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Feasibility of Pellet Material Incorporating Anti-Stripping Emulsifier and Slaked Lime for Pothole Restoration

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Abstract: Climate change has caused a surge in abnormal weather patterns, leading to a rise in cracks, plastic deformation, and pothole damage on road surfaces. In order to fabricate a ready-mix admixture of warm asphalt mixture (WMA) for pothole restoration, this study aimed to develop a neutralized anti-stripping material in pellet form by extruding a combination of slaked lime and a liquid emulsifier additive. Slaked lime (1% by weight of aggregate) was chosen for its ability to enhance moisture resistance, while a liquid emulsifier (wax + vegetable oil + surfactant + water) was added to create a pellet-type stripping inhibitor for WMA. After successfully fabricating the pellet admixture, this study evaluated the performance of two asphalt mixtures: conventional Slaked Lime Hot Mix Asphalt (LHMA) and the Pellet-Type Anti-Stripping Warm Mix Asphalt (PWMA). Several compatibility tests were conducted to evaluate the quality of the developed material. The results showed that the fatigue resistance of the developed material (PWMA) improved by over 20%, indicating an extended fatigue life for the pavement. The LHMA and PWMA met the quality standard for asphalt mixtures, with a TSR value of approximately 83%. Both mixtures demonstrated improved rutting resistance compared to HMA. The PWMA required 16,500 cycles, while the LHMA required 19,650 cycles to reach a settlement of 20 mm, indicating better moisture resistance than the control mix (13,481 cycles). The modified mixture performed properly in the Cantabro test, with loss rates below 20%, indicating their ability to retain their aggregate structure. The PWMA also showed superior resistance to plastic deformation, with a 12.5% lower phase angle (35°) at a reduced frequency of 10^{-3}. In general, the application of PWMA not only prolongs the pavement lifespan but also reduces the production temperature by over 20 °C, leading to lower emissions and energy consumption. This makes it an environmentally friendly option for pavement applications and contributes to sustainable road construction practices.

Keywords: pothole; anti-stripping agent; pellet type; pellet type anti-stripping agent; asphalt pavement

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1. Introduction

The escalating impacts of climate change, including a rise in the average temperature of approximately 1.7 °C over the past century, have led to a surge in extreme weather events, such as heavy snowfall, torrential rain, and cold waves, since 2000. Consequently, there has been a significant increase in early damage to infrastructure, such as cracks, permanent deformation, and potholes [1,2]. The frequent occurrence of road damage, particularly potholes, due to continuous rainfall and snowfall driven by climate change, poses a severe threat to safe driving conditions [3–5].

Potholes result from moisture infiltration beneath the asphalt pavement, causing the stripping and weakening of the adhesive force between the aggregate and asphalt binder [6,7]. This can occur as a result of inadequate drainage, which impedes moisture removal and creates localized areas saturated with excessive moisture. This leads to breakage and the formation of potholes [8]. However, recent studies have demonstrated that moisture damage in asphalt may be primarily caused by the presence of acidic aggregate, which inherently has a weaker bond with asphalt, and that the long-term aging of asphalt can further worsen this problem [9]. In addition, potholes have been attributed to various causes in the literature [10,11]. This can be caused by various factors, including traffic loads generating shear stress, inadequate drainage, and insufficient compaction during construction. Firstly, traffic loads generate shear stress, resulting in microcracks that evolve into fatigue cracks [12]. Moisture seeps into these cracks, undergoing freezing and thawing cycles, which cause the expansion and contraction of the underlying layers. This leads to a gap between the pavement and subgrade, making the pavement susceptible to damage [13]. In addition to these factors, temperature fluctuations can also lead to pothole formation. In colder climates, freeze-thaw cycles can cause the expansion and contraction of water within the pavement, leading to the formation of potholes. Similarly, in warmer climates, excessive heat can cause the pavement to expand, leading to cracking and potholes. Secondly, inadequate drainage impedes moisture removal, creating localized areas saturated with excessive moisture and contributing to pothole formation [14]. Lastly, insufficient compaction during construction increases porosity, allowing moisture to penetrate the mixture and weaken the adhesive force between the aggregate and binder, leading to pavement deterioration and pothole formation [15]. Optimal mixing design and thorough compaction management are necessary preventive measures [16,17].

