



Article

Advanced Asphalt Mixtures for Tropical Climates Incorporating Pellet-Type Slaked Lime and Epoxy Resin

Sang-Yum Lee ¹ and Tri Ho Minh Le ^{2,*}

¹ Faculty of Civil Engineering, Induk University, 12 Choansan-ro Nowon-gu, Seoul 01878, Republic of Korea; yummy10041004@gmail.com

² Faculty of Civil Engineering, Nguyen Tat Thanh University, 300A Nguyen Tat Thanh Street, District 4, Ho Chi Minh City 70000, Vietnam

* Correspondence: lhmtri@ntt.edu.vn

Abstract: The escalating impacts of climate change have led to significant challenges in maintaining road infrastructure, particularly in tropical climates. Abnormal weather patterns, including increased precipitation and temperature fluctuations, contribute to the accelerated deterioration of asphalt pavements, resulting in cracks, plastic deformation, and potholes. This study aims to evaluate the durability of a novel pellet-type stripping prevention material incorporating slaked lime and epoxy resin for pothole restoration in tropical climates. The modified asphalt mixtures were subjected to a series of laboratory tests, including the Tensile Strength Ratio (TSR) test, Indirect Tension Strength (ITS) test, Hamburg Wheel Tracking (HWT) test, Cantabro test, and Dynamic Modulus test, to assess their moisture resistance, rutting resistance, abrasion resistance, and viscoelastic properties. Quantitative results demonstrated significant improvements in the modified mixture's performance. The TSR test showed a 6.67% improvement in moisture resistance after 10 drying–wetting cycles compared to the control mixture. The HWT test indicated a 10.16% reduction in rut depth under standard conditions and a 27.27% improvement under double load conditions. The Cantabro test revealed a 44.29% reduction in mass loss, highlighting enhanced abrasion resistance. Additionally, the Dynamic Modulus test results showed better stress absorption and reduced likelihood of cracking, with the modified mixture demonstrating superior flexibility and stiffness under varying temperatures and loading frequencies. These findings suggest that the incorporation of slaked lime and epoxy resin significantly enhances the durability and performance of asphalt mixtures for pothole repair, making them a viable solution for sustainable road maintenance in tropical climates.

Keywords: climate change; pothole restoration; slaked lime; epoxy resin; asphalt pavements; moisture resistance



Citation: Lee, S.-Y.; Le, T.H.M. Advanced Asphalt Mixtures for Tropical Climates Incorporating Pellet-Type Slaked Lime and Epoxy Resin. *J. Compos. Sci.* **2024**, *8*, 442. <https://doi.org/10.3390/jcs8110442>

Academic Editor: Peng Zhang

Received: 19 September 2024

Revised: 17 October 2024

Accepted: 24 October 2024

Published: 30 October 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Climate change has increasingly posed challenges in maintaining road infrastructure [1]. Abnormal weather patterns, including increased precipitation, temperature fluctuations, and extreme weather events, contribute to the accelerated deterioration of asphalt pavements [2]. These climatic changes result in common pavement issues such as cracks [3], plastic deformation, and potholes, posing severe threats to road safety and increasing maintenance costs [4]. As such, there is a critical need for innovative and durable materials to address these challenges, particularly in tropical climates where these conditions are more pronounced [5]. Potholes are primarily caused by moisture infiltration, which weakens the bond between the asphalt binder and the aggregate, leading to stripping and eventual pavement failure [6]. Traditional methods for pothole repair, such as cold patching and temporary repairs, often provide short-term solutions that fail under repeated traffic loading and adverse weather conditions [7,8]. Therefore, developing materials with enhanced moisture resistance and durability is essential for sustainable road maintenance

practices. Recent advancements in moisture resistance technologies have introduced innovative approaches, such as waste plastic powder coating on aggregates. For instance, the study of Xiao et al. highlights the effectiveness of using hydrophobic waste plastic materials to coat aggregate surfaces [9]. This method enhances moisture resistance by preventing water infiltration and reducing the stripping of asphalt binder from the aggregate surface, offering promising results for improving asphalt durability under challenging conditions.

Several studies have investigated the performance of various additives in asphalt mixtures to enhance durability and resistance to environmental factors. For instance, Zhang et al. (2023) found that incorporating polymer-modified binders significantly improved the fatigue resistance and asphalt pavement rutting performance. Similarly, Hesami et al. (2017) stated that the use of anti-stripping agents enhanced the moisture resistance of asphalt mixtures [10]. Rahman et al. (2024) reported that the addition of fibers to asphalt mixtures increased tensile strength and reduced the rate of crack propagation under repeated loading [11]. Moreover, Chen et al. (2023) demonstrated that using nanomaterials as modifiers could improve the mechanical properties and extend the service life of asphalt pavements [12]. Research by Li et al. (2023) highlighted the potential of using recycled materials, such as polyurethane cold-cycled mixtures, to enhance the durability and sustainability of asphalt mixtures [13]. Zhang et al. (2024) suggested that styrene-butadiene rubber (SBR) additives can improve the performance of asphalt mixtures in practical conditions [14]. Furthermore, Gong et al. (2023) showed significant improvements in moisture resistance and mechanical performance with the integration of advanced binders into asphalt mixtures [15]. These various studies underscore the potential of different additives to improve the durability and performance of materials used for pothole repair, particularly by enhancing moisture resistance, mechanical strength, and overall longevity under adverse conditions [16].

In order to enhance the performance of asphalt mixtures, anti-stripping agents and additives have been the focus of recent developments in road-building materials [17,18]. It is commonly known that slaked lime strengthens the binding between the aggregate and binder in asphalt mixtures, increasing their resistance to moisture [19]. When used as a filler or additive, slaked lime introduces calcium hydroxide ($\text{Ca}(\text{OH})_2$) ions, which react with the acidic components in the aggregate, neutralizing them and thereby improving adhesion [20]. However, while slaked lime effectively mitigates moisture-induced damage, it is often associated with issues such as dust generation and uneven mixing when added in powder form. To address these challenges, pellet-type slaked lime stripping prevention materials have been developed. These materials combine slaked lime with a liquid emulsifier additive to form stable pellets that can be easily handled, stored, and uniformly dispersed within the asphalt mixture [21]. The liquid emulsifier, typically composed of wax, vegetable oil, surfactants, and water, helps to stabilize the slaked lime and ensures its effective distribution during the mixing process. This innovative approach not only reduces dust generation but also enhances the overall performance of the asphalt mixture by ensuring consistent moisture resistance.

In addition to slaked lime and emulsifiers, the incorporation of epoxy resin as an additive has shown promise in further improving the durability and performance of asphalt mixtures [22]. Epoxy resin is known for its excellent adhesive properties and resistance to environmental factors, making it an ideal candidate for enhancing the bond strength between the binder and aggregate [22]. When added to the pellet-type stripping agent, epoxy resin helps to create a more robust and durable asphalt mixture capable of withstanding the harsh conditions typical of tropical climates [23,24].

The pellet-type slaked lime is an innovative solution that addresses the limitations of traditional slaked lime in powdered form, such as dust generation, uneven distribution, and poor workability. By combining slaked lime with a liquid emulsifier, the pellet form produces stable, easily handled pellets that disperse uniformly throughout the asphalt mixture, ensuring consistent performance and enhanced durability, particularly in high-moisture environments. When combined with epoxy resin, this approach is further advanced, as

epoxy resin enhances the adhesive bond between the binder and aggregate. Known for its mechanical strength, chemical resistance, and durability in harsh environmental conditions, epoxy resin significantly improves the moisture resistance, rutting resistance, and overall longevity of the asphalt mixture. This dual-component system is particularly effective in tropical climates, where pavements are exposed to frequent moisture and temperature fluctuations, providing a robust solution for long-term pavement durability.

With an emphasis on the material's performance in tropical climates, this investigation intends to assess the long-term viability of a pellet material for pothole rehabilitation that incorporates slaked lime and an anti-stripping emulsifier. The research introduces epoxy resin as a new additive and assesses its impact on the durability of the modified asphalt mixtures. The study is divided into two phases: Phase 1 involves the preparation and testing of asphalt mixtures incorporating the pellet-type stripping agent and epoxy resin, while Phase 2 focuses on evaluating the performance of these mixtures under simulated tropical climate conditions. The materials and methods used in this study are consistent with previous research but with a specific emphasis on durability under tropical climate conditions. The asphalt mixtures were subjected to a series of drying and wetting cycles using rainwater from Vietnam to simulate the effects of repeated moisture exposure. The drying process involved curing the samples at 60 °C, while the wetting process involved cooling the samples to temperatures below 20 °C. With the use of this method, the modified asphalt mixtures' durability and resistance to moisture could be thoroughly assessed. The efficiency of the epoxy resin and pellet-type stripping agent in extending the lifespan of asphalt combinations was assessed using performance tests, including the dynamic modulus assessment, the Cantabro evaluation, the Hamburg Wheel Tracking, and the TSR and ITS experiment. These tests provided valuable insights into the long-term performance of the mixtures under simulated field conditions, helping to identify the most promising materials for sustainable pothole restoration in tropical climates. The general research flowchart of this research is shown in Figure 1.

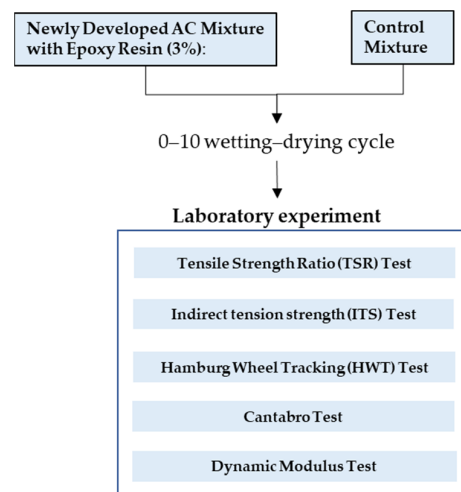


Figure 1. Research flowcharts.

2. Materials and Methods

2.1. Materials

2.1.1. Slaked Lime

Slaked lime, also known as calcium hydroxide ($\text{Ca}(\text{OH})_2$), is a critical component in enhancing the moisture resistance of asphalt mixtures. The use of slaked lime in asphalt mixtures has been well-documented, particularly for its ability to improve the bond between the asphalt binder and aggregate, thereby increasing the mixture's overall durability and resistance to moisture-induced damage [19,20]. Typically, slaked lime is incorporated into the aggregate before it is mixed with the asphalt binder, serving as a replacement for conventional limestone powder filler. This substitution not only enhances the moisture

resistance but also helps neutralize the acidic components present in the aggregate, which can weaken the asphalt–aggregate bond.

