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Optimizing Rural Pavements with SBS-Modified Asphalt Binders and Petroleum Resin

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Abstract: This study addresses the imperative for enhancing asphalt mixtures tailored for rural pavements, focusing on optimizing RAP mixtures with styrene–butadiene–styrene (SBS)-modified asphalt binders incorporating petroleum resin and oil. Through systematic investigation, the study examines the impact of varying RAP content (25% and 50%) and two SBS-modified asphalt binder types (Type 1 and Type 2) on mechanical properties and sustainability. Laboratory tests reveal that the mix of 25% RAP + 75% Type 1 exhibits exceptional flexibility, evidenced by a high ductility value of 880 mm at 25 °C, enhancing pavement resilience. Conversely, the 50% RAP + 50% Type 2 mixture displays vulnerability to fatigue cracking, while 25% RAP + 75% Type 1 demonstrates superior resistance, with a fatigue vulnerability value of 1524 kPa. The Hamburg Wheel Tracking test highlights the influence of RAP content on rut depth, with the mix of 50% RAP + 50% Type 1 achieving the lowest rutting at 3.9 mm. Overlay test results show the mix of 25% RAP + 75% Type 2's resilience, with the lowest load reduction at 64.5%, while the mix of 50% RAP + 50% Type 1 exhibits substantial load reduction at 82.1%. Field tests unveil differences in pavement bearing capacities, with the mix of 25% RAP + 75% Type 2 demonstrating a remarkable elastic modulus of 58.5 MPa, indicating heightened bearing capacity. The investigation underscores the significant role of SBS-modified asphalt binders with incorporated petroleum resin and oil in enhancing fatigue resistance for sustainable rural pavements.

Keywords: rural pavement; asphalt mixtures; extracted RAP binder; Hamburg wheel tracking; falling weight deflectometer

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1. Introduction

The imperative for upgrading rural pavements stems from their pivotal role in the economic and agricultural landscape [1], with a focus on rice and fruit cultivation [2]. Reliable road networks are crucial for transporting perishable goods to urban markets [3], especially with evolving logistic demands such as increased container usage [4]. Rural pavements face unique challenges like adverse weather [5] and heavy agricultural machinery traffic, leading to accelerated deterioration and impacting safety and transportation efficiency [6]. Recognizing the economic importance of rural areas, systematic upgrades are essential to address degradation and yield profound economic benefits [7], fostering development and enhancing the quality of life for these communities [8]. Upgrading rural pavements is not just a technical necessity but a pivotal step towards sustainable development, ensuring the resilience and vitality of these transportation networks [9].

Recycled asphalt pavement (RAP) has gained widespread application in modern pavement construction as a sustainable and cost-effective alternative [10,11]. RAP, derived from reclaimed asphalt materials, is reintegrated into new pavement mixes, contributing to resource conservation and reducing environmental impact [12,13]. Its use aligns with the principles of circular economy, as it minimizes waste while capitalizing on the valuable properties of aged asphalt [14]. Incorporating RAP into pavement projects enhances sustainability by reducing the demand for virgin materials and lowering energy consumption during production [15]. The application of RAP not only addresses environmental concerns but also proves advantageous in improving pavement performance, including enhanced durability, flexibility, and rutting resistance [16,17]. This approach, combining environmental stewardship with engineering efficiency, underscores RAP's pivotal role in modern pavement practices [18–20].

Styrene–butadiene–styrene (SBS)-modified asphalt has become a focal point in pavement research and construction due to its exceptional performance-enhancing properties. SBS, a polymer additive, is incorporated into asphalt binder to improve its resistance to temperature fluctuations, fatigue cracking, and deformation under heavy loads [21,22]. This modification enhances the overall durability and longevity of asphalt pavements, making them better suited to withstanding the challenges of diverse climatic conditions and high traffic volumes [23]. The elastic and adhesive qualities of SBS-modified asphalt contribute to reduced rutting and cracking, providing significant advantages for both road safety and maintenance costs [24]. The current application of SBS asphalt in pavement research reflects a commitment to optimizing asphalt mixtures for superior performance and longevity, addressing the evolving demands of modern transportation infrastructure [25,26].

The application of RAP in rural areas faces certain limitations that warrant attention. In many cases, the utilization of RAP in these settings is hindered by the heterogeneous nature of reclaimed materials, varying significantly in composition and properties. Additionally, there is a lack of comprehensive research focus on the incorporation of SBS in RAP mixtures due to the increased stiffness issue [27]. This gap in research inhibits a nuanced understanding of the interaction between SBS-modified binders and high percentages of reclaimed materials, crucial for optimizing pavement performance. Furthermore, the behavior of the aging process on these binders remains insufficiently studied, impeding the development of robust pavement designs that account for the long-term effects of environmental exposure and traffic loading. Addressing these limitations is imperative to unlocking the full potential of RAP in rural pavement applications and to advance the utilization of SBS-modified asphalt in large RAP mixtures, contributing to sustainable and resilient infrastructure development.

This research introduces a pioneering approach to address the specific challenges of rural pavement development. Focused on upgrading rural infrastructure, the study investigates the application of RAP and SBS asphalt in asphalt mixtures. The research delves into the limitations of RAP in rural areas, the lack of research on large RAP mixtures (up to 50%), and the aging behavior of these binders. By evaluating sensitivity to fatigue cracking, and storage stability, and conducting field tests using a Light Falling Weight Deflectometer (LFWD), the study provides a comprehensive understanding of the performance of these asphalt mixtures in real-world rural conditions. This holistic and innovative approach positions the research at the forefront of advancing sustainable and resilient solutions for rural pavement challenges.

In this study, an extensive experimental program was conducted to assess the performance of asphalt mixtures designed for rural pavement applications. The materials utilized include RAP and SBS asphalt binder, with a particular emphasis on mixtures containing up to 50% RAP. This study investigates the influence of different RAP binder proportions, specifically 25% and 50% extracted RAP binders, combined with two types of modifiers (Type 1 and Type 2). The asphalt binder properties were characterized through Asphalt Binder Tests, Dynamic Shear Modulus (G) tests, and sensitivity to fatigue cracking assessments. Additionally, storage stability tests were conducted to evaluate the long-term structural integrity of rural pavement materials, including Control, Type 1, and Type 2 formulations. The performance of the asphalt mixtures was comprehensively evaluated through the Hamburg Wheel Tracking (HWT) test, Overlay Test (OT), and field tests employing the Light Falling Weight Deflectometer (LFWD). These diverse testing methods provide a robust foundation for analyzing the impact of RAP and SBS asphalt on rural pavement performance, setting the stage for a thorough exploration of sustainable and resilient solutions in this critical infrastructure domain. In general, this study innovatively evaluates the performance of asphalt mixtures for rural pavements by examining recycled asphalt pavement (RAP) with styrene–butadiene–styrene (SBS)-modified asphalt binders containing petroleum resin and oil, offering insights into the nuanced interplay between varying RAP content and modifier types on mechanical properties and sustainability. The overview of the research is presented in Figure 1.