In recent years, there has been a growing trend towards innovative approaches in the rehabilitation and maintenance of asphalt pavements, particularly in addressing the persistent issue of potholes. Traditional methods such as cold patching and temporary repairs have proven to be temporary solutions, leading to the need for more sustainable and long-lasting alternatives [12,18]. This has driven the development of advanced techniques, such as infrared asphalt repair, spray injection patching, and the use of polymer-modified materials [19]. These methods aim to improve the quality and durability of pothole repairs, providing longer-lasting solutions and reducing the need for frequent maintenance interventions. Additionally, advancements in technology, such as the use of robotics and automation, are being explored to enhance the efficiency and accuracy in the pothole repair processes [20–22]. Research by Tao Wang et al. demonstrated the effectiveness of cold asphalt patching repair in achieving durable and seamless pothole repairs [23], while Sainz highlighted the advantages of spray injection patching in terms of the improved adhesion and reduced future deterioration [18]. However, despite these advancements, limitations persist in terms of cost-effectiveness, scalability, and compatibility with various pavement conditions [24]. Further research is needed to address these limitations and optimize the pothole rehabilitation and maintenance practices for asphalt pavements, ensuring safer and more resilient road networks.

While advancements in pothole rehabilitation and maintenance techniques have shown promise, several limitations still need to be addressed. One significant limitation is the time required for repairs [12,18]. Many existing methods, such as modified asphalt repair or spray injection patching, can be time-consuming, leading to road closures and traffic disruptions [25]. Another challenge is the quality of the restoration. Debonding issues, where the repaired area fails to bond properly with the surrounding pavement, can occur, compromising the longevity of the repair [26]. Moisture impacts are another concern, as water infiltration can lead to further deterioration and the premature failure of the repaired area [27]. Furthermore, compatibility between the materials used for repairs and the existing pavement is crucial but often problematic [28]. One promising idea that has emerged is the development of sustainable warm mix asphalt (WMA) technologies, which could significantly reduce the environmental impact of pothole restoration. However, despite these efforts, the current WMA strategies still rely on high temperatures and result in high emissions, making them less than ideal from an environmental standpoint [29]. Incompatibilities can result in differential performances and premature distress, necessitating additional maintenance efforts. Addressing these limitations requires further research and development to optimize repair techniques, enhance the bond between the repair materials and existing pavement, and improve the resistance to moisture damage [17]. Strategies such as developing better adhesion-promoting agents, optimizing material compositions, and refining application processes are vital for overcoming these challenges and ensuring effective, durable, and time-efficient pothole repairs [30,31].

Pellet asphalt technology and pellet material in asphalt production, a relatively new development in the field of road construction and pavement maintenance, has garnered significant attention in recent years. This innovative technology involves the production of compacted asphalt pellets using a combination of asphalt binder and aggregate materials [32]. These pellets are designed to be easy to handle, transport, and store, offering numerous advantages over traditional hot mix asphalt. Several studies have examined the potential benefits and applications of pellet asphalt technology. For instance, a study conducted by Lee et al. (2023) investigated the energy savings achieved during the manufacturing and application processes of asphalt pellets. The results suggest a substantial reduction in energy consumption compared to hot mix asphalt, contributing to a more sustainable approach [32]. Furthermore, research by Sahebzamani and colleagues explored the workability and compaction characteristics of pelletized materials in asphalt [33]. The findings revealed improved workability and compaction compared to traditional asphalt mixtures, leading to enhanced pavement quality and performance. Additionally, the literature emphasizes the environmental benefits of pellet technology. Related research explored the recycling and reusability of polymer materials through palletization [34]. The related findings indicated that pelletized materials in asphalt can facilitate the incorporation of recycled asphalt pavement (RAP) materials, thereby reducing waste and promoting a circular economy in road construction.

While the use of pellet material in asphalt technology shows promise as a sustainable and innovative approach to road construction, it is important to acknowledge certain limitations and identify the research needs for further exploration [35,36]. Firstly, additional studies are needed to assess the performance and durability of pelletized asphalt under different load conditions. This would provide a comprehensive understanding of the technology's applicability and performance in diverse environments. Secondly, research is required to investigate the compatibility of pelletized asphalt with the existing positive additives. Understanding the interactions between pelletized asphalt and other materials will help ensure its seamless integration and prevent potential issues. Therefore, further research on pellet asphalt is essential to overcome limitations, expand our understanding, and facilitate its effective application in road construction and maintenance. This study focuses on tackling pothole formation by developing advanced materials that enhance the moisture sensitivity and stripping resistance in asphalt mixtures. To prioritize worker safety and minimize air pollution, a pellet-type additive called slaked lime has been formulated. Furthermore, an improved pellet-type stripping inhibitor for warm mix asphalt (WMA) with enhanced moisture resistance properties has been introduced.

