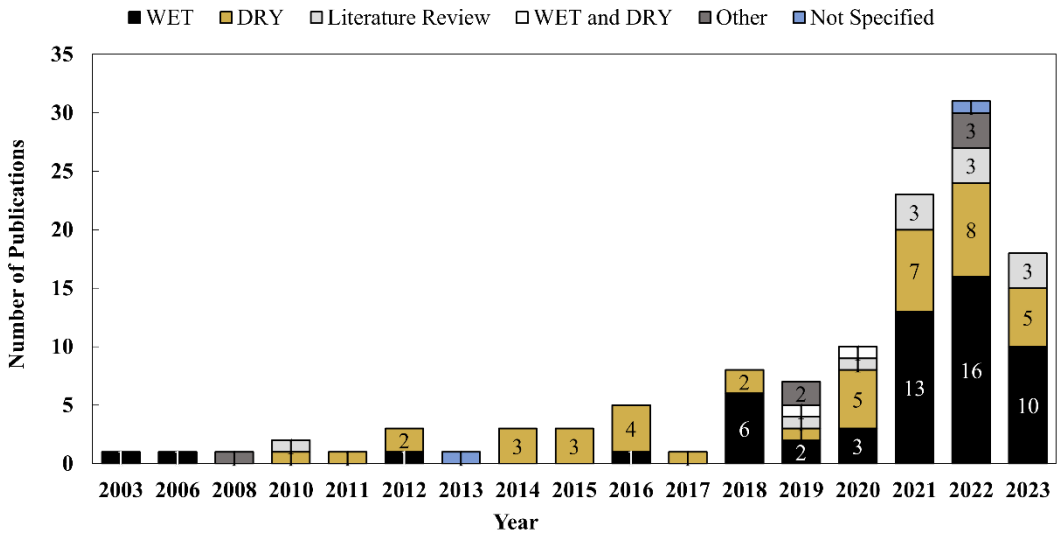

Figure 2.4 Number of publications over the years on the use of WP in asphalt mixtures based on the incorporation method.

As previously mentioned, WP use in HMA is a newer research topic, with the earliest publication being from 20 years ago. Many publications started in 2018, probably due to the unprecedented ban on waste importation imposed by China in 2017. China represented one of the major importers of solid waste globally, importing over 8 million tons of plastic annually. However, in 2017, China decided to mitigate the situation by banning its imports, which culminated in a sharp decline in global plastic waste trade flow, resulting in changes in the treatment structure of many countries and enormous impacts on global environmental sustainability [34]. With the ban, countries and regions that exported their waste to China needed new ways to manage it. Given that the paving application is an alternative solution, this could explain the increased scientific research on this topic. The highest publication numbers are from

2020 to 2023 (60.50% of all the reviewed papers), which could be correlated to the increase in plastic production during COVID-19. With higher amounts of mismanaged WP, new alternatives are needed to treat the WP. Additionally, similar trends were observed in the report conducted by NCAT [4] in 2021. The report showed that the largest number of documents was released from 2017 to 2021 and that the wet process was the most researched incorporation method.

Figure 2.5 shows the number of publications considering each type of WP and incorporation method. Considering the types of plastics most explored in paving applications (HDPE, LDPE, PET, and PP), the dry procedure was the most used incorporation method, except for PP.

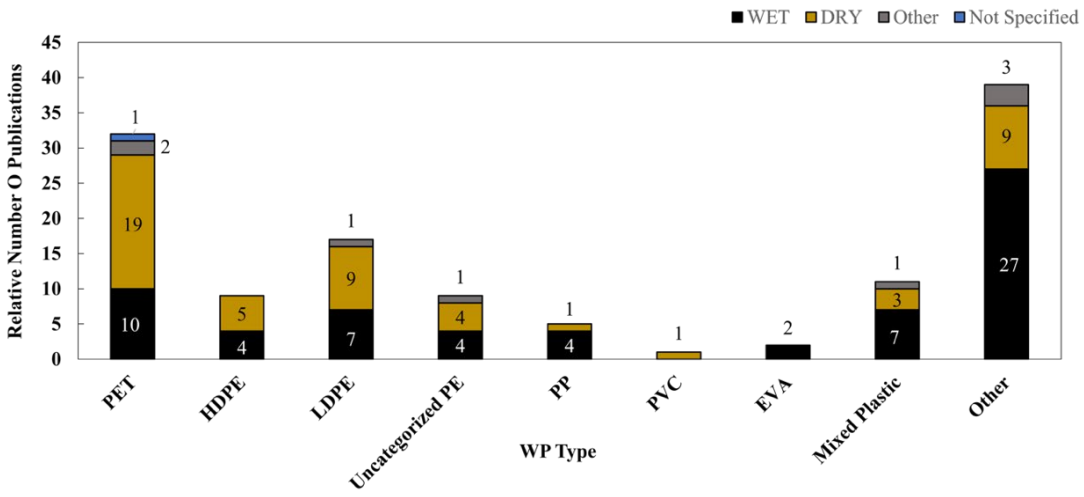

Figure 2.5 Total number of journal article publications considering each type of WP.

2.3 WP Properties and Their Effects on Plastic Modified Asphalt Mixture Performance

For proper incorporation of the WPs into the HMA, many properties of WPs must be considered. Specific gravity, for example, is related to compatibility/incompatibility between WP and both the binder and aggregates, affecting the mixture's volumetric parameters and the

interaction among the mixture's components. When plastic is added through the wet method, the difference between the specific gravity of the WP and the asphalt binder can directly affect the microstructure and compatibility of the materials, leading to poor storage stability and phase separation. When incorporated through the dry methodology, the WP can affect the mixtures' volumetric parameters due to the large difference in specific gravity between them and the aggregates [4,8].

The melting point of WPs also plays an important role in the procedure selection. Plastics with higher melting points (i.e., above 160 °C), such as PET and PP, are generally used in the dry process. That is because the melting point is usually higher than the binder's mixing temperature, which makes it hard for the WP to be blended with the binder if added through the wet process [4].

Another crucial property is the particle size and shape of WPs. Plastic can be added to HMA in many shapes with varied sizes, such as powder (0.035–0.25 mm) [35,36], pellets (5–10 mm) [37], fibers (6.5–30 mm) [38–40], flakes (0.63–10 mm) [41–44], or granules (0.3–0.6 mm) [45,46]. WPs can also go through some processes for size reduction, such as shredding, grinding, crushing, and cutting [8,47–49]. Smaller particle sizes lead to more homogenous blends in both wet and dry methods. Powdered WP is the best option for the wet method because it provides a larger surface area per unit mass of plastic, facilitating the melting of the WP [15].

The dry process accepts bigger sizes of WPs than the wet method, and different shapes can be used. Nonetheless, the smaller the particle size, the better the distribution of aggregates and the binder during the mixing process [4]. Movilla-Quesada et al. [11] even suggest that to

achieve better coating of aggregates with WP and better performance in the presence of water, the ideal particle size in the dry method should be smaller than 2 mm.

As mentioned, the WPs can be added to the HMA in either dry (i.e. WP added to the aggregates) or wet (i.e. WP added to the asphalt binder) approaches. The wet procedure can become more expensive since it often requires either pre-processing WPs to produce small particle sizes or the incorporation of agitation systems inside the asphalt plants' binder tanks to reduce the separation tendency between the binder and the WP [4,50]. Concerning the number of WPs re-used or post-secondary effects, the dry procedure can lead to a larger incorporation of WPs into the HMA, representing a more convenient alternative. However, the lack of normative guidance following the wet method needs to be addressed [27].

2.4 Studies of WP Incorporation via Dry Method

The comprehensive evaluation regarding the effects of the incorporation of WP into the HMA following the dry approach helps identify the effects of size, shape, and percentage of WP in different mixing procedures. Since there is no standard procedure, different addition methods may have different impacts on WP behavior in HMA. This session focused on the effects of each type of WP studied.

2.4.1 Polyethylene Terephthalate (PET)

PET is a polyester thermoplastic resin, used mainly for beverage bottles. It is a result of the polymerization between ethylene glycol and terephthalic acid, with a chemical composition of $C_{10}H_8O_4$. Its chemical structure can be semi-crystalline, amorphous, or a mixture of both. As mentioned, the melting point of PET (around 250 °C) is higher than most binders' mixing temperatures. Utilizing it through the wet procedure could cause excessive binder oxidation, compromising the mixture. Therefore, most papers consider its use following the dry method (as

shown in Figure 2.5) [51–53]. Table 2.2 presents the PET characteristics and procedures adopted by different authors through the dry approach.

Table 2.2 Different shapes, sizes, percentages, and approaches for dry incorporation of PET in asphalt mixtures.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Moghaddam et al., [41]	1	<2.36	Flakes	0.1–1% (+0.1%), by weight of aggregates	Step 1. Pre-heated aggregates at 160 °C were mixed with a pre-heated binder at 130 °C. Step 2. WP was then added to the mixture.
Moghaddam et al., [42]				0.5% and 1%, by weight of aggregate	Step 1. Pre-heated aggregates at 160 °C were mixed with a pre-heated binder at 130 °C. Step 2. WP was then added to the mixture.
Moghaddam et al., [43]				0.2–1% (+0.2%), by weight of aggregate	Step 1. Pre-heated aggregates at 160 °C were mixed with a pre-heated binder at 160 °C. Step 2. WP was then added to the mixture.
Moghaddam et al., [49]			Crushed	0.2–1% (+0.2%), by weight of aggregates	Step 1. Pre-heated aggregates at 160 °C were mixed with a pre-heated binder at 130 °C. Step 2. WP was then added to the mixture.
Moghaddam et al., [54]				0.5% and 1%, by weight of aggregates	Step 1. Pre-heated aggregates at 160 °C were mixed with pre-heated binder at 160 °C. Step 2. Pre-heated WP was then added to the mixture.
Ferreira et al., [55]			Micro PET	2% and 4% (by weight of sand) and 8% (by weight and volume of sand)	N.S.
Herraiz et al., [56]	1		N.S.	0.5–2% (+0.5%) and 4% by weight of aggregate	N.S.
Ziari, et al., [47]		>12.5	Cut	0.25–1% (+0.5%), by weight of aggregate	Step 1. Pre-heated aggregates at 180 °C were mixed with a pre-heated binder at 150 °C. Step 2. WP was then added to the mixture.
Esfandabad et al., [57]		N.S.	Granules	30, 50, 70, and 100% (replacing by volume pass. #4 and retained #8 aggregate)	N.S.
Xiao et al., [58]			Powdered	3.22%, 3.28%, and 2.89% by weight of aggregate	Step 1. Sprayed over the wet aggregates (0.5% of water). Step 2. The mixture was heated at 270 °C to melt the WP.
Mabui et al., [59]			N.S.	0.5–2.5% (+0.5), by total weight of aggregate	N.S.
Modarres and Hamedi, [60]	2	<2.36	Crushed	2–10% (+2%), by the weight of binder	The binder and aggregates were mixed before adding the WP.
Taherkhani, and Arshadi, [61]				2–10% (+2%), by the weight of binder	Step 1. Pre-heated aggregates at 200 °C were mixed with a pre-heated binder at 150 °C. Step 2. WP was then added to the mixture.
Ahmadinia et al., [62]			N.S.	2–10% (+2%), by the weight of binder	Step 1. Pre-heated aggregates at 200 °C were mixed with a pre-heated binder at 150 °C. Step 2. WP was then added to the mixture.
Ahmadinia et al., [10]					Added to pre-heated aggregates at 200 °C.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Modarres and Hamedi, [63]				2–10% (+2%), by the weight of binder	N.S.
El-Naga and Ragab, [64]		N.S.	Crushed	10–15% (+1%) by the weight of binder	Step 1. Melted WP at 300 °C. Step 2. Melted WP was added to pre-heated aggregates at 250 °C. Step 3. Then, the pre-heated binder at 140 °C was added to the mixture.
Movilla-Quesada et al., [44]	3	<2.36	Flakes	6–22% (+4%) by weight of the binder	N.S.
Abdo et al., [38]		>12.5	Fibers	0.5% and 1% by weight of the mixture	WP was added to aggregates before mixing with the binder.

Notes: N.S. = not specified; 1 = aggregate replacement; 2 = partial substitution for bitumen; 3 = additive

As noted, many different procedures were used, differentiated mainly by the order in which the materials were added to the mixture and the temperatures used. Additionally, the authors utilized different PET sizes, shapes, and percentages. To simplify, the use of PET can be divided into three categories as follows:

(a) Shape and Size:

For most authors, PET sizes were smaller than 2.36 mm, showing improvements in the fatigue life [41–43,49,54] and rutting resistance [10,62]. However, when used as flakes, there can be negative impacts on the indirect tensile strength, Marshall coefficient, and air voids, increasing the permanent deformation of the mixture [41–44]. For coarser PET (>12.5 mm), Ziari et al. [47] noticed no significant improvements in mixture performance, as it was only able to increase flow number and reduce rut depth by 1 cm in comparison with the control mixture. Taherkhani and Arshadi [55] also stated that crushed coarse PET decreased rutting resistance and flow number.

When using PET as fibers, Abdo et al. [38] noticed that larger PET fibers became stiffer during the mixing process, and after compaction, they started to stick out of the samples. However, the PET addition enhanced both cracking and rutting resistances at high temperatures by increasing

the indirect tensile strength and flow number. However, the WP led to sudden failure at low temperatures, which was evaluated by a BMD-recommended test (semi-circular bending test). Finally, PET in a powdered form improved the moisture damage resistance. When melted and coating the aggregates, it can increase the non-polar components of the asphalt mixture and improve the binder-aggregate adhesion [58].

(b) WP percentage:

Lower percentages of PET (from 0.1 to 0.2% of aggregates) seem to be the optimum content to enhance the mixture's properties, while higher PET content could decrease the tensile strength and Marshal quotient [41–43,49,54]. For hot regions, this value could be increased up to 1% by the weight of aggregates [38]. When adding PET by weight of the binder, higher contents could be used to enhance the tensile strength and resilient modulus on the HMA, varying from 2 to 12% [10,61,64].

(c) Mixing Procedure:

Different mixing procedures were adopted when PET was added to the HMA via the dry method. The most utilized procedure consisted of adding PET to the "pre-heated mixture" (WP added after blending pre-heated binder and aggregates) at temperatures ranging from 130 to 200ºC [41–43,47,49,54,61,62]. However, Moghaddam et al. [49] stated that the mixing of aggregates with PET would cause the aggregate surface to be coated by the molten part of PET (PET would melt partially), which could eventually contribute to less adherence between aggregate particles and the asphalt cement. Additionally, Taherkhani and Arshadi [61] concluded that the mixing procedure caused the amorphous part of PET to melt while the crystalline part remained intact. Therefore, having partially melted and partially solid PET over the aggregates decreased binder–aggregate adhesion, reducing the mixture's resistance.

Ahmadinia et al. [10] added PET to pre-heated aggregates at a temperature below its melting point so that the WP would not melt. In this case, having solid PET (as another aggregate in the mixture) did not improve moisture damage resistance.

Some authors added PET to non-preheated aggregates before mixing with the binder. In this case, the performance of the mix was directly related to the PET percentage and shape. For fiber and powered PET (low percentages), there was an increase in the cracking and rutting [38] and moisture damage resistance [58]. Additionally, Xiao et al. [58] concluded that after adding the WP to wet aggregates and heating the aggregate-PET blend, the WP was melted over the aggregate surface (plastic coating), improving the resistance against moisture damage. When compared to other types of WPs (PE, PP, and PVC), PET showed the least effective coating, which could be related to the WP not melting completely due to its high melting point.

Finally, other procedures were adopted, such as melting the PET before mixing with the aggregates. El-Naga and Ragab [61] concluded that the procedure produced plastic-coated aggregates, resulting in higher stiffness, indirect tensile strength, and rutting resistance.

2.4.2 High-Density Polyethylene (HDPE)

HDPE is a type of thermoplastic plastometer that can be used in paving applications to reduce permanent deformation and increase the rigidity of the mixture. It is produced from ethylene, which has a chemical formula of $(C_2H_4)_n$ and high crystallinity (around 80– 90%) [5]. HDPE can be found in plastic cups, milk and shampoo bottles, and pipes. Because of its low melting point, between 130 °C and 149 °C, it can be used as a binder [15,65]. However, as shown in Figure 2.5, there are more publications regarding the dry procedure than the wet method. Table 2.3 presents the HDPE characteristics and procedures adopted by different authors through the dry approach.

Table 2.3 Different shapes, sizes, percentages, and approaches for dry incorporation of HDPE in asphalt mixtures.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Xiao et al., [36]	1	<2.36	Powder	0.4–1.2% (+0.4%) (for 35 μm) and 0.5–2% (+0.5%) for 75 μm) by weight of aggregates	WP + ethanol solution (fluidized bed) sprayed over pre-heated aggregates at 180–190 °C, resulting in plastic-coated aggregates.
Xiao et al., [58]		N.S.	Powder	2.34, 2.29, and 2.01% by weight of aggregates	Step 1. WP was sprayed over wet aggregates (0.5% of water). Step 2. The mixture was heated at 180 °C to melt the WP.
Xiao et al., [66]				0.5–2% (+0.5%) by weight of aggregates	A WP + ethanol solution (fluidized bed) was sprayed over pre-heated aggregates at 180–190 °C, resulting in plastic-coated aggregates.
Ullah et al., [7]			N.S.	5, 15, and 25% by weight of aggregates	N.S.
Haider et al., [16]	2	N.S.	N.S.	9% by weight of the binder	Added to aggregates before mixing with the binder.

Notes: N.S. = not specified; 1 = aggregate replacement; 2 = partial substitution for bitumen

Similarly to PET, different mixing procedures were used (including different sizes, percentages, and shapes). To simplify, the use of HDPE can be divided into three categories as follows:

(a) Shape and Size:

Xiao et al. [36] verified that HDPE in powder form and with smaller particle sizes (<2.36 mm) are more efficient in the plastic-coating process, showing greater improvements in moisture damage resistance.

(b) WP percentage:

For HDPE, there was greater variability regarding the optimum percentage. For HDPE in powder form [36,58,66], the WP content varied from 0.5 to 2.5% by weight of aggregates. In another case, Ullah [7] suggested that 15% HDPE by weight of the aggregates was the optimum content to improve HMA's Marshall stability, flow, and dynamic modulus values. Finally, when added by weight of the binder, 9% of HDPE could improve the mixture's rutting resistance and reduce its stability loss [16].

(c) Mixing Procedure:

Different mixing procedures were employed to incorporate HDPE into the HMA. Haider et al. [16] added the WP to non-preheated aggregates, noticing a decrease in binder-aggregate adhesion compared to adding HDPE via the wet method. Nonetheless, it was able to improve rutting resistance and stability. Similar to PET, Xiao et al. [58] obtained plastic-coating after melting the WP over the aggregate surface, showing improved wettability, moisture damage resistance, and energy ratio, reducing the debonding tendency. HDPE-coating presented better results than PET.

As an alternative method for powdered WP, Xiao et al. [36,66] sprayed powdered HDPE over pre-heated aggregates at 180ºC using a fluidized bed (ethanol solution). The pre-heating temperature was higher than the WP's melting point to ensure that the HDPE would melt and coat the aggregates. With that, the WP improved moisture damage resistance by increasing binder-aggregate adhesion.