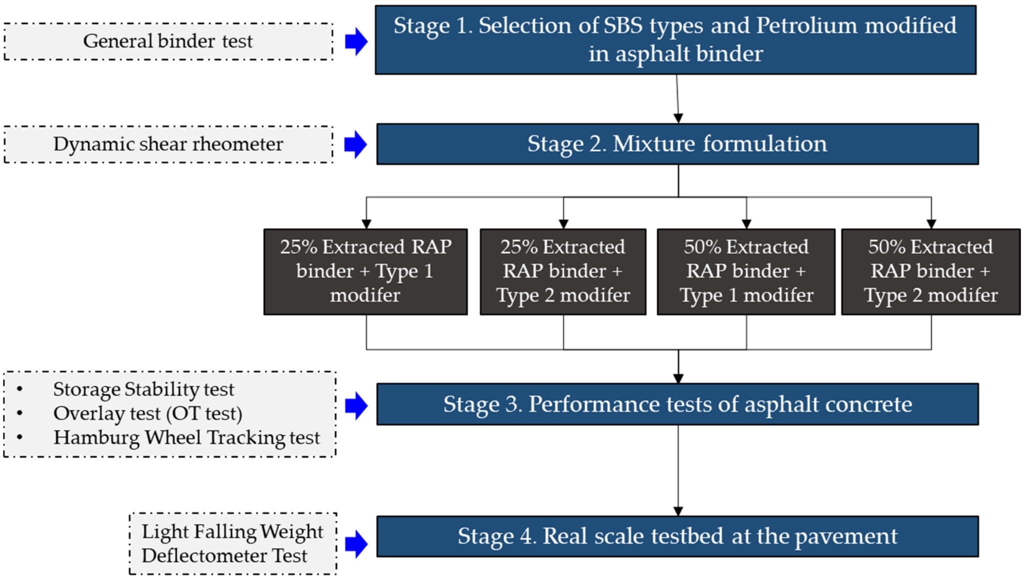


Figure 1. Research flowchart.

2. Materials and Methods

2.1. Materials

2.1.1. Recovery of RAP Binder

The selection of materials in this study is crucial for understanding the characteristics and performance of the asphalt binders. The following subsection provides a detailed overview of the materials employed in the research, encompassing the RAP binder, SBS binders (Type 1 and Type 2), and the specifications governing their use. The general properties of RAP and virgin binder used in this research are shown in Table 1.

Table 1. General properties of virgin and RAP binders.

Property	RAP	New Binder (PG64-22)
Penetration (1/10 mm) at 25 °C	82.5	64
Softening Point (°C)	68.7	50
Ductility (cm/min) at 5 °C	>100	>100

2.1.2. Recycled Asphalt Pavement Binder

The RAP binder used in this study was extracted from reclaimed asphalt pavement obtained from road resurfacing projects. The RAP material was carefully sampled and processed to isolate the binder content. The extraction process involved the use of a solvent, typically trichloroethylene, in accordance with established protocols such as ASTM D2172 [28]. The recovered RAP binder represents the aged asphalt binder present in the reclaimed pavement, which adds a unique dimension to the study by incorporating real-world, field-aged binder into the experimental matrix.

2.1.3. Styrene-Butadiene-Styrene Binders

Two distinct types of SBS binders, denoted Type 1 and Type 2, were employed in the investigation. These binders were selected based on their proven effectiveness in enhancing asphalt properties in previous research. The SBS polymers were sourced from reputable manufacturers, ensuring a consistent and high-quality supply. Both SBS binders were designed to modify and improve the rheological properties of asphalt binders, offering enhanced elasticity, durability, and resistance to aging.

2.1.4. Binder Blending Ratios

The binder combinations were formulated by blending the RAP binder with the SBS binders in different weight ratios. Two main combinations were investigated: 25% RAP binder with 75% SBS (Type 1, Type 2) and 50% RAP binder with 50% SBS (Type 1, Type 2). The rationale behind these ratios lies in achieving a balance between the rejuvenating effects of the RAP binder and the performance-enhancing properties of the SBS polymers. The selection of these ratios was informed by preliminary investigations and optimization studies, aiming to guarantee a thorough exploration of the binder space.

The recognition that the incorporation of polymer with RAP necessitates the addition of rejuvenating materials, preferably in liquid form, introduces a pivotal aspect of the discourse on asphalt binder formulation. This acknowledgment underscores the potential challenges associated with employing polymer-modified binders in the presence of RAP, emphasizing the need to address concerns related to stiffness and rejuvenation. In response to this valuable insight, the study strategically incorporates liquid rejuvenating agents, specifically petroleum resin (GX140) and oil, into the asphalt binder compositions. This purposeful integration seeks to improve the compatibility of the polymer with RAP, alleviate stiffness-related issues, and contribute to an overall enhancement of mechanical properties. Opting for liquid rejuvenators adheres to industry standards, providing a pragmatic solution to optimize asphalt mixtures for rural pavement applications, thereby ensuring improved performance and long-term durability.

2.1.5. SBS Molecular Structure Selection

In the realm of asphalt concrete materials, the judicious selection of SBS molecular structures emerges as a critical determinant for achieving optimal performance in rural pavement applications. Table 2 serves as a guide on this exploratory journey, categorizing SBS asphalt binder materials into two primary structural types while delineating their fundamental properties. The 3-Linear type, characterized by a softening point of 105.5 °C, an elevated ductility of 140 cm, and a penetration depth of 20.8 dm, epitomizes heightened flexibility and workability.

Table 2. Variations in Asphalt binder with SBS structures.

Property	3-Linear Type 1	3-Linear Type 2	3-Radial Type
Softening Point (°C)	105.5	92.4	111.3
Ductility (cm at 25 °C)	140	140	68
Penetration (dm at 25 °C, 100 g, 5 s)	20.8	23.4	13.6
Viscosity (cPs at 135 °C)	4800	5600	10,000
Elastic Recovery (% at 25 °C)	93	87	91

Conversely, the 3-Radial type, distinguished by a higher softening point of 111.3 °C, manifests with reduced ductility (68 cm) and a more restrained penetration (13.6 dm). A noteworthy contrast lies in the viscosity at 135 °C, where the 3-Linear type demonstrates a lower value of 4800 cPs compared to the 3-Radial type's 10,000 cPs. This structural differentiation significantly influences the elastic recovery rate, a pivotal attribute in asphaltic applications.

The 3-Linear type, boasting a superior elastic recovery rate of 93% at 25 °C, signifies resilience and the capacity to regain shape after deformation. In contrast, the 3-Radial type, with a marginally lower elastic recovery rate of 91% at the same temperature, introduces a nuanced aspect to the asphaltic composition. This nuanced exploration underscores the intricacies involved in the deliberate selection of SBS molecular structures for rural pavement, ultimately impacting performance metrics critical for the success of asphalt concrete materials.

Regarding the characterization testing process, the Softening Point, measured according to ASTM D36 [29], provides insights into the asphalt binder's temperature susceptibility. Penetration at 25 °C (100 g, 5 s), following ASTM D5 [29], offers a measure of the binder's consistency and hardness. Viscosity at 135 °C, conducted in triplicate according to ASTM D4402 [30], sheds light on the binder's flow behavior under elevated temperatures. Elastic Recovery at 25 °C, adhering to ASTM D113 [31], gauges the binder's ability to rebound after deformation. These additional tests contribute valuable information to the material characterization, ensuring a thorough understanding of the asphalt mixtures' properties and behaviors.

2.1.6. Selection of Enhanced Adhesion Agents

Ensuring the durability and integrity of the asphalt pavement while preventing damage and joint detachment requires a meticulous selection of adhesion agents that enhance the cohesion of materials.

In response to the Korean refined Company oil suggestion and trial test recommendation, the selection of enhanced adhesion agents for asphalt binder modification leans towards the application of GX140 petroleum resin.