For this study, slaked lime was incorporated at a ratio of 1% by weight of the aggregate. This proportion was selected based on previous research that has demonstrated its efficacy in improving moisture resistance without adversely affecting the workability of the asphalt mixture. The slaked lime used in this study was mixed with a liquid emulsifier additive to form a pellet-type anti-stripping agent. This innovative approach ensures better handling, reduced dust generation, and improved dispersion in the asphalt mixture.

The asphalt mixture becomes more stable overall as a result of this reaction, which also releases heat and increases volume. Slaked lime's significant alkalinity (pH of 11) makes it an efficient tool for raising the adhesive strength among aggregate and bitumen binder.

Through an extrusion process, slaked lime was combined in a 20:80 ratio with a liquid emulsifier in order to be integrated into the pellet-type anti-stripping agent. The manufacture of stable pellets that are manageable and evenly distributed throughout the asphalt mixture is guaranteed by this procedure. By creating a strong and durable link between the aggregate and the binder, the pellets lessen the damage caused by moisture and increase the life of the asphalt surface. The general properties of slaked lime are presented in Table 1.

Table 1. Properties for slaked lime.

Property	Description
Chemical composition	$\text{Ca}(\text{OH})_2$
Appearance	Fine white powder
pH value	11
Specific gravity	2.24
Solubility in water	Slightly soluble (1.73 g/L at 20 °C)
Bulk density	0.5–0.8 g/cm ³
Particle size distribution	Typically <75 µm
Moisture content	≤2%
Heat of hydration	Exothermic reaction when mixed with water, releasing heat
Calcium content	≥90%
Impurities	≤2% (includes magnesium oxide, silicon dioxide, and iron oxide)
Neutralizing value	120–135 (compared to pure calcium carbonate with a value of 100)

2.1.2. Anti-Stripping Technology

In order to improve the bonding between the asphalt binder and aggregate, an anti-stripping technique is essential [25,26]. This increases the asphalt mixtures' resilience to moisture and overall strength. Anti-stripping compounds are primarily used to stop the stripping impact, which is caused by water seeping into the asphalt pavement and breaking the aggregate's binding with the binder. In this investigation, slaked lime and a liquid emulsifier ingredient were combined to create a pellet-type anti-stripping agent. Wax, vegetable oil, surfactants, and water were combined to create the emulsifier [26,27].

The selection of this combination was determined by its demonstrated ability to improve asphalt mixtures' durability against moisture. Calcium hydroxide ($\text{Ca}(\text{OH})_2$) is created when quick lime (CaO) reacts with water to create hydrated lime. The process increases volume and produces heat, both of which are good for the stability of the asphalt mixture. When SiO^- ions on the aggregate surface react with CaOH^+ ions introduced by hydrated lime, an intense chemical connection is formed that increases the adhesive strength between the aggregate and the bitumen adhesive. The longevity of the pavement is ensured by this connection, which stops moisture-induced deterioration. The mechanism of anti-stripping is shown in Figure 2.

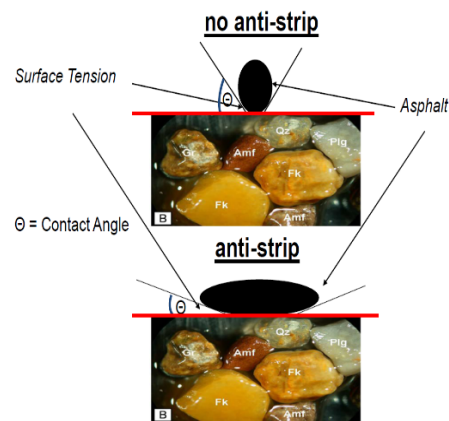


Figure 2. Mechanism of anti-stripping.

2.1.3. Pellet-Type Slaked Lime for Asphalt Durability

The development of a pellet-type slaked lime stripping prevention material aims to enhance the durability and moisture resistance of asphalt mixtures by combining slaked lime with a liquid emulsifier additive in a stable pellet form [28]. The liquid emulsifier, consisting of wax, vegetable oil, surfactants, and water, is mixed with slaked lime in a 20:80 ratio and extruded to form pellets [25]. These pellets provide better handling, storage, and equal distribution in the mixture of asphalt while addressing problems including dust formation and uneven mixing. The pellets ensure structural stability, preventing crumbling and degradation. When mixed with asphalt aggregate at a 1% proportion by weight, the pellets improve moisture resistance by forming strong chemical bonds between the binder and aggregate and enhancing adhesion through reduced contact angles. Figure 3 shows an overview of the developed material.



Figure 3. Pellet-type stripping material.

The 1% slaked lime content was chosen because previous research has demonstrated that this concentration is effective in improving moisture resistance without negatively affecting the workability or compaction of asphalt mixtures. Research has shown that slaked lime, when added in small percentages (typically between 1% and 2%), significantly enhances the bond between the asphalt binder and aggregate by mitigating moisture damage and preventing stripping. The 1% ratio provides an optimal balance between improving moisture resistance and maintaining the mechanical properties of the mixture.

2.1.4. Design and Advantages of Pellet-Type Stripping Agent for Warm Mix Asphalt

The pellet-type stripping agent for Warm Mix Asphalt (WMA) is designed to enhance the moisture resistance and durability of asphalt mixtures by incorporating slaked lime and a liquid emulsifier additive into a pellet form [29–31]. Traditional slaked lime can pose issues such as dust generation and uneven mixing with aggregates. To address these challenges, the pellet-type agent combines slaked lime with wax, vegetable oil, surfactants,

and water. This mixture is then extruded into pellets, which ensures uniform dispersion and stability during handling and mixing. The liquid emulsifier used in the pellet-type agent includes various oils and waxes that provide structural stability and prevent the pellets from crumbling [32]. For instance, a blend of ethylene wax, olive oil, mineral oil, and fatty acid amine surfactant was found to be particularly effective [21]. The emulsifier composition was optimized based on several trial mixes to ensure the pellets' active ingredients remained stable and effective. The extrusion process forms pellets that can be easily stored, handled, and mixed with asphalt aggregates. This uniformity ensures that the anti-stripping agent is evenly distributed throughout the asphalt mixture, enhancing its overall performance. The pellet-type agent's stability reduces dust and improves the safety and cleanliness of the mixing process.

The pellet-type stripping agent is produced through an extrusion process.

- In this method, slaked lime ($\text{Ca}(\text{OH})_2$) is combined with a liquid emulsifier in a ratio of 20:80 by weight, where the emulsifier consists of wax, vegetable oil, surfactants, and water. The mixture is extruded into pellets, which are subsequently cooled and dried to ensure structural stability. This extrusion process creates uniform pellets with consistent size and shape, allowing for easier handling, storage, and integration into asphalt mixtures. The extrusion ensures that the slaked lime is evenly coated with the emulsifier, reducing dust generation and improving distribution in the asphalt matrix.
- The liquid emulsifier is composed of 8% ethylene wax, 3% olive oil, 5% mineral oil, and 7% fatty acid amine surfactants, with the remaining 77% consisting of water. These proportions were determined based on trials to achieve optimal pellet stability, moisture resistance, and ease of mixing. The emulsifier serves to bind the slaked lime particles together, forming stable pellets that resist crumbling and ensure even distribution during asphalt mixing.
- Each constituent material plays a critical role in the formulation. Slaked lime ($\text{Ca}(\text{OH})_2$) acts as the primary anti-stripping agent, improving moisture resistance by enhancing the bond between the binder and aggregate. Wax (ethylene) provides structural stability to the pellets, preventing them from disintegrating during storage and handling, and ensuring that they maintain their shape during mixing. Vegetable oil (olive oil) enhances the flexibility and workability of the pellets, ensuring they remain stable during the asphalt production process. Mineral oil acts as a lubricant to ease the extrusion process and improve the consistency of the pellets. Surfactants (fatty acid amine) assist in reducing the surface tension between the binder and aggregate, enhancing the adhesive properties of the asphalt mixture and improving the dispersion of slaked lime throughout the asphalt.
- The optimal particle size for the pellets was determined through experimental trials, with a target size of approximately 3–5 mm in diameter. This size was chosen to ensure that the pellets could be evenly distributed in the asphalt mixture without segregation. Additionally, this size range ensures that the slaked lime within the pellets remains effective in enhancing moisture resistance without causing mixing issues or negatively affecting the workability of the asphalt. The particle size was also optimized to ensure minimal dust generation during handling and mixing.
- The pellet-type particles possess several key characteristics. First, they have structural stability, maintaining their integrity during storage, handling, and mixing, ensuring that they do not break down prematurely. Second, they allow uniform dispersion, as they are designed to disperse evenly throughout the asphalt mixture, ensuring consistent moisture resistance across the entire pavement structure.

2.1.5. Decomposition and Dispersion of Pellet-Type Material During Hot Mixing

- The pellet-type material is specifically designed to fully decompose during the hot mixing process. At typical asphalt production temperatures, ranging between 135 °C and 160 °C, the emulsifier components in the pellet, such as wax, vegetable oil, surfactants, and water, melt and break down. This allows the slaked lime to be released

and evenly dispersed within the asphalt mixture. As the emulsifier decomposes, it facilitates the uniform integration of the slaked lime, ensuring that its beneficial properties, particularly in enhancing moisture resistance, are effectively retained without any remnants of the pellet structure remaining.

- To evaluate the dispersion of the slaked lime after the decomposition of the pellets, several tests were conducted. Visual and microscopic inspections of the asphalt mixture confirmed the complete dissolution of the pellets, with no residual material detected. Additionally, key performance indicators such as the Tensile Strength Ratio and Hamburg Wheel Tracking tests were used to assess the effectiveness of the dispersion. The uniform improvements in moisture resistance and rutting resistance observed across multiple samples demonstrate that the slaked lime was well-dispersed throughout the mixture. The consistent high performance in these tests supports the conclusion that the pellet material fully decomposes and integrates evenly into the asphalt matrix.