2.4.3 Low-Density Polyethylene (LDPE)

Similar to HDPE, LDPE is also a type of thermoplastic plastometer that can be used in paving applications to reduce permanent deformation and increase the rigidity of the mixture. It has the same chemical composition as HDPE but with longer, linear, and flexible ethylene chains, presenting lower crystallinity (around 55–65%) [5] LDPE can be found in packaging films and plastic bags. LDPE has the lowest melting point out of the most used WPs in asphalt mixtures (between 110 °C and 120 °C), which indicates a huge potential for binder modification. Lower melting points require lower mixing speed, making the process more economical [15,65]. Still, more research has been conducted on the use of LDPE through the dry method, as shown in Figure 2.5, suggesting a necessity to comprehend the different procedures adopted. Table 2.4

presents the LDPE characteristics and procedures adopted by different authors through the dry approach.

Table 2.4 Different shapes, sizes, percentages, and approaches for dry incorporation of LDPE in asphalt mixtures.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Xiao et al., [36]	1	<2.36	Powder	0.4–1.2% (+0.4%) (for 35 μm) and 0.5–2% (+0.5) (for 75 μm) by weight of aggregates	A WP + ethanol solution (fluidized bed) was sprayed over pre-heated aggregates at 180–190 °C.
Xiao et al., [58]		N.S.	Powder	2.17, 2.21, and 1.95% by weight of aggregates	Step 1. WP was sprayed over the wet aggregates (0.5% of water). Step 2. The mixture was heated at 160 °C to melt the WP.
Xiao et al., [66]				0.5–2% (+0.5%) by weight of aggregates	A WP + ethanol solution (fluidized bed) was sprayed over pre-heated aggregates at 180–190 °C.
Radeef et al., [8]		4.75–12.5	Shredded	1.0% by weight of aggregates	Step 1. Added to pre-heated coarse aggregates at 180 °C. Step 2. A small amount of binder was mixed with coarse-coated aggregates before adding fine aggregates and the remaining binder.
Ullah et al., [7]		N.S.	N.S.	5–25% (+10%) by weight of aggregates	N.S.
Assefa [67]		2.36–4.75	Shredded	6–18% (+3%) by the weight of OBC	Added to pre-heated aggregates at 165 °C.
Almeida et al., [17]	2	N.S.	Flakes	2–8% (+2%) by weight of binder	N.S.
Almeida et al., [68]				6.0% by weight of the binder	N.S.
Haider et al., [16]			N.S.	9% by weight of the binder	Added to aggregates before mixing with the binder.

Notes: N.S. = not specified; 1 = aggregate replacement; 2 = partial substitution for bitumen

Similar to PET and HDPE, different shapes, sizes, percentages, and mixing procedures were used. To simplify, the use of LDPE can be divided into three categories as follows:

(a) Shape and Size:

Same as for HDPE, Xiao et al. [36] verified that powdered and fine (<2.36 mm) LDPE is more efficient in the plastic-coating process, showing greater improvements in moisture damage resistance. For coarse LDPE (from 4.75 – 12.5mm), the WP-modified mixes presented higher

stability but reduced stiffness [9]. In some cases, LDPE as flakes could reduce moisture damage resistance, flow, and indirect tensile strength [17,68].

(b) WP percentage:

The WP percentage depended on the adopted procedure, shape, and size. For powdered LDPE, the percentages ranged from 0.5% to 2.2% by weight of aggregates [36,58,66], while for other cases, the optimum content was around 15% by weight of aggregates to improve stiffness values [7].. When added by weight of the binder, 6% of LDPE could improve the mixture's fatigue and rutting resistance [17].

(c) Mixing Procedure:

Different mixing procedures were used for incorporating LDPE into the HMA. Radeef et al. [9] added the WP to pre-heated coarse aggregates, producing plastic-coated coarse aggregates. The final mixture was less susceptible to moisture damage and showed improved resilient modulus, creep stiffness, and rutting resistance (evaluated using the Hamburg-Wheel Tracking Test). After long-term aging, the mixture showed even higher resistance to permanent deformation. When LDPE was added to pre-heated aggregates (coarse and fine), the plastic-coated aggregates increased Marshall stability, flow, stiffness, and moisture damage resistance [67].

When added to non-preheated aggregates, there was higher binder coating loss compared to the wet method. Nonetheless, the WP was able to improve rutting resistance and stability, the same as for HDPE [16]. Finally, when melted over the aggregate surface (plastic-coated aggregates), the LDPE addition improved wettability and moisture damage resistance, while presenting the best coating efficiency among all tested WPs (HDPE, PP, PET, and PVC) [58].

2.4.4 Polypropylene (PP)

PP is a semi-crystalline (around 40–60%) vinyl thermoplastic plastometer derived from propylene with the chemical formula of $(C_3H_6)_n$. It is commonly used for food packaging, microwave-safe containers, and pipes. It presents a higher melting point than HDPE and LDPE (around 160°). Studies on PP as a binder modifier reported mixing temperatures up to 190 °C, which could cause premature aging of the binder [65,69]. Therefore, even though Figure 2.5 reports that 75% of all the reviewed publications utilized PP following the wet approach, the dry method might be used more often. Only one study in the used database (Web of Science) attempted to use PP in HMA. Table 2.5 presents the WP characteristics and mixing procedures followed in this study.

Table 2.5 Different shapes, sizes, percentages, and approaches for dry incorporation of PP in asphalt mixtures.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Xiao et al., [58]	1	N.S.	Powder	2.11, 2.15, and 1.90% by weight of aggregates	Step 1. WP was sprayed over the wet aggregates (0.5% of water). Step 2. The mixture was heated at 190 °C to melt the WP.

Notes: N.S. = not specified; 1 = aggregate replacement

Xiao et al. [58] added around 2% of powder PP to wet aggregates before heating the blend to produce plastic-coated aggregates. The plastic coating increased the polar components of the aggregate surface, increasing the dry adhesion energy between asphalt and aggregate, improving wettability, moisture damage resistance, and the energy ratio, and reducing debonding tendency.

2.4.5 Polyvinyl Chloride (PVC)

Polyvinyl chloride is a thermoplastic with long repeating chains of vinyl chloride, with both amorphous and crystalline phases, and a chemical formula of $(C_2H_3Cl)_n$ [70]. This WP needs special attention when utilized in paving applications. Since it has a high melting point, which varies from 150 °C to 298 °C, heating the WP at such elevated temperatures could produce harmful chlorine-based dioxide emissions because of the vinyl chloride present in its composition [4]. Therefore, PVC is not indicated for use in HMAs, which could also explain the lack of publications on the topic. Only Xiao et al. [58] evaluated its use, as shown in Table 2.6.

Table 2.6 Different shapes, sizes, percentages, and approaches for dry incorporation of PVC in asphalt mixtures.

Reference	Addition Method	WP Size (mm)	WP Shape	%WP	Mixing Procedure
Xiao et al., [58]	1	N.S.	Powder	3.23, 3.30, and 2.91% by weight of aggregates	Step 1. WP was sprayed over the wet aggregates (0.5% of water). Step 2. The mixture was heated at 190 °C to melt the WP.

Notes: N.S. = not specified; 1 = aggregate replacement

Xiao et al. [58] used the same procedure as for the other WPs (PET, HDPE, LDPE, and PP), which consisted of spraying powdered WP (around 3% by weight of aggregates) over aggregates (non-pre-heated) and melting the WP over the aggregate surface. The same improvements were observed for PVC, including enhanced wettability, moisture damage resistance, energy ratio, and reduced debonding tendency. However, PVC was the least effective coating, similar to PET.

2.4.6 Summary of the Procedures Used to Add WP in the Dry Methods

To optimize the use of WPs in asphalt mixtures, it is crucial to determine the best mixing approach for each type of plastic. The summary of the mixing procedures adopted for each type

of plastic (following the dry method) is shown in Figure 2.6. The two most used procedures were adding WP to pre-heated mixture (utilized strictly for PET) or adding WP to non-pre-heated aggregates. Due to its high melting point, adding PET to a pre-heated mixture (or even aggregates) would cause the aggregate surface to be coated by partially molten PET, which could reduce the adhesion within the mixture's components [42]. Furthermore, the negative results found in the studies indicate that this procedure was not the most effective in improving the performance of mixtures with PET addition.

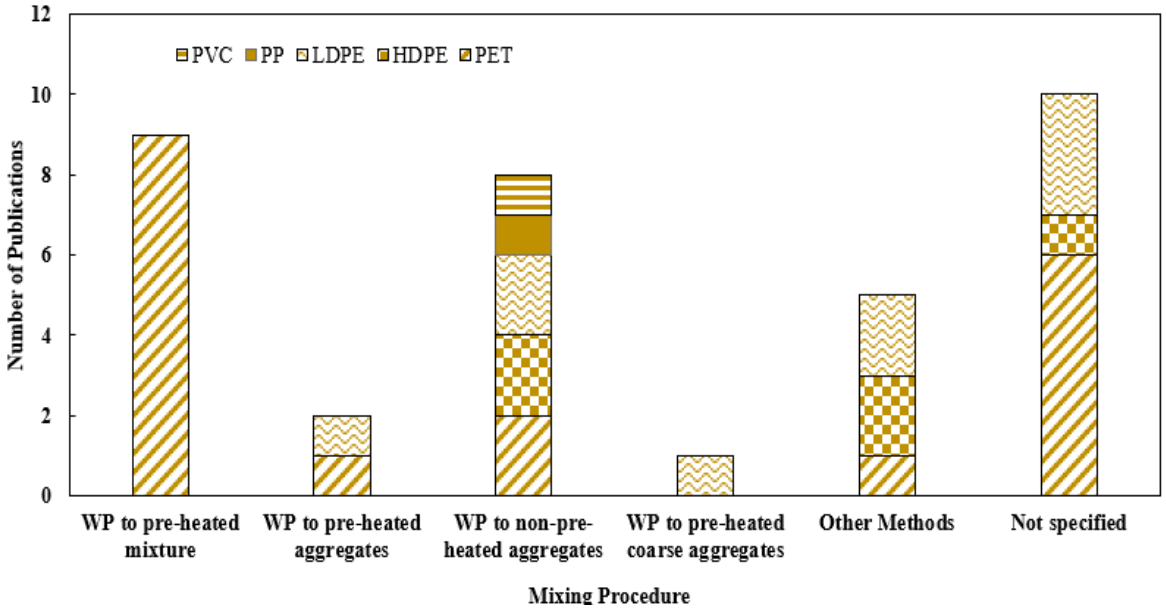

Figure 2.6 Summary of all adopted mixing procedures according to each type of WP.

For HDPE and LDPE, the most common procedures were either adding powdered WP, using a fluidized bed, to pre-heated aggregates at a temperature higher than the WP's melting point to produce plastic-coated aggregates (under *other methods*), or adding the WP to non-pre-heated aggregates before placing the blend into the oven, melting the WP, and allowing it to coat

the aggregates. For PVC and PP, the mixing procedure consisted of melting the WP over non-pre-heated aggregates, resulting in a WP coating.

The most adopted procedures targeted the production of plastic-coated aggregates by either adding WP to pre-heated aggregates to pre-heated coarse aggregates, melting WP before adding to the aggregates, or melting WP over the aggregates (both aggregates and WP were put in an oven set to a temperature higher than the plastic's melting point). Coating the aggregates with WP improved many parameters, especially moisture damage resistance. Those procedures can be more challenging for PET because of its high melting point, but El-Naga and Ragab [64] and Xiao et al. [58] managed to produce PET-coated aggregates with satisfactory results.

The type of WP and, consequently, their physical-chemical characteristics, require different incorporation methods. For example, higher degrees of orientation in the WP chemical structure result in higher glass transition temperatures (going from brittle to viscous behavior), service temperatures (the maximum temperature at which the WP can be exposed for a long period with no significant consequences), and melting points [51]. As previously mentioned, melting points higher than the binder's mixing temperature are not recommended for the wet procedure, which is the case with PP and PET. For mixed plastic, the performance of the mixture can be compromised by the difference between melting points, which can result in some plastics not melting, while others reach their decomposition temperature [5]. Finally, the chemical composition can influence the WP crystallinity levels, which can affect the interaction between the WP and the binder. Although HDPE has a low melting point (below the binder's mixing temperature), it shows high crystallinity (over 80%), compromising its ability to be immersed into the binder, which makes it appropriate for use in the dry process [8].

2.5 Summary of Literature Review

The literature review demonstrated that the "use of WP in asphalt pavements" is a recent research topic, with 60.5% of all the reviewed papers published from 2020 to 2023, possibly correlating with the increase in plastic generation during the COVID-19 pandemic. There is a clear need for alternatives to waste management.

According to the literature review, key conclusions were as follows:

- Particle Size: Smaller particle sizes (<2.36 mm) seemed to enhance the mixtures' properties at a higher rate than larger particles. This could be related to their potential for better distribution in the HMA, presenting better mixture homogeneity. Smaller particles also appeared to be more effective in the aggregate-coating process, which represented the best alternative to enhance the mixture's performance, especially moisture damage resistance

- WP Percentage: Lower WP percentages best enhanced the mixture's properties. The optimum percentages (by weight of aggregates) ranged from 0.1 to 0.2% for PET, 0.5 to 2.5% for PE, and 2% for PP.

- Type of WP: The performance of PET-modified mixes is strictly related to pre-heating and mixing temperatures. Adding PET to pre-heated aggregates at relatively low temperatures (lower than its melting point) would cause the WP to melt partially. In this case, having partially molten and partially solid PET can compromise the binder-aggregate adhesion and decrease the mixture's performance. It is worth noting that PET can present the least effective coating alongside PVC, mainly due to its high melting point. The use of PE (HDPE or LDPE) can improve the mixture's performance independently of the procedure used. However, coating aggregates with melted PE represents an adequate procedure to enhance moisture damage resistance. Because of its low melting point, PE can provide a more effective coating than PET and PVC. Powder PP can also effectively enhance the HMA's performance but with less coating efficiency than PE. Finally, PVC should not be used in paving applications due to the emission of toxic gases when heated at high temperatures.

- Procedure: Employing a method that results in plastic-coated aggregates appeared to be the most beneficial for improving asphalt mixture performance. Various approaches were observed, including adding WP to pre-heated aggregates and pre-heated coarse aggregates, melting WP before aggregate inclusion, and melting the WP over the aggregate surface. This method proved to be effective across all types of WP, enhancing rutting and moisture resistance by improving the binder-aggregate adhesion. For this approach, it is crucial to determine the effects of the pre-heating temperature of the aggregates on the plastic coating and the overall mixture's performance.

Finally, the utilization of WPs displays a way to enhance the asphalt mixture performance, potentially providing an alternative strategy for plastic waste management. However, 92% of the papers analyzed during the literature review focused on checking volumetric parameters instead of performance criteria. To further validate the results, it is crucial to evaluate critical pavement distress such as moisture damage, rutting, and cracking, using performance tests recommended by the BMD protocol.

Chapter 3 Materials, Test Methods, and Field Implementation

This chapter details the materials, testing methods, and performance evaluation procedures adopted in this research. Furthermore, it presents details from the large-scale field construction using plastic-modified Nebraska SPR mixtures. To accomplish the goals of this research, this study was divided into four major steps (highlighted in blue in Figure 3.1).

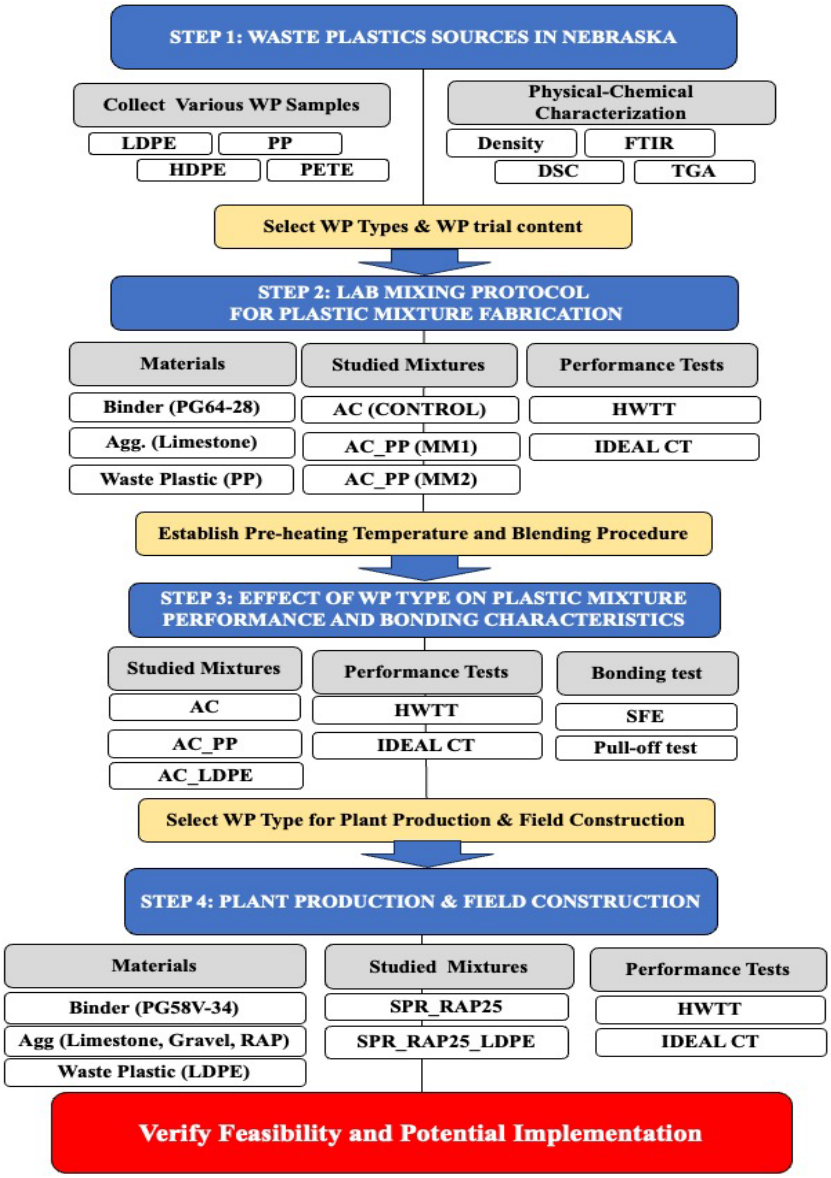

Figure 3.1 Experimental plan adopted in this study.

3.1 Materials

3.1.1 Waste Plastics

All WP samples were obtained from First Star recycling facility, located in Omaha, Nebraska. For Steps 1-3, post-industrial WP samples were selected to have a clear WP characterization and verify the effect of individual type of WP on HMA performance, without having contamination or mixed plastics, which are typically found on post-consumer WPs.

In total, 2 kg (4.4 lbs.) of four different post-industrial WP samples—PET, HDPE, LDPE, and PP—were collected in various shapes depending on their availability. For instance, PET, HDPE, and LDPE were processed in the recycling facility through a mechanical crushing process having a final shredded shape, while PP was available in pellets as originally received by the recycling facility. The samples were clear and homogeneous, with consistent sizes ranging from 2 to 5 mm (0.08 to 0.2 in). The small size range was chosen to have a better dispersal of the polymer inside the HMA, increasing its likelihood to adhere to the aggregates and to disperse homogeneously [11,72]. Figure 3.2 presents all the collected WP samples.

Figure 3.2 WP samples used in this study (from left to right): PET, HDPE, LDPE, PP.

For Task 4 (plant production and field construction), part of the WP used was post consumers LDPE obtained from Goodwill recycling program in South Sioux City. The material was further processed in the recycling facility, i.e., shredded randomly in sizes ranging from 1 to 15 cm, as show in Figure 3.3. Additional shredded LDPE WP samples were supplied by the recycling facility to supplement the required amount for field construction.

