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Effects of the simultaneous use of post-industrial polypropylene waste plastic and soybean oil recycling agent on the performance of high-RAP recycled mixtures

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ABSTRACT

Using reclaimed asphalt pavement (RAP) in asphalt concrete (AC) reduces the need for nonrenewable resources. However, excessive RAP can cause premature cracking in pavements due to its stiff and aged nature. To address this issue, studies propose the incorporation of recycling agents (RA) in RAP recycled mixtures. Nevertheless, incorporating RA may reduce mixture's rutting and moisture resistance. Alternatively, incorporating waste plastic in AC can positively balance the RA negative effects. Therefore, this study explores the simultaneous use of polypropylene (PP) waste plastics and soybean oil RA to improve the overall performance of high-RAP mixtures. Due to its high melting point, PP can have different roles in the asphalt mixture depending on the mixing temperature used. To explore that, three different methods of incorporating PP into a high-RAP mixture were attempted. Five different mixtures were developed varying the binder (virgin and modified with RA), and the PP mixing procedure. Then, the mixtures were subjected to performance-based testing procedures (SCB IFIT and HWTT) as well as to boiling test to verify binder-aggregate adhesion. It was confirmed that the use of soybean oil enhances the cracking performance of the high-RAP mixtures, but the rutting and moisture performances were compromised. However, incorporating PP made the mixture more resistant to moisture and rutting in different instances. It was found that pre-heating the aggregates at higher than PP melting point allows a better coating of aggregates by PP, and results in improved binder-aggregate adhesion, leading to better cracking, rutting, and moisture performance of high-RAP mixtures.

1. Introduction

There has been a growing concern about sustainability in different aspects of flexible pavement construction, including the selection of alternative sustainable materials for the asphalt concrete (AC) surface layer in lieu of non-renewable natural resources [1–7]. Among the recycled materials successfully applied in AC, recycled asphalt pavement (RAP) has one of the biggest proportions. According to a 2019 report by the National Asphalt Pavement Association (NAPA, 2019), 21.1 percent of RAP is recycled, and the percentage of RAP use is growing yearly [8]. There are several attempts to increase the amount of RAP on hot mix asphalt (HMA) [9,10]. However, despite the benefit of RAP in AC rutting resistance [11,12], there is a growing concern about AC cracking susceptibility. Most of the studies reported that RAP, being a stiff and aged material, has a higher propensity to reduce the AC cracking performance [13–17]. Untimely, the premature failure of pavement structures due to cracking has been reported [10,11]. There is a need to seek alternatives to using high-RAP mixtures to balance the rutting and cracking performance.

In this periphery, researchers are utilizing additives known as recycling agents to enhance the performance of high-RAP mixture [18,19]. Different categories of recycling agents, from waste engine oil to vegetable oils, have been utilized to enhance the cracking performance of the high-RAP mixture [6,20]. However, in most cases, using highly

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processed commercial recycling agents has increased the cost of producing asphalt mixtures [21,22]. Therefore, consideration has been given to such recycling agents which are locally available and economically feasible. Because of their cost and environmentally friendly nature, vegetable oils such as soybean and corn oils are commonly considered potential candidates as recycling agents [22,23]. Ahmed et al. [24] and Jie et al. [22] recently showed that these oils could enhance the performance of high-RAP HMA. The authors have shown that with the addition of vegetable-based recycling agents into virgin asphalt binder, a desirable cracking performance was gained; however, the moisture performance was observed to be reduced. Some authors suggested that a potential drop in moisture performance of mixtures using vegetable-based recycling agents can be attributed to the prevalence of hydroxyl functional groups on such types of oils, leading to poor binder-aggregate adhesion and, consequently, making the asphalt mixture more susceptible to moisture-induced damage [25,26]. However, it is important to mention that the effect of these additives on asphalt mixture's moisture damage resistance is still not clearly proven. Still, it is well known that using hydrated lime and other commercial moisture-resistive additives could enhance the moisture resistance of HMA, but this process can also result in increased costs and might not serve as an environmentally friendly approach [27,28]. Therefore, other alternatives, such as waste plastics (WPs), must be further explored as a few studies provided evidence that WPs could enhance moisture damage resistance [4,5].

Studies about the use of waste plastics on asphalt pavement are of current focus, and there are many knowledge gaps that need to be addressed. Moreover, there is a need to find recycling strategies for reusing WPs, considering millions of different waste plastics are generated annually. In the current state, the recycling of plastics is minimal; for instance, in the United States, only eight percent of plastic waste was recycled in 2017. Therefore, federal and state government agencies and private plastics industries have been actively exploring sustainable strategies for plastic waste disposal and recycling. One of the potential applications identified is as an HMA constituent material for the surface layer of asphalt pavements. At the current stage of adopting WPs in HMA, there had been a mixed ideology on WPs' effectiveness in enhancing performance. Many studies have shown that adding WPs in HMA enhanced AC tensile strength, cracking, and moisture and rutting resistance [4,5,29,30]. However, the results are dependent on the type and shape of plastic used, the amount of the material added, the addition method, etc. Some studies have reported negative effects on cracking and moisture damage resistance, especially for plastics with high melting point (e.g., [31,32]).

There are two approaches for adding waste plastics to asphalt pavements: (i) wet process: adding the waste plastic directly to the asphalt binder as a polymer modifier or asphalt replacement, and (ii) dry process: adding the waste plastic as either aggregate replacement, mixture modifier, binder modifier, or a combination thereof. In some studies, adding waste plastics improved several HMA performances, such as stiffness modulus, fatigue behavior, rutting resistance, moisture susceptibility, and temperature susceptibility of the mixture [4,5,30, 33–35]. The dry process of incorporating waste plastic into asphalt concrete offers some advantages. Firstly, it allows for the acceptance of a wider variety of waste plastics (WPs) as, irrespective of their melting points, they can be used in melted form or as aggregate substitutes [5]. The dry process can be applied to a wider variety of waste plastics than the wet process, which is only applicable to waste plastics with a lower melting point [34]. There is evidence to suggest that the stiffness of asphalt concrete increases when the dry process is used with low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyethylene terephthalate (PET), and polypropylene (PP) addition [27,28]. In the dry method, one common procedure is to add WPs directly to the pre-heated aggregates at binder mixing temperature [33]. Nevertheless, the impact of waste plastics on asphalt concrete (AC) performance can vary depending on their melting temperature. In some cases, WPs might fully melt, coating the aggregates, while in others, they may only partially melt and serve as additional aggregates [5,34]. This variability leads to distinct effects on different types of cracking rutting and moisture damage resistance when incorporating waste plastics into the mix. In particular, some studies provided evidence that using plastic-coated aggregates could result in enhanced moisture damage resistance due to enhanced adhesion mechanisms between HMA components and the formation of hydrophobic coatings due to plastics [34–36]. However, a comprehensive evaluation is still necessary to fully understand the implications of WPs addition on the overall performance of asphalt concrete.