2.1.6. Epoxy Resin Used in Asphalt

Epoxy resin is incorporated into asphalt mixtures to significantly enhance their durability, adhesive strength, and resistance to environmental factors [33]. Known for its excellent mechanical properties and chemical resistance, epoxy resin is an effective additive for improving the performance of asphalt pavements, particularly in challenging conditions such as tropical climates. In this investigation, 3% by weight of epoxy resin was included in the asphalt mixture [34].

The 3% epoxy resin content was selected based on its proven ability to enhance the adhesive strength between the binder and aggregate, while also improving the overall mechanical properties of the asphalt mixture. Previous studies have indicated that epoxy resin, when used in similar proportions, significantly enhances the durability, stiffness, and flexibility of asphalt mixtures. A 3% ratio was found to be optimal in balancing the improvement of moisture resistance, rutting resistance, and flexibility without leading to excessive stiffness, which could cause brittleness or cracking under varying environmental conditions. Additionally, this ratio was chosen to ensure the cost-effectiveness and practical feasibility of incorporating epoxy resin into large-scale pavement applications [35]. The asphalt mixture's durability against deformation under recurrent loading is further enhanced by the inclusion of epoxy resin. This is particularly important for regions with heavy traffic and varying environmental conditions, as it helps to maintain the pavement's structural integrity over time. The epoxy resin enhances the elastic modulus of the asphalt mixture, reducing susceptibility to temperature-induced cracking and plastic deformation. Table 2 presents the comparison of the control mix and epoxy resin-modified mix components while Table 3 presents the overview of the liquid emulsifiers used in this research [36].

Table 2. Comparison of control mix and epoxy resin modified mix components.

Component	Control Mix	Modified Mix with Epoxy Resin
Wax	8.0 (Ethylene)	6.0 (Ethylene)
Vegetable oil	3.0 (Olive)	1.5 (Olive)
Mineral oil	5.0	4.5
Surfactants (Fatty acid amine)	7.0	6.0
Additive	0.2	0.2
Water	76.8	78.8
Epoxy resin	-	3.0

Table 3. Qualities of liquid asphalt emulsifiers for WMA.

Property	Control Mix	Modified Mix with Epoxy Resin
Exterior	Milky liquid	Milky liquid
Stability	7 days or less	15 days or less
Condition	Liquid	Liquid

Table 3. Cont.

Property	Control Mix	Modified Mix with Epoxy Resin
Smell	Odorless	Slightly resinous
Active ingredient	24%	27%

2.1.7. Preparation and Mix Design of Modified Asphalt Concrete Mixtures

The preparation of modified asphalt concrete mixtures involved incorporating the pellet-type stripping agent with slaked lime and epoxy resin into the asphalt mix. This section outlines the materials, mix design, and preparation process used for creating the modified asphalt concrete mixtures, which were then subjected to various performance tests. The materials included aggregates and mineral fillers provided by a local supplier, with properties conforming to relevant standards for asphalt mixture production, a conventional asphalt binder with the binder content optimized based on previous research and recommendations, and the pellet-type stripping agent containing a mix of slaked lime and liquid emulsifier with 3% epoxy resin prepared using the extrusion process described earlier. The mix design followed the Superpave method, aiming to optimize the asphalt mixture's resistance to rutting, and thermal cracking, with the target binder content set at 5.6% by weight of the total mix and aggregate gradation designed to meet the specifications for a 10 mm Stone Mastic Asphalt type [37–39].

The preparation process began with drying the aggregates to remove any moisture content, ensuring accurate measurement of aggregate weight and consistent mixing with the asphalt binder. The dried aggregates and asphalt binder were then heated to the appropriate mixing temperature to ensure proper coating of the aggregates with the binder while maintaining workability. The heated aggregates were first mixed with the pellet-type stripping agent at a proportion of 1% by weight and then combined with the heated asphalt binder to ensure thorough coating and uniform distribution of the stripping agent. The mixed asphalt was compacted using a Superpave Gyratory Compactor [40,41] to produce cylindrical specimens, aiming to achieve a density representative of field conditions. Finally, the compacted specimens were allowed to cool to room temperature before being subjected to performance tests, with storage in a controlled environment to prevent any moisture or temperature variations that could affect the test results. Table 4 presents the properties of aggregate materials, including bulk-specific gravity, moisture absorption, aggregate impact value, Los Angeles abrasion loss, and shape index. Table 5 shows the sieve size gradation of the materials, detailing the percentage passing through various sieve sizes from 19.0 mm down to 0.075 mm.

Table 4. Properties of aggregate materials.

Materials	Properties	Value
Aggregate	Bulk specific gravity [42]	2.65
	Moisture absorption [42]	0.150%
	Aggregate impact value [43]	21.4%
	Los Angeles abrasion loss [44]	23.8%
	Shape index [45]	10.2%
Mineral filler	Bulk density [46]	2.45
	Fineness modulus [46]	0.85%

Table 5. Sieve size gradation.

Sieve Size (mm)	Percentage Passing (%)
19.0	100
12.5	95.3
9.5	82.7
4.75	60.2

Table 5. *Cont.*

Sieve Size (mm)	Percentage Passing (%)
2.36	42.5
1.18	28.3
0.600	18.9
0.300	12.7
0.150	7.4
0.075	4.8

2.1.8. Development of Dry–Wet Cycle

The wet–dry cycle method was selected as a well-established laboratory simulation technique for accelerated aging and moisture damage assessment in asphalt mixtures. While it is recognized that in tropical climates roads are indeed often exposed to prolonged periods of high-temperature rainwater, the dry–wet cycle remains an effective proxy for evaluating long-term moisture-related deterioration.

In real-world tropical environments, pavements are exposed to more than just prolonged periods of water. They also undergo drying phases between rainfalls or during the day as water evaporates due to high surface temperatures. The wet–dry cycle test effectively simulates this alternating exposure to moisture and drying, capturing the real-world effects of tropical rain combined with intermittent drying phases, which subject the pavement to cyclic stress. The drying phase at elevated temperatures is critical, as it accelerates the breakdown of the asphalt binder–aggregate bond, a process that becomes more pronounced with repeated moisture infiltration followed by drying. This cyclic exposure replicates the natural fatigue experienced by pavements in tropical climates, where heavy rainfall and high temperatures often occur. This approach offers a more comprehensive evaluation of long-term pavement performance than continuous immersion in water alone. Wet–dry cycles are widely used in moisture sensitivity tests like the Tensile Strength AASHTO T 283 standard [47], ensuring that this methodology aligns with established standards and allows for reliable comparisons with existing research on pavement performance under tropical conditions.

2.2. Laboratory Tests

The asphalt mixtures were prepared by integrating the pellet-type stripping agent, which included slaked lime and a liquid emulsifier with 3% epoxy resin, at a rate of 1% by weight of the total aggregate. Table 6 presents a comparison of materials used in performance tests between the Slaked Lime AC Mixture (2%) and the Newly Developed AC Mixture with Epoxy Resin (3%). It details the percentages of slaked lime and epoxy resin content, mixing temperatures, and quantities of aggregate, anti-stripping agent, and asphalt used for each mixture.

Table 6. Materials used in the performance test.

Material	Slaked Lime AC Mixture (2%)	Modified Mixture with Epoxy Resin (3%)
Slaked lime content (%)	2.0	1.0
Epoxy resin content (%)	-	3.0
Mixing temperature (°C)	155	135
Aggregate (g)	499.8	504.9
Anti-stripping agent (g)	10.0	5.1
Asphalt (g)	16	16

2.2.1. TSR Test

The asphalt mixtures' endurance and resistance to moisture were evaluated using the TSR experiment, following the AASHTO T 283 standard [47]. The methodology involved

preparing cylindrical asphalt specimens incorporating the pellet-type stripping agent with slaked lime and 3% epoxy resin at a proportion of 1% by weight. The specimens were compacted using a Superpave Gyratory Compactor (SGC) to achieve a target density representative of field conditions. The TSR test utilized cylindrical asphalt specimens with a standard size of 150 mm in diameter and 95 mm in height, with each test being replicated three times to ensure the accuracy and reliability of the results. The specimens were then divided into two sets: One set was subjected to moisture conditioning by saturating with water under vacuum, followed by freezing at $-18\text{ }^{\circ}\text{C}$ for 16 h and then thawing in a $60\text{ }^{\circ}\text{C}$ water bath for 24 h; the other set was kept dry as a control. After conditioning, the indirect tensile strength of both sets was measured at $25\text{ }^{\circ}\text{C}$ using a loading rate of 50 mm/min. The TSR value was determined by dividing the average tensile strength of the conditioned specimens by that of the dry specimens. This test indicated the mixture's ability to resist moisture-induced damage, with higher TSR values reflecting better moisture resistance.

2.2.2. Indirect Tension Strength Test

The Indirect Tension Strength Experiment was conducted following ASTM D6931 [48] guidelines, involving the careful preparation of cylindrical specimens measuring 150 mm in diameter and 63.5 mm in height using a gyratory compactor. In our study, the primary method for assessing moisture resistance was the Tensile Strength Ratio (TSR). Six specimens were prepared for each RAP combination, ensuring a consistent porosity of $7.0 \pm 0.5\%$. Three of these specimens underwent a comprehensive freeze–thaw moisture treatment, while the other three served as control specimens, being submerged in a water bath at $60\text{ }^{\circ}\text{C}$ for 2 h.

2.2.3. HWT Test

The HWT experiment was performed to evaluate the moisture susceptibility and rutting resistance of the asphalt mixtures, following the AASHTO T 324 standard [49]. The methodology involved preparing cylindrical asphalt specimens incorporating the pellet-type stripping agent with slaked lime and 3% epoxy resin at a proportion of 1% by weight. The HWT test utilized cylindrical asphalt specimens with a standard size of 150 mm in diameter and 95 mm in height, with each test being replicated three times to ensure the accuracy and reliability of the results. The specimens were compacted using an SGC to achieve a target density representative of field conditions. The compacted specimens were then submerged in a water bath maintained at $50\text{ }^{\circ}\text{C}$ and subjected to repeated loading using a steel wheel that applied a load of $705 \pm 4.5\text{ N}$ (see Figure 4). The wheel tracking device passed over the specimens for 20,000 cycles or until a rut depth of 20 mm was reached. The rut depth was measured continuously during the test to monitor the progression of deformation. This test provided a measure of the mixture's resistance to rutting and moisture-induced damage, with lower rut depths indicating better performance. The findings from the HWT provided insights into the enhanced durability and stability of the modified asphalt mixtures under simulated field conditions.