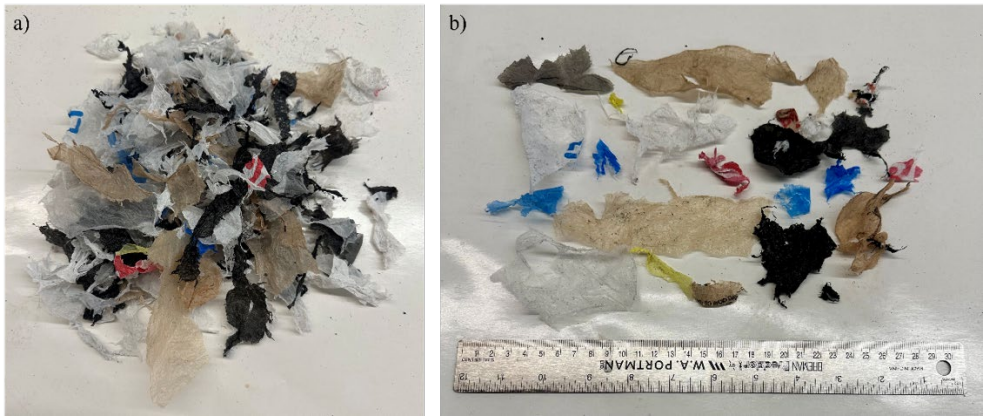

Figure 3.3 Post-Consumer LDPE: a) sample; b) Size range.

All WP samples went through a fingerprint identification using Fourier Transform Infrared Spectroscopy (FTIR) analysis to verify the authenticity of each plastic type. Furthermore, the melting point and thermal degradation of the materials were also assessed based on Differential Scanning Calorimetry (DSC) and thermogravimetric analysis (TGA) tests, respectively.

3.1.2 Binders

For Tasks 1-3, the virgin binder was a PG 64-28 (less modified binder) supplied by Flint Hills Resources, with characterization conducted by Bastola [23] and Ahmad et al. [71].

The asphalt binder utilized in Task 4 was a PG 58H-34 supplied by Jebro with 0.7% Cargill 1501 additive and modified with Elvaloy reactive polymer. The mixing and compaction temperatures provided by the supplier are shown in Table 3.1.

Table 3.1 Asphalt binders used in this study.

Tasks	Performance Grade	Mixing Temperature	Compaction Temperature
1-3	PG 64-28	156°C (313°F)	143°C (290°F)
4	PG58H-34	149°C (300°F)	135°C (275°F)

3.1.3 Aggregates

Commonly used Nebraska aggregates were used to produce the studied mixtures. They consisted of limestone, 47B (gravel), and RAP. The final combined aggregate gradation was designed to meet the NDOT SPR gradation specification.

For Tasks 1-3, to focus on the effect of WP on mixture performance and minimize the variability induced by different sources of aggregates—especially RAP aggregates—only limestone aggregates were used. For Task 4, an NDOT approved SPR mixture containing 75% natural aggregates (quartz and sand) and 25% of RAP was used. The aggregate particle size distributions and the minimum and maximum control points set by NDOT and Superpave (represented in the graph as “SP”) are shown Figure 3.4.

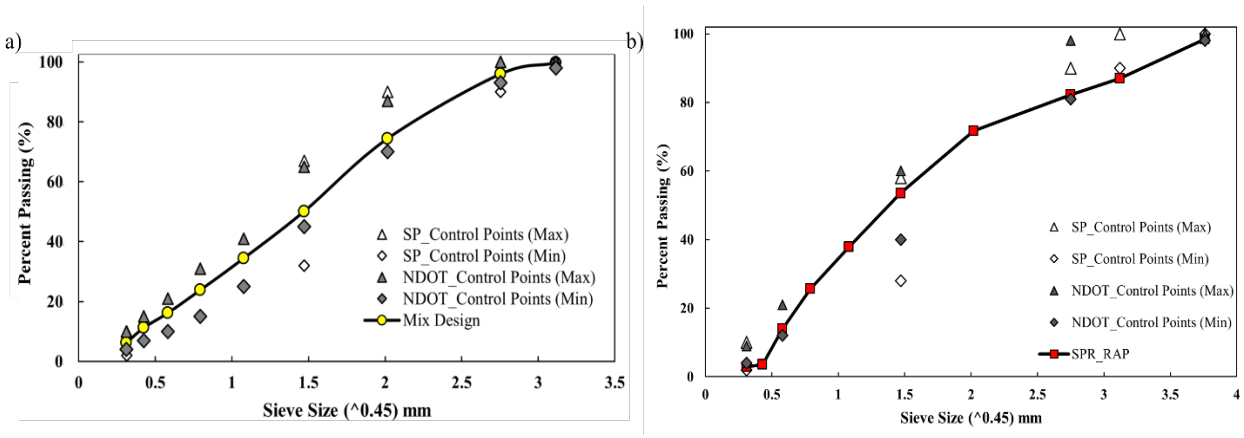

Figure 3.4 Selected aggregate gradation: (a) Tasks 1-3; (b) Task 4.

3.2 Studied Mixtures and Mixing Methods

3.2.1 Determination of Lab Mixing Protocol for Plastic Mixtures

To determine the mixing procedure, polypropylene (PP) WP was initially selected. PP is one of the most globally manufactured plastics and is a major source of plastic waste, particularly from packaging, food containers, and various consumer products. Also, PP was initially selected due to its melting point being the closest to conventional asphalt mixing temperatures.

First, a volumetric mix design was performed for the control mixture without WP (hereafter AC). The AC optimum binder content (OBC) was established based on volumetric analysis, according to the SP Mix Design procedure. An OBC of 5% was determined, targeting 4±1% air voids. The same binder content was utilized for plastic-modified mixtures.

For the mixtures with added PP, 1% WP was added to pre-heated aggregates considering two different pre-heating temperatures. The percentage of WP addition was determined based on the literature review [27]. Thus, a preliminary analysis was made to verify the influence of the pre-heating temperature on the PP particles and aggregate coating, and overall mixture performance. Two mixing methods (MM) were proposed for this analysis:

- MM1: Coarse aggregates were pre-heated at the mixing temperature (156°C or 313°F) for one hour, and then PP WP was added.
- MM2: Coarse aggregates were pre-heated at a temperature of 40°C higher than the PP WP melting point (194°C or 381°F) for one hour, and then PP WP was added. An increment of 40 °C was recommended in the literature to allow the complete melting of the WP. Previous studies have reported that the coating mechanism is only possible when aggregates are pre-heated to a temperature 30–70 ºC above the melting point [55,66,67].

For all mixtures, the binder was heated at 156°C (313°F). The main difference among the mixing procedures studied herein was related to the process of pre-heating the aggregates. For AC, the aggregates (coarse and fine) and binder were pre-heated in the oven until they reached the binder's mixing temperature (156°C) before blending.

For mixtures with PP, the PP pellets were added to pre-heated CA for one hour at temperatures of 156°C (313°F) for MM1 and 194°C (381°F) for MM2. Concomitantly, fine aggregates (FA) were pre-heated for two hours at 156°C (313°F). The PP-CA blend was then mixed with 11% of the binder content. Finally, the PP-CA-binder blend was mixed with FA and the remaining binder content. Figure 3.5 illustrates the two-step mixing procedures for AC-PP-MM1 and AC-PP-MM2 mixtures, and Figure 3.6 shows the actual loose mixtures produced.

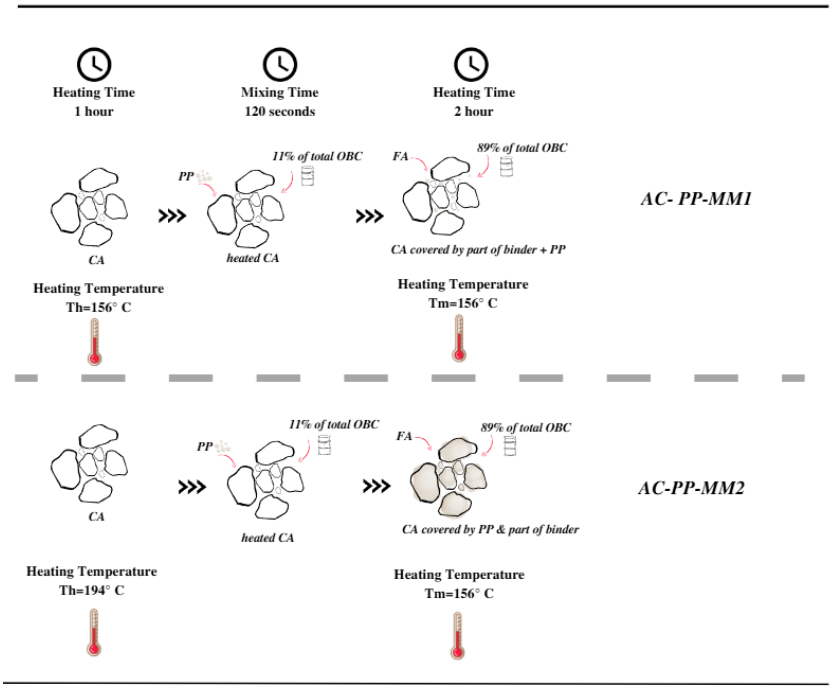

Figure 3.5 Mixing procedure for AC-PP-MM1 and AC-PP-MM2.

a) b)

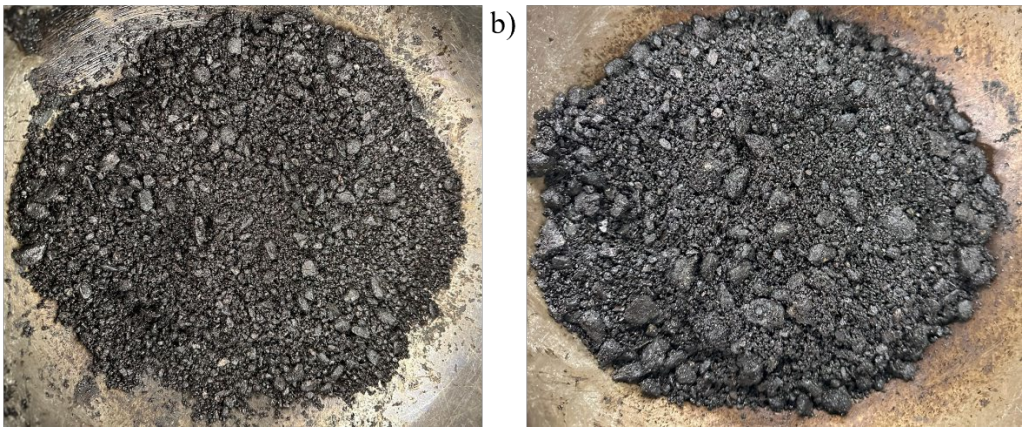

Figure 3.6 PP-modified mixtures: (a) AC-PP-MM1; (b) AC-PP-MM2.

All loose mixtures were subjected to short-term aging (four hours at 135°C or 275°F) for further mechanical testing following the AASHTO R30 protocol [73]. Then, cylindrical SGC specimens of each studied mixture were compacted at the binder's compaction temperature

(143°C or 290°F) with a 150mm diameter and 62 ± 1mm height, targeting 7 ± 0.5% of air voids as recommended by the performance tests standard procedures. Finally, compacted samples were subjected to performance tests: the Hamburg Wheel Tracking test (HWTT) to assess rutting and moisture susceptibility, and the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) to evaluate mid-temperature cracking resistance.

3.2.2 Effects of WP type on Plastic Mixtures Mechanical Performance and Bonding Characteristics

After determining the mixing method, the effects of different types of WPs were studied. Two types of WP (PP and LDPE) were selected since their melting points were the closest to HMA mixing temperatures. Thus, three mixtures were studied in this part of the study: AC, AC-LDPE (AC with 1% of LDPE addition by weight of aggregates), and AC-PP (AC with 1% of PP addition by weight of aggregates).

The mixing procedure adopted for the AC-LDPE and AC-PP was adjusted to optimize the process and better represent the conditions of an asphalt plant, where coarse and fine aggregates are heated together. Therefore, the aggregates (CA and FA) were pre-heated for two hours at a temperature 40 ºC higher than the WP melting point (163ºC or 325ºF for LDPE and 193ºC or 380ºF for PP), following the recommended temperature range [65,74,75]. Then, 1% of WP by weight of the aggregates was mixed with the pre-heated materials for two minutes in a mechanical mixer to produce plastic-coated aggregates. The WP-aggregate blend was then left in the oven for 15 minutes at 156 ºC (313ºF) before mixing with the asphalt binder, which was also pre-heated at the binder's mixing temperature. The established procedure could also be mimicked in the asphalt plants, in which the WP is added to the pre-heated aggregates through a separate conveyor belt. Figure 3.7 illustrates the mixing procedure for the plastic mixtures.

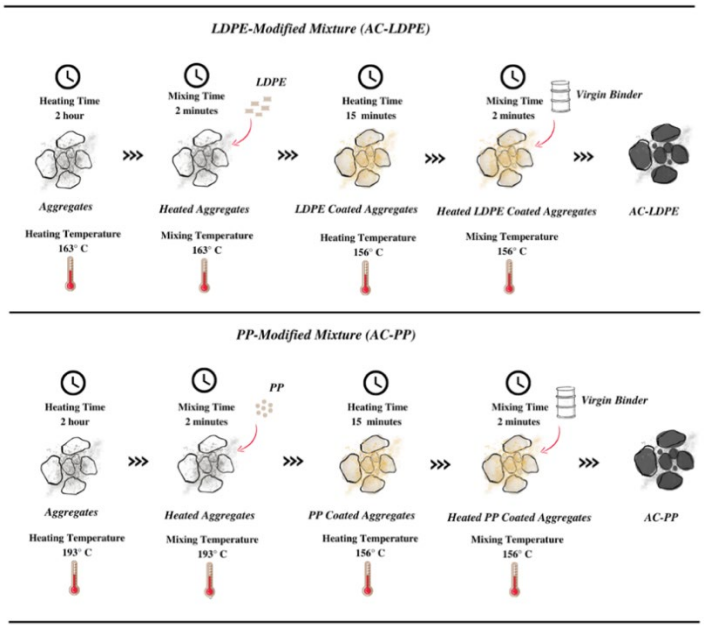

Figure 3.7 Mixing procedure for PP and LDPE.

All loose mixtures were then subjected to short-term aging (four hours at 135°C or 275°C) for further mechanical testing, following the AASHTO R30 protocol [73]. For performance analysis, seven specimens of each mixture were compacted using the SGC at 143ºC (290ºF), targeting 7 ± 0.5% of air voids. The plastic-modified samples were left in the compactor for 10 minutes before being extruded to account for the swelling of the WP and minimize AV variability. The specimens of 62 ± 1mm height and 150mm diameter were tested for rutting and moisture susceptibility using the HWTT and for intermediate-temperature cracking using IDEAL-CT.

3.2.3 Effects of 1% LDPE Addition on Recycled Nebraska Mixtures (NDOT SPR)

According to the results obtained in Task 3, LDPE WPs was the best candidate to move forward to the plant-production stage. Two mixtures were developed in the laboratory to evaluate the effects of 1% LDPE addition to NDOT SPR mixes: SPR_RAP_L (laboratory-produced

control mixture containing 25% of RAP aggregates) and SPR_RAP_LDPE_L (SPR_RAP_L with 1% addition of LDPE by weight of aggregates).

The mix design parameters for the control mixture are presented in Table 3.2. The RAP binder content of 5.75% was determined using the ignition oven method (AASHTO T308). Therefore, an additional 4.78% of virgin asphalt binder (PG58H-34) was added to the mix to achieve a total binder content of 6.15%. The mixing procedure for SPR_RAP_L was as follows: the virgin aggregates, RAP, and the asphalt binder were individually pre-heated for two hours at 149ºC (300ºF). All the materials were then blended for two minutes utilizing a mechanical mixer.

For the SPR_RAP_LDPE_L mixtures, the virgin aggregates were pre-heated for two hours at 163ºC (40ºC above LDPE's melting point). Simultaneously, the RAP aggregates and the asphalt binder were pre-heated at 149ºC in a different oven. Then, 1% of LDPE was added and blended with the pre-heated virgin aggregates using a mechanical mixer for two minutes. During the two-minute mixing procedure, the temperature of the materials decreased closer to the binder's mixing temperature. Finally, the RAP and the asphalt binder were added to the mixing bucket and blended for an additional two minutes with the WP-coated aggregates. Figure 3.8 illustrates the mixing procedure used for SPR_RAP_LDPE_L.

Table 3.2 SPR_RAP_L mix design.

Total Binder Content (%)	6.15
Gmb @ N des	2.35
Gmm	2.42
Air voids (%)	3.0
VMA (%)	14.7
VFA (%)	80.5
AC in RAP (%)	5.75

All loose mixtures were subjected to short-term aging (two hours at 135°C or 275°C) for further mechanical testing, following the updated AASHTO R30 protocol [76]. For performance analysis, seven specimens of each mixture were compacted using the SGC at 135ºC (275ºF), targeting 7 ± 0.5% of air voids. The plastic-modified samples were left in the compactor for 10 minutes before being extruded to account for the swelling of the WP and to minimize AV variability. The specimens of 62 ± 1mm height and 150mm diameter were tested for rutting and moisture susceptibility using the HWTT and for intermediate-temperature cracking using IDEAL-CT.

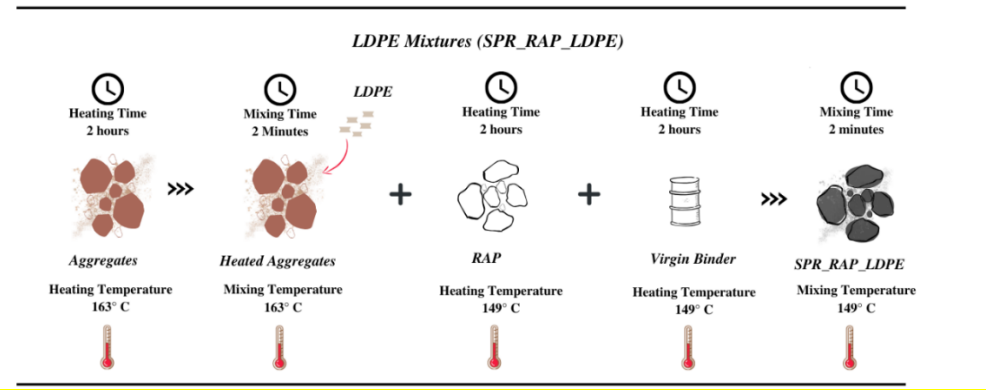

Figure 3.8 Mixing Procedure for SPR_RAP_LDPE_L.

3.2.4 Field Implementation

The feasibility and implementation of a Nebraska Superpave Recycled Mixture (SPR NDOT) with WP addition were verified with a field project constructed in South Sioux City, NE (**Figure 3.9**). The project consisted of paving a gravel road at 1801 Veterans Drive. Two test sections were constructed with a 6.5" AC base course (regular SPR mix) and a 3" surface course, using the selected recycled mixtures. For this stage, the two lab-produced NDOT SPR mixtures were selected (i.e., SPR_RAP_L and SPR_RAP_LDPE_L) to be replicated in the asphalt plant.

The plant-produced mixtures followed the same mix design and materials as the lab-produced mixtures. To differentiate lab- and plant-produced mixtures in further analysis, the plant produced control and plastic-modified mixtures were named SPR_RAP_P and SPR_RAP_LDPE_P, respectively.

For the SPR_RAP_LDPE_P, the LDPE was incorporated using a metering machine attached to a vacuum pump to ensure a constant rate of plastic addition throughout the process. The shredded WP was pumped into the RAP inlet and then added to the pre-heated aggregates. Simultaneously, RAP was added to the drum. Finally, the asphalt binder was added to the blend at 149ºC (300ºF). A mix design quality control was performed by the contractor after producing the SPR_RAP_LDPE_P, attesting to the final aggregate blend within the NDOT SPR gradation limits and the 6.15% binder content used in the plant-produced mixture. No issues were observed during the mixing process. However, for being a lightweight material, some LDPE particles were flying out of the box during the pumping procedure. The mixing procedure is shown in Figure 3.10.