GX140 is a thermoplastic resin derived from petroleum-based feedstocks. Its intricate composition involves the polymerization of hydrocarbons, resulting in a high-quality resin with distinctive properties. The development process focuses on achieving a fine balance between molecular weight, softening point, and compatibility with asphalt. The trial tests have highlighted its favorable characteristics, including a high softening point of 140.2 °C, making it ideal for demanding conditions requiring superior temperature resistance and asphalt adhesion. This strategic decision to utilize GX140 as the primary adhesion agent in the development of Type 1 and Type 2 modifiers is expected to enhance the overall performance and durability of the asphalt binders, aligning with the project's specific requirements. Table 3 provides a concise overview of the updated physical properties of the adhesion agent.

Table 3. Physical properties of enhanced adhesion agents.

Property	Petroleum Resin GX140
Softening Point (°C)	140.2
Stripping Resistance (kgf/cm at 90 °C)	2.15
Softening Point (°C)	140.2
Compatibility with Asphalt	Excellent

2.1.7. Asphalt Binder Formulation: Crafting Specialized Solutions

The asphalt pavement was meticulously developed, considering key components such as petroleum resin. Delving into the nuances of these formulations, Table 4 unveils the intricate compositions that lay the foundation for tailored filling asphalt materials, specifically engineered for pavement development. It should be noted that the inclusion of oil in the asphalt binder composition serves a multifaceted purpose. Its primary role is to replenish the aged, extracted asphalt binder from recycled asphalt pavement (RAP), contributing to the overall rejuvenation of the mixture. Furthermore, the strategic balance between asphaltene and oil content is crucial for achieving optimal binder properties.

Table 4. Composition of asphalt binder with modifiers for the research.

Division	Composition Ratio (%)	
	Type 1	Type 2
Asphalt (PG 64-22)	80	80
SBS	5	8
	5	2
Petroleum Resin (GX140)	8	7
Oil	2	3
Mineral	0	0

This nuanced composition strategy enables the creation of distinct filling asphalt materials, finely tuned to meet the specific demands and applications associated with pavement development. The goal is to contribute significantly to enhanced road infrastructure performance and longevity.

In-depth scrutiny of the quality test results highlights the success of the asphalt binder formulation. The meticulous balance achieved not only meets industry standards but also introduces substantial improvements in key physical properties. This ensures optimized performance across diverse environmental conditions, positioning the developed asphalt pavement as a robust and reliable solution for infrastructure longevity.

Table 5 outlines the exceptional performance of the initial rural pavement material (Type 1 and Type 2) designed to surpass ASTM D 6297 [32]. Both types exceed requirements for softening point, ductility, and adherence to the recommended application heating range, ensuring robust performance in diverse climates. The enhanced values for ductility, softening point, penetration, and viscosity reaffirm the material's suitability.

Table 5. Updated characteristics of binder.

ASTM D6297	ASTM Unit	Spec.	Type 1	Type 2
Softening Point D36	°C	83	108.0	103.0
Ductility (at 25 °C) D113	mm	>400	755	885
Recommended Application Heating	-	185–195	Satisfied	Satisfied
Penetration (at 25 °C, 100 g, 5 s) D5	dm	-	28.0	33.0
Elastic Recovery (at 25 °C)	%	-	77	94
Viscosity (at 135 °C) D446	cPs	-	6600	5700

Table 6 provides a detailed examination of the physical properties of the final rural pavement material (Type 1 and Type 2), meticulously evaluated against ASTM standards [32]. Both types exhibit outstanding performance, surpassing requirements for softening point, tensile adhesion, ductility, and cone penetration. Notably, the revised values for softening point, tensile adhesion, and ductility reinforce the material's exceptional suitability for diverse construction applications, promising longevity and reliability in various environmental conditions [33].

Table 6. Updated physical properties of final developed pavement material.

ASTM D6297	ASTM Unit	Spec.	Type 1	Type 2
Softening Point D36 [34]	°C	83	102.5	104.0
Tensile Adhesion D5329 [35]	%	>700	825	780
Ductility (at 25 °C) D113 [36]	mm	>400	765	560
Cone Penetration (at 25 °C, 100 g, 5 s) D5329 [35]	unit	<75	24.0	17.5
Cone Penetration (at −18 °C, 200 g, 60 s) D5329 [35]	unit	>10	11.0	10.6
Flow (at 60 °C, 5 h) D5329 [35]	mm	<3.0	0.55	0.51

Table 6. *Cont.*

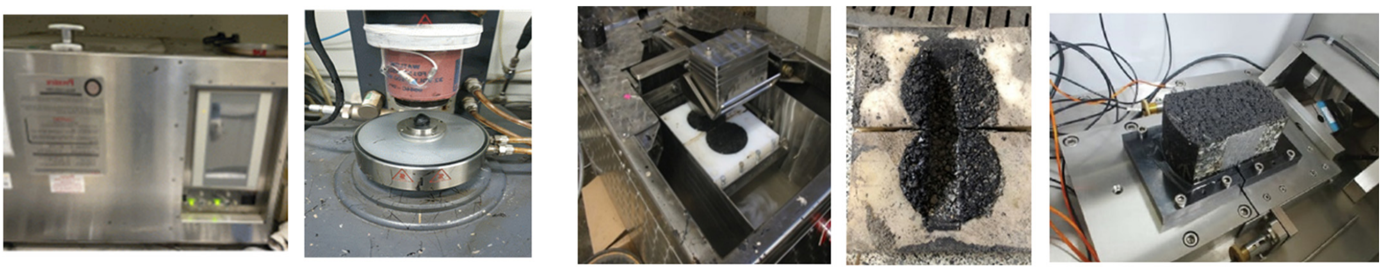
ASTM D6297	ASTM Unit	Spec.	Type 1	Type 2
Resiliency (at 25 °C) D5329 [35]	%	40–70	66.1	61.1
Asphalt Compatibility D5329 [35]	-	Pass	Pass	Pass
Recommended Application Heating Temperature Range	-	182–199	Satisfied	Satisfied
Bond 3 Cycles (at −7 °C, 100% Elongation) D5329 [35]	-	Pass	Pass	Pass
Flexibility (at 23 °C)	-	Pass	Pass	Pass
Penetration (Max. at 25 °C, 100 g, 5 s) D5 [36]	dm	-	34.0	20.0
Elastic Recovery (at 25 °C)	%	-	77	100
Viscosity (at 135 °C) D446 [37]	cPs	-	3200	4500

2.1.8. Binder Blending

The binder blending process plays a pivotal role in formulating a high-performance asphalt pavement. This section outlines the meticulous steps undertaken for binder blending, emphasizing the careful selection of materials and their precise proportions to achieve the desired characteristics.

The primary constituents for binder blending include the extracted RAP binder and SBS polymer binders of Type 1 and Type 2. The blending ratios were systematically varied to explore different binder combinations, specifically 25% extracted RAP binder with 75% SBS (Type 1, Type 2) and 50% extracted RAP binder with 50% SBS (Type 1, Type 2). These combinations were chosen to strike a balance between the rejuvenating properties of the RAP binder and the enhanced performance attributes imparted by the SBS polymer binders.

Following the binder blending, the resultant mixtures underwent an aging process through the Pressure Aging Vessel (PAV) method (see Figure 2a). This controlled aging procedure simulates the long-term oxidative aging that asphalt binders experience during service. The PAV method allows for the assessment of binder performance under realistic aging conditions based on AASHTO R28 [38], providing valuable insights into the long-term durability and stability of the blended binders. After aging, the blended binders were subjected to a battery of performance tests to evaluate crucial properties such as stiffness, elasticity, and resistance to high-temperature distress.



