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Exploring the effects of waste plastic aggregate on styrene-butadiene-styrene-modified asphalt binders for sustainable rural pavements

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ABSTRACT

In addressing the imperative need for sustainable and cost-effective solutions in rural pavement development, this study navigates the intricate balance of environmental and financial constraints to ensure the resilience of infrastructure in communities with limited resources. The focal point is the integration of waste plastic aggregate (WPA) into hot mix asphalt, augmented by the inclusion of styrene-butadiene-styrene (SBS) for an elevated level of performance. The findings underscore a gradual decrease in the tensile strength ratio, emphasizing a manageable impact, transitioning from 82.4% in the control to 73.7% at 6% WPA. Noteworthy is the observation of marginal reductions in indirect tensile strength and stiffness, particularly notable at higher WPA levels. Dynamic modulus testing highlights susceptibility to rutting at lower frequencies, while high-frequency results demonstrate stability up to 6% WPA. The Hamburg wheel tracking test signals heightened rutting at 3% and 6% WPA, indicating potential challenges in deformation resistance. Despite a slight dip in strength, the discernible magnitude of this reduction is not substantial. This affirms that the incorporation of WPA achieves a harmonious enhancement of sustainability without compromising critical mechanical properties.

1. INTRODUCTION

The global predicament of plastic waste has reached staggering proportions, with an estimated 368 million tons of plastic produced annually worldwide (Abduljabbar et al., 2022). The exponential increase in plastic consumption raises urgent environmental concerns, emphasizing the imperative to devise sustainable strategies for plastic waste management. In this context, the innovative repurposing of plastic waste as WPA in bitumen mix emerges as a persuasive avenue to address both the eco-friendly effect of plastic pollution and the need for resource-efficient infrastructure solutions (Franesqui et al., 2023).

Extensive research has been conducted on the application of modified asphalt binders and recycled materials to improve asphalt mixture properties. Recent research collectively explores the utilization of by-products in building materials, with a focus on enhancing sustainability and performance. For example, Agha et al. (2023) evaluated the effectiveness of incorporating polyethylene terephthalate (PET) in bitumen mixes; Audy et al. (2022) introduced a tool for selecting recycled plastics; and Franesqui et al. (2023) investigated the reusing of plastic waste in conjunction with porous aggregates. Exploring innovative avenues for sustainable asphalt solutions, Narendra Goud et al. (2023) investigated the application of waste plastics to reduce pavement noise, while Silvestre et al. (2013) delved into the possibilities presented by ceramic waste. In a parallel vein, Ullah et al. (2021) scrutinized the physical and mechanical properties of asphalt incorporating polyethylene waste, and Xiao et al. (2023) examined the thermodynamic properties of aggregates coated with waste plastic. Together, these studies provide a cohesive understanding of how diverse waste materials can collectively enhance both the environmental sustainability and structural integrity of asphalt pavements.

Rural pavements constitute a distinct category within the realm of infrastructure, characterized by specific features that warrant focused attention. Unlike their urban counterparts, rural pavements often face challenges associated with lower traffic volumes, varying soil conditions, and limited financial resources. Characteristics of rural pavements, as explored by Tang et al. (2022), encompass a distinctive set of challenges arising from lower traffic volumes, diverse soil conditions, and constrained financial resources. Correspondingly, research efforts by Saniga et al. (2023) and others have delved into tailoring pavement solutions to address the specific demands of rural settings. Currently, there is a noticeable gap in research attention directed toward this specific type of pavement, with fewer studies dedicated to addressing the unique challenges and requirements of rural infrastructure.

Studies also investigated the use of SBS-modified asphalt which has shown promising results in enhancing elasticity and durability (Manosalvas-Paredes et al., 2016). Additionally, the incorporation of crumb rubber powder from recycled tires has gained attention for its potential to improve various performance aspects (Duarte & Faxina, 2021). Yet, research on the impact of WPA on bitumen mixtures, particularly in rural settings, has been limited. Despite the progress made in sustainable asphalt technologies, a comprehensive understanding of how WPA affects rural pavement performance is lacking. Previous studies have frequently concentrated on specific modifiers or additives, neglecting the potential advantages or disadvantages associated with incorporating WPA. Acknowledging these gaps, our research aims to bridge this divide by methodically assessing the influence of WPA at different concentrations. This approach offers crucial insights for optimizing WPA utilization in asphalt mixtures tailored for rural applications.