Figure 4. HWT test.

2.2.4. Cantabro Test

The Cantabro test was conducted to evaluate the resistance of the asphalt mixtures to abrasion and aggregate loss, following the KS F2492 standard [50]. The methodology involved preparing cylindrical asphalt specimens incorporating the pellet-type stripping agent with slaked lime and 3% epoxy resin at a proportion of 1% by weight. The Cantabro test utilized cylindrical asphalt specimens with a standard size of 100 mm in diameter and 63.5 mm in height, with each test being replicated three times to ensure the accuracy and reliability of the results. The specimens were compacted using an SGC to achieve a target density representative of field conditions. After compaction, the specimens were allowed to cool to room temperature. The cooled specimens were then placed in a Los Angeles (LA) abrasion machine without any steel spheres. The machine was rotated at a speed of 30–33 revolutions per minute for a total of 300 revolutions. After the test, the specimens were removed, and the mass loss was calculated by measuring the difference in weight before and after the test. The mass loss percentage was used to assess the durability and cohesion of the asphalt mixtures, with lower mass loss percentages indicating better resistance to abrasion and aggregate loss. This test provided insights into the long-term performance of the asphalt mixtures under simulated wear and tear conditions.

2.2.5. Dynamic Modulus Test

The Dynamic Modulus Test was conducted to determine the viscoelastic properties of the asphalt mixtures, following the AASHTO TP62 [51] as shown in Figure 5. The methodology involved preparing cylindrical asphalt specimens incorporating the pellet-type stripping agent with slaked lime and 3% epoxy resin at a proportion of 1% by weight. The Dynamic Modulus Test utilized cylindrical asphalt specimens with a standard size of 100 mm in diameter and 150 mm in height, with each test being replicated three times to ensure the accuracy and reliability of the results. The specimens were compacted using an SGC to achieve a target density representative of field conditions. After compaction, the specimens were subjected to a series of sinusoidal loading cycles at various temperatures (4 °C, 20 °C, 40 °C, and 54 °C) and loading frequencies (25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz, and 0.1 Hz). The test was performed using a dynamic testing machine capable of applying cyclic compressive loads to the specimens. The resulting stress and strain responses were recorded to calculate the dynamic modulus ($|E^*|$) and phase angle (δ) of the asphalt mixtures. The dynamic modulus provided a measure of the stiffness of the asphalt mixtures under different loading conditions and temperatures, with higher dynamic modulus values indicating stiffer mixtures. This test helped to evaluate the performance and structural integrity of the asphalt mixtures under varying environmental and loading conditions.



Figure 5. Dynamic modulus testing.

3. Results and Discussions

3.1. TSR Test Results

The TSR test results demonstrated the enhanced moisture resistance and durability of the modified asphalt mixtures compared to the control as shown in Figure 6. The TSR values for the modified mixture incorporating 3% epoxy resin and the control mixture were assessed at 0, 5, and 10 drying–wetting cycles. Initially, at 0 cycles, the modified mixture demonstrated a TSR value of 90%, significantly higher than the 84% achieved by the control mixture. This initial high TSR value highlights the enhanced moisture resistance imparted by the epoxy resin. As the number of drying–wetting cycles increased, both mixtures showed a decrease in TSR values, reflecting the impact of repeated moisture exposure and the associated stress on the materials. However, the modified mixture consistently maintained superior performance, with TSR values of 87% and 80% at 5 and 10 cycles, respectively, compared to the control mixture's 82% and 75%. The ability of the modified mixture to retain higher TSR values despite the increasing number of cycles underscores. This demonstrates the strength and resilience offered by the epoxy resin, strengthening the link between the aggregate and bitumen binder. This improvement in moisture resistance ensures that the modified mixture can better withstand the cyclical stresses of drying and wetting, common in real-world environmental conditions. Consequently, the inclusion of epoxy resin not only improves the initial moisture resistance of the asphalt mixture but also provides sustained protection against moisture damage over time, making it a promising solution for enhancing the durability and longevity of asphalt pavements under adverse environmental conditions.

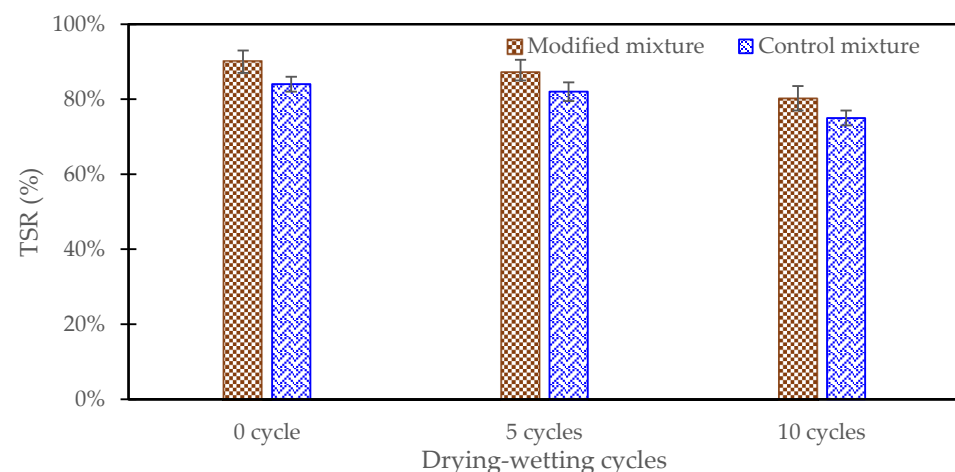


Figure 6. Moisture resistance test results.

3.2. ITS Test Results

The test results demonstrated the superior performance of the modified asphalt mixture with epoxy resin compared to the control mixture as shown in Figure 7. Initially, the modified mix exhibited an indirect tensile strength of 0.90 MPa, which is approximately 7.1% higher than the control mix's ITS of 0.84 MPa. Additionally, the modified mix had a stiffness of 3.2 kN/mm, about 10.3% higher than the control mix's stiffness of 2.9 kN/mm. After undergoing 10 drying–wetting cycles, simulating repeated environmental exposure, the modified mix retained a higher ITS of 0.80 MPa, only an 11.1% decrease from its initial value, compared to the control mix which saw a 10.7% decrease to 0.75 MPa. The stiffness of the modified mix decreased to 3.0 kN/mm, a 6.3% reduction, whereas the control mix decreased to 2.6 kN/mm, an 11.1% reduction. These results indicate that the modified mix not only starts with higher tensile strength and stiffness but also maintains better performance after environmental stress, demonstrating enhanced durability and resistance to moisture-induced damage, making it a more effective solution for pothole repair in tropical climates.

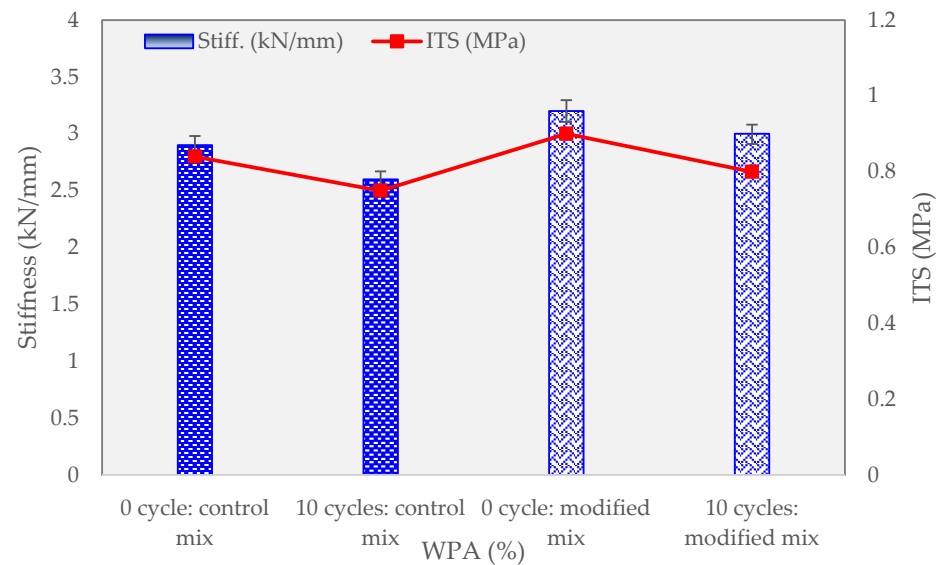


Figure 7. ITS test results.

3.3. HWT Test Results

The HWT results provided comprehensive insights into the rutting resistance and durability of the modified and controlled asphalt mixtures under various conditions. As presented in Figure 8, initially, all mixtures demonstrated a sharp increase in rutting depth within the first 1000 cycles, with depths escalating from 0 to 1.5 mm, followed by a significant rise to 3 mm. This rapid initial increase indicates the mixtures' susceptibility to deformation under early loading conditions. However, after this initial phase, the rate of rutting depth increase diminished, suggesting that the mixtures began to stabilize and resist further deformation to some extent.