(a) (b) (c) (d) (e)

Figure 2. Illustration of the laboratory tests. (**a**) PAV curing of specimens; (**b**) dynamic shear rheometer; (**c**) HWT test; (**d**) HWT specimens; (**e**) OT test.

2.1.9. Mixing of Aggregate to the Proposed Binders

In the meticulous mixing phase, the designated binders, enriched with petroleum resin and oil, are expertly combined with the chosen aggregate, utilizing a Nominal Maximum Aggregate Size (NMAS) of 13 mm. This intricate process occurs at controlled mixing temperatures, specifically set at 160 °C for optimal blending and interaction between the binders and aggregates. The mixture undergoes precise compaction using a gyratory compactor, where the compaction temperature is carefully maintained at 150 °C. These temperature-controlled procedures are foundational in shaping the subsequent testing and evaluation phases, providing crucial insights into the performance and sustainability aspects of the asphalt mixtures tailored for rural pavement applications. The aggregate gradation used in the research is shown in the following Table 7.

Table 7. Aggregate gradation of proposed mixtures.

Percent Passing (%)	20 mm	13 mm	10 mm	5 mm	2.5 mm	0.6 mm	0.3 mm	0.15 mm	0.075 mm
13 mm PMA	100	83.9	62.1	43.5	32.6	18.3	12.1	7.2	3.8

2.2. Testing Methods

In the comprehensive evaluation of asphalt pavement to ascertain its enhanced performance, a meticulously devised and quantitative testing protocol was rigorously implemented. This section delineates the detailed methodologies employed to assess the physical and mechanical properties of the blended binders and the resulting asphalt mixtures, adhering strictly to industry-standard procedures and specifications.

2.2.1. Binder Performance Testing

Dynamic Shear Rheometer (DSR) Test: The DSR test, precisely conforming to the stringent ASTM D7552 standards [39], was used to meticulously assess the viscoelastic properties of the binders (see Figure 2b). The specimens, measuring 25 mm in diameter and 1.5 mm in thickness, underwent a comprehensive testing regime. The frequency sweep test spanned from 0.1 to 10 Hz, and the temperature ramp test ranged from −16 to 76 °C. Each binder specimen underwent triplicate testing, ensuring a robust characterization of rheological properties, and contributing to the comprehensiveness and precision of the performance analysis.

2.2.2. Mixture Performance Testing

Hamburg Wheel Tracking Test (HWT): The HWT, adhering strictly to AASHTO T324 [40], was used to conduct a meticulous examination of the asphalt mixtures' resistance to rutting (see Figure 2c,d). The specimens, 150 mm in diameter and 63.5 mm in height, underwent precisely 20,000 loading cycles, allowing for an in-depth assessment of the mixtures' rutting resistance. The triple replication of this test guaranteed the consistency and replicability of the observed data, providing a reliable basis for the ensuing performance evaluations and analysis.

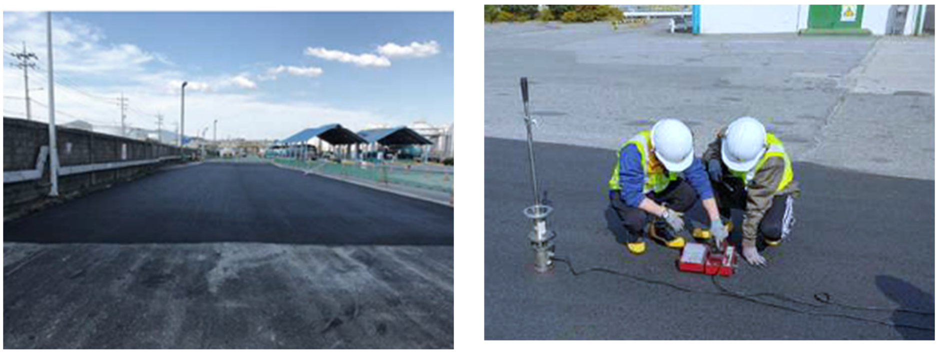
Overlay Test (OT): The crack resistance of asphalt mixes was systematically assessed through a laboratory test known as the Overlay Test (OT). This evaluation method, aligned with the TxDOT Tex-248-F standard [41], serves as a crucial measure for potential crack reflection within the asphalt mixtures. The specimens undergo assessment at a controlled temperature of 25 °C, employing the OT method to determine the mix's resistance to cracking. The evaluation is based on the number of cycles required to induce failure, with a focus on the number of OT loops needed to achieve a 93% reduction in the initial load during the first cycle. The experiment is designed to cease if the specified reduction is not observed within a maximum set number of iterations, ensuring a comprehensive understanding of the mix's crack resistance. In this study, a total of 1000 loading cycles were applied, or until the experiment was stopped, providing valuable insights into the asphalt mixtures' durability and performance under overlay conditions.

This comprehensive and meticulously detailed testing methodology, crafted in strict adherence to standardized protocols, incorporated replicates and precise specimen sizes. This meticulous approach ensured a thorough and reliable assessment of the asphalt-polymer performance, underlining the credibility and accuracy of the ensuing analysis and evaluation.

2.3. Field Application

The empirical validation of the proposed methodology was meticulously conducted through a field testbed within the GS Caltex Complex, an industrially significant petrochemical entity situated in Yeosu City, South Korea. Recognizing the natural degradation of asphalt pavement subjected to vehicular loads over time, a periodic repair protocol was instituted. The test construction meticulously involved sequential processes such as transportation, laying, and compaction. The dimensions of the strategically positioned testbed within the GS Caltex Complex were 50 m in length and 10 m in width.

Throughout the service duration, the compaction dynamics of the asphalt pavement were diligently scrutinized via advanced non-destructive testing instruments, encompassing the Light Falling Weight Deflectometer (LFWD). The strategic selection of testing points for these field experiments is depicted in Figure 3.



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

Figure 3. On-site use of Light Falling Weight Deflectometer on the field test bed: (**a**) pavement at the field, (**b**) LFWD test.

Light Falling Weight Deflectometer Test

The Light Falling Weight Deflectometer (LFWD) is employed in this study to directly measure the elastic modulus of asphalt mixtures in the field. By assessing pavement deflection caused by a falling weight, the LFWD provides a non-destructive and efficient method to gauge material stiffness and deformation under load. This in situ approach offers valuable insights into real-world performance, aiding in the optimization of pavement design for enhanced durability.

To quantitatively assess the post-construction pavement performance, the deflection magnitude and modulus of elasticity were systematically evaluated, leveraging the LFWD and following the stringent guidelines outlined in ASTM 2835 [42]. This compact version of the Falling Weight Deflectometer (FWD) was used to effectively measure deflection induced by the impact load of a falling weight. The LFWD test facilitated a rapid and robust assessment of the elastic settlement of the ground, with the measured elastic settlement promptly transmuted into an elastic modulus through the integration of a data logger. The LFWD field test conditions, detailed in Table 8, incorporated a load plate diameter of 150 mm, a load weight of 15 kg, a load height of 27 inches, and a Poisson's ratio of 0.4.

Table 8. LFWD field test conditions.