Moreover, while incorporating waste plastics (WPs) into asphalt concrete (AC) has demonstrated various advantages, its effects on high-RAP mixtures necessitate further investigation. The recommendation of pre-heating aggregates to facilitate WPs incorporation raises concerns about potential extra-aging of RAP, possibly leading to premature cracking failures. Conversely, the addition of WPs could potentially offset some of the negative effects caused by rejuvenator agents in high-RAP mixtures. The simultaneous utilization of WPs and RA in high-RAP mixtures is a relatively recent concept that demands in-depth exploration. Therefore, this study aims to explore the synergistic use of WPs and soybean oil RA to enhance the overall performance of high-RAP mixtures. This study emphasizes polypropylene (PP) as it represents the most prevalent form of municipal solid WP in the United States. Given its significant presence in the waste stream and limited recycling rates, investigating the use of PP in this research becomes especially relevant and crucial to address sustainability challenges to some extent and explore potential solutions for its effective utilization in high-RAP asphalt mixtures modified with vegetable oil-based recycling agent.

2. Objectives and scope

The main objective of this study is to evaluate the effect of different methods of PP addition on the mechanical performance of high-RAP Superpave recycled mixtures (SPR) produced with unmodified and modified binders by soybean oil. More specifically, the objectives of this study are:

- Verify the effects of mixing temperature to enhance PP-aggregate's adhesion: A preliminary visual analysis was conducted to observe the coating of the aggregates used herein (RAP and virgin aggregates), PP, and binder.
- Compare the mechanical performance of high-RAP mixtures with and without the use of crude soybean oil and with the addition of PP in three different mixing methods.

Fig. 1 illustrates the experimental plan adopted in this study. As presented, five different asphalt mixtures were utilized considering the use of virgin binder (VB), virgin binder blend with soybean oil (MB), and three different PP incorporation methods referred to as PP1, PP2, and PP3. More details on these mixtures are provided in the sections that follow.

3. Materials and methods

3.1. Materials

3.1.1. Asphalt binder and recycling agent

A virgin asphalt binder with a performance grade (PG) 64–28 was used in this study. Also, to restore the RAP binder properties, crude soybean oil was used as the recycling agent to produce modified binder samples (MB). The optimum dosage of the recycling agent was determined as 3.5% based on the total weight of the binder according to the PG approach, where the consideration had been made to balance the PG of the blend of 65% recycled asphalt binder and virgin binder at a targeted level. Notably, the PG of extracted and recovered binder from RAP

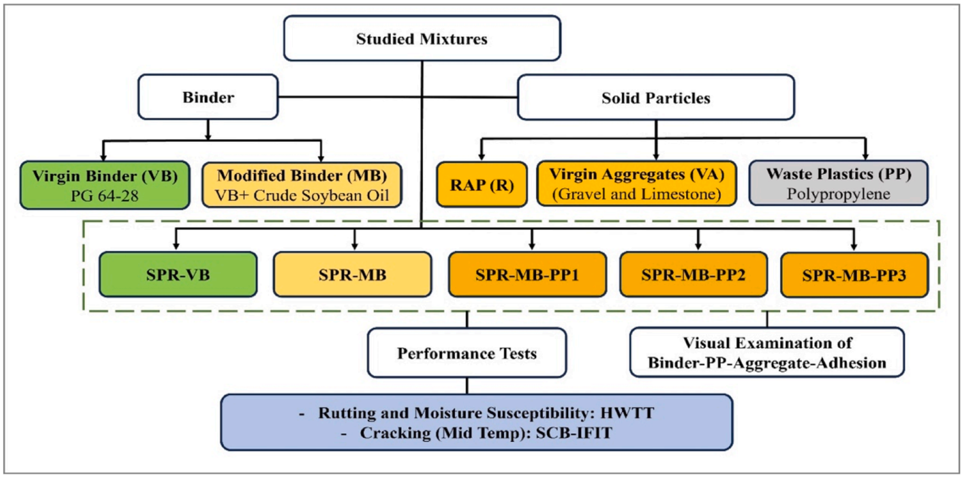

Fig. 1. Experimental plan.

was 81.8–18.0, and the targeted PG was PG 64–28. The necessary details on the procedure of blending the recycling agent and binder are outlined in the study conducted by Ahmed et al. [24].

3.1.2. Aggregates

Virgin aggregates (limestone and gravel) and RAP were used in this study to produce asphalt mixtures with a nominal maximum aggregate size (NMAS) of 12.5 mm. To produce high-RAP recycled HMA, 65% of RAP particles were blended with 35% of virgin materials, percentages with respect to the total mixture weight. This amount of RAP was selected considering the Nebraska Department of Transportation's (NDOT) willingness to use that percentage in the near future. Fig. 2 shows the gradation of the field-collected RAP (after been submitted to the ignition test), the virgin aggregates, the final blend of virgin and RAP materials, and the minimum and maximum control points set by the NDOT.

3.1.3. Polypropylene waste plastic samples

The WPs are oftentimes available in a mixed blend of several types of plastics. However, to limit the number of variables in this study and clearly see the effect of one specific type of WP, one homogenous sample from post-industrial consumers was selected inside the recycling facility. In this study, polypropylene (PP) waste plastics were selected, considering their highest share among all other types of plastic waste [37]. A 2 kg sample was collected in the shape of pellets. Figs. 3a and 3b show a sample of the collected PP and its particle size distribution. In addition,

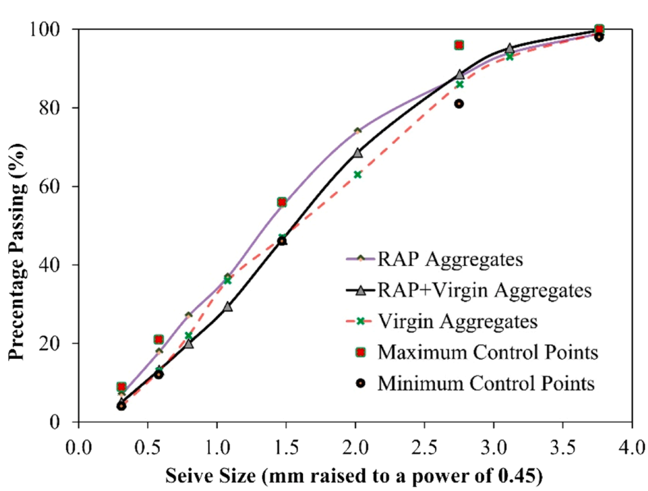

Fig. 2. Aggregate gradation chart.