This study focuses on an in-depth examination of WPA's influence on SBS mixture performance for rural pavement applications. This study thoroughly examines how different WPA percentages (0%, 3%, and 6%) impact crucial features such as rutting resistance, stiffness, dynamic modulus, and the tensile strength ratio (TSR). By gradually changing the WPA concentration, the objective is to obtain subtle insights that can guide the optimization of WPA in asphalt mixes for sustainable rural pavement construction. The experimental studies are based on a mixture design that includes WPA at various doses. This method identifies the delicate balance between sustainability goals and the conservation of critical mechanical properties in asphalt mixtures. This detailed examination of the interactions between WPA and SBS-modified asphalt provides the way for important findings and recommendations to assist the development of environmentally conscious rural pavements.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Development of asphalt mixture

SBS modification has gained widespread acceptance in the asphalt industry recently as a tried-and-true method of improving the elasticity and fatigue resistance of asphalt binders. Comparing the SBS-modified asphalt used in our investigation to traditional asphalt binders, the former showed better properties. The SBS modifier was utilized at a concentration of 3% of the total asphalt binder content in the asphalt mixture. Referencing Table 1, which outlines essential properties of the SBS-modified asphalt (Lee & Le, 2023a), a penetration value of 35.2, a softening point of 58.7°C, and a ductility measurement of 85.4 cm could be observed. These results underscore the efficacy of SBS modification in improving key aspects of asphalt binder performance. These properties are indicative of the asphalt's resistance to deformation, temperature susceptibility, and ability to undergo tensile elongation, respectively (Lee & Le, 2023a). The high softening point suggests enhanced resistance to high temperatures, while the increased ductility indicates improved flexibility.

Table 1. SBS-modified asphalt

Property	Value
Penetration at 25°C (ASTM D5, 2019)	35.2 mm
Softening Point (AASHTO T 48, 2022)	58.7°C
Ductility (AASHTO T 240, 2013)	85.4 cm

2.1.2. Waste plastic aggregate

Waste plastic aggregate (WPA) plays a pivotal role in this study, focusing on optimizing asphalt mixture properties (Figure 1a). The WPA utilized consists of recycled plastic particles uniformly sized between 0.075 and 4 mm, with a consistent density of 0.85 g/cm³ (Lee & Le, 2023b). The inclusion of WPA in the mix at varying percentages (i.e., 0%, 3%, and 6%, representing the control and two experimental scenarios, respectively) corresponds to a deliberate effort to maintain a consistent chemical composition of WPA across different percentages, ensuring 60% polyethylene, 25% polypropylene, and 15% polystyrene. This intentional uniformity enables a focused assessment of WPA's impact on asphalt mixture performance, providing valuable insights into its effectiveness at different concentrations.

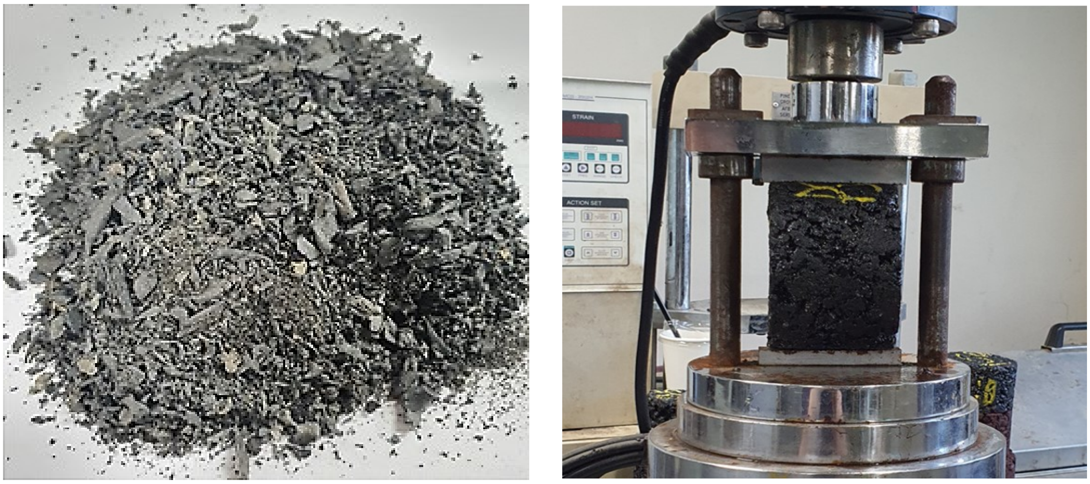

(a) (b)