LFWD Test Conditions	
The diameter of the load plate	150 mm
The weight of the load	15 kg
Load height	27 inches
Poisson's ratio	0.4″

3. Results and Discussions

3.1. Binder Test Results

3.1.1. General Binder Test

This section delves into the specific findings of the Asphalt Binder Test, a critical phase in evaluating the performance and characteristics of various asphalt mixtures for rural pavements. The focus is on understanding the nuanced behaviors of asphalt binders under different compositions, shedding light on their influence on the overall performance of rural pavement.

The asphalt binder properties depicted in the table showcase distinct characteristics among various mixture compositions, providing insights into their thermal and mechanical behaviors. As presented in Table 9, the softening point, a key parameter reflecting the binder's vulnerability to high temperatures, exhibits a range of values. The mix of 50% RAP + 50% Type 2 demonstrates the highest softening point at 108.3 °C, indicating its superior resistance to deformation under elevated temperatures. In contrast, the mix of 25% RAP + 75% Type 2 has the lowest softening point at 102.5 °C, suggesting a binder more susceptible to temperature-induced changes. Ductility, representing the binder's ability to deform without breaking, is most pronounced in the mix of 25% RAP + 75% Type 1, boasting a value of 880 mm at 25 °C. This indicates excellent flexibility and resilience against deformation. On the other hand, penetration, a measure of binder consistency and hardness, is highest in the mix of 25% RAP + 75% Type 2, with a value of 34.4 dm at 25 °C, suggesting a softer binder. These nuanced variations emphasize the intricate interplay between RAP content and modifier type, influencing the thermal and mechanical properties of the binder. Such detailed insights are vital for tailoring asphalt mixtures to specific performance requirements, guiding the optimization of pavement design for enhanced durability and longevity in real-world applications.

Table 9. General asphalt binder test results.

Mixture Composition	Softening Point (°C)	Ductility (mm at 25 °C)	Penetration (dm at 25 °C)
25% RAP + 75% Type 1	103.4	880	33.9
25% RAP + 75% Type 2	102.5	760	34.4
50% RAP + 50% Type 1	104.5	760	27.8
50% RAP + 50% Type 2	108.3	570	20.4

The outcomes of this study are in line with previous research on asphalt mixtures for rural pavements, underscoring the intricate relationship between recycled asphalt pavement (RAP) content and modifier type. The observed patterns, such as the association between higher RAP content and elevated softening points, resonate with the established literature [43]. This alignment substantiates the reliability and relevance of the results, emphasizing their contribution to optimizing asphalt mixtures for enhanced durability and longevity in rural pavement applications.

3.1.2. Dynamic Shear Modulus (G) Test Results

In the Dynamic Shear Modulus (G) Test, the asphalt binder mixtures exhibit distinctive mechanical responses, particularly noteworthy in the cases of the 25% RAP + 75% Type 2 and 50% RAP + 50% Type 1 compositions. As shown in Figure 4, the former stands out as the softest among the tested mixtures at low temperatures, a characteristic attributed to its combination of low RAP content and the presence of the Type 2 modifier. With a limited RAP content, this mixture showcases enhanced flexibility, and the Type 2 modifier further contributes to its softer behavior, rendering it more susceptible to deformation under lower temperature conditions. Conversely, the latter composition, featuring 50% RAP + 50% Type 1, emerges as the stiffest among the tested mixtures at low temperatures. The pronounced stiffness can be primarily ascribed to the higher RAP content in this mixture, underscoring the dominant influence of RAP content on the mechanical response of the binder. This composition exhibits notable resistance to deformation at lower temperatures, highlighting the crucial role of RAP concentration in shaping the mixture's rheological properties.

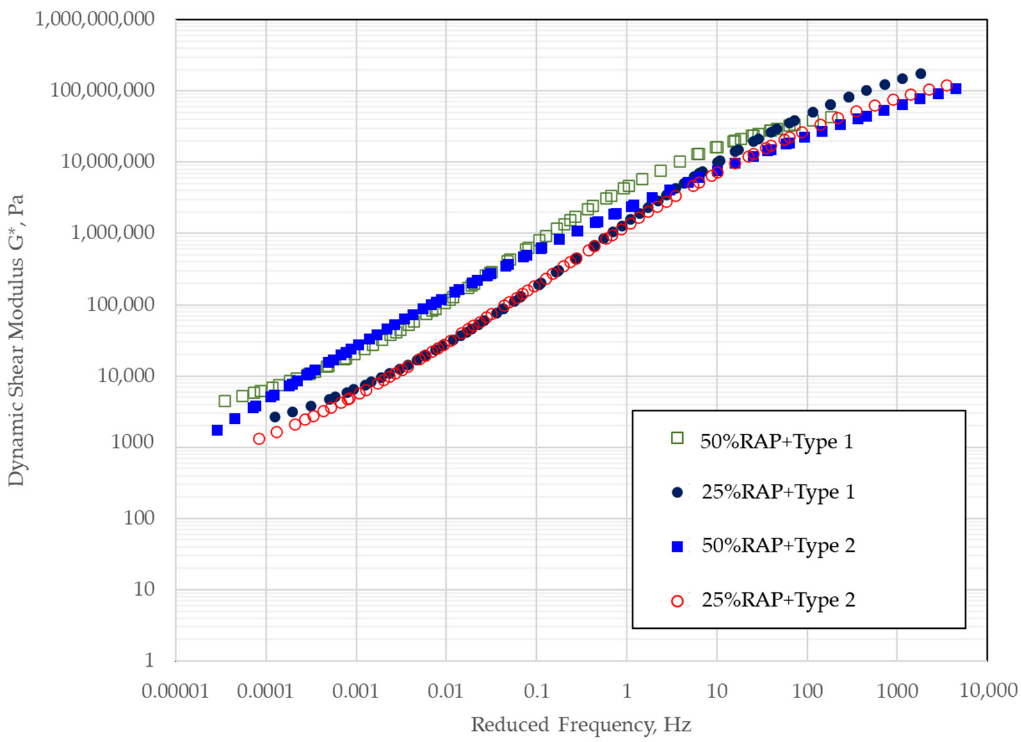


Figure 4. Dynamic shear modulus (G*) test results.

These results in the Dynamic Shear Modulus Test echo established research [44], underscoring the pivotal role of RAP content in asphalt binder performance. In line with the existing literature, our study reaffirms that lower RAP content, as in the 25% RAP + 75% Type 2 mixture, promotes flexibility and softness. Conversely, higher RAP concentration, exemplified by the 50% RAP + 50% Type 1 composition, results in increased stiffness and heightened resistance to deformation at lower temperatures. This concordance with prior findings enhances the credibility of our study and contributes to the collective understanding of the interplay between binder composition and rheological characteristics.

3.1.3. Sensitivity to Fatigue Cracking

The fatigue characteristics of the asphalt binder mixes were systematically evaluated across varying temperature ranges, ranging from 34 to 90 °C, as illustrated in the provided Figure 5. The susceptibility to fatigue crack initiation, as measured by the fatigue values (G*sin δ), is a critical parameter in assessing the thermal cracking resistance of asphalt binders. The Figure further elucidates the results of the Sensitivity to Fatigue Cracking Test after Pressure Aging Vessel (PAV) conditioning.