FTIR analysis was performed to validate the collected plastics as PP, and the test results are presented in Fig. 3c. The peaks observed from FTIR analysis confirmed the plastic type as PP. Similar peaks at around the wavelength of 1500 and 2900 cm^{-1} have been reported in different studies conducted by other researchers [37,38].

3.2. Studied mixing methods for PP addition

WPs, when added in the dry method, can have different roles on the mixture, i.e., as an aggregate particle, as a mixture modifier, as a binder modifier, or a combination of these (NCHRP 9–66). As an aggregate particle, it is not expected that the WPs will melt. However, at temperatures above the melting point, it is expected that part or total WPs particles will melt and work as a mixture or binder modifier. To capture those scenarios and considering the melting temperature of PP approximately 160–165° C [27], three mixing methods were evaluated in this study. The details for each of the procedures are described in the following paragraphs and illustrated in Fig. 4.

Mixing Method 1 (MM1): PP, RAP, virgin aggregates (VA) and modified binder (MB) are mixed at the binder mixing temperature. Adding PP to a heated RAP at binder mixing temperature could be more feasible considering the current practices in asphalt plants.
Mixing Method 2 (MM2): RAP is heated at 180° C for one hour and mixed with PP. Then the mixture of RAP and PP was heated at a mixing temperature of 156° C alongside VA for two hours and eventually mixed with MB maintained at the mixing temperature.
Mixing Method 3 (MM3): PP is added to virgin coarse aggregates heated to 180° C, forming PP-coated coarse aggregates. The coated virgin coarse aggregates are mixed with RAP, fine aggregates, and binder maintained at 156° C for two hours. This case doesn't age the RAP binder as in cases I and II, considering a higher temperature exposure.

3.3. SPR mix design

A total of five SPR mixtures were evaluated in this study. All mixtures were prepared considering the aggregate distribution shown in Fig. 2. Initially, two reference SPR mixtures (SPR-VB and SPR-MB) were produced to see the effect of the recycling agent on the mixture performance. In the case of SPR-MB, first MB was prepared by replacing the part of the virgin binder with soybean oil, and eventually, MB was added into the mixture to maintain the total binder content of 5.2%, which is the recommended binder dosage in the NDOT specifications for SPR mixtures. This method of recycling agent addition was utilized

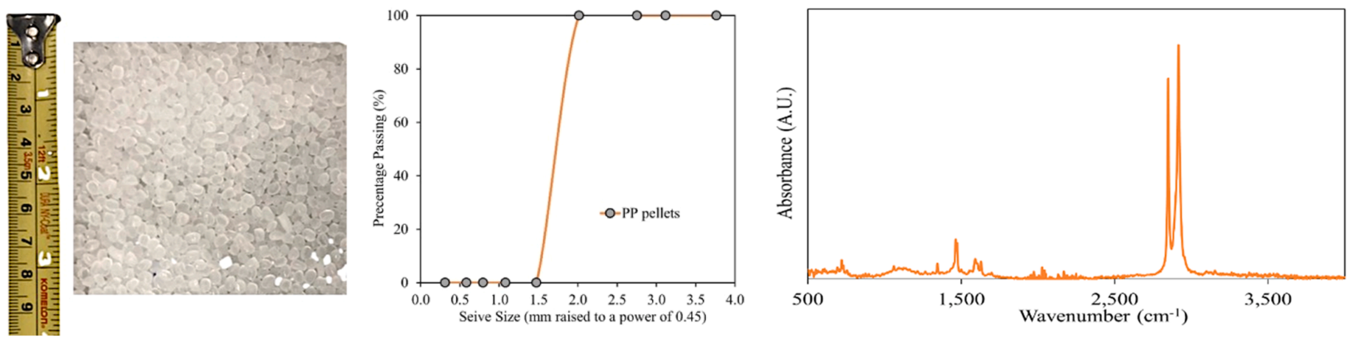

Fig. 3. The polypropylene waste used in this study: (a) photograph; (b) gradation of sample; (c) FTIR analysis of PP samples.