Figure 3.9 Location map of the project site in South Sioux City, Nebraska.

Plant-produced HMA samples were collected and transported to the lab. Those mixtures were heated for two hours at 135 ºC (275 ºF) to reach compaction temperature and SGC compacted specimens, targeting 7 ± 0.5% of air voids were produced. Seven specimens of each mixture with 62 ± 1mm height and 150mm diameter were produced for HWTT and IDEAL-CT tests. Again, all plastic-modified samples were left in the compactor for 10 minutes before extrusion to account for potential swelling of the WP particles. Finally, the performance of lab and plant-produced samples was compared to evaluate the scalability of a laboratory-developed procedure for WP incorporation in a full-scale asphalt plant.

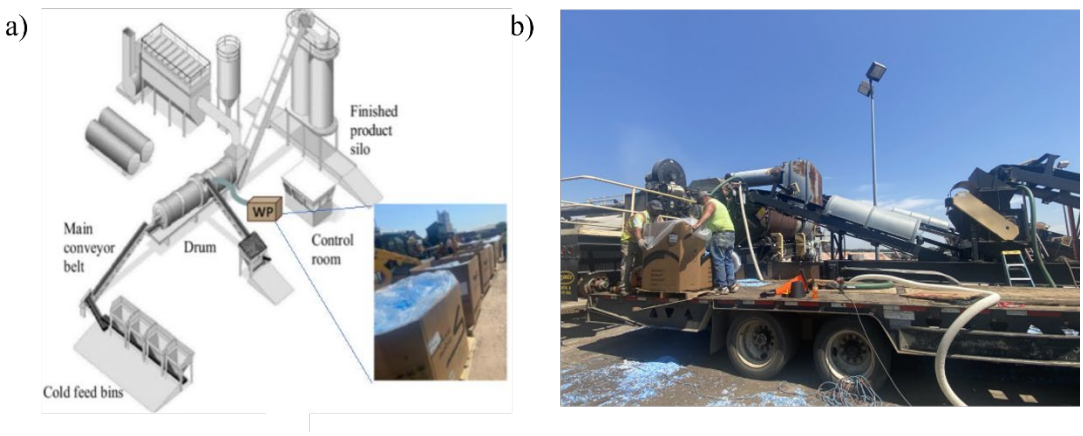

Figure 3.10 Mixing procedure for plant-produced mixes: a) asphalt plant scheme with WP pump device (image adapted from pavementinteractive.org); b) WP incorporation in the trial project.

After the plant production of SPR_RAP_P and SPR_RAP_LDPE_P, a test section of 4,000 feet in length and 27 feet in width was successfully paved in two segments using a Super 2000-3i Vögele tracked paver (Figure 3.11a). The first segment of 3,900 linear feet used the plastic-modified mix (SPR_RAP_LDPE_P) and the second segment of 100 linear feet used the reference mixture (SPR_RAP_P). The segments were then compacted at 135°C using a vibratory roller, as shown in Figure 3.11b and Figure 3.11c. Once again, no issues were reported during

the compaction of the field section, demonstrating the feasibility of applying the mixtures on real pavement projects. As a follow-up, long-term performance tests and field monitoring will be performed in the coming years.

Figure 3.11 Field implementation: (a) Paving; (b) compaction of SPR_RAP25 (plant-produced); (c) compaction of SPR_RAP25_LDPE$_2$ (plant-produced).

3.3 Testing Methods

3.3.1 WP Chemical-Physical Characterization

A fingerprint assessment was conducted to verify the authenticity of the post-industrial WP samples and confirm the absence of any other type of plastic or contaminants. For this purpose, a Fourier Transform Infrared Spectroscopy (FTIR) analysis was performed by measuring the amount of infrared radiation absorbed by each WP sample, allowing the identification of the functional groups present in its chemical composition. The FTIR spectrum contains absorbance peaks corresponding to vibration frequencies between the atoms and their bonds. The spectrum is unique to each material, similar to a fingerprint, allowing the assessment of the WP chemical structure [77,78].

The melting point is crucial for establishing the pre-heating temperature of the aggregates to achieve an effective plastic coating. To verify the melting point of the WPs, each sample underwent two heating cycles using Differential Scanning Calorimetry (DSC). The test measured

the amount of energy required to maintain the WP at a similar temperature to a reference sample. The first cycle allowed the WP sample to start melting and fill the bottom of the sample holder. The second cycle was conducted to obtain a more accurate measurement of the melting point, given that the entire bottom of the sample holder was coated with the WP. During the test, the material absorbed energy during the continued heating and cooling cycles until it reached the endothermic peak, also known as the melting point. For this analysis, the actual melting point is the range between the endothermic peaks measured in each cycle [79]. Figure 3.12 shows the equipment and expected curve during the DSC test.

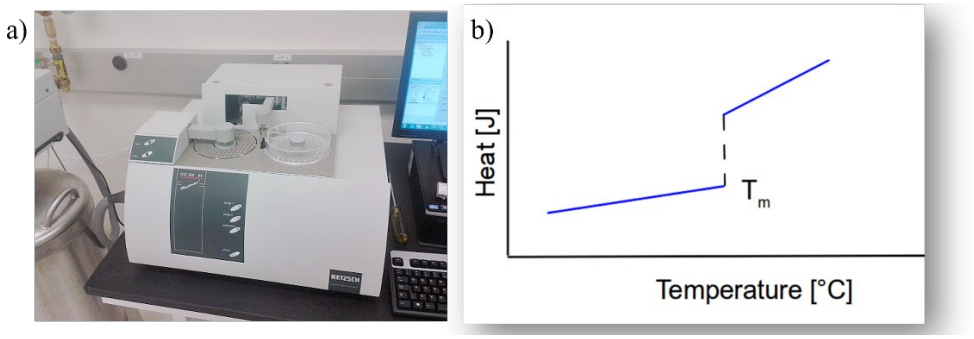

Figure 3.12 DSC test: a) Equipment; b) Expected curve.

Since the proposed mixing procedures used herein to produce the studied recycled asphalt mixtures require the addition of WPs to pre-heated aggregates at temperatures 40°C above the WP melting point, it is crucial to ensure that the high pre-heating temperatures used in the first contact of virgin aggregates and WPs would not lead to thermal degradation of the LDPE particles, especially during the procedure in the asphalt plant. Therefore, a thermogravimetric analysis (TGA) using the NETZSCH TG 209 F1 Libra thermobalance was conducted on the post-consumer WP samples. The LDPE samples underwent a heating cycle from 25°C to 600°C (5°C/min heating rate), while the change in mass during the process was recorded. The test was

also conducted on samples with four different colors (i.e., white, black, beige, and blue). Figure 3.13 shows the TGA equipment.

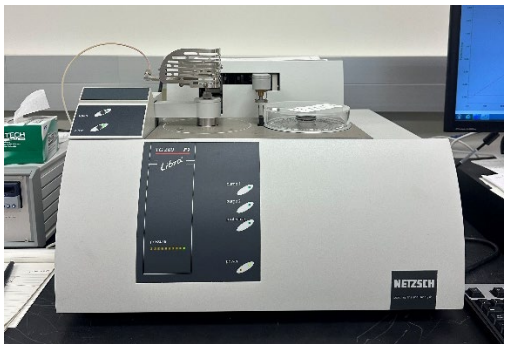

Figure 3.13 TGA equipment.

3.3.2 Asphalt Concrete Performance Tests

3.3.2.1 Hamburg-Wheel Tracking Test (HWTT)

Rutting and moisture susceptibility of all mixtures were evaluated considering performance-based parameters derived from HWTT outputs, based on the AASHTO T 324-22 standard [80]. Four cylindrical specimens with 150 mm diameter, 62 mm height, and 7 ± 0.5 percent air void of each mixture (two pairs) were trimmed and then submerged in water at 50°C. Then, each pair was placed on one side of the equipment. The test ran for 20,000 cycles or until a deformation of 25mm was reached, whilst a wide steel wheel with a load of 703 ± 4.5 N rolled across the surface of the specimens at a rate of 52 ± 2 passes across the specimen per minute. The test output consists of a graph of wheel cycles x rut depth for each pair of specimens. For rutting resistance, the typical pass-fail criteria correspond to the number of load cycles for a 12.5 mm deformation, while the moisture susceptibility is usually evaluated by the stripping inflection point (SIP) [80–82]. Figure 3.14 shows the test procedure and an example of a graphic representation of the test.

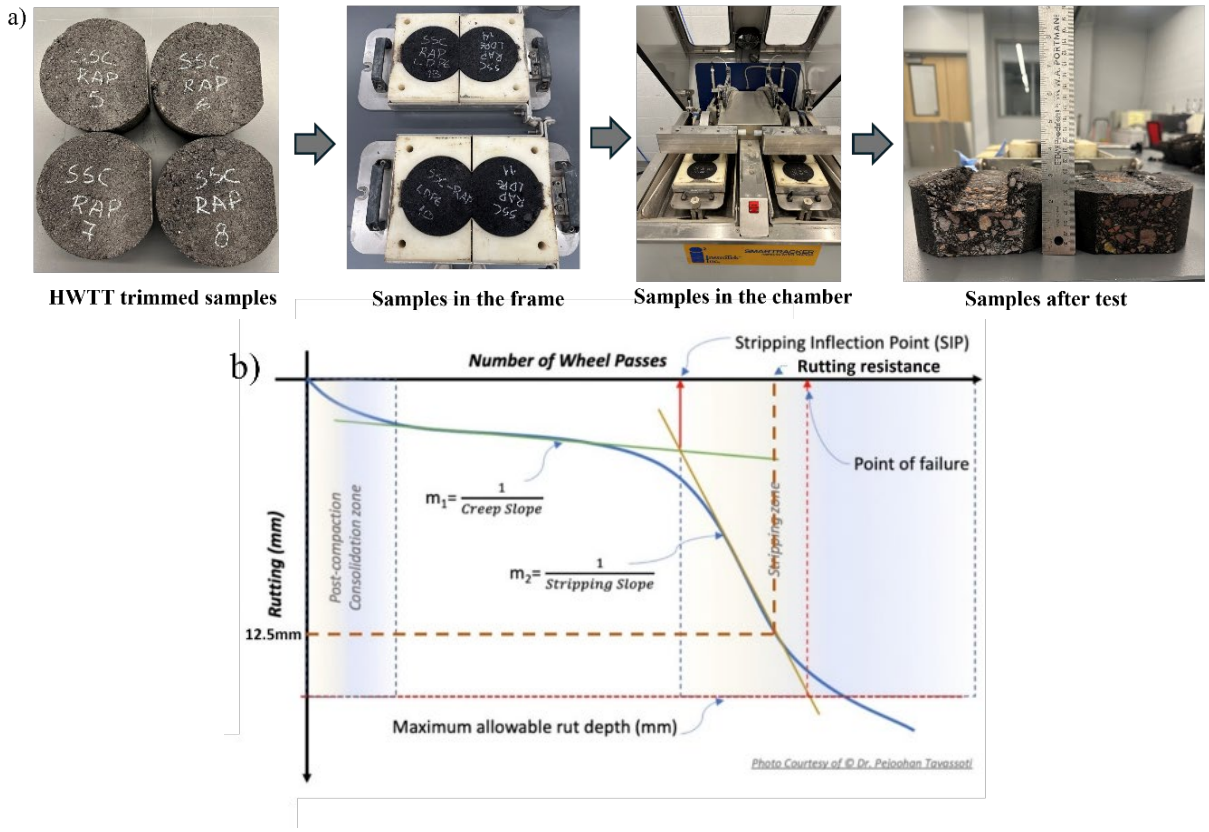

Figure 3.14 Hamburg Wheel Tracking Test: (a) Test procedure; (b) test output. Adapted from Tavassoti et al. [83].

Considering the preliminary analysis of pre-heating temperatures for the establishment of a mixing protocol for WP incorporation, only the conventional parameters (i.e., SIP and number of cycles corresponding to 12.5mm deformations) were evaluated. However, for the evaluation of the effects of different types of WP (Task 3) and the incorporation of WP into a Nebraska SPR mixture (Task 4), additional analyses were conducted to separate the damage caused by stripping and load application, following the protocol proposed by Yin et al. [84]. This could provide further investigation of the real effects of WP coating on the moisture damage resistance of asphalt mixtures.

To separate the viscoplastic deformation due to the load application (during pos-compaction and creep phases) and stripping, additional analysis was conducted based on Yin et

al. [84] protocol. The authors introduced a new parameter named stripping number (LC_{SN}), which represents the maximum number of wheel cycles resisted by the mixture before adhesive failure occurs between the binder and aggregates (represented by the inflection point of the load cycles curve). For that reason, any deformation until LC_{SN} is primarily correlated with viscoplastic deformation due to load cycles. The LC_{SN} can be calculated by curve-fitting the results from HWTT, using the equations below. Higher LC_{SN} values correspond to lower moisture susceptibility within the material.

$$\boldsymbol{RD_{LC} = \rho \left[\ln\left(\frac{LC'}{LC}\right)\right]^{\frac{-1}{\beta}}} \quad \textbf{(3.1)}$$

$$\boldsymbol{LC_{SN} = LC'\left(e^{\frac{-\beta+1}{\beta}}\right)} \quad \textbf{(3.2)}$$

where: RD_{LC} is the total rut depth at a certain number of load cycles (LC) and ρ, β, and LC' are coefficients obtained in this study from curve fitting using MathWorks Matlab software.

Additionally, the total strain of the mixture (ε_T) at a certain LC is calculated by dividing the RD_{LC} by the thickness of the specimen (62mm). As mentioned previously, the total rutting of the HMA after the stripping number can be divided into two components: viscoplastic deformation due to the load application (during pos-compaction and creep phases) and stripping. The total viscoplastic strain (ε_{VP}) is determined by fitting the post-compaction and creep phases of the graph using the Tseng–Lytton Model (Eq. 3.3), which can also be projected into the stripping phase, as shown in Figure 3.15. The stripping strain (ε_{ST}) can be calculated by subtracting the ε_{VP} from ε_T. Additionally, the stripping strain curve is fitted using Equation 3.4. Finally, the total deformation due to stripping can be calculated by determining the additional number of cycles (LC_{ST}) to reach the typical rut-depth failure criteria (12.5mm), also known as the stripping life of the mixture. (Eq. 3.5) [84].

$$\varepsilon_{VP} = \varepsilon'_{VP}\left(exp\left(-\frac{\alpha}{LC}\right)^{\lambda}\right) \quad (3.3)$$

$$\varepsilon_{ST} = \varepsilon'_{ST}\{exp[\theta(LC - LC_{SN})] - 1\} \quad (3.4)$$

$$LC_{ST} = \frac{1}{\theta}\ln\left(\frac{12.5}{62*\varepsilon'_{ST}} + 1\right) \quad (3.5)$$

where: ε'_{VP}, ε'_{ST}, α, λ, θ are model parameters obtained from curve fitting using MathWorks Matlab software.

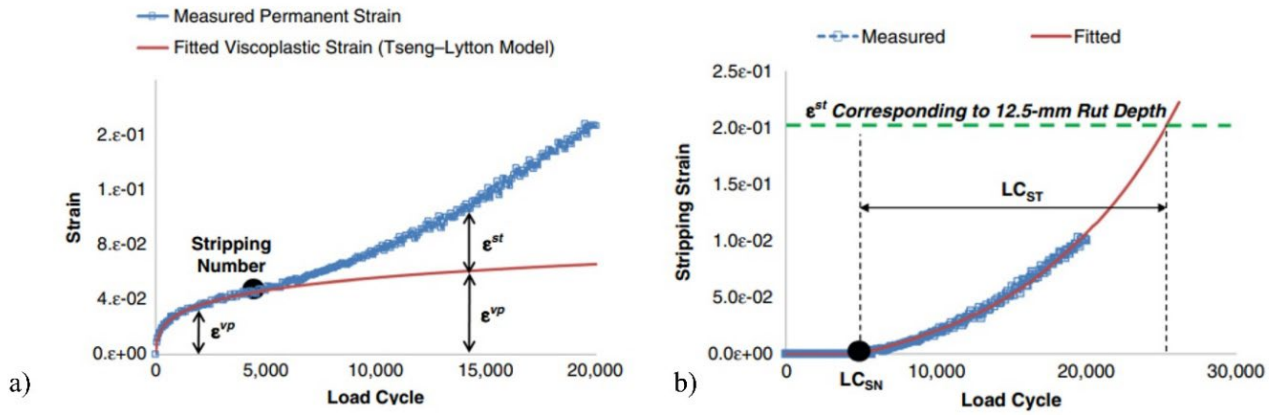

Figure 3.15 Example of curve-fitting for HMA: (a) Fitted viscoplastic strain; (b) Fitted stripping strain [84].

Additionally, Yin et al. [84] proposed a viscoplastic strain increment (ΔεVP) parameter to evaluate the mixture performance against rutting, corresponding to the slope of the fitted viscoplastic strain at 10,000 cycles. This parameter only considers deformation on the creep phase, excluding deformations due to post-compaction (first 1,000 cycles) and stripping. Higher ΔεVP (Eq. 3.6) values indicate higher rutting susceptibility.

$$\Delta\varepsilon_{VP} = \alpha^{\lambda}\lambda\varepsilon'_{VP}exp\left[-\left(\frac{\alpha}{10000}\right)^{\lambda}\right](10000)^{-(1+\lambda)} \quad (3.6)$$

3.3.2.2 Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

The cracking resistance at an intermediate temperature of all asphalt mixtures was evaluated based on the analysis of the Cracking Tolerance (CT) index derived from IDEAL-CT test following the ASTM D8225 standard [85]. In this test, a sample is placed in the middle of the fixture (Figure 3.15a) whilst a compression load is applied to maintain a constant load-line displacement (LLD) at a rate of 50±2 mm/min. The output consists of a graph of load versus LLD as shown in Figure 3.16b.

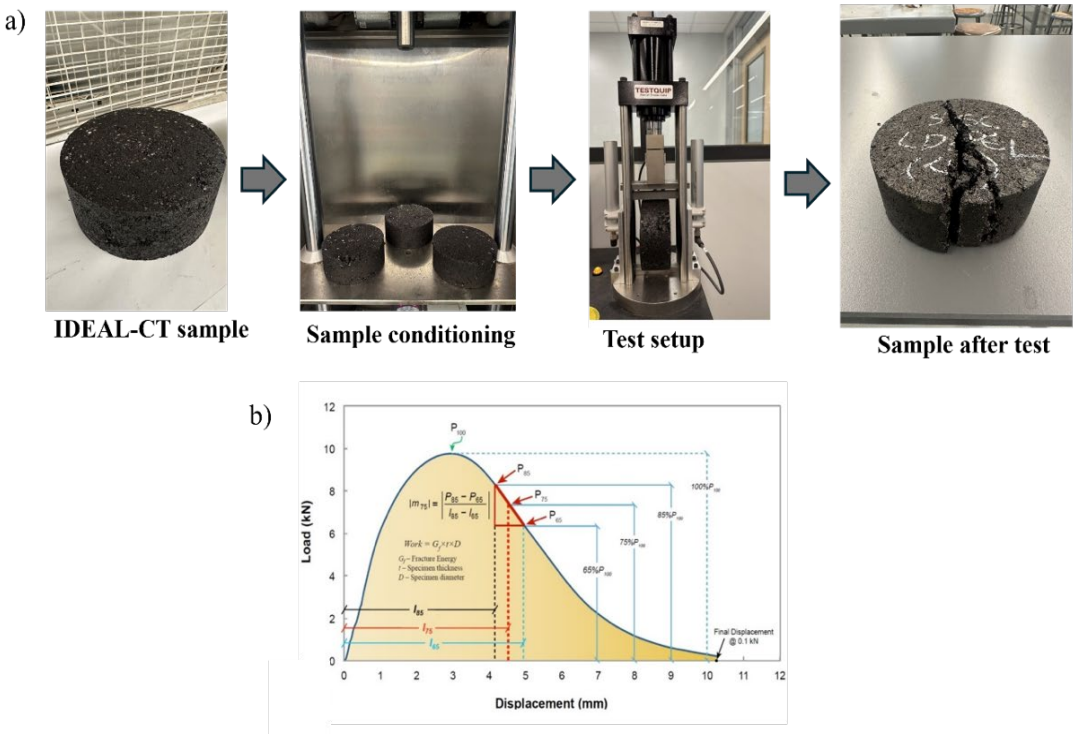

Figure 3.16 IDEAL-CT test: (a) test procedure; (b) test output [86].