The Sensitivity to Fatigue Cracking Test after PAV conditioning provides valuable insights into the thermal cracking resistance of asphalt binder mixes. The fatigue characteristics, measured in terms of fatigue values (kPa), are indicative of the susceptibility of each mixture to fatigue cracking, especially under low-temperature conditions. Examining the results, the mixture composition with 50% RAP + 50% Type 2 modifier stands out with the highest fatigue value at 23,874 kPa, suggesting a notable vulnerability to fatigue cracking. On the contrary, the composition of 25% RAP + 75% Type 1 exhibits the lowest fatigue value at 1524 kPa, indicating superior resistance to thermal cracking. This observed trend aligns with the general understanding that higher RAP content and specific modifier types contribute to enhanced resistance against fatigue-induced thermal cracking. The intricate mechanism at play involves the dynamic interaction between RAP and the modifier, influencing the binder properties and, subsequently, the overall performance of the asphalt mixture under diverse temperature conditions. These results underscore the nuanced relationship between binder composition and fatigue resistance, emphasizing the need for careful consideration in designing asphalt mixtures for optimal performance and longevity.

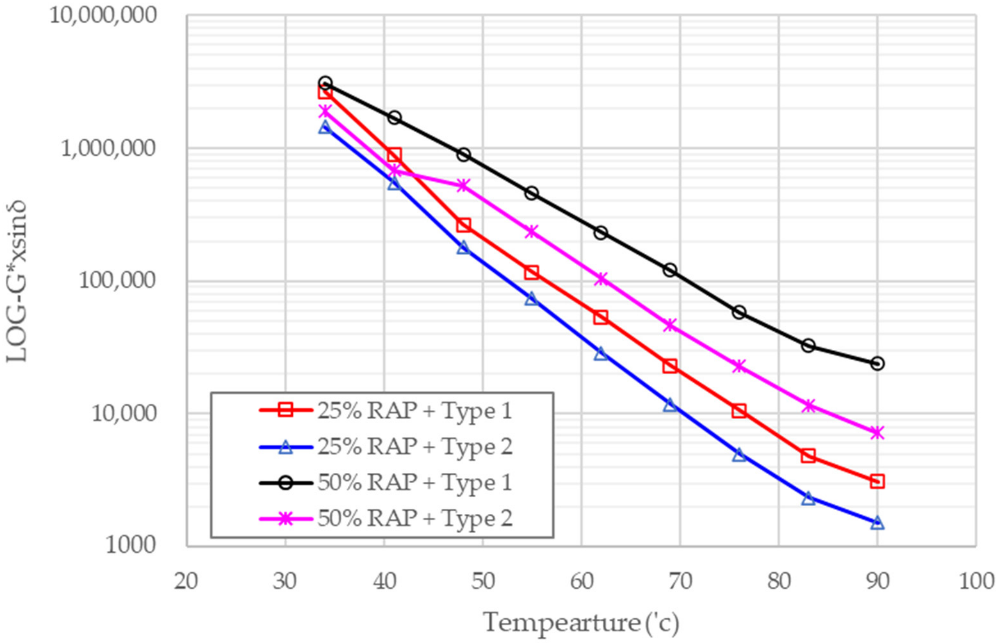


Figure 5. Sensitivity to Fatigue Cracking test results.

This sensitivity to fatigue cracking result aligns with previous studies, reinforcing the correlation between higher RAP content, specific modifier types, and enhanced resistance against fatigue-induced thermal cracking [45]. The observed trends substantiate the established understanding in the literature. This concordance underscores the reliability and consistency of our findings with the broader body of research in asphalt mixture behavior and design.

3.1.4. Analysis of Softening Point Variation in Storage Stability Test

The following Figure 6 outlines findings from the Storage Stability Test, specifically focusing on softening point variations in Type 1 and Type 2 asphalt binder samples. In their unaged states, Type 1 shows a softening point of 64.5 °C, slightly lower than Type 2's 65.2 °C. Post the storage stability test, both types are evaluated in their upper and lower sections.

Remarkably, Type 1 consistently maintains the highest softening point, recording 64.9 °C on top and 64.8 °C at the bottom. Conversely, Type 2 displays lower values, with 64.1 °C on top and 64.2 °C at the bottom. The softening point difference, indicating the change between the top and bottom sections post-test, is minimal for Type 1 at 0.3 °C, highlighting exceptional uniformity and stability. In contrast, Type 2 exhibits a slightly higher difference of 0.6 °C.

These results emphasize that Type 1 exhibits superior storage stability, with less variation between its top and bottom sections compared to Type 2. This is crucial for potential applications in expansion joints, ensuring improved long-term performance and resistance to temperature-induced changes.

This corroborates findings from other studies [46], reinforcing the importance of binder selection, for applications requiring enhanced long-term stability, such as in expansion joints. Our research substantiates these trends and contributes to the collective understanding of asphalt binder performance, providing valuable insights for optimizing asphalt mixtures in real-world pavement applications.

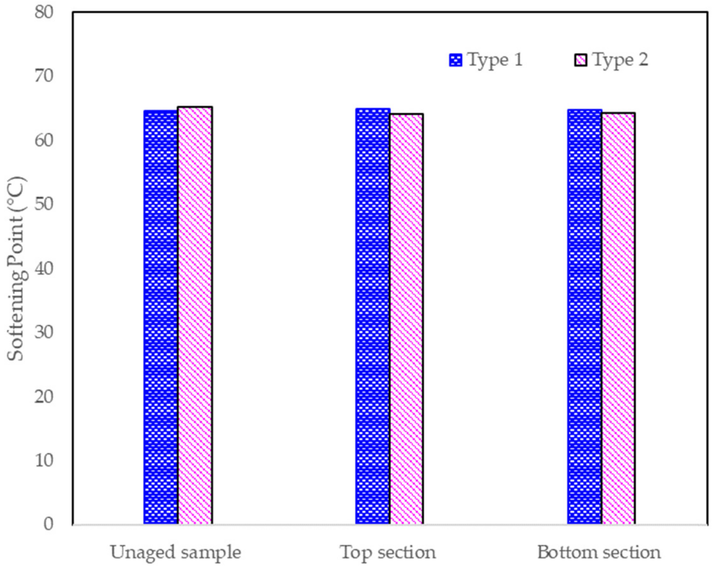


Figure 6. Storage stability test results are based on the difference in the softening point.

3.2. Asphalt Concrete Test Results

3.2.1. Hamburg Wheel Tracking (HWT) Test Results

The Hamburg Wheel Tracking (HWT) test is a crucial evaluation of asphalt concrete mixtures' rutting resistance, simulating the effects of repeated wheel loading and moisture infiltration. In this study, four distinct asphalt concrete mixtures were examined: 25% RAP + 75% Type 1, 25% RAP + 75% Type 2, 50% RAP + 50% Type 1, and 50% RAP + 50% Type 2.

Figure 7 details the HWT test results, offering a comprehensive view of rut depth variations across distinct asphalt concrete mixtures. Notably, the mixture composition featuring 25% RAP + 75% Type 1 modifier exhibits the highest rut depth at 5.4 mm. This seemingly counterintuitive result can be ascribed to the relatively lower RAP content, contributing to a softer mix that is more prone to rutting. In contrast, the composition with 50% RAP + 50% Type 1 modifier showcases the lowest rut depth of 3.9 mm, indicating a stiffer mix with heightened resistance to rutting. Here, the RAP content plays a pivotal role in mitigating rutting effects, underscoring the intricate interplay between RAP content and mixture performance. The mixtures with 25% RAP + 75% Type 2 and 50% RAP + 50% Type 2 fall between the extremes, portraying a balanced performance in rutting resistance. These findings illuminate the nuanced impact of RAP content and modifier type on rut depth, emphasizing the need for a holistic evaluation strategy that considers various mixture components for optimal performance across diverse conditions in real-world applications.