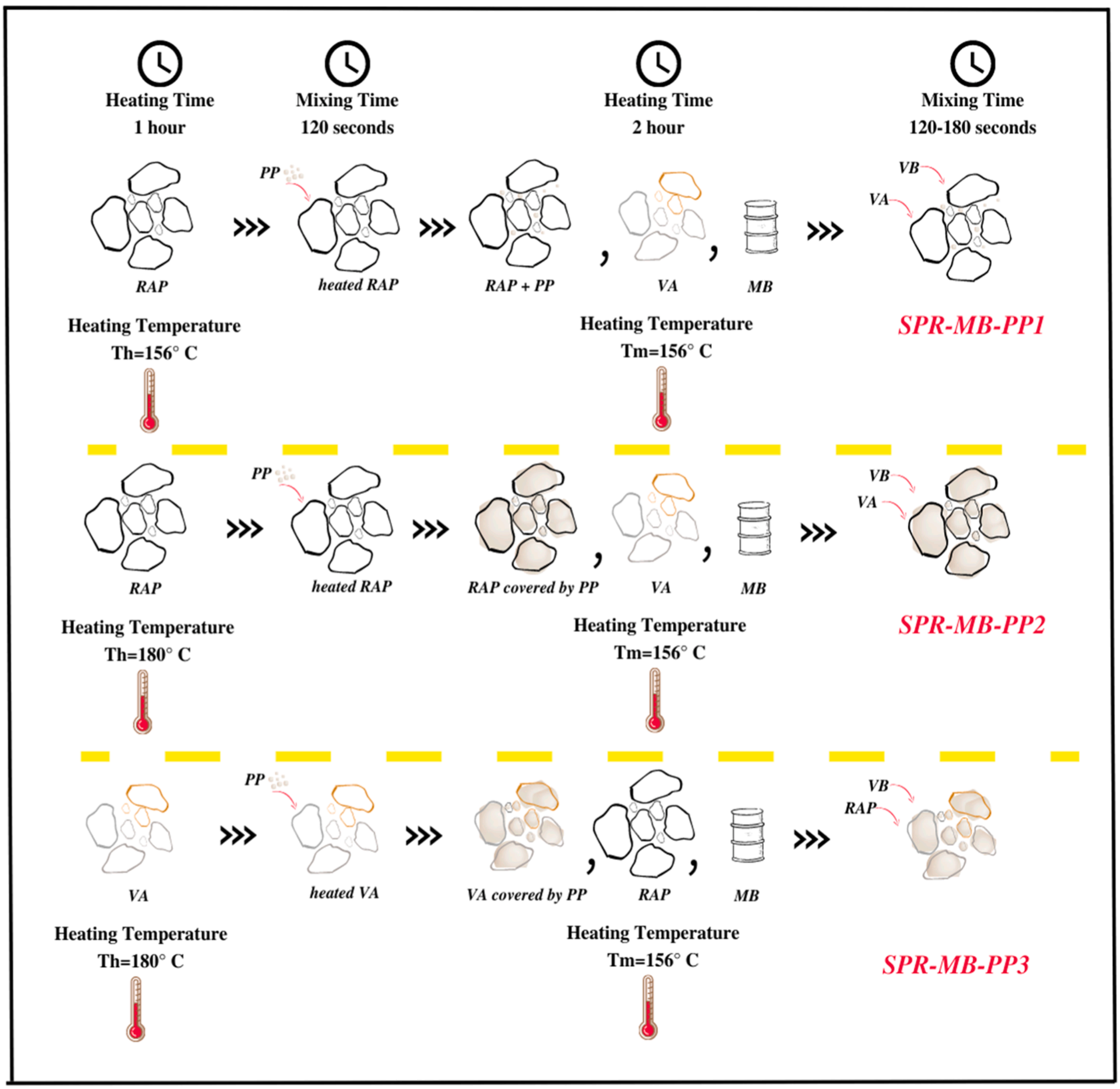

Fig. 4. Diagram showing each mixing method (MM), labeled as MM1, MM2, and MM3.

Table 1
Volumetric Parameters for SPR-VB and SPR-MB mixtures.

Properties	NDOT		
	SPR Requirement	SPR-VB	SPR-MB
Binder Content (%)	>5%	5.20	5.20
Dust to Binder Ratio	0.7–1.70	0.96	1.00
Air Voids (%)	3 ± 1%	2.80	2.89
Voids in Mineral Aggregate (%)	N/A	12.92	12.84
Voids Filled with Asphalt (%)	N/A	78.30	77.43

considering the easier and more practical implementation aspect of this method. The volumetric parameters for both mixtures are presented in Table 1. Then, three mixtures with the addition of 1% PP by the total weight of aggregates were explored using different PP incorporation methods. The use of WPs in asphalt mixtures via dry method has been reported in many studies, and usually, a dosage of 0.5–3% by the total weight of aggregates is recommended. Since this study focuses on using WP in high-RAP mixtures, a small amount was arbitrarily selected for this initial trial because some stiffening effects of WP in asphalt mixture have been reported in many studies. Table 2 presents the nomenclature used to distinguish the studied mixtures, as well as the percentages of RAP and virgin materials, and waste plastics.

3.4. Performance tests

3.4.1. Boiling test

The boiling test according to ASTM D3625–20 was performed to investigate the adhesion behaviors of the soybean oil and waste plastics modified high-RAP mixtures. This test is recommended to verify the binder-aggregate adhesion. In this study, it was used to verify the particle's coating-related behaviors of the different mixing. For that, each aggregate type was mixed with PP using the studied mixing methods, and further mixed with binder. Then, the aggregate-PP-binder samples were heated in boiling distilled water for 10 minutes. Eventually, visual observations and image collection were performed before and after the test. The efficiency of PP to improve the overall coating of the aggregates was quantified based on the coating areas observed on the surface of the different aggregates. A higher amount of visible coating was an preliminary indicator of a better binder-aggregate adhesion.

3.4.2. Semi-circular bending Illinois Flexibility Index Test (I-FIT)

The I-FIT was adopted to evaluate the cracking performance of the asphalt mixtures at mid-temperature. The short-term aged mixture was utilized at this stage for fabricating performance test specimens, as the prime focus was to verify the initial effects of WP incorporated at different mixing temperatures. A 170 mm gyratory compacted sample with 7 ± 0.5% air void was initially fabricated considering the requirement for performance testing. Then, after slicing 10 mm from both ends due to the concern of variable air voids, a 50 mm thick specimen was utilized for testing. The testing was performed based on the AASHTO T 393 protocol, where the test specimen was conditioned at 25° C for 2 hours before testing in a universal testing machine (UTM) at a load rate of 50 mm/min. Eventually, load versus displacement plots were captured and utilized further for cracking performance assessment. From load versus displacement plots, the flexibility index (FI) was calculated and used to assess cracking performance considering its suitability to rank RAP mixtures [39]. Eq. 1 describes the FI mathematically, and a higher FI relates to a better-performing mixture.

$$FI = A\frac{G_f}{|m|} \tag{1}$$

Where G_f is the fracture energy (J/m^2), |m| is the absolute value of the post-peak slope, and A is the unit conversion factor.

3.4.3. Hamburg Wheel Tracking Test (HWTT)

The HWTT was incorporated into this study to evaluate the moisture and rutting performance of different asphalt mixtures, being one of the most widely utilized tests in current BMD efforts [4,14]. For this test, 62 mm thick gyratory compacted specimens were prepared targeting the air void levels of 7 ± 0.5% as required by the performance test based on short-term aged conditions of the mixture. The specimen was trimmed based on the AASHTO TP 324 procedure. A metallic wheel loading of 52 passes per minute was applied to the test specimen maintained at 50° C. With the progression of the test, the number of wheel passes and respective rutting depth were recorded in the system. That data was utilized to understand the rutting and moisture performance of the asphalt mixtures. For this study, the number of cycles at 12.5 mm rutting depth was utilized as a rutting performance indicator, while stripping inflection point (SIP) was used as a moisture performance indicator.

Table 2
Studied SPR mixtures and their composition.