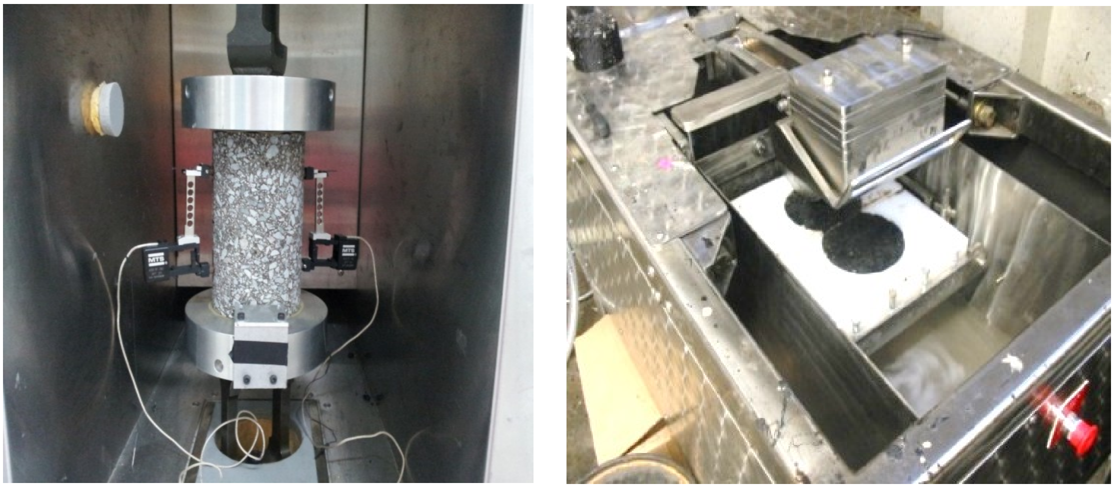
Figure 1. (a) WPA aggregate and (b) IDT test

2.1.3. Mixing and compaction

The Superpave method served as the guiding principle for proportioning asphalt mixtures in this study. This method systematically determined the optimal combination of aggregates, asphalt binder, and filler to achieve the desired performance characteristics. The proportions were meticulously adjusted to incorporate SBS asphalt at approximately 6% by weight of the mixture and 90% aggregate and 4% filler combined, ensuring a balanced and effective composition for the experimental scenarios. The asphalt samples were meticulously fabricated using the Superpave method, adhering to a simplified set of WPA percentages– specifically, 0%, 3%, and 6%. The compaction process involved heating the aggregates to a compaction temperature of 150°C, followed by the addition of SBS-modified binder at a mixing temp of 160°C (Lee & Le, 2023b). Cylindrical samples, measuring 100 mm in diameter and 150 mm in height, were prepared from the compacted mixtures for each WPA percentage for the following test, ensuring a representative evaluation. To ensure the results are relevant to real-world situations, the compaction process imitated field conditions using the Superpave gyratory compactor. The simplified selection of 0%, 3%, and 6% WPA compositions aimed to provide focused insights into the influence of WPA on critical performance parameters.

2.2. Testing method

This research conducted standard tests to study the general properties of the WPA mix, including indirect tensile strength (ITS) (ASTM D6931, 2017), tensile strength ratio (TSR) (AASHTO T283, 2018), Dynamic modulus (AASHTO TP62, 2017), and Hamburg wheel-tracking test (HWTT) (AASHTO T324, 2014). Considering the specimen's size, ITS testing used disk-shaped specimens (150 mm diameter, 63 mm thickness) to evaluate tensile strength and resistance to cracking (Figure 1b). Dynamic modulus testing assessed stiffness and deformation resistance using cylindrical specimens under varying conditions (Figure 2a). The HWT used slab specimens (300 mm length, 150 mm width, 63 mm height) to evaluate rutting resistance under simulated traffic conditions (Figure 2b). These tests provided comprehensive insights into the mixtures' behavior and performance, ensuring a thorough assessment of their suitability for real-world applications.