The Cracking Tolerance (CT) index is calculated using the equation 3.7, in which *t* and *D* are the specimen's thickness and diameter ,G_f is the failure energy calculated by dividing the area under the curve by the cross-sectional area of the specimen, l_{75} is the displacement at 75%

of the peak load after the peak, and $|m_{75}|$ is the absolute value of the post-peak slope. Higher CT indices may be correlated to higher resistance to cracking at mid-temperatures [82,85,87].

$$CT\ Index = (t/62) \times (Gf/|m75|) \times (l75/D) \quad (3.7)$$

From the Force vs Load Line Displacement curve, some additional observations can be drawn. The initial slope can be correlated to the material's initial stiffness when there is no severe damage on the specimen. The post-peak slope is an indicator of the rate of cracking propagation in the mixture. Steeper post-peak slopes can indicate that cracks propagate at a higher rate, showing that the mixture may have a lower resistance to cracking propagation, i.e., low CT index [88].

In this study, three specimens with a 150 mm diameter, 62 mm height, and 7 ± 0.5 percent air void of each mixture were tested, and the average results are reported.

3.3.3 Bonding Characteristics

3.3.3.1 Thermodynamic Properties

The addition of WP in pre-heated aggregates could affect the binder-aggregate adhesion. To verify this hypothesis, thermodynamic properties of limestone particles were assessed before and after being coated by WP and surface free energy concepts were used to assess key components related to water affinity of the materials.

According to the acid-base theory developed by Good-van Oss-Chaudhury [89–91], the total Surface Free Energy (SFE or ɣ) of any material is composed of the sum of two distinct components: a non-polar component, also known as Lifshitz-van der Waals ($ɣ^{LW}$) interactions (i.e., dispersion and dipole-dipole), and a polar component, also known as the Lewis acid-base ($ɣ^{AB}$) interactions (i.e., hydrogen bonds). The polar components can be further divided into Lewis acid ($ɣ^{+}$) and basic ($ɣ^{-}$) components as shown in the equation below [58,92,93].

$$ɣ^{AB} = 2\sqrt{ɣ^{+}ɣ^{-}} \quad \textbf{(3.8)}$$

The SFE components of the binder and the aggregates were obtained indirectly through contact angle analysis based on the Sessile Drop (SSD) method. The contact angles (θ) between a drop of probe liquid (L) and the solid surface (S) were measured using a goniometer from Ramé-hart Instrument Co. (Figure 3.17). The total work of adhesion (W^a_{SL}) of the S-L system can be determined using the Young-Dupre equation (Eq. 3.9) [94] which can be combined with the acid-base theory to correlate SFE components and the measured contact angle at the S-L interface (Eq. 3.10) [58,92,93].

$$(\mathbf{1}+\cos\boldsymbol{\theta})\,\gamma_L = \boldsymbol{W^a_{SL}} \tag{3.9}$$

$$(\mathbf{1}+\cos\boldsymbol{\theta})\,\gamma_L = \mathbf{2}\left(\sqrt{\gamma_L^{Lw}\gamma_S^{Lw}} + \sqrt{\gamma_L^{+}\gamma_S^{-}} + \sqrt{\gamma_L^{-}\gamma_S^{+}}\right) \tag{3.10}$$

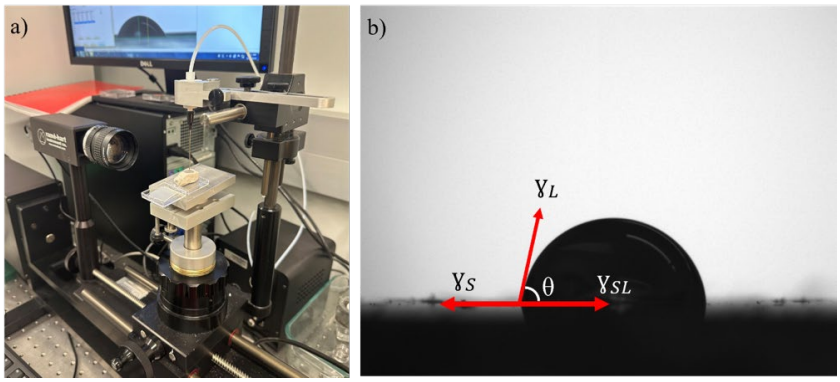

Figure 3.17 SSD method: (a) Ramé-hart goniometer dropping distilled water on the aggregate surface; (b) contact angle measurement on S-L interface, in which γ_L and γ_S are the total SFE of the probe liquid and solid surface, respectively, and γ_{SL} is the surface tension on the S-L interface.

For contact angle measurements, four different probe liquids with known SFE components were utilized, as shown in Table 3.3.

Two polar (distilled water and formamide) and one non-polar liquid (diiodomethane) were chosen to determine the SFE of the aggregates due to recommendations by other researchers [92]. For the asphalt binder analysis, diiodomethane was replaced by glycerol.

For sample preparation, the binder was poured into a silicone mold while LDPE and PP WPs were added to pre-heated aggregates at 163ºC (325ºF) and 193ºC (380ºF), respectively. Although the aggregate mix is composed of gravel and LS aggregates, only the LS was analyzed due to its higher representativeness in the mix (95%). This analysis used crushed LS aggregate particles that are used in asphalt mixtures. The LS surface with and without plastic coating was cleaned and polished. Finally, four drops of each probe liquid were placed on the aggregate and binder, taking ten contact angle measurements for each.

Table 3.3 SFE components of the probe liquids utilized in this research.

Probe Liquid	**SFE components (mJ/m^2)**				
	γ	γ^{Lw}	γ^{AB}	γ^{+}	γ^{-}
Distilled Water	72.8	21.8	51	25.5	25.5
Formamide	58.0	39.0	19.0	2.28	39.6
Diiodomethane	50.8	50.8	0	0	0
Glycerol	64.0	34.0	30.0	3.92	57.4

3.3.3.2 Binder-aggregate Bond Strength (BBS)

The change in binder-aggregate adhesion due to the addition of WP was also verified based on mechanical bonding gain. For that, a Pull-off Tensile Strength (POTS) test was performed using a PosiTest AT-A (Automatic Pull-off Adhesion Tester) equipment, model ATA50A from DeFelsko (Figure 3.18a). The equipment measures the higher tensile force supported by the binder before it is detached from a substrate of interest. The test was performed following the ASTM D4541 [95] and D7234 [96], and AASHTO T 361-16 [97] standards.

For this test, a large rock sample with similar mineralogical characteristics to the LS aggregates used in this study was collected from a quarry. The rock sample was cut into smaller pieces to produce aggregate samples with a flat surface for further use in the POTS test. The WP was added to the clean aggregate sample (preheated at 163ºC for LDPE and 193ºC for PP). Plastic-coated and non-coated aggregate samples were then mixed with 50 g of binder at 156ºC (313ºF) to promote full asphalt coating and maintain a similar binder film thickness (Figure 3.18b).

The test setup consisted of attaching two pull-off stubs of 50 mm diameter (dollies) to the coated aggregate surface using the glue specified by the manufacturer (Figure 3.18c). Before the gluing process, the base of the dollies was scrubbed with an abrasive pad to remove any contaminants. The glue was cured for 24 hours at 25ºC (77ºF), and the equipment's actuator was attached to the dolly (Figure 3.18d). The pull-off rate was set to 24 psi/s, and the test was performed, measuring the maximum tensile strength on each dolly [98]. One aggregate sample for each condition (binder-aggregate, binder-LDPE-aggregate, and binder-PP-aggregate) was evaluated, considering the average pull-off strength between the two attached dollies.

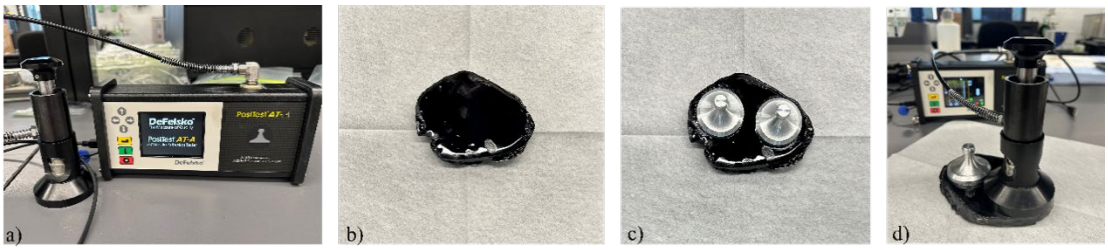

Figure 3.18 POTS test set-up: (a) Equipment; (b) Coated aggregate sample; (c) Dollies glued to the sample; (d) Actuator attached to the dolly.

Chapter 4 Laboratory Test Results and Discussion

4.1 WP Characterization

The fingerprint of all post-industrial WP samples is shown in Figure 4.1. Additionally, Table 4.1 shows the wavelength values (peaks) and their corresponding function groups for each type of plastic, according to the literature [78]. The FTIR analysis revealed that most WP samples present peaks similar to those reported in the literature [78], indicating authentic samples with no contamination. The PET fingerprint, however, presented distinct peaks at 1400 and 800 cm^{-1}, which could indicate possible contamination, mixed plastic, or background noise collected by the equipment.

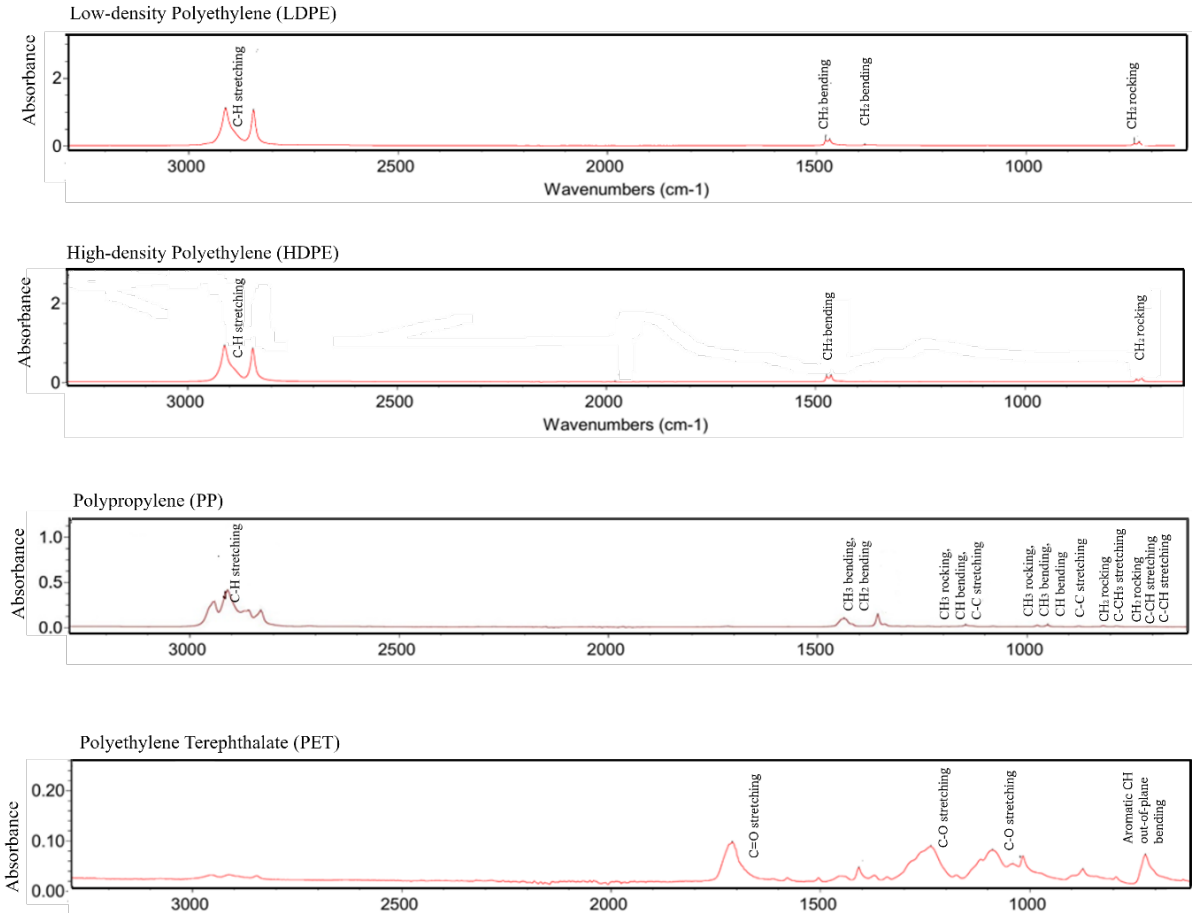

Figure 4.1 FTIR spectrum of the studied post-industrial WP samples.

Table 4.1 Evaluation of the functional groups according to the literature

Post-Industrial WP sample	Peaks (cm^{-1})	Functional Group	Status
LDPE	2915 - 2845	C–H stretching	Present
	1472 - 1462	CH_2 bending	Present
	13777	CH_2 bending	Present
	730 – 717	CH_2 rocking	Present
HDPE	2915 - 2845	C–H stretching	Present
	1472 - 1462	CH_2 bending	Present
	730 – 717	CH_2 rocking	Present
PP	2950 - 2838	C–H stretching	Present
	1455	CH_2 bending	Present
	1377	CH_3 bending	Present
	1166	CH_3 rocking, CH bending, C–C stretching	Present
	997	CH_3 rocking, CH_3 bending, and CH bending	Present
	972	CH_3 rocking, C–C stretching	Present
	840	CH_2 rocking, C–CH_3 stretching	Present
	808	CH_2 rocking, C–C stretching, C–CH stretching	Present
PET	1713	C=O stretching	Present
	1241	C–O stretching	Present
	1094	C–O stretching	Present
	720	Aromatic CH out-of-plane bending	Present

The DSC test results for the post-industrial WP samples are shown in Figure 4.2. The peaks correspond to the melting temperatures from each cycle. As observed, there was no significant difference in the peaks between the cycles for each type of WP. The melting point ranges from 122.9 to 123.5 ºC (253.2 to 254.3 ºF) for LDPE, 139.7 to 140.2 ºC (283.5 to 284.4 ºF) for HDPE, 151.8 to 153.0 ºC (305.2 to 307.4 ºF) for PP, and 249.9 to 252.9 ºC (481.8 to 487.2 ºF) for PET are consistent with values reported in the literature [65,74,75].

Based on the melting point results, two types of WP were chosen for further evaluation of their effects when incorporated into the HMA: LDPE (due to its lower melting point compared to

the other plastic types, which could facilitate the coating process) and PP (since its melting point is closer to the binder's mixing temperature).

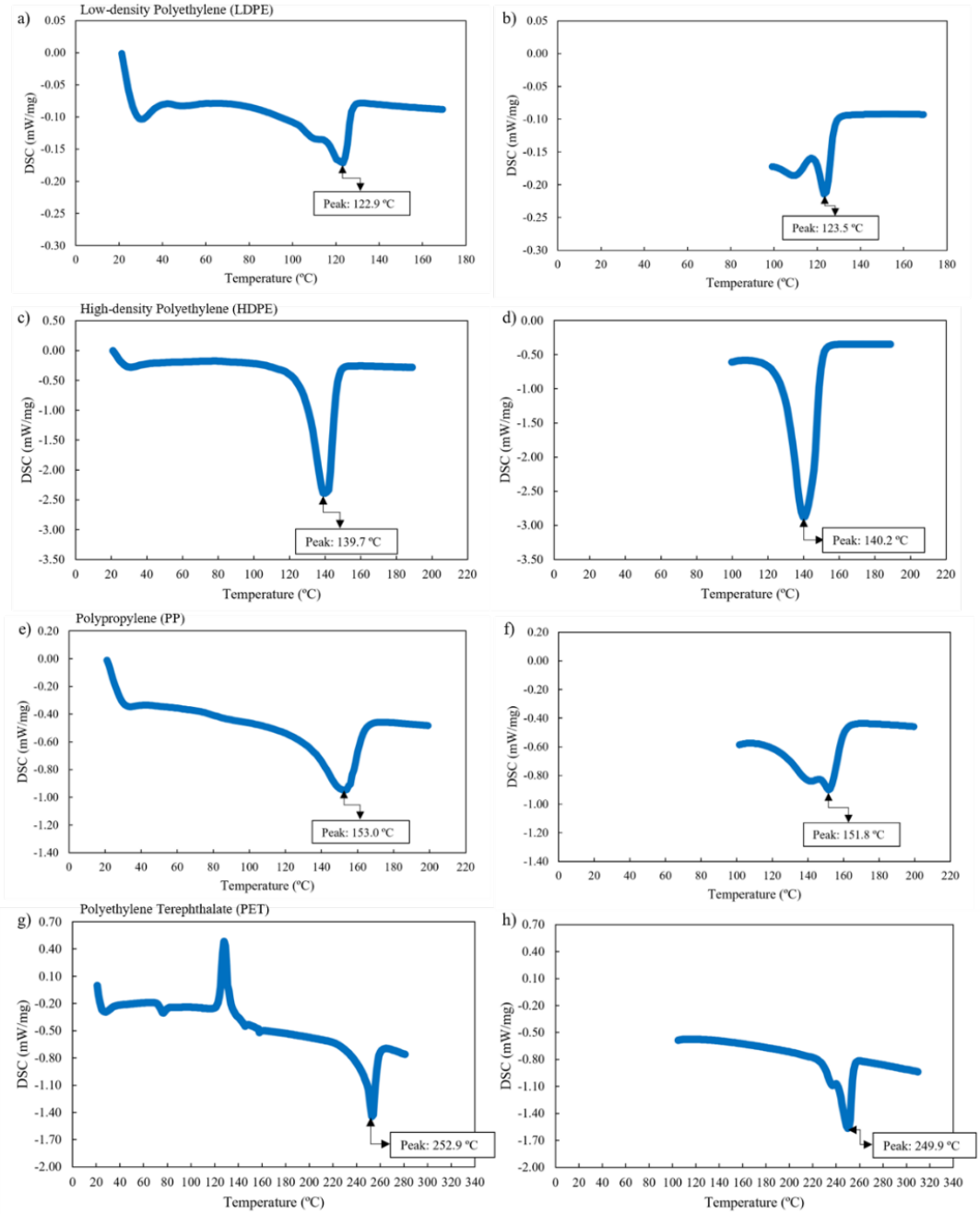

Figure 4.2 DSC test results: (a) LDPE first heating cycle; (b) LDPE second heating cycle; (c) HDPE first heating cycle; (d) HDPE second heating cycle; (e) PP first heating cycle; (f) PP second heating cycle; (g) PET first heating cycle; and (h) PET second heating cycle.