These HWT test results illuminate the complex interplay between RAP content and asphalt binder properties, providing valuable information for optimizing asphalt concrete mixtures to meet specific performance requirements in real-world pavement applications.

In general, this study's HWT test results are consistent with existing literature [47], emphasizing the intricate relationship between RAP content and modifier type in asphalt concrete mixtures. The higher rut depth in the 25% RAP + 75% Type 1 mixture aligns with prior research due to the softer characteristic, highlighting the nuanced impact of RAP proportions on asphalt stiffness. Concurrently, the superior rutting resistance in the 50% RAP + 50% Type 1 mixture corresponds to the recognized stiff benefits of increased RAP content. These findings reinforce the significance of considering RAP proportions and modifier types for optimizing asphalt mixtures, contributing valuable insights to pavement design and durability.

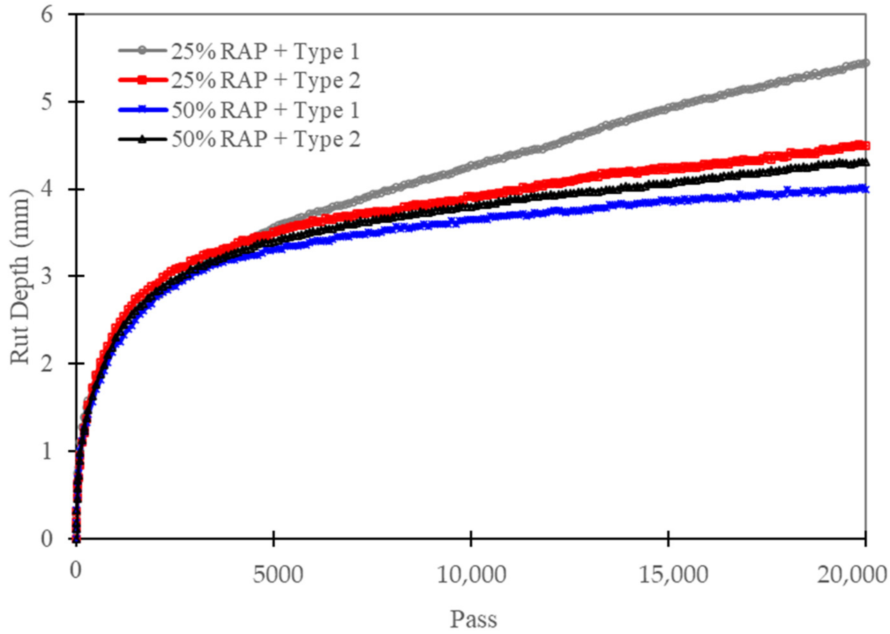


Figure 7. Hamburg Wheel Tracking Test results.

3.2.2. Overlay Test (OT) Results

The OT results reveal distinct patterns in the performance of asphalt concrete mixtures under simulated overlay conditions. The findings align with the overall trend observed in all asphalt concrete performance tests, highlighting specific characteristics of each mixture composition.

The outcomes depicted in Figure 8, derived from the OT, unfold a comprehensive narrative regarding the intricate interplay between varying asphalt concrete mixtures and their performance under simulated overlay conditions. The load reduction after 1000 cycles serves as a critical indicator, with higher percentages suggesting diminished resistance to overlay-induced distress. Surprisingly, the composition featuring 25% RAP + 75% Type 2 modifier exhibits remarkable resilience, showcasing the lowest load reduction at 64.5%. In contrast, the mixture with 25% RAP + 75% Type 1 modifier registers a slightly higher load reduction of 69.8%. The most intriguing revelation comes from the composition with 50% RAP + 50% Type 1 modifier, displaying a substantial load reduction of 82.1%. This unexpected outcome prompts a reevaluation of assumptions, indicating that higher RAP content contributes to a stiffer mixture, resulting in heightened vulnerability to overlay-induced distress. This insight challenges conventional expectations and underscores the need for a nuanced understanding of the relationship between RAP content, modifier type, and mixture stiffness in the context of overlay conditions. A deeper exploration of these findings is imperative for guiding informed decisions for optimizing asphalt mixtures, ensuring enhanced pavement durability in the face of overlay challenges.

A higher percentage of RAP, as seen in the 50% RAP + 50% Type 1 modifier composition, induces a stiffer mixture, amplifying its susceptibility to distress under overlay conditions. The stiffness of the asphalt concrete, in this case, hinders its ability to flex and accommodate dynamic forces, leading to increased susceptibility to cracking and rutting. On the contrary, the mixture with 25% RAP + 75% Type 2 modifier, displaying superior resilience with the lowest load reduction, suggests a more balanced blend of flexibility and stiffness. The interaction between RAP content and modifier type unfolds a complex dynamic, highlighting the need for a nuanced approach in mixture design. These findings underscore the importance of deciphering the intricate mechanisms governing asphalt mixture behavior under overlay conditions, paving the way for tailored solutions that prioritize durability and performance.

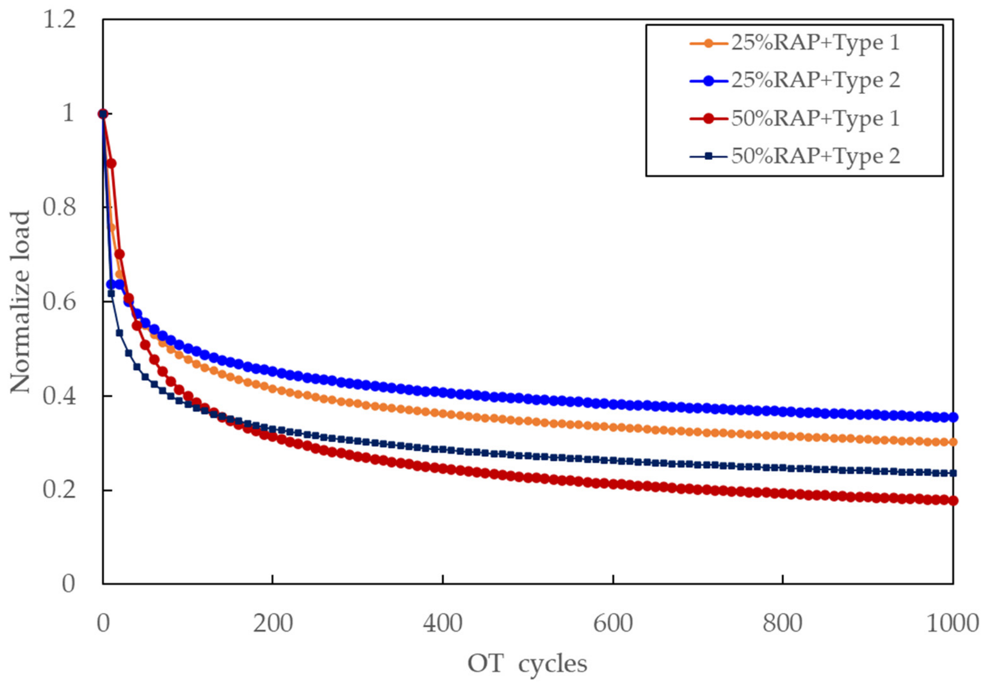


Figure 8. OT test results.