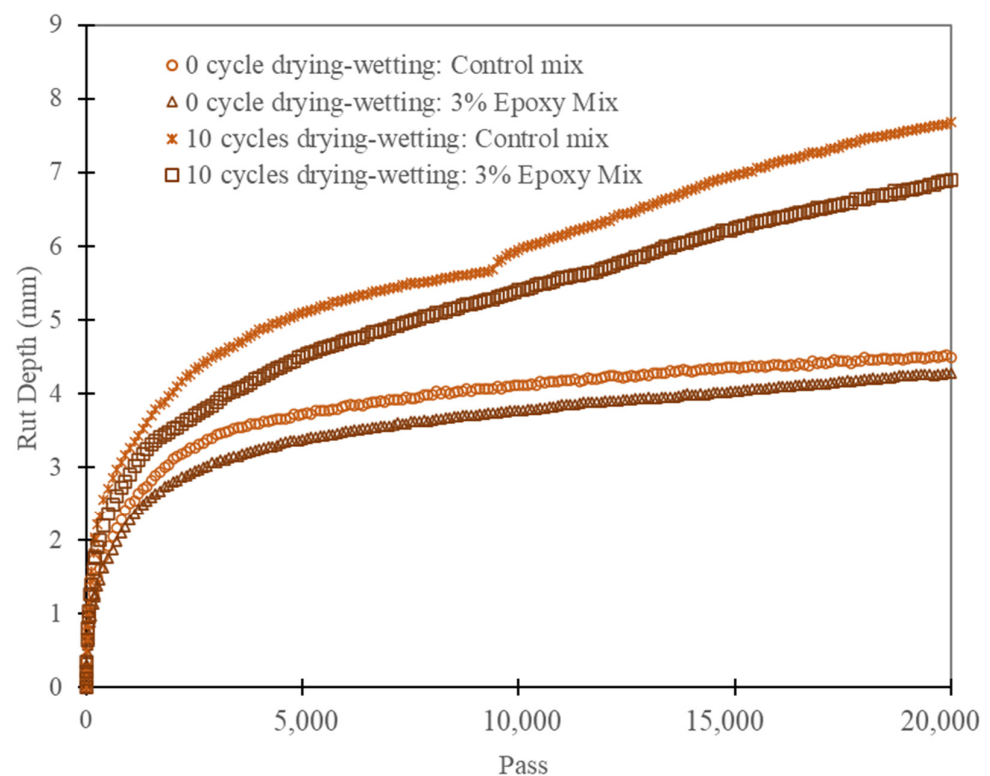


Figure 8. Hamburg wheel tracking test results.

For mixtures subjected to 0 drying–wetting cycles, both the control and modified (epoxy mix) mixtures exhibited a gradual increase in rutting depth from 3 mm to 4 mm. This stage reflects the continued but more controlled deformation under prolonged loading. Notably, the gap between the two mixtures became more pronounced from 2000 to 5000 HWT passes, with the modified mix consistently showing around 10% lower rutting depth than the control mix. This indicates that the modified mixture’s enhanced formulation, including the epoxy resin, provided better resistance to rutting under these conditions. By the final stage of 20,000 passes, the rutting depth of the control mixture reached 4.49 mm, whereas the modified mix exhibited a slightly lower rutting depth of 4.27 mm. This small but significant difference underscores the modified mixture’s superior performance in maintaining structural integrity over an extended period.

When subjected to 10 drying–wetting cycles, the performance differences between the mixtures became more pronounced. Both the control and modified (epoxy mix) mixtures experienced a sharp increase in rutting depth from 4 mm to 7 mm, reflecting the added stress from repeated moisture exposure and subsequent drying. This stage simulates real-world conditions where pavements are subjected to cyclic environmental changes. Similar to the 0 cycle condition, the gap between the control and modified mixtures was more pronounced from 2000 to 5000 HWT passes, maintaining around a 10% difference. At the end of the 20,000 passes, the rutting depth of the control mixture was significantly higher at 7.67 mm compared to 6.89 mm for the modified mix. The larger gap in rutting depths after 10 cycles indicates the epoxy resin’s effectiveness in enhancing moisture resistance and reducing deformation.

Furthermore, the test revealed a critical difference in the stripping performance of the mixtures. A stripping point, indicating significant moisture-induced damage and loss of binder–aggregate adhesion, was recorded for the control mixture at 9400 passes. In contrast, no stripping point was observed for the modified mixture under any condition. This absence of a stripping point in the modified mix highlights the substantial improvement in moisture resistance and structural stability provided by the epoxy resin. The modified mixture’s ability to maintain integrity without stripping under repeated drying–wetting cycles is a crucial advantage for long-term pavement durability.

The inclusion of epoxy resin not only improved the mixture’s ability to withstand initial deformation but also provided sustained protection against moisture-induced damage. This makes the modified mixture a robust and reliable choice for pavement applications in regions with harsh and variable environmental conditions, ensuring longer service life and reduced maintenance requirements.

The double HWT load condition was designed to simulate the actual traffic loads experienced during rush hours and traffic jams (see Figure 9). This condition applies a higher stress level to the asphalt mixtures, providing a more rigorous assessment of their performance under heavy traffic conditions. Only the 10-cycle group was tested under this double load condition. The results showed distinct differences in the performance of the control and modified (epoxy mix) mixtures. From 0 to 12,000 passes, both mixtures exhibited a gradual increase in rutting depth from 0 to less than 7 mm. However, the rutting depth in the control mixture was consistently greater, approximately 12% higher than that of the modified mixture. This indicates that the modified mixture had better resistance to initial deformation under the increased load.

From 13,000 to 20,000 passes, both mixtures showed a sharp increase in rutting depth, reflecting the severe stress conditions simulated by the double load. During this phase, the rutting depth of the control mixture increased significantly from 7 mm to 22 mm. In contrast, the modified mixture experienced a slower rise, reaching a rutting depth of 16 mm from an initial 7 mm. This notable difference highlights the superior performance of the modified epoxy mixture in withstanding higher loads and repeated stress cycles, making it particularly suitable for high-traffic areas prone to congestion and heavy traffic.

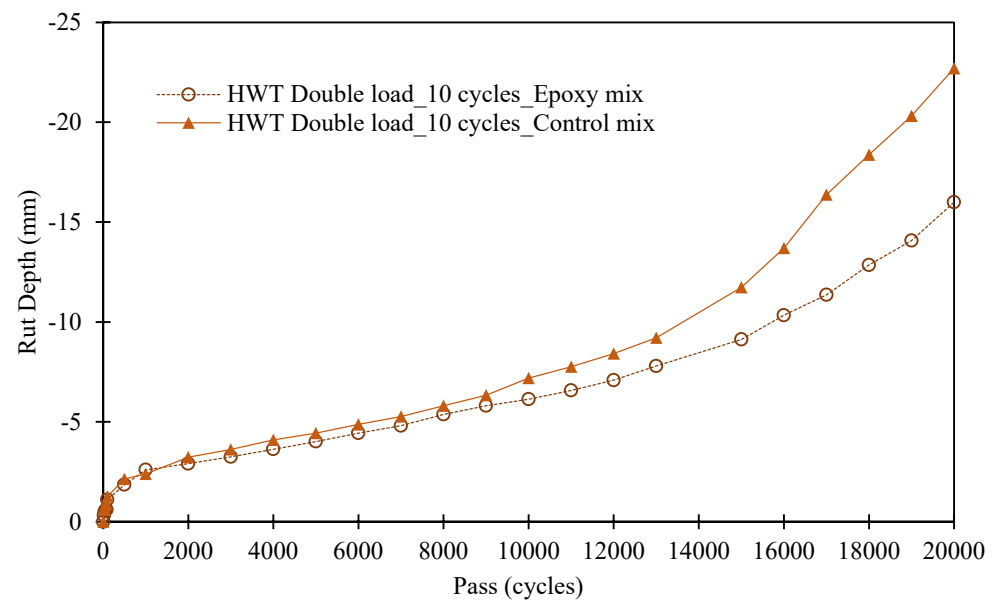


Figure 9. Double load HWT test results.

3.4. Cantabro Test Results

The test results provided valuable insights into the resistance of the asphalt mixtures to abrasion and aggregate loss, critical for assessing the long-term durability of pavement materials under wear and tear conditions as presented in Figure 10. This test is particularly relevant for evaluating the performance of asphalt mixtures in environments subjected to frequent traffic and harsh weather conditions, which can lead to significant mechanical degradation over time.

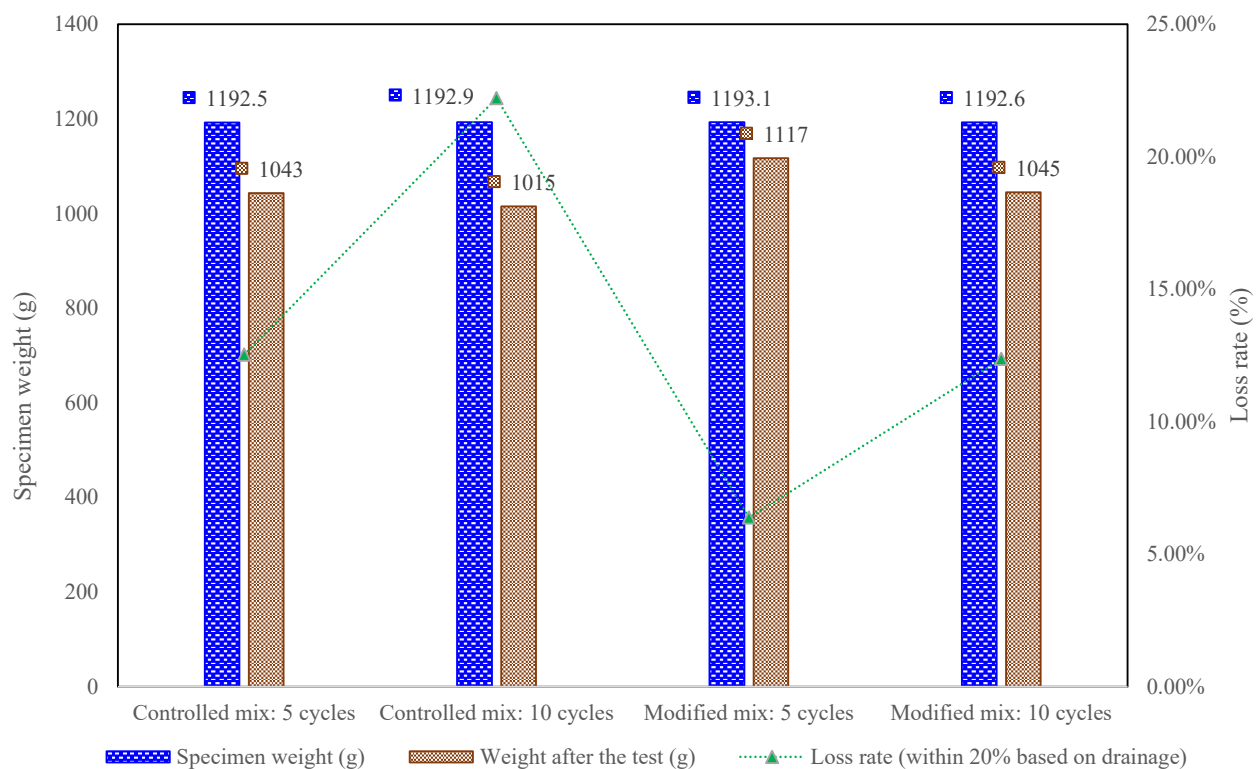


Figure 10. Cantabro test results.