Figure 4.3 shows the TGA results for post-consumers LDPE samples used on Task 4, where the baseline of all curves was corrected to eliminate the negative residual mass due to the systematic error of the TGA equipment. The correction does not affect the shape of the curves nor the degradation temperatures. From the results, it can be seen that severe thermal degradation occurred around 266°C to 271°C for beige and black plastic samples, respectively, 356°C for white, and 441°C for blue plastic samples. Therefore, the pre-heating temperatures adopted during the mixing process must be lower than the degradation temperatures. Since the melting point of LDPE is around 123°C, it is assumed that the adopted aggregate pre-heating temperature in the lab will not lead to severe plastic degradation. Furthermore, in the asphalt plants, the temperatures achieved by heated aggregates in the dryer drum at the burner end can be as high as 200°C for parallel-flow drum-mix plants, which is still under the thermal degradation temperatures found for the studied LDPE samples used herein.

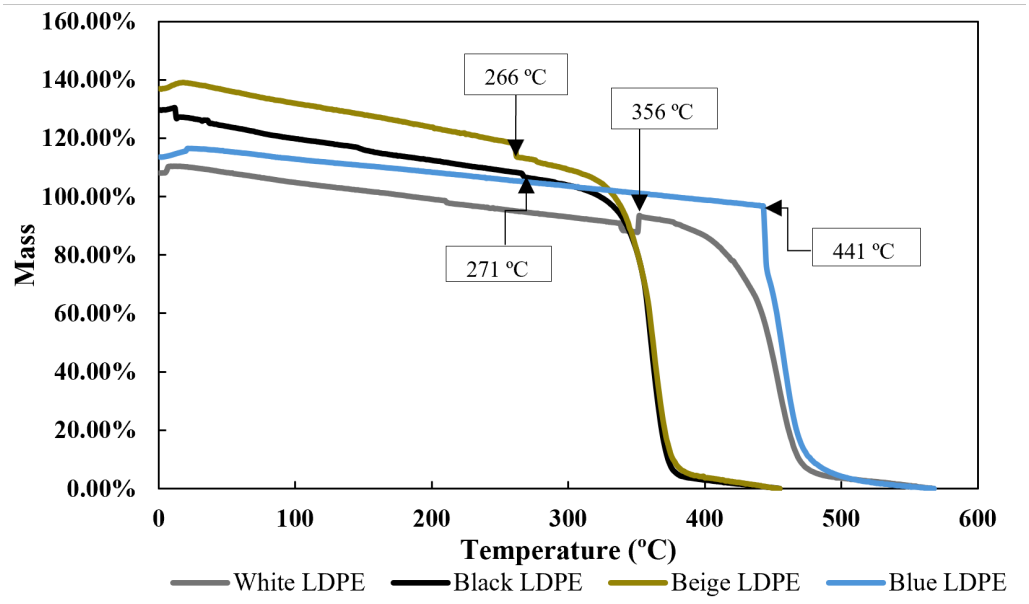

Figure 4.3 TGA test results for the post-consumer WP samples.

4.2 Visual Observations from Different Lab Mixing Protocols for Plastic Mixture Fabrication

As mentioned previously, this preliminary analysis focused on proposing a lab mixing protocol for plastic mixtures by evaluating how the aggregates' pre-heating temperatures affected the WP coating and the overall mixture's performance. For that reason, two mixing methods to blend PP with coarse aggregates were proposed: MM1, in which the CA were pre-heated at 156°C (313°F), and MM2, in which the CA were pre-heated at 194°C (381°F). The results for the CA and WP blend are shown in Figure 4.4.

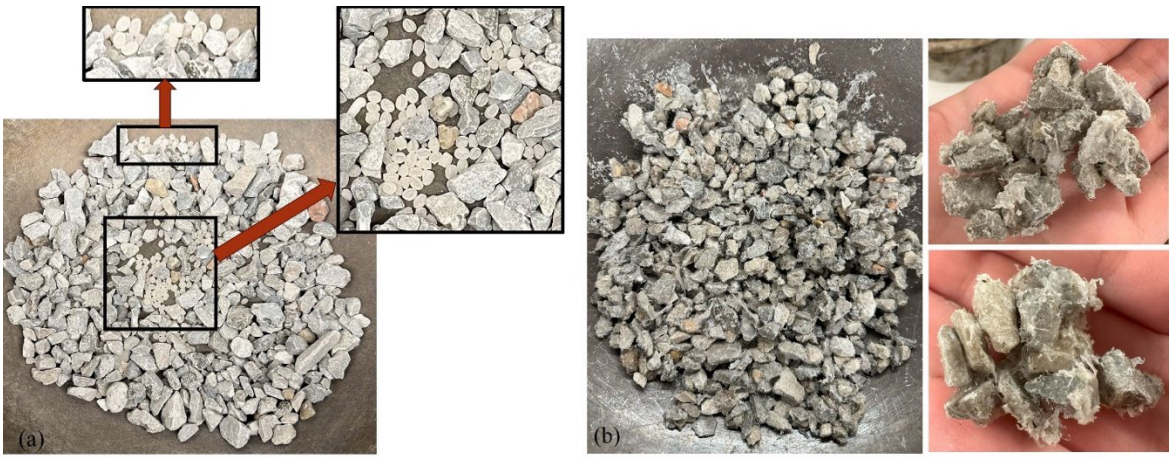

Figure 4.4 Aggregates and PP mixed at: a) 156ºC; b) 194ºC.

Based on visual observations, the MM1 did not result in the melting of the PP WP; instead, the pellets became softer, indicating the possible start of the melting process, but not enough to coat the CA. In this case, the PP particles acted as another aggregate in the mixture. Temperatures higher than the WP's melting point are required for the complete melting of the material, as suggested by other authors [59], [69], [70], [71], [72], [73]. Considering the MM2, a temperature of 40°C above the PP melting point was required to melt the WP particles, allowing them to properly coat the CA, acting as a mixture modifier. After this initial observation, the fine

aggregates and asphalt binder were added to the PP-coarse aggregates blend, following the mixing procedure proposed in 3.2.1, and short-term aged compacted samples underwent further performance evaluation.

4.2.1 Rutting and Moisture Damage Resistance

The effects of PP addition on the rutting and moisture damage resistance of the studied mixtures were evaluated using the HWTT. The parameters obtained during the test for each pair of samples are shown in Table 4.2. Additionally, the average rutting and moisture resistance indices are presented in Figure 4.5.

Table 4.2 HWTT parameters and coefficient of variation (COV).

Mixture	Sample pair	Number of Cycles at 12.5mm	Avg. Number of Cycles at 12.5mm	COV	SIP	Avg. SIP	COV
AC1	1	7632	7619	0.17%	5452	5000	9.04%
	2	7606			4548		
AC-PP-MM1	1	4825	5084	5.09%	3572	3469	2.98%
	2	5342			3365		
AC-PP-MM2	1	9416	>14708	-	6251	8305	24.73%
	2	>20000			10359		

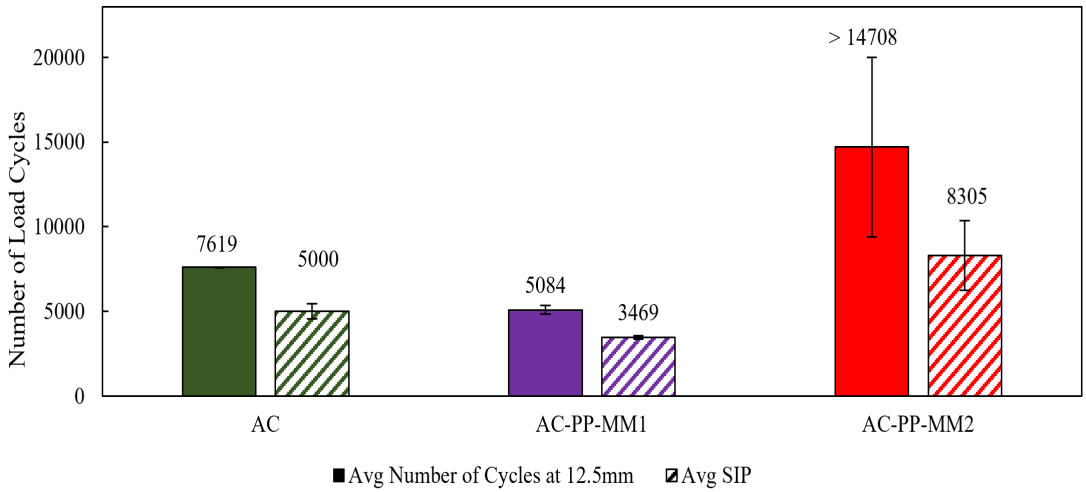

Figure 4.5 Average HWTT parameters for each studied mixture.

Compared to the control mixture, the addition of PP using MM2 was able to improve both rutting and moisture damage resistance by 93% and 66%, respectively. Some studies correlated this enhanced performance with an increase in the stiffness of the mixture after WP coating [99–101]. Additionally, the improvement in rutting resistance could be due to the WP promoting better adhesion and mechanical friction between all components of the mixture, and consequently, the bonding between the binder and aggregate. This hypothesis was further investigated in the section 4.3.3.

Finally, coating aggregates with plastic can prevent water penetration between the binder and aggregates, reducing the moisture susceptibility of the mixture. As seen in Figure 4.5, AC-PP-MM2 presents the highest SIP value among all mixtures. Previous studies concluded that WP coating can change the properties of the aggregate surface, increasing the dry adhesion energy between asphalt and aggregate, reducing debonding tendency, and consequently, moisture susceptibility [36,58,66]. It is worth noting the high variability within the results for MM2, which may indicate a necessity to optimize the mixing procedure.

AC-PP-MM1, however, had the worst performance of all mixtures. Adding PP as another aggregate (not melted) into the mixture had a negative impact on both rutting and moisture damage resistance. One reason could be related to the shape of the PP particles. Angular and cubed-shaped aggregates are known to provide better interlocking between all aggregates in the mixture, increasing the internal friction, and consequently, the rutting resistance [102]. PP pellets were rounded into a disk-like shape, which tends to be flaky and have higher breakage potential, leading to incompatibility with the other aggregates in the mixture and increased permanent deformation [102].

Another reason could be related to PP (as another aggregate) leading to a reduced binder film thickness while maintaining the same OBC to coat all the aggregates, which could result in a lower resistance to rutting and moisture damage compared to AC-PP-MM2. The HWTT results indicated that using WP as a mixture modifier (MM2) and properly coating the aggregates appears to be the best alternative to enhance the mixture's resistance to rutting and moisture damage, endorsing the findings presented in the literature review (Chapter 2).

4.2.2 Intermediate Temperature Cracking Performance

Figure 4.6 a and b show the average Load x LLD curves obtained for the studied mixtures in Task 2 and their CT indexes, respectively. Table 4.3 presents the IDEAL CT parameters obtained after the test for the mixtures modified with PP.

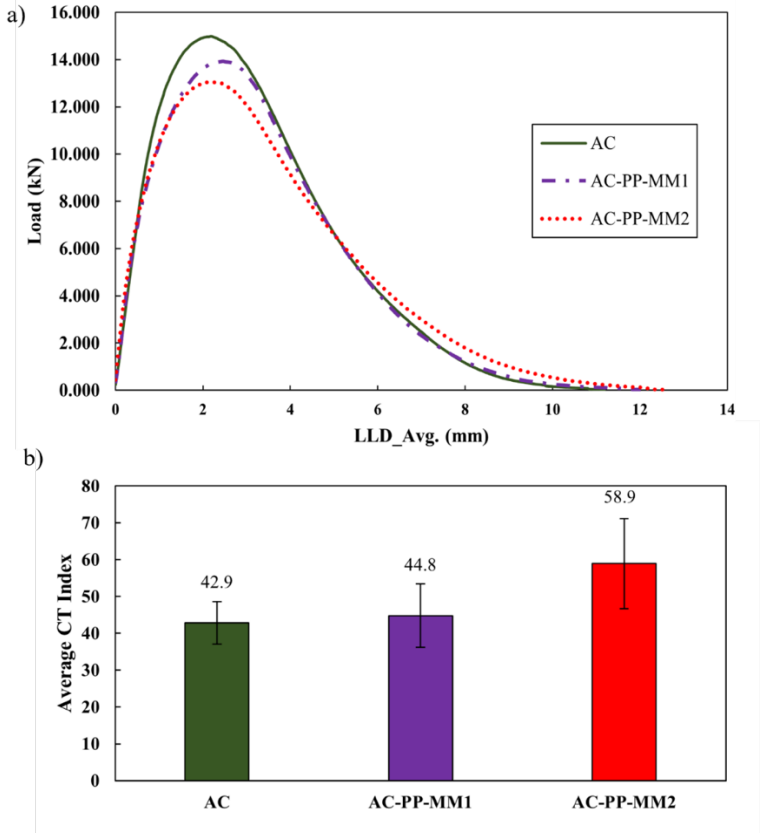

Figure 4.6 IDEAL-CT results: a) Average Load x LLD curves; b) Average CT index.

Table 4.3 Fracture energy parameters for CT index calculation.

Mixture	Sample	Gf (J/m²)	m75 (kN/mm)	l75 (mm)	CT index	Avg CT index
AC	1	6951.1	4.400	3.344	35.2	42.9
	2	7455.7	3.793	3.754	49.2	
	3	7255.9	4.437	4.054	44.2	
AC-PP-MM1	1	7399.7	3.799	4.120	53.5	44.8
	2	6264.0	4.514	3.570	33.0	
	3	7000.5	3.813	3.915	47.9	
AC-PP-MM2	1	6836.1	2.579	3.758	66.4	58.9
	2	6418.8	2.613	4.190	68.6	
	3	7449.2	4.245	3.541	41.7	

Although AC presents the highest peak load of all mixtures, its post-peak behavior shows the steepest slope (higher |m75| value), which may indicate macro-crack propagation at a faster rate and justify the lowest CT index. Regarding PP addition, AC-PP-MM1 shows a slight change in the post-peak slope compared to AC, which might explain the small increase in the CT index. For AC-PP-MM2, it is noticeable that the post-peak slope became even less steep (lower |m75| values, especially for samples 1 and 2), which can indicate a less brittle behavior, resulting in the highest CT index among all mixtures.

Possibly, coating the aggregates with the WP could have made a greater contribution to the adhesion between all the components of the mixture, enhancing the mixture's cracking resistance. Additionally, AC-PP-MM2 presents a slight difference in the pre-peak slope compared to AC and AC-PP-MM1, which may indicate that adding WP as a mixture modifier may provide a higher initial stiffness present, corroborating the HWTT results. Nonetheless, both plastic-modified mixes suggest improved cracking resistance due to a higher CT index.

Although the average CT index value for plastic-modified mixes increased, AC, AC-PP-MM1, and AC-PP-MM2 exhibited similar fracture energies and l_{75} values. Therefore, to further

verify the significance of the difference between the CT indexes of the three mixtures, a statistical analysis was performed.

Tukey's Honestly Significant Difference (HSD) test was conducted at a 95% confidence level, after determining the p-value through an Analysis of Variance (ANOVA) with a significance level of $\alpha = 0.05$. A p-value lower than this significance level indicates that at least one mixture differs significantly from the others. From Tukey's HSD analysis, all mixtures were categorized into a single group (A). Mixtures within the same group are not significantly different from each other. The results are presented in **Table 4.4**.

Table 4.4 Tukey's HSD results considering the CT indexes of the mixtures.

Mixture	Mean	Std deviation	Group
AC	42.87	5.79	A
AC-PP-MM1	44.80	8.61	A
AC-PP-MM2	58.90	12.20	A

The results indicate that WP addition as either an aggregate (AC-PP-MM1) or a mixture modifier (AC-PP-MM2) did not result in any statistically significant changes in the intermediate cracking resistance of the control mixture (AC). However, the change in the mixture's behavior observed in the curves presented in Figure 4.6, especially for AC-PP-MM2, suggests the need for further studies to evaluate the effects of PP addition on the cracking resistance of the HMA, specifically considering long-term performance.

It is worth mentioning that one of the main concerns when adding plastic to HMA is the increase in brittleness of the mixture, demonstrated by a steeper post-peak slope, which results in lower mid-temperature cracking performance. [8,103]. This was not the case observed in the study. One possibility is that the WP coating can improve the overall adhesion between all the

components of the mixture. According to Radeef et al. [9], the enhanced dry method could have also boosted the plastic digestion process by creating a thin layer of WP-modified binder on the aggregate surface, improving the binder's rheological properties and maintaining the mixture's resistance to macrocrack initiation and propagation.

4.3 Effects of WP type on Plastic Mixtures Mechanical Performance and Bonding Characteristics

From this stage, MM2 was used to produce new asphalt mixtures to verify the effects of WP type (i.e., LDPE and PP) on HMA performance and bonding among the HMA components.

4.3.1 Rutting and Moisture Damage Resistance

The strain x load cycles graphs and curve-fitting process for each mixture are shown in Figure 4.7. The indices next to the mixtures (1 and 2) represent the left and right wheel results, respectively. Additionally, Table 4.5 and Table 4.6 show the parameters obtained for each pair of samples and the average results, considering both moisture susceptibility and rutting performance.

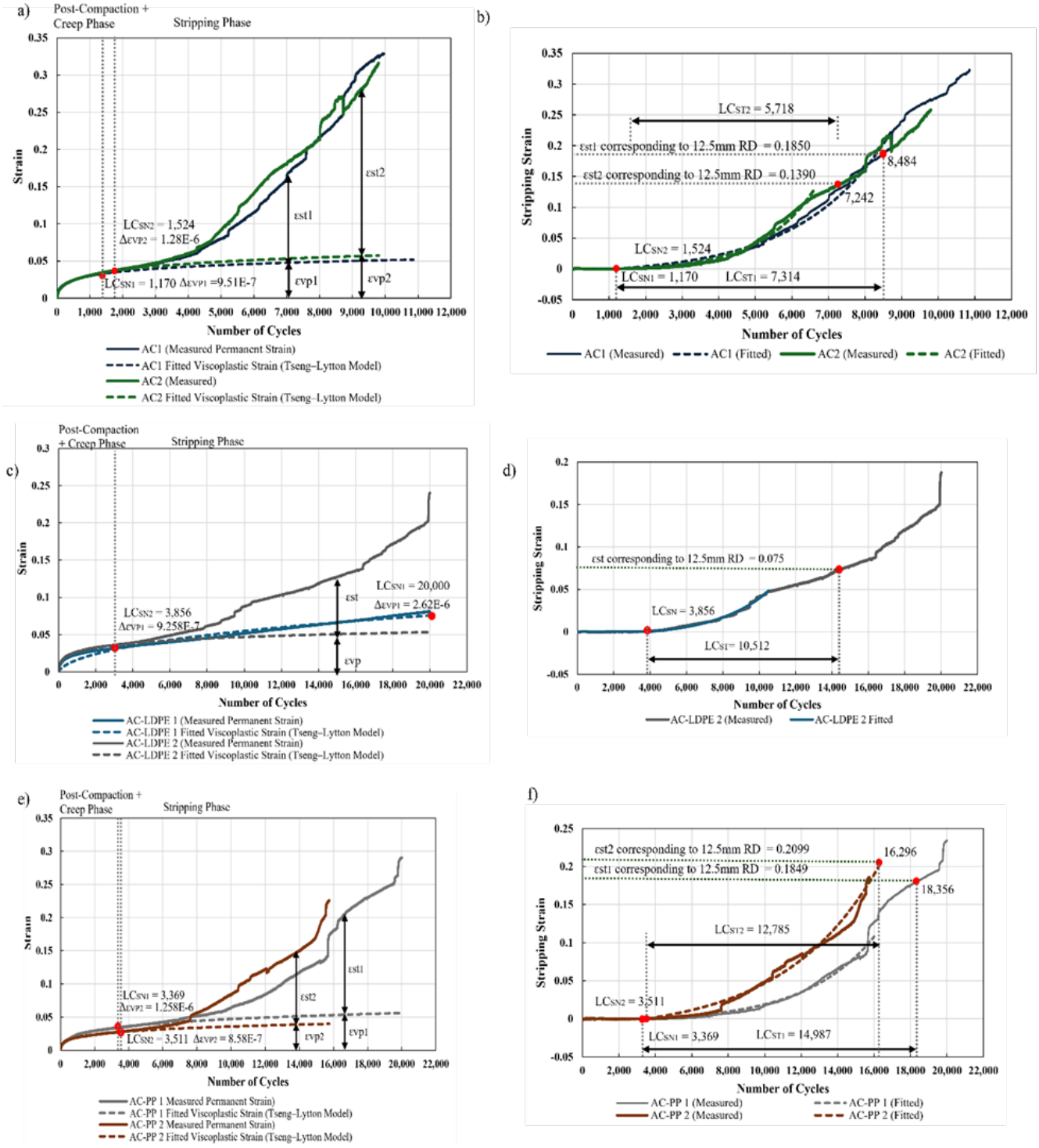

Figure 4.7 Curve fitting results: (a) Viscoplastic Strain for AC; (b) Stripping Strain for AC; (c) Viscoplastic Strain for AC-LDPE; (d) Stripping Strain for AC-LDPE; (e) Viscoplastic Strain for AC-PP; (f) Stripping Strain for AC-PP.