Sample ID	Percentage of Materials	Recycling Agent	Waste Plastics
SPR-VB	65% RAP + 35% virgin materials (aggregates + VB)	No	No
SPR-MB	65% RAP + 35% virgin materials (aggregates + MB)	Yes	No
SPR-MB-PP1	SPR-MB+ 1% PP by the total weight of aggregates added using MM1	Yes	Yes
SPR-MB-PP2	SPR-MB+ 1% PP by the total weight of aggregates added using MM2	Yes	Yes
SPR-MB-PP3	SPR-MB+ 1% PP by the total weight of aggregates added using MM3	Yes	Yes

4. Results and discussions

4.1. Preliminary analysis of PP addition methods

After implementing three different methods, some preliminary visual observations can be pointed out regarding the mixing procedures used herein. As PP has a melting temperature above the common range of binder mixing temperature, the mixing temperature of 156° C used in MM1 was not high enough to melt the PP and coat the aggregates, as shown on the top left side of Fig. 5. PP can still be seen in solid pellet form based on visual observation of the mixtures. However, when the mixing temperature was increased to 180° C, such as in MM2 and MM3, the PP particles properly coated the aggregate particles, which can be seen on the top right side and on the bottom of Fig. 5, respectively. One of the important observations in MM3 was related to the formation of clumps in between the aggregates with plastics. Those clumps were not observed when PP was added to the RAP, possibly due to the workability gain caused by the presence of RAP aged binder. Mechanical performance tests were further conducted to evaluate the effect of mixing temperature and role of PP on the studied high-RAP recycled mixtures.

4.2. Boiling test results

The boiling test was further performed to visually see any potential binder-aggregate adhesion improvement on the studied plastic-modified particles. The captured images after performing the boiling test were processed into binary images to facilitate a proper distinction between the coated and uncoated aggregates. Each image was converted into binary images under a saturation of 400% and color tone of 8800 K, and eventually, visual observations were performed at this stage. Fig. 6 shows the results on a white background.

The boiling test analysis results showed that the SPR-MB-PP1 particles presented the most potential to loss of binder adhesion. The partial

Fig. 5. PP mixed with RAP at 156° C (left), RAP at 180° C (center), and virgin aggregates at 180° C (right).

loss of coating was observed in all three types of aggregates. In this case of PP incorporation followed in this study, PP WPs were not melted and, therefore, might not have played a significant role in improving aggregate-binder adhesion. However, in the particles from SPR-MB-PP2, i.e., the case where PP was incorporated at a high temperature with RAP, a qualitative visual observation showed a lower amount of areas not covered by binder. Higher blending temperature of plastics and RAP created a layer of aged binder-PP-binder around the RAP potentially leading to an improved adhesion between the mixture components. For SPR-MB-PP3 particles, the binder-aggregate adhesion was intermediate between SPR-MB-PP1 and SPR-MB-PP2. The coating of plastics on the virgin aggregates resulted in a better binder-aggregate adhesion. The effect was more prominent on limestone and gravels. However, the mixture prepared for this case also had a lesser coating before the boiling test, which might be related to the rough texture and angularity of the plastics coated aggregate. Souza and Kim [40] provided evidence that the angularities on the surface of the aggregates require an excess of the binder. However, in this study, the optimum binder content was the same for all the plastic modified mixtures.

4.3. Cracking performance

Fig. 7a shows the load vs displacement curves obtained after performing the SCB-IFIT test, and Fig. 7b presents the FI and standard deviation calculated based on six specimens in each mixture type.

Comparing SPR-VB and SPR-MB, differences in the pre-peak slope, peak-load, and post-peak slope can be observed. As can be seen in Fig. 7a, the pre-peak slope in the SPR-MB mixture is comparatively lower than in the SPR-VB. Rejuvenator agents tend to reduce the stiffness of the asphalt mixture [14,15,24,41]. This effect could be observed in Fig. 7, demonstrating the softening effect attributed to the use of binder modified by soybean oil, which led to a reduced initial stiffness. Furthermore, the SPR-MB presented a lower peak-load and less steep post-peak slope at the inflection point than the SPR-VB mixture, demonstrating a more ductile behavior, which increases its ability to dissipate energy through deformation before cracking in comparison with the mixture without RA [26,42]. In SPR-VB, the prevalence of aged binder within the RAP leads to a stiff mixture, that can withstand more load but with fast crack propagation, as it can be observed by the post-peak slope. This behavior is characteristic of brittle materials, and this effect of RAP on AC behavior has been reported in numerous studies, suggesting the use of rejuvenator agents in RAP-recycled mixtures to improve mixture flexibility [6,43,44]. The addition of PP lead to an increase in the mixture's initial stiffness but a more ductile, as noticed from the post- peak curve. As many other studies reported that the addition of plastics makes the asphalt stiffer and more prone to cracking [45,46]. However, this behavior changed depending on the PP mixing method used.

Based on the FI results from Fig. 7b, a relatively better cracking resistance was attributed to SPR-MB in comparison to SPR-VB. An increase in the FI could be attributed to the use of modified binder by soybean oil in the SPR-MB mixtures, which could provide sufficient room to incorporate waste plastics in high-RAP mixtures without compromising the cracking performance to a great extent. The addition of PP made the recycled mixture stiffer but still presented satisfactory flexibility. To further verify the significance of those observed differences, a statistical analysis based on Tukey's Honestly Significant Difference (HSD) test was performed at a confidence level of 95% after confirming the p-value obtained after the Analysis of Variance (ANOVA) test was less than the α-level (i.e., 0.05). A p-value less than the α- level suggested that at least one mixture existed that was significantly different from the other mixture, and as a result, Tukey's HSD test was followed. Eventually, grouping was provided for each mixture, as shown in Table 3. In this case, three groups (A, B, and C) were observed from Tukey's HSD test corresponding to all the mixtures. The mixtures sharing the same groups were not statistically different from each other, and further descriptions are provided in the following paragraphs.

Based on Tukey's HSD test results, it was observed that the FI results from SPR-MB is statistically different than the other mixtures. Furthermore, the three different mixing methods were not significantly different as all the samples, irrespective of the mixing method, were in the same HSD group. However, it is interesting to note that the PP incorporation using the mixing method MM3 to produce the mixture SPR-MB-PP3 shared the same grouping with the SPR-VB mixture, and it had the lower average FI value among the three mixtures with PP addition. Although this method was investigated to lessen the effect of further aging of RAP by pre-heating the virgin aggregates only, the non-uniform dispersion of plastics and the formation of clumps in plastics made the mixture more brittle. The place where the plastic clump formation occurred might be assumed to be the stress accumulation zone, resulting in an abrupt failure. It was observed in most of the samples that the failure in SPR-MB-PP3 was in between the coated plastics and coarse aggregate, and they were separated after the test. This cracking propagation behavior was not seen in the mixture SPR-MB-PP2 which potentially led to a better cracking resistance. Fig. 8 illustrates the crack path observed as the aggregate's surfaces after cracking.