The test results, detailed in Figure 10, highlight the comparative performance of the controlled and modified mixtures after 5 and 10 cycles of drying and wetting.

For the controlled mixture, the loss rate after 5 cycles was 12.53%, indicating a moderate level of material degradation. However, after 10 cycles, the loss rate increased dramatically to 22.21%. This sharp increase demonstrates that the controlled mixture's ability to resist abrasion and aggregate loss deteriorates significantly with extended exposure to moisture and mechanical stress. Such a high loss rate suggests that the controlled mixture is less durable and may require more frequent maintenance or replacement in real-world applications, leading to higher lifecycle costs and potential disruptions in service.

In contrast, the modified mixture, which incorporates 3% epoxy resin, exhibited superior performance in resisting abrasion and aggregate loss. After five cycles, the modified mixture showed a loss rate of only 6.38%, which is significantly lower than the controlled mixture. This lower loss rate indicates a much stronger bond between the asphalt binder and aggregate, resulting in higher durability and resistance to wear. Even after 10 cycles, the modified mixture maintained a loss rate of 12.37%, which, although higher than the 5-cycle loss rate, was still considerably lower than the 22.21% observed for the controlled mixture after 10 cycles.

The inclusion of epoxy resin in the modified mixture plays a crucial role in enhancing its durability. The epoxy resin improves the adhesive properties of the binder, ensuring a stronger bond with the aggregate. This enhancement helps to prevent the loss of aggregate particles during mechanical stress and exposure to moisture, thereby maintaining the structural integrity of the asphalt mixture. The lower loss rates observed in the modified mixture indicate that it can better withstand the cyclical stresses of drying and wetting, which are common in real-world environmental conditions.

Additionally, the improved performance of the modified mixture can lead to several practical benefits in pavement applications. Reduced material loss translates to longer service life and fewer maintenance interventions, which can result in lower maintenance costs and less disruption to traffic. Furthermore, the enhanced durability of the modified mixture makes it a more sustainable choice, as it reduces the frequency of repairs and replacements, thereby minimizing the environmental impact associated with pavement construction and maintenance activities.

3.5. Dynamic Modulus Test Results

The results provided critical insights into the viscoelastic properties of the asphalt mixtures, particularly how they respond to different frequencies of loading, which simulate various traffic conditions and weather scenarios. The dynamic modulus ($|E^*|$) is a key indicator of the stiffness and elasticity of the asphalt mixtures, influencing their ability to withstand deformation and stress.

For the 0 cycles group (see Figure 11), the dynamic modulus values were generally lower compared to the 10 cycles group. This indicates that the asphalt mixtures are less stiff and potentially more susceptible to deformation before undergoing any drying–wetting cycles. This initial lower stiffness can be beneficial in terms of flexibility but might compromise the mixture's ability to resist permanent deformation under load.

The control mixture's E modulus was 401 MPa at low frequency, which mimics hot weather and slow traffic at junctions. In contrast, the epoxy-modified mixture's E modulus was 278 MPa. This suggests that under these circumstances, the combination treated with epoxy is softer and more flexible. Given that asphalt tends to grow softer and more prone to rutting in high-temperature environments, the epoxy mix's lower modulus indicates that it can better absorb and disperse stress.

In high-frequency simulations of frigid climate or fast traffic, the E modulus values of the modified and control mixtures were around 190,000 MPa. This high rigidity is essential to preserving the integrity of the structure and guarding against damage from chilly or fast-moving traffic. However, the similar modulus values for both mixtures at high frequency indicate that while they provide comparable resistance to deformation,

the control mixture's higher stiffness might lead to brittleness and increased susceptibility to cracking under cold conditions. In contrast, the slightly lower modulus of the epoxy-modified mixture allows for better absorption and dissipation of stresses, reducing the likelihood of cracking and deformation, which is beneficial in preventing brittle failure in cold climates.

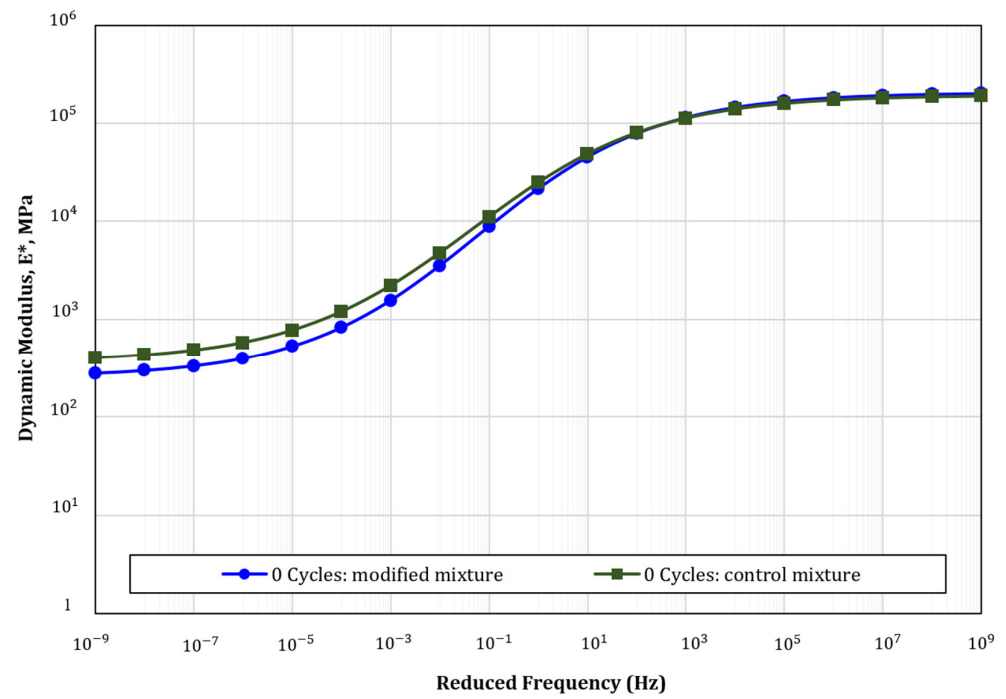


Figure 11. Dynamic modulus test results of 0 drying–wetting cycle samples.

For the 10 cycles group as shown in Figure 12, the dynamic modulus values were generally higher compared to the 0 cycles group, indicating increased stiffness after repeated drying and wetting cycles. This suggests that the asphalt mixtures gain stiffness over time due to the effects of moisture exposure and subsequent drying, enhancing their resistance to permanent deformation under certain conditions.

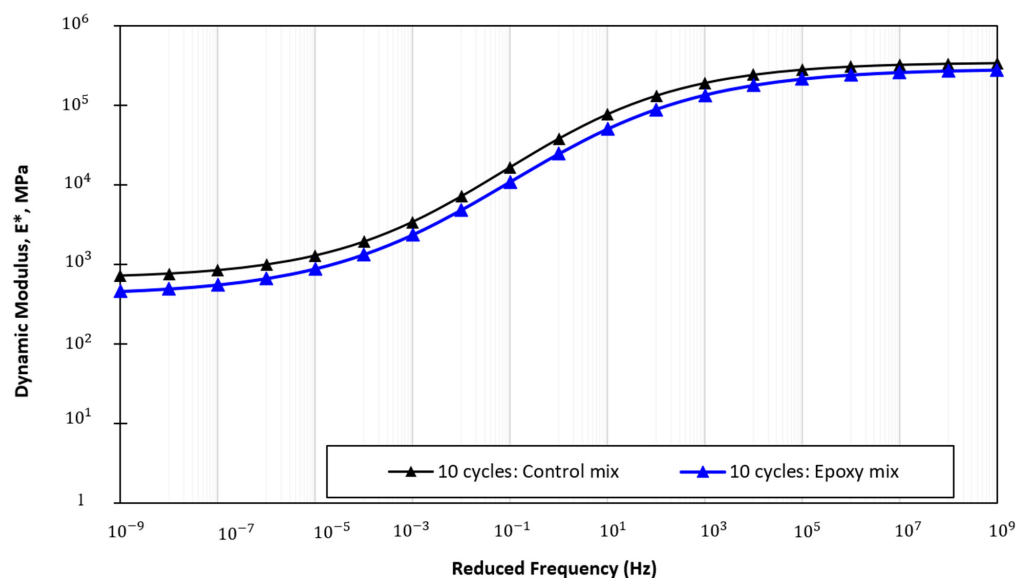


Figure 12. Dynamic modulus test results of 10 drying–wetting cycle samples.

At low frequencies, the E modulus of the control mixture was 720 MPa, while the E modulus of the epoxy-modified mixture was 460 MPa. This indicates that the epoxy-modified mixture remains more flexible and softer under these conditions, even after 10 cycles. The lower modulus suggests that the epoxy mix can continue to absorb and dissipate stress effectively, reducing the likelihood of cracking and deformation in high-temperature conditions where asphalt tends to become softer and more susceptible to rutting.

At high frequencies, the E modulus values were significantly higher for both mixtures. The control mixture showed an E modulus of 341,462 MPa, whereas the epoxy-modified mixture had an E modulus of 277,476 MPa. These higher values reflect the increased stiffness of the asphalt mixtures under such conditions, which is crucial for maintaining structural integrity and preventing damage from high-speed traffic or low temperatures. However, the control mixture's higher modulus indicates it is stiffer, which might offer better resistance to deformation under heavy and fast-moving traffic. Conversely, the slightly lower modulus of the epoxy-modified mixture suggests that it can better absorb and dissipate stress, reducing the likelihood of cracking and deformation in cold weather conditions or high-speed traffic scenarios. The enhanced flexibility of the epoxy-modified mixture is beneficial in preventing brittle failure and maintaining pavement integrity in varying environmental conditions.

Overall, the Dynamic Modulus Test results highlight the differences in the performance characteristics of the control and epoxy-modified mixtures across different loading conditions and cycles. The control mixture's higher stiffness at both low and high frequencies suggests it might be more resistant to deformation under certain conditions, but this comes at the cost of reduced flexibility, which can lead to increased susceptibility to cracking. Conversely, the epoxy-modified mixture, with its lower modulus at both frequency ranges, demonstrates greater flexibility and the ability to absorb and dissipate stresses more effectively. This balance of properties makes the epoxy-modified mixture a versatile option that can perform well under a variety of environmental and traffic conditions, offering enhanced durability and longevity for asphalt pavements.