Table 4.5 Moisture susceptibility parameters.

Mixture	Sample pair	LC_{SN}		LC_{ST}		SIP	
		LCS_N	Avg. LC_{SN}	LC_{ST}	Avg. LC_{ST}	SIP	Avg. SIP
AC	1	1,170	1,347	7,314	6,516	5,452	5,000
	2	1,524		5,718		4,548	
AC-LDPE	1	>20,000	>11,928	-	>10,512	19,999	15,835
	2	3,856		10,512		11,670	
AC-PP	1	3,369	3,440	14,987	13,886	11,653	10,330
	2	3,511		12,785		9,006	

Table 4.6 Rutting parameters.

Mixture	Sample pair	$\Delta\varepsilon_{VP}$		Number of Cycles @ 12.5 mm RD	
		$\Delta\varepsilon_{VP}$	Avg. $\Delta\varepsilon_{VP}$	Number of Cycles	Avg. Number of Cycles
AC	1	9.51E-07	1.12E-06	7,632	7,619
	2	1.28E-06		7,606	
AC-LDPE	1	2.62E-06	1.77E-06	>20000	>19,924
	2	9.25E-07		19,848	
AC-PP	1	1.25E-06	1.05E-06	16,536	16,006
	2	8.57E-07		15,476	

Considering only moisture damage, AC, AC-PP, and AC-LDPE (sample pair 1) mixtures present a stripping phase, which indicates that the stripping effects occurred within the 20,000 load cycles. Consequently, their permanent strain values result from both load application (viscoplastic strain) and moisture damage (stripping strain). For AC-LDPE (sample pair 2), no stripping phase was observed during the load cycles, which could suggest that the applied load was responsible for all the permanent strain on the samples. Figure 4.8a shows the average results for LC_{SN}, LC_{ST}, and $\Delta\varepsilon_{VP}$.

For AC samples, moisture effects are induced in the mixtures after 1,347 cycles, while for AC-PP and AC-LDPE 1, they occur after 3,440 and 3,856 cycles, respectively. The higher LC_{SN} for plastic-modified mixtures correlates to lower moisture susceptibility compared to the

control mixture. For AC-LDPE 2, the LC_{SN} is considered to be 20,000 cycles, as no stripping occurred during the test. Considering the stripping life parameter, mixtures with higher LC_{ST} values tend to be less susceptible to moisture after reaching the stripping number. This is observed for AC-PP (13,886 cycles) and AC-LDPE 1 (10,512 cycles) compared to AC (6,516 cycles) [84]. The increase in the stripping number and stripping life after WP coating was 155.38% and 113.10% for AC-PP, and 785.52% and 61.32% for AC-LDPE (considering samples 1 and 2, with AC-LDPE 2 not having an LC_{ST} number). These results suggest that WP coating, especially with LDPE, can improve the moisture damage resistance of the control mixture and reduce stripping.

For rutting analysis, the $\Delta\varepsilon_{VP}$ parameter increased from 1.12E-06 to 1.77E-06 for AC-LDPE and decreased to 1.05E-06 for AC-PP. The higher value for AC-LDPE is due to the lack of a stripping phase for AC-LDPE 2, which indicates that the viscoplastic strain is responsible for all permanent strain on the sample. It is worth mentioning that all results remain similar to the control mixture, suggesting that the increase in viscoplastic strain did not significantly alter the mixture's performance after WP addition. For this reason, it is not possible to correlate WP coating with the rutting resistance.

The results obtained using the new protocol can also be compared to the commonly analyzed performance parameters. Figure 4.8b shows the average number of load cycles at 12.5 mm rut depth and SIP for all mixtures. Considering moisture susceptibility, higher SIP values can be correlated with greater resistance to water damage. Coating the aggregates with WP increased the number of cycles corresponding to SIP by 216.70% for LDPE and 106.60% for PP, showing trends similar to those observed in the LC_{SN} and LC_{ST} analyses. The number of cycles corresponding to 12.5 mm rut depth also increased for WP-modified mixtures, particularly for

LDPE, which may indicate higher rutting resistance. As previously mentioned, the current methodology does not differentiate rut depth caused by load application from that caused by stripping, which may explain the differences in the number of load cycles to the $\Delta\varepsilon_{VP}$ parameter analyzed in the new protocol.

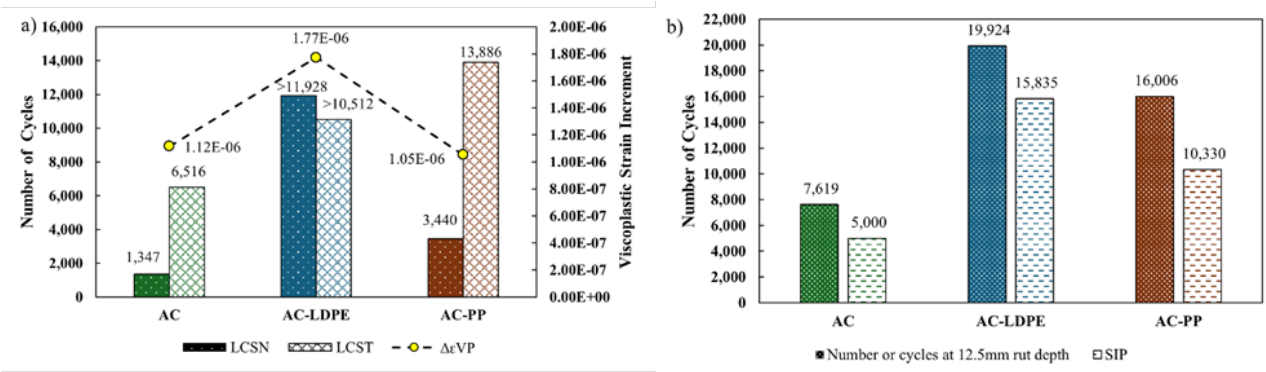

Figure 4.8 Average HWTT results: (a) LC_{SN}, LC_{ST}, and $\Delta\varepsilon_{VP}$; (b) Number of cycles at 12.5mm rut depth and SIP.

4.3.2 Intermediate Temperature Cracking Performance

Figure 4.9 (a and b) shows the average Load x LLD curves and CT indices, respectively. Table 4.7 presents fracture parameters obtained from the test.

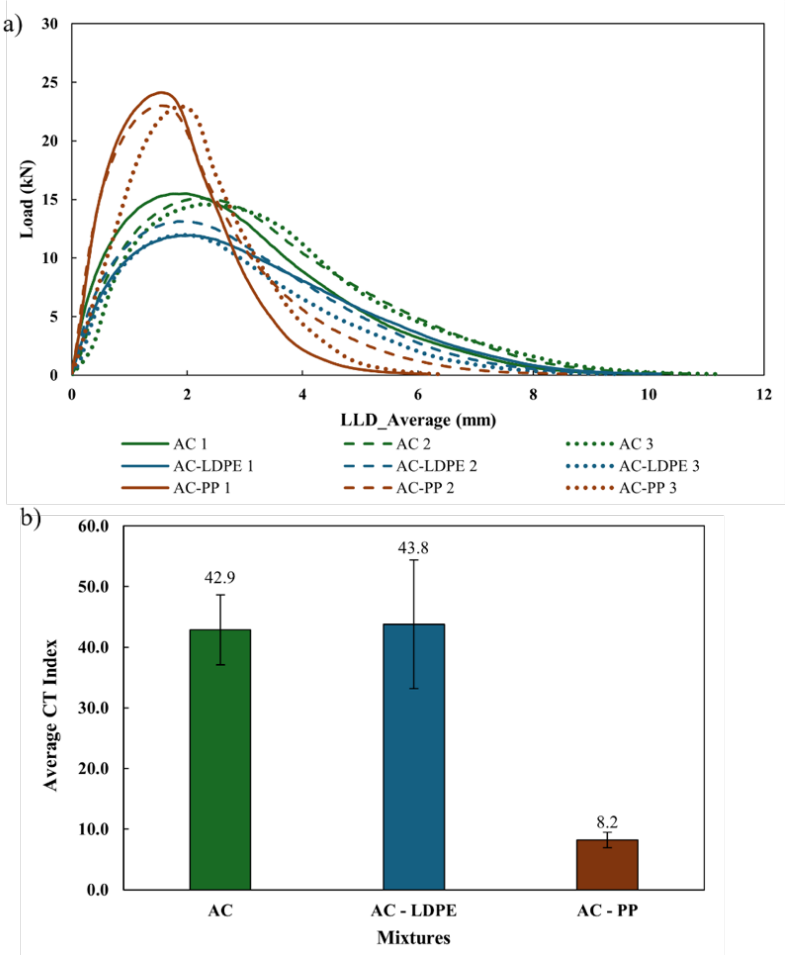

Figure 4.9 IDEAL-CT results for AC, AC-LDPE, and AC-PP mixtures: a) Average Load x LLD curves; b) Average CT index.

Table 4.7 IDEAL-CT parameters of AC, AC-LDPE, and AC-PP.

Mixture	Sample	Gf (J/m²)	m75 (kN/mm)	l75 (mm)	CT index	Avg CT index
AC	1	6951.1	4.400	3.344	35.2	42.9
	2	7455.7	3.793	3.754	49.2	
	3	7255.9	4.437	4.054	44.2	
AC - LDPE	1	5857.9	2.467	3.639	57.6	43.8
	2	5914.0	3.198	3.400	41.9	
	3	5506.0	3.388	3.228	31.8	
AC - PP	1	6199.9	13.795	2.211	6.6	8.2
	2	7114.2	11.185	2.292	9.7	
	3	6181.9	12.495	2.496	8.2	

From the results, it can be observed that even though the control mixture (AC) presents higher fracture energy and peak-load, the addition of LDPE WP resulted in a less steep post-peak behavior (lower |m75| value), indicating a slower macro-crack propagation rate. This resulted in similar CT indices for both mixtures.

Regarding the addition of PP, the outcomes were different from expected. The results obtained in Task 2 suggested that coating the aggregates with WP could improve the rutting and minimize moisture susceptibility without compromising the cracking resistance. This conclusion was valid for AC-LDPE. However, for AC-PP, the post-peak slope increased by 197% and 314% compared to AC and AC-LDPE, respectively, indicating that the cracks propagate extremely fast, which may justify the low CT index. Additionally, the displacement after peak (l75 value) decreased after PP incorporation, resulting in less ductile behavior.

It is important to recall that the mixing procedure from Task 2 was adjusted for Task 3 and 4. The two main changes consisted of 1) adding WP to the full aggregate blend (coarse and fine aggregates, rather than just the coarse aggregates, and 2) adding part of the binder in the initial mixing process. One hypothesis is that not all PP particles were able to melt in the adjusted mixing procedure. In Task 2, PP particles in contact with pre-heated coarse aggregates alone could melt more easily. Additionally, adding just a fraction of the OBC to the plastic-coated coarse aggregates can create a thin layer of modified binder and boost the plastic digestion process, promoting complete melting of the WP [8,9] while not significantly impacting the cracking resistance. In the case of LDPE, since the melting point is lower, its addition to the full blend of pre-heated aggregates was enough to melt the WP, resulting in an improved bonding resistance.

To further verify the significance of the difference between the CT indexes of the mixtures, especially AC and AC-LDPE, a statistical analysis following Tukey's HSD test was conducted at a 95% confidence level, after determining the p-value through ANOVA with a significance level of $\alpha = 0.05$. After analysis, all mixtures were categorized into two distinct groups (A and B), as shown in Table 4.8. As expected, the CT index for AC-PP was categorized into group B, verifying the sharp decrease in the mixture's cracking resistance after PP addition. Additionally, no statistically significant changes were noticed in the overall cracking resistance of the control mixture after LDPE incorporation, maintaining similar performance.

Table 4.8 Tukey's HSD results considering the CT indexes of AC, AC-LDPE, and AC-PP.

Mixture	Mean	Std deviation	Group
AC	42.9	5.79	A
AC-LDPE	43.8	10.62	A
AC-PP	8.2	1.26	B

4.3.3 Bonding Characteristics

4.3.3.1 Thermodynamic Properties

The measured contact angles for the asphalt binder and LS aggregates, with and without coating, are shown in Table 4.9. The results for LS without plastic coating are similar to values reported by other authors [92,104]. Considering the water contact angles, the wettability of the aggregate surface can be inferred. Generally, a solid surface is considered hydrophobic when the contact angle exceeds 90º. That indicates that the surface's wettability is reduced, weakening the attraction forces between the solid surface and water as the contact angle increases [93]. For both WP coatings, the water contact angles increased compared to the original aggregate, particularly

for LDPE. This suggests that the hydrophilic LS surface (θ = 61.41 ºC) may have been transformed into a hydrophobic material (θ = 96.66 ºC).

Table 4.9 Contact angle measurements.

Material	Distilled water		Formamide		Diiodomethane		Glycerol	
	θ (º)	SD	θ (º)	SD	θ (º)	SD	θ (º)	SD
LS	61.41	5.02	48.71	6.52	66.18	1.58	-	-
LS + LDPE	96.66	2.12	78.24	6.01	64.32	1.79	-	-
LS + PP	83.69	0.53	71.43	8.31	65.69	4.73	-	-
Binder	101.92	1.76	98.39	4.12	-	-	100.83	4.53

To further verify the results when calculating change in water contact angle of the aggregate surface, a statistical analysis was performed using Tukey's Honestly Significant Difference (HSD) methodology (confidence level of 95%) and the Analysis of Variance (ANOVA), with a significance level of α = 0.05. The three aggregate samples were classified into distinct groups: Group A (LS+LDPE), Group B (LS+PP), and Group C (LS). Since no aggregate surface belongs to the same group, this indicates that the contact angle values are significantly different from each other. This conclusion aligns with previous findings that the WP coating may reduce the hydrophilicity of the aggregate surface, making it less susceptible to water damage [58,66].

After measuring the contact angles, the SFE components of the materials were determined using Equation 3.10. The results in Figure 4.10 show that WP coating reduced the polar components of the solid surface, particularly with LDPE. Since the binder is primarily a non-polar material, reducing the polar components of the aggregate surface could improve binder-aggregate adhesion.

Compared to the Lewis acid-base results, the effects of WP coating on the polar components were less pronounced, showing only a slight increase in the Lifshitz-van der Waals values. Additionally, the polymeric treatment reduced the total SFE of the material, likely due to the inherently lower SFE components of the polymer itself. These findings indicate that the WP coating can alter the overall aggregate surface properties, a trend also observed in previous studies [58,66].

Xiao et al. [58] suggested that the decrease in the total SFE of the aggregate surface could indicate higher wettability to either the asphalt binder or water. The reduced water wettability was already correlated with increased contact angles and HWTT results (higher LC_{SN}, LC_{ST}, and SIP values). To further investigate the effects of WP on binder-aggregate adhesion and wettability, the BBS test was conducted.

It is worth mentioning that the SFE values presented in this paper differ from those obtained in the literature. Many studies reported varying SFE component values for LS [58,66,92,104], highlighting the variability in the results. This variation could be attributed to the use of different probe liquids, testing methodologies (i.e., Universal Sorption Device (USD) [58,66] or SSD [92,104] different binder and aggregate sources, and variability within the contact angle readings. Therefore, it is important to acknowledge the complexity in determining the accuracy of the results. However, similar trends were observed regarding the polarity of the materials. For example, LS is a basic rock, which is confirmed by its higher ɣ- components.

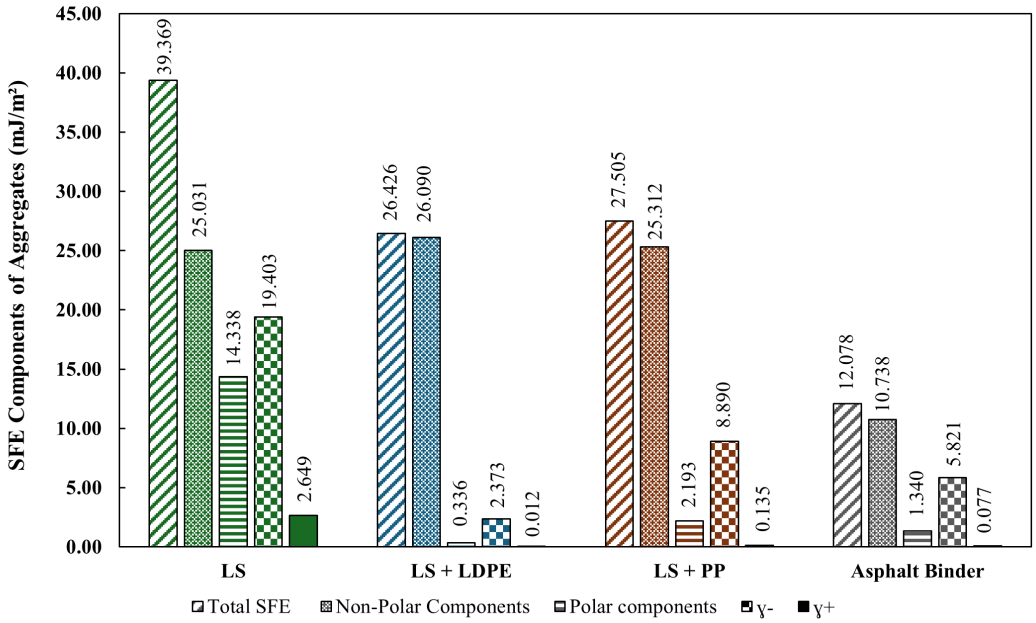

Figure 4.10 SFE components of the materials.

4.3.3.2 Binder-aggregate Bond Strength

Figure 4.11 shows the average pull-off tensile strength for aggregate particles with and without plastic coating. After the addition of plastic, the maximum pull-off strength required to detach the dolly from the solid surface increased by 244.09% for LDPE and 155.91% for PP, which may indicate an improvement in the binder-aggregate adhesion. Other authors observed similar trends, even with different BBS test methodologies. For example, Lucas Júnior et al. [105] evaluated the bond strength between binder and plastic-bag-coated phonolite aggregates using a Lottman test, finding higher adhesiveness between the materials and, consequently, greater moisture damage resistance. Goli et al. [103] coated the aggregates with shredded waste polyethylene (at 4%, 6%, and 8%), also noting an increase in bond strength, especially for higher WP contents.