4.4. Rutting and moisture performance

The HWTT results for five different mixtures are presented in Fig. 9. As can be seen, it is confirmed that the rutting resistance of SPR-VB was better than SPR-MB because of the higher stiffness of this mixture, as also observed in Fig. 7a. The use of soybean oil as a recycling agent made the mixture soft and reduced its rutting resistance. These are the effects of using recycling agents in the RAP mixture [14,15,24,47]. Hence, three different PP incorporation methods were explored, and the results

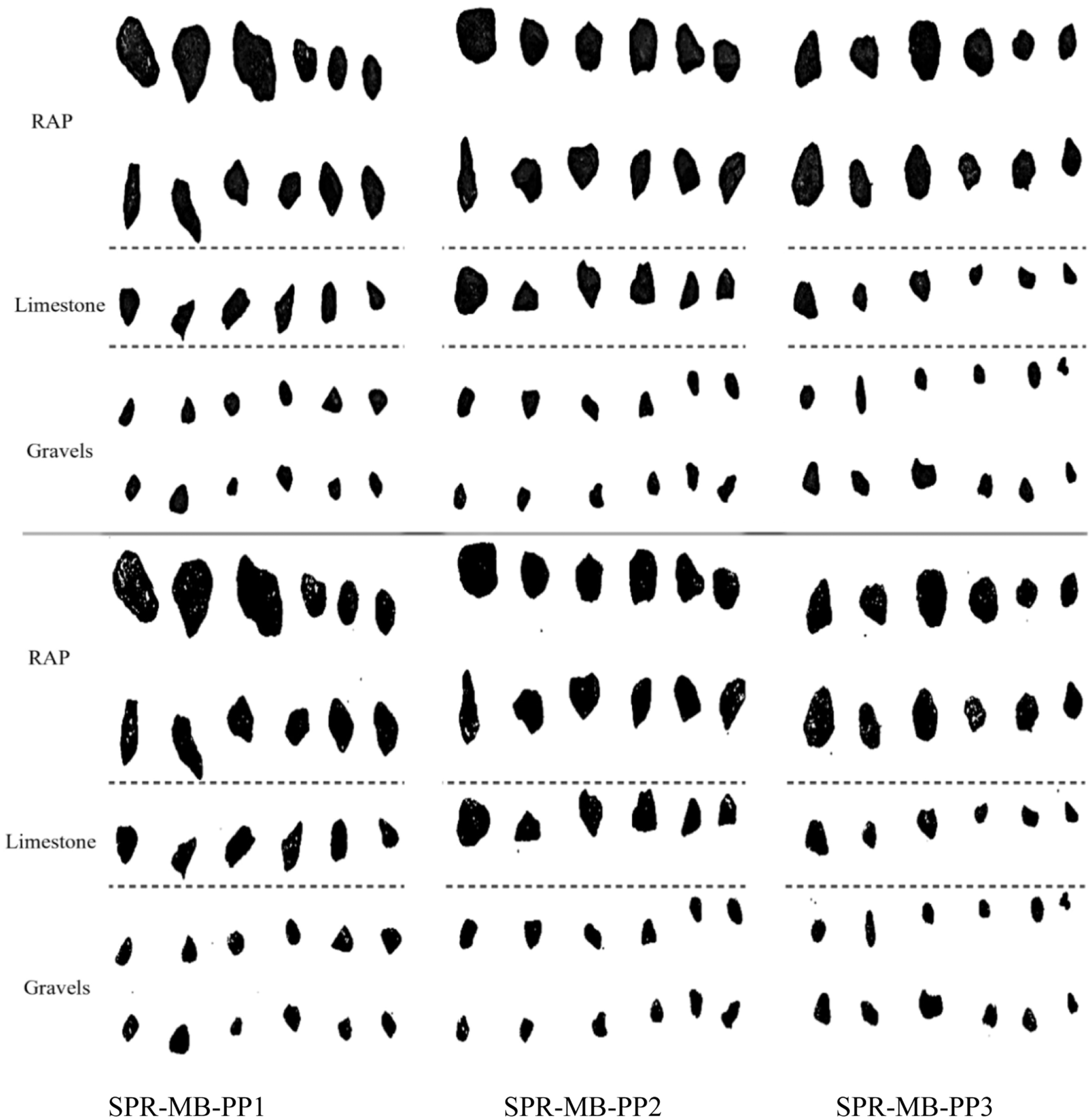

Fig. 6. Results from the boiling test: top images (image as obtained) and bottom images (binary processed) for the SPR-MB-PP1 (left), SPR-MB-PP2 (center), and SPR-MB-PP3 (right) particles.

showed an increasing trend in rutting resistance when WP was added. It is observed that SPR-MB-PP1 presented the least gain in rutting resistance when compared to SPR-MB. In SPR-MB-PP1, the RAP was pre-heated at a lower temperature than in the other two cases, leading to less additional aging effects during the mixing process. Also, the PP pellets were not melted and were more uniformly distributed. In this case, PP pellets might have acted like low-stiffness aggregates. The PP pellets could not provide sufficient stiffness to increase the rutting resistance and acted as a rounded aggregate, which tends to reduce the asphalt mixture's rutting resistance [41]. However, the other two methods (MM2 and MM3) used to produce SPR-MB-PP2 and SPR-MB-PP3 resulted in an enhanced rutting performance. This clearly shows that the PP acted as a mixture enhancer when melted, potentially stiffening the mixture (even the binder) and improving the binder-aggregate adhesion, which results in a stronger material's bonding, leading to a better resistance to load. This is consistent with the research that shows the addition of waste plastics stiffens asphalt mixtures [5,48]. Apart from that, in the mixture SPR-MB-PP2, the RAP was heated to meet the requirement of PP's melting point, which could lead to aging-induced stiffness gain to some level and enhanced rutting performance [49]. This further aging of RAP was minimized in SPR-MB-PP3, and the mixture had a comparatively lower rutting resistance than SPR-MB-PP2. In this case, inhomogeneity in the plastic particles with fracture-inducing clumps (Fig. 8) combined with a less stiff mixture resulted in lower rutting performance.