3.6. Discussion on Anti-Stripping Effects of Pellet-Type Slaked Lime and Hydrated Lime Powder

The primary focus of this study was to evaluate the combined effects of the pellet-type slaked lime agent with epoxy resin; however, the importance of comparing the anti-stripping effects of pellet-type slaked lime to traditional hydrated lime powder is recognized. Both forms of slaked lime are widely used as anti-stripping agents in asphalt mixtures due to their ability to enhance moisture resistance and prevent the stripping of the asphalt binder from the aggregate.

Existing research has demonstrated that the pellet-type material offers several advantages over the traditional powder form, particularly in terms of handling, storage, and ease of distribution within the asphalt mixture. The pellet form reduces the dust-related issues commonly associated with the use of hydrated lime powder, improving both safety and environmental conditions during mixing. Additionally, the uniformity of the pellets ensures a more consistent distribution of slaked lime throughout the asphalt matrix, which contributes to enhanced moisture resistance and durability.

Although this study did not include a direct comparison between the anti-stripping performance of pellet-type slaked lime and traditional powder, the performance tests, including the TSR and HWT tests, demonstrated that the pellet-type material provides significant improvements in moisture resistance and rutting resistance. These results align with findings from previous studies where pellet-type material has been shown to perform comparably or better than hydrated lime powder under similar conditions.

Given the promising results, a direct comparative study between the pellet-type slaked lime and traditional hydrated lime powder could offer further insights into the differences in anti-stripping performance. Such a comparison would provide a more comprehensive evaluation of their respective effectiveness in asphalt mixtures. Future

research is recommended to conduct such a direct comparison to fully assess the potential benefits of the pellet-type material relative to the traditional powder form.

3.7. Discussion on Mechanisms of Epoxy Resin in Enhancing Asphalt Mixtures

Epoxy resin enhances moisture resistance and bonding in asphalt mixtures through several key physical and chemical mechanisms:

Epoxy resin forms strong covalent bonds with both organic and inorganic materials. When incorporated into asphalt mixtures, it reacts with both the asphalt binder and the aggregate surface, creating a robust adhesive layer that strengthens the bond between them. This chemical bond is highly resistant to moisture infiltration, preventing the weakening or stripping that typically occurs when water penetrates asphalt layers. Additionally, epoxy resin forms cross-links, further reinforcing the bond and contributing to a cohesive and durable structure.

A key physical property of epoxy resin is its hydrophobic nature. It forms a protective barrier within the asphalt mixture, repelling water and preventing its penetration into the binder–aggregate interface. This water-repellent effect reduces the potential for moisture-induced damage, such as stripping or debonding, which is especially beneficial in tropical climates with high humidity and frequent rain.

Epoxy resin enhances the adhesive properties of the asphalt binder, improving the overall bond between the binder and aggregate. This increased adhesion improves cohesion within the mixture, preventing aggregate particles from dislodging under stress or moisture exposure. Furthermore, the resin imparts flexibility to the asphalt mixture, allowing it to absorb and dissipate stresses from traffic loads and environmental conditions, such as temperature fluctuations, thus preventing cracking and maintaining the structural integrity of the pavement.

In addition to moisture resistance, epoxy resin improves the long-term durability of asphalt mixtures by resisting oxidation and aging. Asphalt binders tend to become brittle over time due to oxidative aging, which can lead to cracking and pavement distress. Epoxy resin slows down this aging process, creating a chemically stable mixture that is less susceptible to oxidation, thereby contributing to the extended lifespan of the pavement and reducing maintenance frequency.

4. Conclusions

This study aimed to evaluate the durability and performance of a pellet-type stripping prevention material incorporating slaked lime and epoxy resin for pothole restoration, particularly under tropical climate conditions. The following key quantitative findings were observed:

- The TSR test results demonstrated that the modified asphalt mixture with 3% epoxy resin maintained significantly higher moisture resistance compared to the control. Initially, at 0 cycles, the modified mixture had a TSR value of 90%, whereas the control had 84%. Following 10 drying–wetting cycles, the modified mixture's TSR value was 80%, while the control mixture's value was 75%, indicating a 6.67% increase in moisture resistance.
- The HWT test results showed superior rutting resistance for the modified mixture. After 20,000 passes under 0 drying–wetting cycles, the modified mixture had a rut depth of 4.27 mm, whereas the control mixture had a rut depth of 4.49 mm, indicating a 4.9% reduction in rut depth for the modified mixture. After 10 drying–wetting cycles, the rut depth for the modified mixture was 6.89 mm, whereas the control reached 7.67 mm, indicating a 10.16% improvement in rutting resistance for the modified mixture.
- Under double load conditions designed to simulate heavy traffic loads, the modified mixture showed significantly better performance. The rut depth for the modified mixture after 20,000 passes was 16 mm, compared to 22 mm for the control, highlighting a substantial 27.27% improvement in rutting resistance under heavy loading.

- The Cantabro test results highlighted the enhanced resistance to abrasion and aggregate loss in the modified mixture. After 5 drying–wetting cycles, the modified mixture had a mass loss of 6.38%, significantly lower than the control mixture’s 12.53%. After 10 cycles, the modified mixture maintained a mass loss of 12.37%, compared to 22.21% for the control mixture. This indicates a substantial 44.29% improvement in resistance to abrasion and aggregate loss for the modified mixture.
- The dynamic modulus test results showcased the viscoelastic properties of the modified mixture under different frequencies and temperatures. At low frequency (simulating hot weather conditions with slow traffic), the epoxy-modified mixture exhibited a modulus of 460 MPa, compared to 720 MPa for the control mixture, indicating greater flexibility. At high frequency (simulating cold weather conditions or high traffic speeds), the modified mixture had a modulus of 277,476 MPa compared to 341,462 MPa for the control, suggesting better stress absorption and reduced likelihood of cracking. After 10 drying–wetting cycles, the modified mixture’s dynamic modulus values increased, reflecting enhanced stiffness and durability under repeated moisture exposure.
- Despite the promising results, this study is limited by the use of simulated tropical climate conditions and laboratory tests, which may not fully replicate real-world environments and long-term performance.
- Future research should focus on field trials to validate these findings, assess long-term durability under actual traffic and environmental conditions, and explore the cost-effectiveness and scalability of implementing the pellet-type materials on a larger scale. Additionally, investigating the environmental impact and lifecycle sustainability of these materials will provide a more comprehensive understanding of their benefits and potential limitations.

Author Contributions: Conceptualization S.-Y.L.; methodology, T.H.M.L.; software, S.-Y.L.; validation, S.-Y.L. and T.H.M.L.; formal analysis, S.-Y.L.; investigation, S.-Y.L.; resources, T.H.M.L.; data curation, T.H.M.L.; writing—original draft preparation, T.H.M.L.; writing—review and editing, S.-Y.L.; visualization, S.-Y.L.; supervision, S.-Y.L.; project administration, S.-Y.L.; funding acquisition, S.-Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Dataset available on request from the authors

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhang, Q.; Yang, S.; Chen, G. Regional Variations of Climate Change Impacts on Asphalt Pavement Rutting Distress. *Transp. Res. Part D Transp. Environ.* **2024**, *126*, 103968. [\[CrossRef\]](#)
2. Liu, T.; Yang, S.; Liao, B.; Yang, E.; Jiang, X. Contribution of Climate Change and Traffic Load on Asphalt Pavement Carbon Emissions. *J. Clean. Prod.* **2024**, *434*, 140553. [\[CrossRef\]](#)
3. Liu, T.; Yang, S.; Jiang, X.; Liao, B.; Castillo-Camarena, E.A. Adaptation Measures for Asphalt Pavements to Climate Change in China. *J. Clean. Prod.* **2023**, *415*, 137861. [\[CrossRef\]](#)
4. Yao, L.; Leng, Z.; Ni, F.; Lu, G.; Jiang, J. Adaptive Maintenance Strategies to Mitigate Climate Change Impacts on Asphalt Pavements. *Transp. Res. Part D Transp. Environ.* **2024**, *126*, 104026. [\[CrossRef\]](#)
5. Swarna, S.T.; Hossain, K.; Bernier, A. Climate Change Adaptation Strategies for Canadian Asphalt Pavements; Part 2: Life Cycle Assessment and Life Cycle Cost Analysis. *J. Clean. Prod.* **2022**, *370*, 133355. [\[CrossRef\]](#)
6. Jwaida, Z.; Dulaimi, A.; Mydin, M.A.O.; Özkılıç, Y.O.; Jaya, R.P.; Ameen, A. The Use of Waste Polymers in Asphalt Mixtures: Bibliometric Analysis and Systematic Review. *J. Compos. Sci.* **2023**, *7*, 415. [\[CrossRef\]](#)
7. Wang, X.; Huang, Y.; Geng, L.; Li, M.; Han, H.; Li, K.; Xu, Q.; Ding, Y.; Zhang, T. Multiscale Performance of Composite Modified Cold Patch Asphalt Mixture for Pothole Repair. *Constr. Build. Mater.* **2023**, *371*, 130729. [\[CrossRef\]](#)
8. Hafezzadeh, R.; Autelitano, F.; Giuliani, F. Asphalt-Based Cold Patches for Repairing Road Potholes—An Overview. *Constr. Build. Mater.* **2021**, *306*, 124870. [\[CrossRef\]](#)
9. Xiao, R.; Zhang, M.; Zhong, J.; Baumgardner, G.L.; Huang, B. Waste Plastic Powder Coating on Acidic Aggregates: A New Hydrophobic Coating Technology to Build Moisture-Resistant Asphalt Mixtures. *Transp. Res. Rec.* **2023**. [\[CrossRef\]](#)