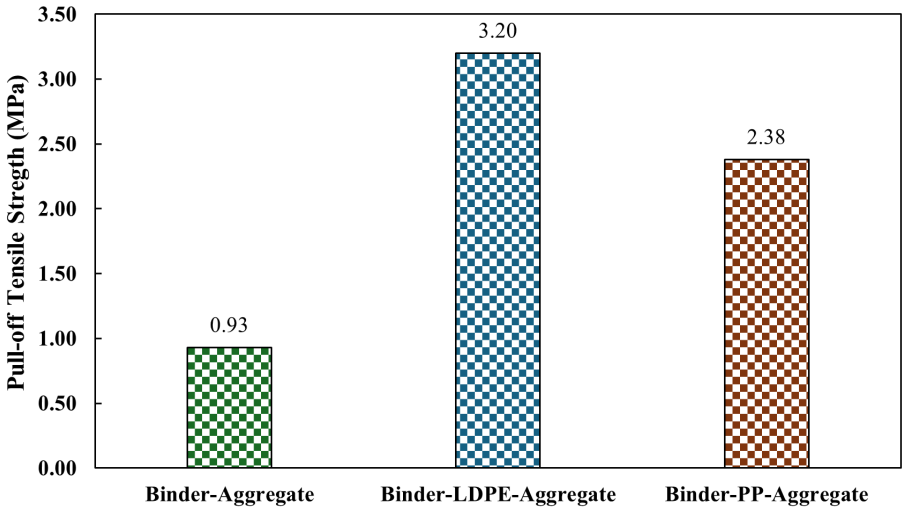

Figure 4.11 POTS test results.

Additionally, Figure 4.12 shows the dollies after detaching from the aggregate surface. For the rock without plastic coating in Figure 4.12a, it is observed that the asphalt binder, along with small parts of the aggregate itself, was detached from the surface, indicating a cohesive failure due to the separation of molecules within the asphalt layer [106,107]. Figure 4.12b and Figure 4.12c represent the dollies after the POTS test for LDPE and PP plastic coating, respectively. In both cases, only parts of the asphalt binder were removed from the aggregate, which could indicate an increase in the adhesion between the materials, as it was harder to detach the binder from the solid surface. For the plastic coating, the failure pattern occurred at the binder-aggregate interface, representing an adhesive failure [106]. When comparing both types of WP, the LDPE coating may have shown higher adhesiveness, as evidenced by the higher pull-off strength and lower amount of binder on the dolly after the POTS test. These results also corroborate the conclusions drawn from the HWTT and SFE measurements.

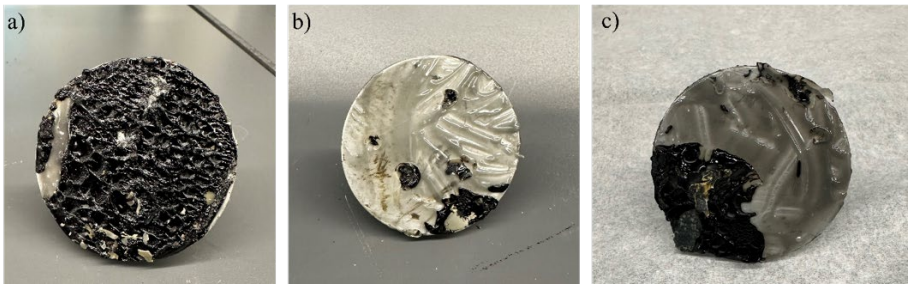

Figure 4.12 Dollies after the POTS test: (a) Binder-Aggregate; (b) Binder-LDPE-Aggregate; (c) Binder-PP-Aggregate.

4.4 Effects of 1% LDPE Addition on Recycled Nebraska Mixtures (NDOT SPR) and Comparison of Lab and Plant-produced Mixtures

4.4.1 Rutting and Moisture Damage Resistance

The load cycles versus rut depth graph for both the lab and plant-produced mixtures is shown in Figure 4.13. The indices next to the mixtures (1 and 2) represent the left and right wheel, respectively. Figure 4.14 also shows the average moisture susceptibility and rutting performance parameters, considering both conventional pass-fail criteria and the separation of stripping and viscoplastic strain.

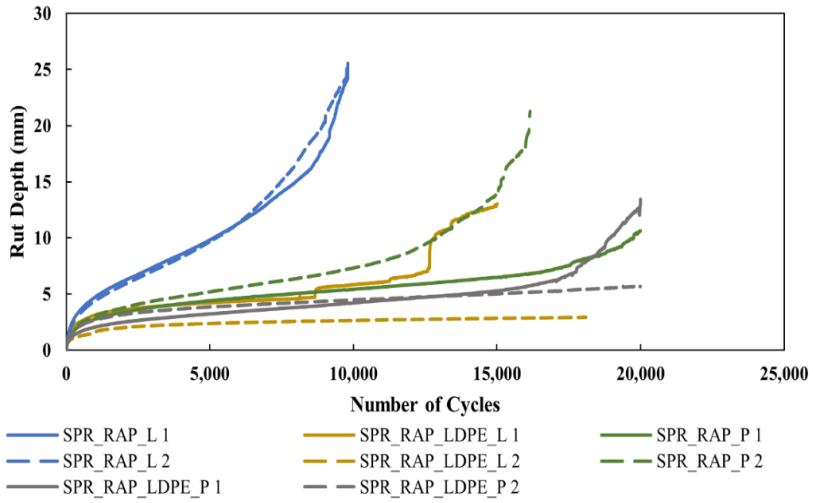

Figure 4.13 Number of cycles versus rut depth graph for SPR_RAP and SPR_RAP_LDPE mixes.

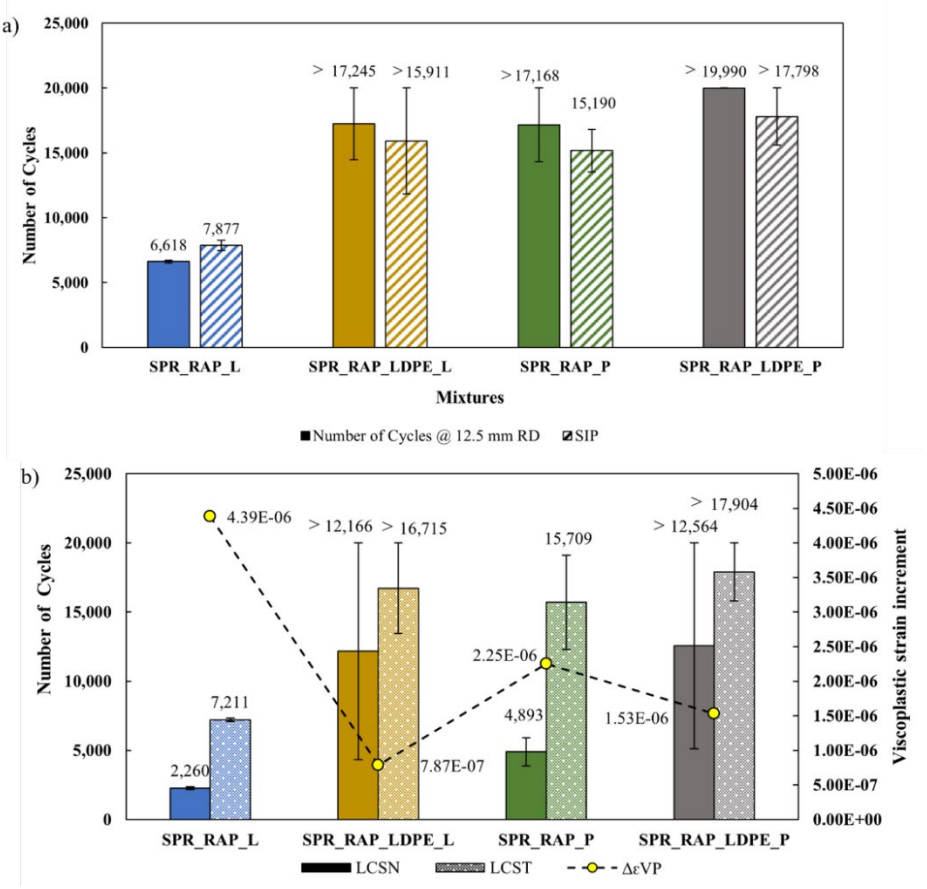

Figure 4.14 Average HWTT results: (a) Number of cycles at 12.5mm rut depth and SIP; (b) LC_{SN}, LC_{ST}, and $\Delta\varepsilon_{VP}$.

From Figure 4.13, for plastic-modified mixes (lab- and plant-produced), one of the samples (i.e., SPR_RAP_LDPE_L 2 and SPR_RAP_LDPE_P 2) did not present a stripping phase within the first 20,000 cycles, suggesting that the applied load was responsible for all the permanent strain on the samples (no damage due to moisture). For the other mixtures, the permanent strain results from load application (viscoplastic strain) and moisture damage (stripping strain).

Considering only the effects of LDPE addition, the WP was able to improve the resistance against rutting and moisture damage in both lab and plant-produced mixes. For SPR_RAP_L, the stripping number of the mixture increased by 161%, while the viscoplastic

strain increment decreased by 82%. Additionally, SPR_RAP_LDPE_L seems to be less susceptible to moisture after the stripping number due to higher LC_{ST} values. Similar trends were observed when analyzing the number of cycles to reach 12.5mm rut depth, which went from 6,618 to 17,245, and the SIP, which increased by 102%. For SPR_RAP_P, the impacts of LDPE addition on the mixture performance, considering the typical pass-fail criteria, were smaller. However, when analyzing the LC_{SN} parameter, the control mixture suffered damage due to stripping after 4,893 cycles, while for SPR_RAP_LDPE_P, that occurred after 12,564 cycles. The higher LC_{SN} and LC_{ST} values for plastic-modified mixtures in both cases can be correlated with lower moisture susceptibility compared with the reference mixture, while the lower $\Delta\varepsilon_{VP}$ numbers indicate higher resistance against permanent deformation.

When comparing the lab and plant-produced mixtures, a similarity was noticed between both LDPE mixes. Although SPR_RAP_LDPE_P presents a slightly higher SIP parameter, the two mixtures show similar stripping numbers and life values, which may indicate equivalent performance against moisture damage. Additionally, while the plant-produced LDPE mix shows a higher number of cycles at 12.5 mm rut depth, the lab-produced mix shows a lower $\Delta\varepsilon_{VP}$ value, indicating enhanced rutting resistance. This highlights the importance of separating the contributions for load application and stripping. Also, both mixtures show matching variability within the results, highlighting the similarity among the mixes. Finally, it was noticed that the control mixtures presented different results when prepared in the lab and at the asphalt plant. SPR_RAP_L presents lower rutting and moisture damage resistance compared to SPR_RAP_P. Further binder studies should be considered to evaluate the rheological properties of the asphalt binder extracted from the lab and plant-produced mixes.

4.4.2 Intermediate Temperature Cracking Resistance

The average Load versus LLD curves and CT indices of both lab and plant-produced mixes are shown in Figure 4.15. Additionally, the fracture parameters obtained during the test are presented in Table 4.10.

When analyzing the LDPE incorporation, SRP_RAP_LDPE_L exhibits higher initial stiffness compared to the control lab-produced mixture (steeper pre-peak slope), which is corroborated by the HWTT results. Although it presents higher fracture energy, it also exhibits a steeper post-peak slope, indicating that cracks may initiate and propagate at a faster rate in the plastic-modified mix, represented by a lower CT index. Similar results were found by other authors (*7*, *38*). For the plant-produced mixes, SPR_RAP_LDPE_P presents a higher displacement after peak (average of 5.421mm compared to 4.791mm of the control mixture), indicating a more ductile behavior. Additionally, the steeper post-peak slopes and lower fracture energies of SPR_RAP_P justify its lower CT index.

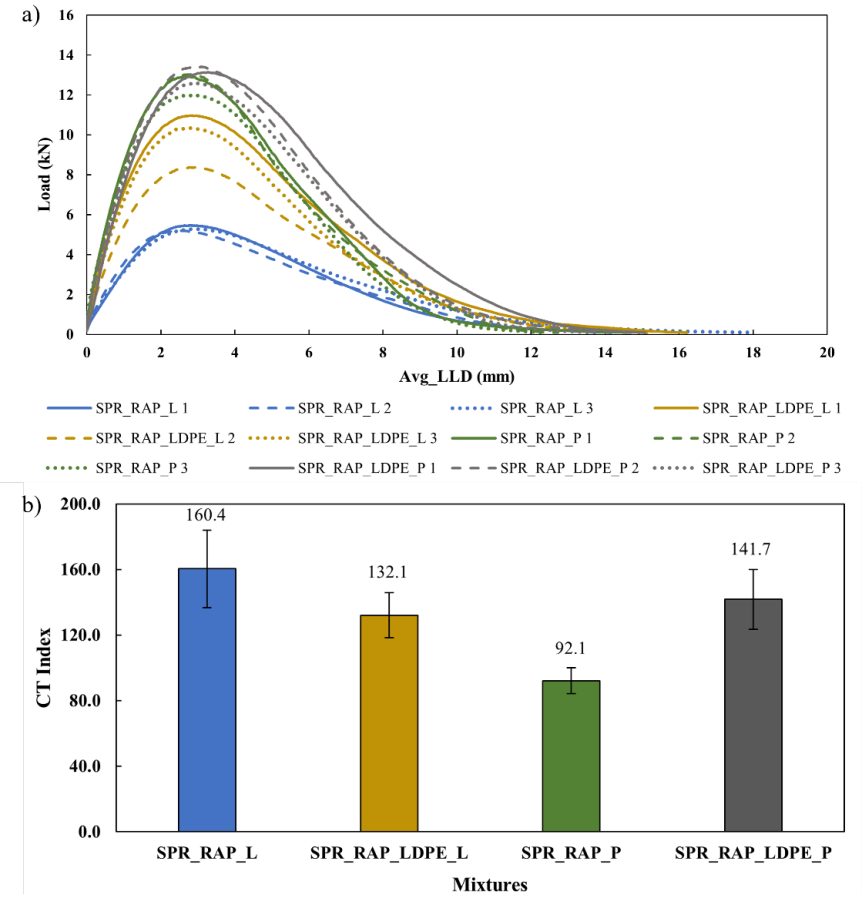

Figure 4.15 IDEAL-CT test results: (a) LLD versus Load curves; (b) average CT indexes.

Table 4.10 IDEAL-CT parameters for NDOT SPR mixtures.

Mixture	Sample	Gf (J/m²)	m75 (kN/mm)	l75 (mm)	CT index	Avg CT index
SPR_RAP_L	1	3611.1	0.869	5.132	141.8	160.4
	2	3598.0	0.763	4.867	152.5	
	3	3996.3	0.759	5.351	186.9	
SPR_RAP_LDPE_L	1	7553.4	1.874	5.095	137	131.9
	2	5729.3	1.337	5.0	142.6	
	3	6720.6	1.893	4.905	116.1	
SPR_RAP_P	1	7908.8	2.596	4.807	97.1	92.1
	2	7953.7	2.938	4.658	83.1	
	3	7337.7	2.48	4.908	96	
SPR_RAP_LDPE_P	1	9452.3	2.231	5.755	162.3	141.7
	2	8832	2.41	5.242	127.9	
	3	8276.9	2.155	5.267	134.9	

When comparing the lab and plant-produced mixtures, plastic-modified mixes presented similar CT indexes, with SPR_RAP_LDPE_P exhibiting a slightly higher value than SPR_RAP_LDPE_L. The control samples, on the other hand, present very distinct cracking performance, with SPR_RAP_P showing the lowest CT index. This outcome corroborates the trends obtained in the HWTT tests, where plant-produced control mixtures showed better rutting resistance than lab-produced samples, which would typically correspond to lower cracking resistance. Additional verifications must be conducted to give conclusive reasons for the different results obtained for the non-plastic (control) mixtures.

To further verify the significance of the difference between the CT indices of the four mixtures, a statistical analysis was conducted using Tukey's HSD test at a 95% confidence level, following an ANOVA analysis with a significance level of $\alpha = 0.05$. The SRP_RAP_L and SPR_RAP_LDPE_P were categorized in the same group (A) (Table 4.11), representing the higher CT indices. SPR_RAP_P was placed under group B, representing the lowest CT index. SPR_RAP_LDPE_L was categorized into both groups (A and B). indicating that the LDPE addition either maintained or improved the intermediate temperature cracking resistance of the control mixtures. Additionally, both plant and lab-produced LDPE mixes exhibited similar performance, indicating the possibility of implementing the mixing protocol in the asphalt plants.

Table 4.11 Tukey's HSD results considering the CT indexes of NDOT SPR mixes.

Mixture	Mean	Std deviation	Group
SPR_RAP_L	160.4	23.57	A
SPR_RAP_LDPE_L	131.9	13.97	A, B
SPR_RAP_P	92.1	7.78	B
SPR_RAP_LDPE_P	141.7	18.18	A

Chapter 5 Conclusions and Recommendations

This study assessed the feasibility and potential implementation of WP into the asphalt concrete, focusing on performance-based parameters recommended by the new BMD protocols. Considering the materials and studied blends used herein, the main conclusions of this study can be seen below:

- When evaluating the effects of the aggregates' pre-heating temperatures, it was noticed that the use of WP, as a mixture modifier (coating the aggregates), enhances both rutting and moisture damage resistance. In contrast, WP as aggregates can negatively impact performance, probably due to the shape of the pellets and reduced film thickness.

- The bonding characteristic tests indicated that the WP coating could result in a more hydrophobic aggregate surface, reducing the polarity of the aggregate surface and increasing the binder-aggregate adhesion.

- Comparing two different types of WPs, LDPE addition resulted in higher performance compared to PP, probably due to its lower melting point, which could have facilitated the coating process.

- Generally, WP addition did not result in any statistically significant change in the cracking performance at short-term aging condition. However, for PP mixes, the resistance decreased considerably compared to LDPE and control samples.

- Considering the effects of 1% WP addition on both lab and plant-produced NDOT SPR mixes, the LDPE was able to improve the respective control mixture's resistance against rutting and moisture damage, as well as cracking performance. Although a reduction in the cracking resistance for plastic-modified mixtures is expected due to an enhancement in their stiffness (steeper pre-peak slopes), no concerns were observed for SPR_RAP_LDPE_L and SPR_RAP_LDPE_P when considering short-term conditions.

- Finally, both lab and plant-produced LDPE mixes showed similar cracking, rutting, and moisture damage performance, indicating that it is feasible to implement the laboratory mixing procedure in a large-scale asphalt plant.

- In general, considering performance-based parameters, the binder-aggregate adhesion, and energy savings, especially due to its lower melting point when compared to other types of WP (such as PP), resulting in lower pre-heating temperatures, LDPE presents itself as a suitable WP alternative for asphalt mixtures modification via the dry method, facilitating the coating process and its implementation into the asphalt plants.

Reccomendations and Suggested Future Studies

- For a continuous evaluation of the feasibility and potential implementation of WP into the HMA, future studies should include analyzing the long-term effects of LDPE addition on both lab and plant-produced mixes. Field monitoring should also be conducted to evaluate the effects of temperature on the HMA. Additionally, other important performance parameters should be evaluated, such as low-temperature cracking.

- Microstructural analysis should also be considered for a deep understanding of the effects of WP addition on both rutting and cracking resistance. Binder extraction and analysis, including rheological parameters and ductility tests, should be conducted to evaluate potential modification of the asphalt binder after WP coating.

- Considering the environmental aspects of WP incorporation, future studies should consider performing a life cycle analysis and evaluating microplastic release and the toxicity of the fumes emitted during the production process. Additionally, the recyclability of RAP containing WP should also be assessed.

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