(a) (b)

Figure 2. (a) Dynamic modulus and (b) HWTT

3. RESULTS AND DISCUSSION

3.1. TSR test

Table 2 provides the TSR values for different percentages of WPA in asphalt mixtures, comparing them to a Control mixture with no WPA. The control mixture without WPA exhibits the highest TSR at 82.4%, indicating its robust tensile strength. Introducing WPA at 3% results in a slightly lower TSR of 80.4%, suggesting a marginal reduction in tensile strength compared to the Control. However, a more significant impact is observed when the WPA content is increased to 6% (WPA6%), leading to a TSR of 73.7%. This substantial decrease in TSR suggests that a higher proportion of WPA, in this case, negatively affects the tensile strength of the asphalt mixture.

While there may be benefits associated with WPA utilization, as seen in the 3% WPA mixture, excessive content of 6% results in a notable decline in tensile strength. Engineers and practitioners should consider these trade-offs, aiming to optimize WPA content to enhance sustainability without compromising essential mechanical properties like tensile strength. This research aligns with previous findings (Prathibha & Karthik, 2022), as incorporating WPA may have a slight impact on the strength of asphalt mixtures, with higher percentages showing a noticeable reduction in tensile strength.

Table 2. Summary of TSR and ITS test results

Test results	WPA0%		WPA3%		WPA6%	
	Mean	SD	Mean	SD	Mean	SD
TSR (%)	82.4	2.31	80.4	1.97	73.7	1.84
ITS (MPa)	1.27	0.036	1.19	0.029	0.88	0.021
Stiffness (kN/mm)	3.2	0.071	2.8	0.056	2.5	0.067

SD: standard deviation

3.2. IDT test results

In Table 2, the ITS and stiffness of tested mixtures are compared across various WPA percentages against the control samples. The control, without WPA, displayed an ITS of 1.27 MPa and 3.2 kN/mm in the stiff value. The introduction of 3% WPCM resulted in a modest reduction in ITS to 1.19 MPa (a 6.3% decrease) and stiffness to 2.8 kN/mm (a 12.5% reduction) compared to the control. However, a more substantial impact occurred with the 6% WPCM mixture, witnessing a drop in ITS to 0.88 MPa (a 30.7% reduction) and stiffness to 2.5 kN/mm. WPA may contribute to a softened state of the SBS asphalt binder, influencing its ability to withstand traffic-induced loads.

In the examination of high-frequency dynamic modulus, the outcomes for all WPA-modified mixtures, encompassing those with 3% and 6%

WPA, consistently bear the label "Similar results" when juxtaposed with the control mix. Notably, the assessment at higher frequencies reveals that the incorporation of up to 6% WPA yields no significant deviations in dynamic modulus values. However, it is imperative to draw attention to the parenthesis's notation, which accentuates a substantial decline in dynamic modulus at low frequencies, notably conspicuous at the 6% WPA level. This underscores the paramount importance of a comprehensive evaluation, taking into account both low and high-frequency results, to discern the nuanced influence of WPA on the mixture's resilience against deformation and rutting.

The observed decreases in dynamic modulus at low frequencies with the addition of 3% and 6% WPA could be explained by changes in the characteristics of the mixes. WPA infusion, especially at high percentages, has the potential to cause fluctuations in the composite material, impacting its stiffness and ability to withstand irreversible deformation. This behavior is consistent with previous research, which indicates that the addition of WPA alters the rheological properties of asphalt mixes, particularly at lower frequencies, as demonstrated by Agha et al. (2023) and Audy et al. (2022). The observed decrease in dynamic modulus indicates an increased vulnerability to rutting, which is a common concern in pavement engineering. The agreement between these findings and previous research emphasizes WPA's continuing influence on mixture deformation resistance. It emphasizes the critical requirement for a detailed evaluation that takes into consideration both low and high-frequency data in order to assess the overall influence of WPA on the performance of asphalt pavements.