The moisture damage resistance of each mixture was assessed based on the SIP calculated from HWTT results, as shown in Fig. 10. Comparing SPR-VB and SPR-MB, it can be observed that the first one presented a higher moisture resistance than the second one. The use of soybean oil as a recycling agent had a negative effect on the mixture's

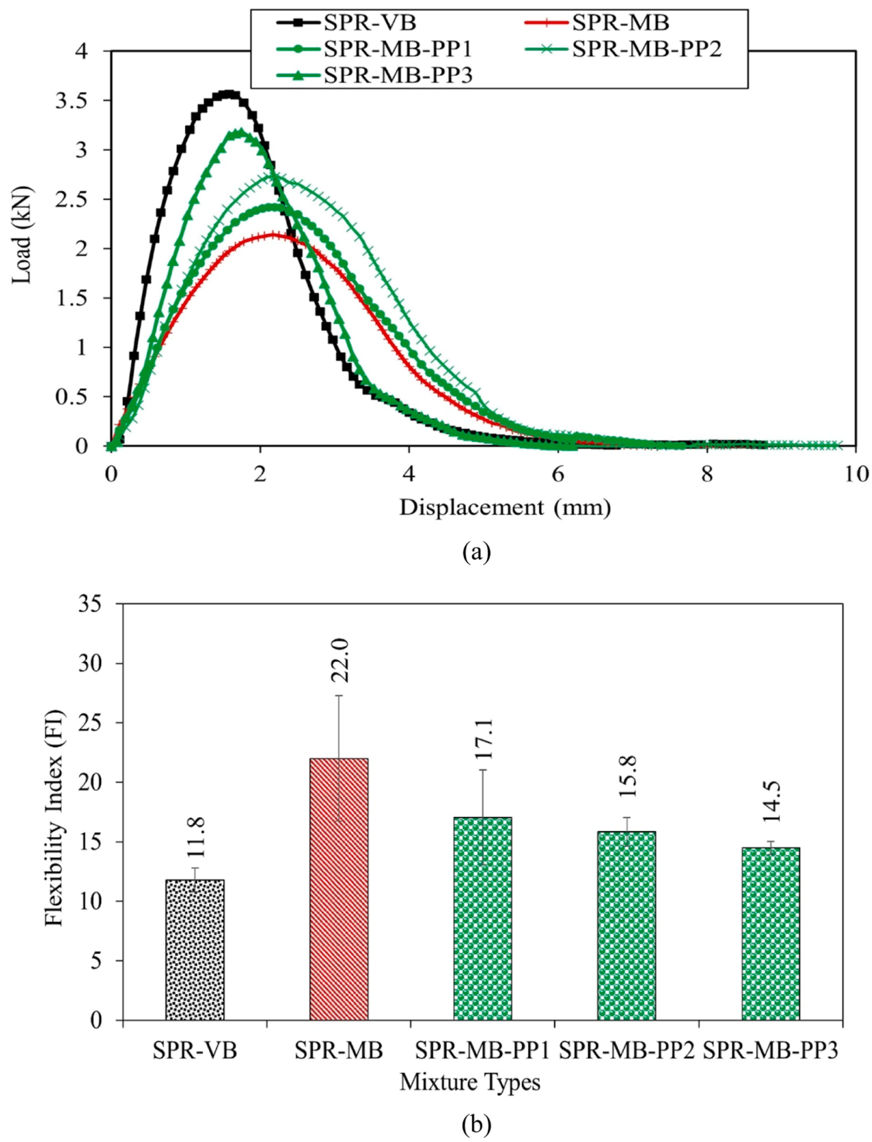

Fig. 7. SCB-IFIT results for the studied mixtures: (a) Load versus displacement relationship, and (b) flexibility indices.

Table 3
Summary of Tukey's HSD test results (α=0.05) for FI values.

Sample ID	Average FI	Grouping		
SPR-VB	11.8			C
SPR-MB	22.0	A		
SPR-MB-PP1	17.1		B	
SPR-MB-PP2	15.8		B	
SPR-MB-PP3	14.5		B	C

moisture resistance. This might be attributed to the effect of the hydroxyl functional group in soybean oil, which helps to attract more water molecules on the surface and results in a mixture with poor moisture resistance [26,49]. The different plastic addition methods explored herein enhanced the moisture performance of the SPR-MB mixture. SPR-MB-PP1 had a small effect on improving the moisture resistance of SPR-MB. Since PP was not heated to the melting point, there was no interaction between the plastics and other mixture components -rather, the plastics acted as an aggregate in this case. However, SPR- MB-PP2 and SPR-MB-PP3 had a higher moisture resistance due to the improved binder-aggregate adhesion on the PP-coated particles. In the case of SPR-MB-PP2, the performance was the highest as uniform

Fig. 8. Development of fracture path outside and inside of the test specimen left- SPR-MB-PP2 & right- SPR-MB-PP3.

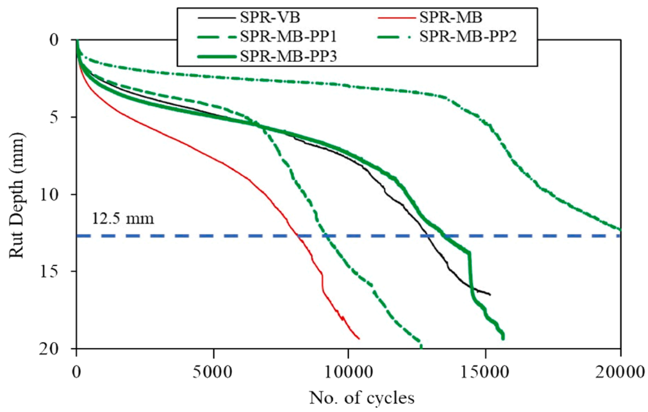

Fig. 9. HWTT results.

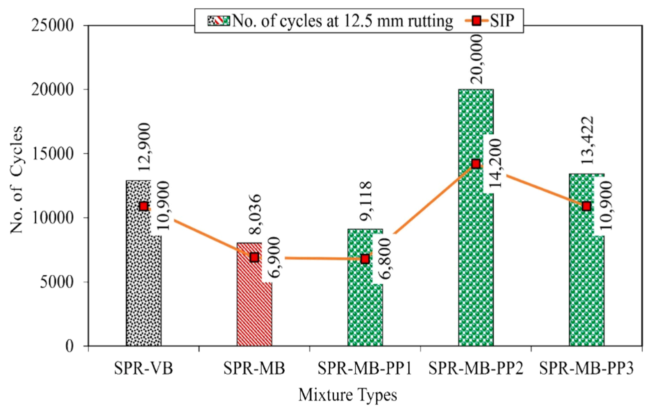

Fig. 10. No. of cycles at 12.5 mm rut depth for all mixtures and SIP.