10. Hesami, E.; Mehdizadeh, G. Study of the Amine-Based Liquid Anti-Stripping Agents by Simulating Hot Mix Asphalt Plant Production Process. *Constr. Build. Mater.* **2017**, *157*, 1011–1017. [\[CrossRef\]](#)
11. Rahman, M.N.; Castro, S.; Noorvand, H.; Kaloush, K.; Mamlouk, M.; Ozer, H. Effect of Low Dosage Fiber Reinforcement on Cracking Performance of Asphalt Concrete. *Constr. Build. Mater.* **2024**, *411*, 134380. [\[CrossRef\]](#)
12. Chen, Y.; Huang, J.; Muhammad, Y.; Zhao, Z.; Fan, S.; Luo, W.; Li, J. Study on the Performance and Mechanism of Carbon Nanomaterials Incorporated SBS Composite Modified Asphalt. *Constr. Build. Mater.* **2023**, *389*, 131795. [\[CrossRef\]](#)
13. Li, Z.; Guo, T.; Chen, Y.; Zhang, T.; Tang, D.; Hao, M.; Zhao, X.; Liu, J. Study on Road Performance of Polyurethane Cold-Recycled Mixture. *Polymers* **2023**, *15*, 1958. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Zhang, Q.; Hou, D.; Li, Z.; Wang, H.; Dong, S. Evaluation of the Thermal Stability and Micro-Modification Mechanism of SBR/PP-Modified Asphalt. *Polymers* **2024**, *16*, 456. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Gong, Y.; Wu, S.; Bi, H.; Tian, L. Study on Thermal Stability and Fatigue Properties of SBS/CNT-Modified Asphalt Sealant. *Polymers* **2023**, *15*, 3968. [\[CrossRef\]](#)
16. Gupta, L.; Bellary, A. Comparative Study on the Behavior of Bituminous Concrete Mix and Warm Mix Asphalt Prepared Using Lime and Zycotherm as Additive. *Mater. Today Proc.* **2018**, *5*, 2074–2081. [\[CrossRef\]](#)
17. Syrmanova, K.; Kaldybekova, Z.; Agabekova, A.; Baizhanova, S. Influence of the Chemical Composition of Kulantau Vermiculite on the Structure of Modified Bitumen Compositions. *J. Compos. Sci.* **2024**, *8*, 118. [\[CrossRef\]](#)
18. Sadeghi, P.; Goli, A.; Fini, E. Carbon Sequestration via Bituminous Composites Containing Recycled High-Density Polyethylene. *J. Compos. Sci.* **2024**, *8*, 100. [\[CrossRef\]](#)
19. Taherkhani, H.; Tajdini, M. Comparing the Effects of Nano-Silica and Hydrated Lime on the Properties of Asphalt Concrete. *Constr. Build. Mater.* **2019**, *218*, 308–315. [\[CrossRef\]](#)
20. Park, S.S.; Park, J.W.; Yoon, K.B.; Park, I.S.; Woo, S.W.; Lee, D.E. Evaluation of Compressive Strength and Thermal Conductivity of Sand Stabilized with Epoxy Emulsion and Polymer Solution. *Polymers* **2022**, *14*, 1964. [\[CrossRef\]](#)
21. Lee, J.S.; Lee, S.Y.; Bae, Y.S.; Le, T.H.M. Development of Pavement Material Using Crumb Rubber Modifier and Graphite Nanoplatelet for Pellet Asphalt Production. *Polymers* **2023**, *15*, 727. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Kong, L.; Su, S.; Wang, Z.; Wu, P.; Zhang, Y.; Chen, Z.; Ren, D.; Ai, C. Microscale Mechanism and Key Factors of Waterborne Epoxy Resin Emulsified Asphalt Enhancing Interlayer Bonding Performance and Shear Resistance of Bridge Deck Pavement. *Constr. Build. Mater.* **2024**, *419*, 135570. [\[CrossRef\]](#)
23. Gao, Y.; Jin, J.; Liu, S.; Du, Y.; Qian, G.; Mao, J.; Zhu, Y. Performance Evaluation of New Epoxy Resin-Based Composite Phase Change Materials and Their Asphalt Mixture. *J. Traffic Transp. Eng. (Engl. Ed.)* **2024**, *11*, 507–522. [\[CrossRef\]](#)
24. Lee, S.Y.; Yun, Y.M.; Minh Le, T.H. Influence of Performance-Graded Binders on Enhancing Asphalt Mixture Performance with Epoxy Resin and Crumb Rubber Powder. *Case Stud. Constr. Mater.* **2023**, *19*, e02628. [\[CrossRef\]](#)
25. Kim, K.N.; Le, T.H.M. Feasibility of Pellet Material Incorporating Anti-Stripping Emulsifier and Slaked Lime for Pothole Restoration. *Buildings* **2023**, *13*, 1305. [\[CrossRef\]](#)
26. Rafiq, W.; Napiah, M.B.; Sutanto, M.H.; Alaloul, W.S.; Zabri, Z.N.B.; Khan, M.I.; Musarat, M.A. Investigation on Hamburg Wheel-Tracking Device Stripping Performance Properties of Recycled Hot-Mix Asphalt Mixtures. *Materials* **2020**, *13*, 4704. [\[CrossRef\]](#)
27. Ye, Y.; Hao, Y.; Zhuang, C.; Shu, S.; Lv, F. Evaluation on Improvement Effect of Different Anti-Stripping Agents on Pavement Performance of Granite–Asphalt Mixture. *Materials* **2022**, *15*, 915. [\[CrossRef\]](#)
28. Okubo, H.; Yao, S. Restoring Mechanism of Mechanical Properties of Recycled Polyethylene Pellet Moldings by a Repelletizing Treatment Using a Twin-Screw Extruder. *J. Mater. Cycles Waste Manag.* **2021**, *23*, 1152–1176. [\[CrossRef\]](#)
29. Renken, P.; Büchler, S.; Falchetto, A.C.; Wang, D.; Wistuba, M.P. Warm Mix Asphalt—a German Case Study. *Asph. Paving Technol. Assoc. Asph. Paving Technol. Tech. Sess.* **2018**, *87*, 685–714. [\[CrossRef\]](#)
30. Barra, F.; Khatib, J.; Castro, A.; Elkordi, A. Effect of Chemical Warm Mix Additive on the Properties and Mechanical Performance of Recycled Asphalt Mixtures. *Buildings* **2022**, *12*, 874. [\[CrossRef\]](#)
31. Advanced Asphalt Technologies, LLC. *NCHRP 673 A Manual for Design of Hot-Mix Asphalt with Commentary*; NCHRP: Washington, DC, USA, 2011. [\[CrossRef\]](#)
32. Babangida Attahiru, Y.; Mohamed, A.; Eltwati, A.; Burga, A.A.; Ibrahim, A.; Nabade, A.M. Effect of Waste Cooking Oil on Warm Mix Asphalt Block Pavement—A Comprehensive Review. *Phys. Chem. Earth* **2023**, *129*, 103310. [\[CrossRef\]](#)
33. Zhang, Z.; Li, J.; Wang, Z.; Long, S.; Jiang, S.; Liu, G. Preparation and Performance Characterization of a Novel High-Performance Epoxy Resin Modified Reactive Liquid Asphalt. *Constr. Build. Mater.* **2020**, *263*, 120113. [\[CrossRef\]](#)
34. Cong, P.; Luo, W.; Xu, P.; Zhang, Y. Chemical and Physical Properties of Hot Mixing Epoxy Asphalt Binders. *Constr. Build. Mater.* **2019**, *198*, 1–9. [\[CrossRef\]](#)
35. Yao, X.; Tan, L.; Xu, T. Preparation, Properties and Compound Modification Mechanism of Waterborne Epoxy Resin/Styrene Butadiene Rubber Latex Modified Emulsified Asphalt. *Constr. Build. Mater.* **2022**, *318*, 126178. [\[CrossRef\]](#)
36. Lee, S.Y.; Kwak, D.Y.; Le, T.H.M. Laboratory Evaluation on the Aging Susceptibility of Reclaimed Asphalt Bitumen Containing Low-Viscosity Binder and Cooking Oil Waste. *Results Eng.* **2023**, *19*, 101260. [\[CrossRef\]](#)
37. Lou, K.; Xiao, P.; Kang, A.; Wu, Z.; Dong, X. Effects of Asphalt Pavement Characteristics on Traffic Noise Reduction in Different Frequencies. *Transp. Res. Part D Transp. Environ.* **2022**, *106*, 103259. [\[CrossRef\]](#)

38. Zhang, W. Effect of Tack Coat Application on Interlayer Shear Strength of Asphalt Pavement: A State-of-the-Art Review Based on Application in the United States. *Int. J. Pavement Res. Technol.* **2017**, *10*, 434–445. [[CrossRef](#)]
39. Alnadish, A.M.; Singh, N.S.S.; Alawag, A.M. Applications of Synthetic, Natural, and Waste Fibers in Asphalt Mixtures: A Citation-Based Review. *Polymers* **2023**, *15*, 1004. [[CrossRef](#)]
40. Luca, J.; Mrawira, D. New Measurement of Thermal Properties of Superpave Asphalt Concrete. *J. Mater. Civ. Eng.* **2005**, *17*, 72–79. [[CrossRef](#)]
41. Al-Khateeb, G.G.; Al-Suleiman Obaidat, T.I.; Khedaywi, T.S.; Elayan, M.S. Studying Rutting Performance of Superpave Asphalt Mixtures Using Unconfined Dynamic Creep and Simple Performance Tests. *Road Mater. Pavement Des.* **2018**, *19*, 315–333. [[CrossRef](#)]
42. *ASTM C127*; Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate. ASTM: West Conshohocken, PA, USA, 2004; pp. 1–5.
43. *ASTM Standard D5821*; Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate. ASTM: West Conshohocken, PA, USA, 2017; pp. 1–6.
44. *ASTM C131/C131M-14*; Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. ASTM: West Conshohocken, PA, USA, 2014; Volume 4, pp. 5–8.
45. *ASTM D 4791*; Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate. ASTM: West Conshohocken, PA, USA, 1999; Volume 4, pp. 1–4.
46. *ASTM D24*; Standard Specification for Mineral Filler for Bituminous Paving Mixtures. ASTM: West Conshohocken, PA, USA, 2001; Volume 4, pp. 1–2.
47. *AASHTO T 283*; Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. ASTM: West Conshohocken, PA, USA, 2018; Volume 3, pp. 1–8.
48. *ASTM D6931*; Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures. ASTM: West Conshohocken, PA, USA, 2017; pp. 1–5.
49. *AASHTO T 324*; Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures. AASHTO Association: Washington, DC, USA, 2022.
50. *KS F 2492*; Cantabro Test Method for Drainage Asphalt Mixtures. Korean National Standard: Maengdong-myeon, Republic of Korea, 2022.
51. *AASHTO TP62-2017*; Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt (HMA). AASHTO Association: Washington, DC, USA, 2017.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.