3.3. HWTT results

The results of the HWTT after 20,000 cycles are shown in Figure 3, which also provides information on the final millimeter rutting depths for asphalt mixtures with varying WPA ratios in relation to the control samples. With no WPA (0%), the control mixture had a final rutting depth of 4.032 mm. The addition of 3% WPA caused the rutting depth to increase by 4.43 mm, which is a 9.7% departure from the control. The ultimate rutting depth then rose to 4.59 mm with 6% WPA, indicating a 13.7% departure from the control. The figures in parenthesis indicate the percentage variation from control, stressing that rutting was significantly increased by both 3% and 6% WPA.

This suggests a potential influence on the asphalt mixture's ability to withstand deformation under the stress of repeated wheel loading conditions. The results suggest that the addition of WPA, especially at the 6% level, may increase the likelihood of rutting in the asphalt mixes. The proportionate difference from the control sample is highlighted by the notation in parenthesis, highlighting the practical significance of these findings for pavement performance. The HWTT insights are essential for assessing how susceptible the combinations are to rutting. Furthermore, by optimizing the WPA content, these insights may help strike a careful balance between sustainable measures and maintaining key pavement attributes.

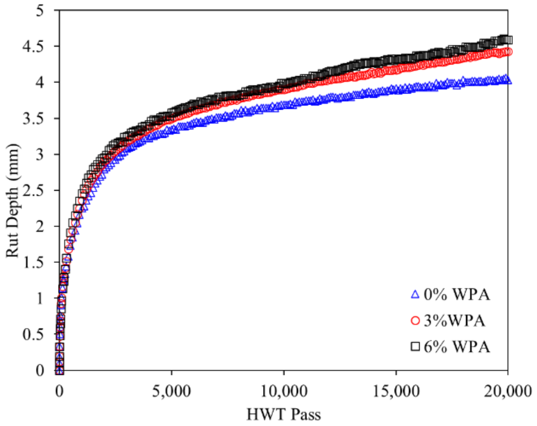


Figure 3. HWTT test results

When considering the incorporation of WPA into hot mix asphalt, especially when combined with SBS alteration, careful thought is required. The data shows a progressive decrease in TSR, which is most noticeable at 6% WPA, underscoring the vital need for precise WPA content optimization. WPA concentrations affect the ITS, and stiffness properties, and dynamic modulus testing demonstrates a frequency-dependent effect. Although high-frequency performance stays consistent up to 6% WPA, rutting depth increases noticeably between 3% and 6% WPA. This implies a balanced approach to optimizing WPA content, which is required for alignment with sustainability goals and successful pavement solutions.

4. CONCLUSION

In-depth insights into improving the performance of SBS-modified asphalt for rural pavement environments are provided by this research, which explores the use of WPA as an asphalt mixed component. Some noteworthy results include that TSR values gradually decreased, moving from 82.4% in the control to 80.4% at 3% WPA and then to 73.7% at 6% WPA. This emphasizes how important it is to adjust WPA content such that sustainability objectives and the maintenance of asphalt mixture tensile strength are harmoniously integrated.

The control mixture showed reductions in both stiffness (3.2 kN/mm to 2.8 kN/mm at 3% WPCM and further to 2.5 kN/mm at 6% WPCM) and ITS (1.27 MPa to 1.19 MPa at 3% WPCM and further to 0.88 MPa at 6% WPCM) in the stiffness and ITS tests, indicating the strong influence of increasing WPA on these critical properties.

According to tests, putting 3% or 6% WPA into asphalt makes it more rut-prone at slower speeds, while keeping it consistent at faster ones. This emphasizes how crucial it is to take into account both speeds to provide a thorough evaluation.

(iv) Employing 3% and 6% WPA produced deeper ruts when the asphalt was subjected to wheel loading, suggesting possible difficulties with managing repeated wheel loads. This highlights the necessity of carefully optimizing WPA content to strike a balance between desired pavement properties and sustainability.

While the study offers insightful information about WPA usage in asphalt, it is not without flaws. Future studies might investigate various WPA concentrations and substitute modifiers while taking the environment's effects into account. This work lays the groundwork for future research aimed at optimizing the use of WPA in asphalt technology, tackling new issues, and advancing environmentally friendly paving solutions.

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