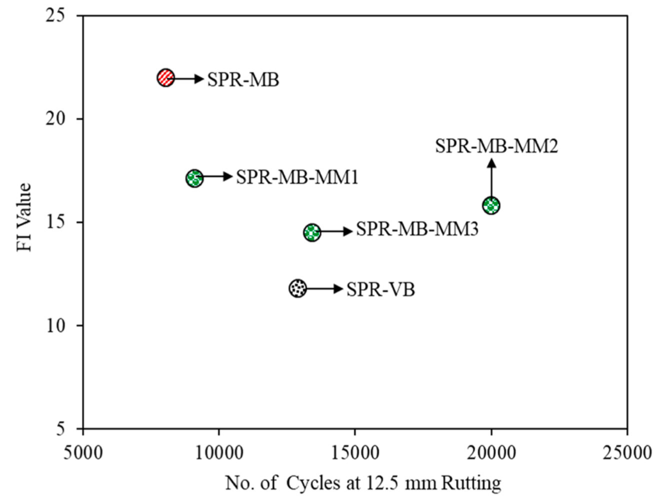

Fig. 11. Performance space diagram comparing rutting and cracking indices of the studied mixtures.

dispersion and blending of PP within the mixture was observed. This might have helped to preserve the adhesion between the binder, RAP, and aggregates. A better adhesion in SPR-MB-PP2 is also shown from the results of the boiling test. As discussed from the boiling test result, in this case, the higher blending temperature of plastics and RAP created a layer of aged binder-PP-binder around the RAP, potentially leading to an improved adhesion between the mixture components. This result could have provided an improved moisture damage resistance as assessed through HWTT for this mixture type. The moisture performance of SPR-MB-PP3 is comparatively lower than SPR-MB-PP2 as, in this case, plastics were more localized on the virgin coarse limestone and gravels. The lack of homogeneity and unequal dispersion of plastic particles inside the test specimen is one of the prime reasons for lesser moisture resistance in this case. Additionally, for the case of SPR-MB-PP3, the rutting and moisture damage resistance were similar to SPR-VB. This emphasized that this method of PP addition did not enhance the rutting and moisture damage resistance but did not negatively affect those performances when compared to SPR-VB. However, an enhancement in performance was observed when compared to SPR-MB, signifying that this method helps to enhance the moisture and damage resistance of the soybean oil-modified mixture.

4.5. Performance space diagram (PSD): relation between cracking and rutting performance

In the current days, considering the evolution of Balance Mix Design (BMD), many researchers are utilizing a PSD to correlate the cracking and rutting performance of an asphalt mixture [50,51]. Such a diagram provides sufficient evidence to balance the two major forms of distress (cracking and rutting). Therefore, this study also explored the cracking and rutting of five different mixtures considering the PSD, and results are presented in Fig. 11. As observed in Fig. 11, the mixture SPR-MB had higher cracking resistance but lower rutting resistance than SPR-VB, which is expected due to the effect of the addition of rejuvenator additives on asphalt mixtures, as previously mentioned. In an attempt to balance cracking and rutting resistance in SPR-MB mixture, PP waste plastic was added. For that, three different methods of PP addition were explored, and it was observed that the melting of PP showed some discernible performances in between the PP-modified mixture. The mixture SPR-MB-MM1, where the PP was not melted, the rutting resistance increment was not so different than SPR-MB, and its cracking resistance was reduced. For SPR-MB-MM2 and SPR-MB-MM3, where the PP was melted during the mixing procedure, it can be observed enhanced rutting resistances in comparison with SPR-MB, being SPR-MB-MM2 the best performance mixture among the three PP modified mixtures. Although cracking resistance was reduced, the SPR-MB-MM2 still presented a satisfactory value on its FI, but a much better rutting and SIP values.

5. Conclusions and recommendations

This study evaluated the effects of polypropylene addition on the mechanical performance of high-RAP asphalt mixtures modified by soybean oil as a rejuvenating agent. Based on the results and discussion, the following conclusions were drawn:

- It has been verified that the behavior of WP in asphalt mixtures varies depending on the mixing temperature used to pre-heat the aggregates before adding this material. In the case of WPs with a high melting point (as the PP used herein), using the conventional binder mixing temperature proved inadequate for melting the PP completely. Consequently, the WP retained its original shape and acted more like an aggregate particle. When melted, the WP can efficiently coat the particles, leading to performance improvements in the asphalt mixture. Therefore, for optimal results, it is essential to utilize an optimized mixing temperature that can melt the WPs.
- Overall, the use of PP can enhance the cracking, rutting, and moisture damage resistance of high-RAP mixtures when added using the dry method. Additionally, utilizing PP as a mixture enhancer, i.e., allowing the PP to melt during the mixing process, results in an overall improved asphalt mixture performance. This improvement is attributed to better binder-aggregate adhesion due to the aggregates being coated by the melted PP layer. The addition of PP to RAP yields a more homogeneous mixture compared to adding it to virgin

aggregates, possibly due to the better workability induced by the presence of the RAP binder during the mixing process.

- Among the three studied WP addition methods, pre-heating RAP at a temperature higher than the conventional binder mixing temperature resulted in the best overall asphalt concrete performance due to improved coating of RAP particles by PP. Despite subjecting the RAP to additional heating before adding the PP, the potential age-related stiffness gain was balanced by the enhanced binder-aggregate adhesion, leading to satisfactory cracking performance and significant improvements in rutting and moisture damage resistance of high-RAP mixtures modified by soybean recycling agents.

The results showed that the polypropylene waste plastic can be potentially incorporated into a high-RAP recycled mixture to enhance the rutting, moisture, and adhesion performances. This preliminary study was more focused on finding an effective way to incorporate polypropylene in a high-RAP recycled mixture at a single dosage. In future studies, more efforts are needed to explore different types of waste plastics and at different percentages. In addition, cost and environmental analysis will provide equal opportunities to understand the impact of using waste plastics in pavement structures to a greater extent.

CRediT authorship contribution statement

Jamilla Emi Sudo Lutif Teixeira: Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Braden Olson:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Nitish R. Bastola:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hamzeh Haghshenas Fatmehsari:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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