Overall, the OT test results align with existing research [12], providing insights into the intricate relationship between asphalt concrete mixtures and their performance under simulated overlay conditions. The observed higher load reduction in the 50% RAP + 50% Type 1 modifier composition is consistent with previous studies, emphasizing that higher RAP content contributes to a stiffer mixture, rendering it more vulnerable to overlay-induced distress. Surprisingly, the composition with 25% RAP + 75% Type 2 modifier exhibits remarkable resilience, challenging conventional expectations. These findings highlight the complex interplay of RAP content and modifier type, urging a nuanced understanding of optimized asphalt mixtures and enhanced pavement durability in overlay scenarios.

3.3. Field Test Results

The detailed examination of field test outcomes, with a specific focus on elastic modulus (MPa), unveils distinctive characteristics in the pavement-bearing capacities of various mixtures. As shown in Table 10, particularly noteworthy is the 25% RAP + 75% Type 2 composition, showcasing a remarkable elastic modulus of 58.5 MPa, indicating heightened bearing capacity in the pavement structure. This aligns with expectations that the specific combination of a higher proportion of the Type 2 modifier and a lower percentage of RAP contributes to enhanced rigidity and, consequently, increased load-bearing capacity. In contrast, the 50% RAP + 50% Type 1 mixture exhibits a relatively lower elastic modulus of 42.3 MPa, suggesting a pavement with reduced bearing capacity. The intricate interplay between RAP content and the type of modifier becomes apparent, influencing the overall bearing capacities of the asphalt mixtures. While the maximum load-bearing capacities of these mixtures are comparable, the nuanced variations in elastic modulus shed light on the complex dynamics governing the performance of these asphalt compositions in real-world field conditions. The test results reveal that the nuanced variations in elastic modulus, as observed between the 25% RAP + 75% Type 2 and 50% RAP + 50% Type 1 mixtures, provide valuable insights for strategic decisions in binder selection and asphalt composition to optimize pavement behavior and achieve superior bearing capacity. The higher elastic modulus in the 25% RAP + 75% Type 2 composition signifies enhanced rigidity and bearing capacity, attributed to the specific combination of a higher proportion of Type 2 modifier and a lower percentage of RAP. Conversely, the lower elastic modulus in the 50% RAP + 50% Type 1 mixture indicates reduced bearing capacity. These findings underscore the importance of carefully balancing RAP content and modifier type in asphalt mixtures, emphasizing the need for tailored solutions in real-world field conditions. Strategic decisions in binder selection should consider the desired level of rigidity and deformation resistance based on pavement performance requirements, ensuring optimal bearing capacity and long-term durability.

Table 10. Summary of LFWD Test results for different asphalt mixtures.

Mixture Composition	Maximum Load (N)	Maximum Displacement (mm)	Elastic Modulus (MPa)
25% RAP + 75% Type 1	4572	0.092	51
25% RAP + 75% Type 2	4590	0.08	58.5
50% RAP + 50% Type 1	4466	0.111	42.3
50% RAP + 50% Type 2	4577	0.117	44.2

In summary, the field test results reveal that the asphalt mixtures, while exhibiting comparable load-bearing capacities, demonstrate nuanced differences in terms of deformation resistance and stiffness. The findings underscore the significance of selecting appropriate binder types and proportions to tailor asphalt mixtures for optimal performance in real-world pavement applications. In general, these field test results, particularly in elastic modulus (MPa), echo trends observed in related research. The 25% RAP + 75% Type 2 composition showcases a notably high elastic modulus of 58.5 MPa, aligning with expectations of enhanced bearing capacity due to a higher proportion of the Type 2 modifier and lower RAP content. Conversely, the 50% RAP + 50% Type 1 mixture exhibits a comparatively lower elastic modulus of 42.3 MPa, indicating reduced bearing capacity. This nuanced interplay between RAP content and modifier type in influencing bearing capacities aligns with broader research trends, emphasizing the critical role of intentional binder selection for optimal pavement performance in real-world conditions.

In general, these research findings align with Zheng et al. in corroborating the impact of varying content [48], specifically RAP-SBS, on asphalt performance. The observed influence of RAP content and loading frequency on viscoelastic properties in Zheng's finding resonates with our study's focus on the nuanced effects of RAP content and SBS-modified binders on mechanical properties. Furthermore, our research confirms the insights from Ahmed et al. [49], emphasizing the importance of additives like aromatic oil and SBS copolymers for enhanced performance. The strategic inclusion of petroleum resin and oil in our asphalt binder compositions corresponds to improved compatibility with RAP, addressing stiffness concerns and ultimately enhancing overall mechanical properties. These comparisons reinforce the relevance of our study in the context of existing research, contributing to the collective understanding of optimal asphalt mixture formulations.

4. Conclusions

This study assesses the performance of asphalt mixtures for rural pavements, specifically examining RAP with SBS-modified asphalt binders containing petroleum resin and oil. The focus is on the impact of varying RAP content (25% and 50%) and two types of SBS-modified asphalt binders (Type 1 and Type 2) on mechanical properties and sustainability. A comprehensive set of laboratory tests, including Asphalt Binder Tests, Sensitivity to Fatigue Cracking assessments, HWT test, OT test, and field tests using the LFWD, is conducted. Key conclusions are presented as follows:

- Regarding asphalt binder properties, the mix of 25% RAP + 75% Type 1 exhibits outstanding flexibility and deformation resistance, evident in its high ductility value of 880 mm at 25 °C, potentially enhancing pavement resilience.

- The mixture with 50% RAP + 50% Type 2 modifier displayed the highest fatigue value at 23,874 kPa, indicating notable vulnerability to fatigue cracking. Conversely, the composition of 25% RAP + 75% Type 1 exhibited the lowest fatigue value at 1524 kPa, showcasing superior resistance to thermal cracking. These findings align with expectations that higher RAP content and specific modifier types enhance resistance against fatigue-induced thermal cracking.
- The storage stability tests reveal that Type 1 asphalt binder consistently maintains higher softening points with minimal variation (0.3 °C) between top and bottom sections, showcasing superior uniformity and stability compared to Type 2
- The HWT test emphasized the nuanced impact of RAP content and modifier type on rut depth. The mixture with 25% RAP + 75% Type 1 exhibited the highest rut depth at 5.4 mm, attributed to its relatively lower RAP content and softer nature. In contrast, the composition with 50% RAP + 50% Type 1 showcased the lowest rut depth of 3.9 mm, indicating heightened resistance to rutting.
- The OT results challenged conventional expectations, revealing unexpected outcomes. The mixture with 25% RAP + 75% Type 2 modifier displayed remarkable resilience, with the lowest load reduction at 64.5%. Surprisingly, the composition with 50% RAP + 50% Type 1 modifier exhibited substantial load reduction at 82.1%, challenging assumptions about higher RAP content contributing to a stiffer mixture.
- The field test results highlighted nuanced differences in pavement bearing capacities among asphalt mixtures. The 25% RAP + 75% Type 2 composition demonstrated a remarkable elastic modulus of 58.5 MPa, indicating heightened bearing capacity. In contrast, the 50% RAP + 50% Type 1 mixture exhibited a relatively lower elastic modulus of 42.3 MPa.
- The study highlights the significant impact of SBS modifiers with petroleum resin and oil on Type 1 and Type 2 asphalt binders, shaping various asphalt mixture properties. Type 2, with 50% RAP, demonstrates balanced flexibility and stiffness, performing well in overlay conditions and field tests. These insights underscore the crucial role of SBS modifiers in customizing asphalt mixture properties for sustainable and resilient pavement design. Limitations include the focus on specific compositions, and future research should explore a broader spectrum of variations for comprehensive pavement design.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: Author Kyungnam Kim was employed by the company Korea Expressway Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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