In light of the above necessities, the objective of this research is to evaluate the performance and applicability of a developed neutralized anti-stripping material in mitigating the detrimental effects of climate change on road infrastructure. The research aims to investigate the effectiveness of the pellet-type stripping inhibitor for WMA in reducing cracks, plastic deformation, and pothole damage on road surfaces. The research needs to assess the compatibility of the developed material with asphalt mixtures and evaluate its resistance to water, plastic deformation, and fatigue. Furthermore, the research methods included laboratory testing to compare the performance of the developed material with existing slaked lime stripping inhibitors and examining properties such as the water resistance, resistance to plastic deformation, fatigue life, and production temperature reduction. The research will provide insights into the potential of the asphalt containing a pellet-type stripping inhibitor as a sustainable solution for road construction, reducing the environmental impact and enhancing pavement durability. Figure 1 summarizes the flowchart of this research.

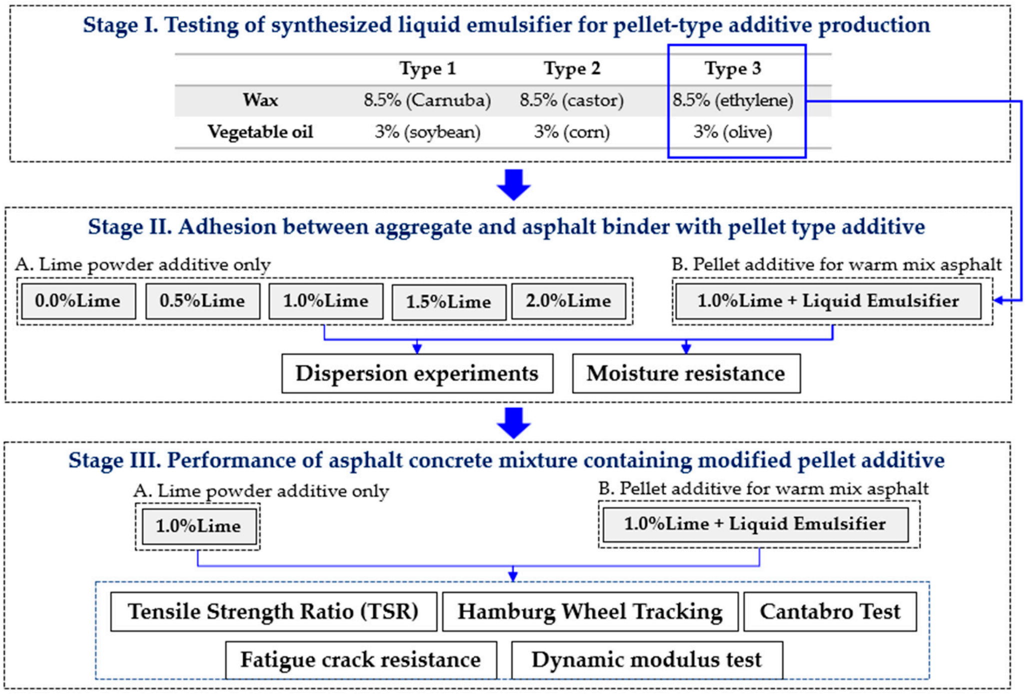


Figure 1. Research flowcharts.

2. Materials and Methods

2.1. Materials

2.1.1. Slaked Lime

In response to the increased risk of asphalt pavement damage caused by climate change-induced heavy rainfall and snowfall, the use of slaked lime has emerged as an adaptive reinforcement technique to replace the conventional limestone powder filler in asphalt mixtures [37]. Typically, slaked lime is added to the aggregate before mixing it with the asphalt binder, serving as a substitute filler. Slaked lime enhances the moisture resistance of the asphalt mixture by improving the bond between the asphalt and the aggregate. Many European countries have been utilizing this technique since the early 2000s, and at present, Belgium, the Netherlands, Sweden, and 26 states in the United States have implemented mandatory or limited obligations [38]. The general practice is to use slaked lime in a proportion of 1 to 1.5% of the total aggregate in place of the existing filler material (limestone powder).

However, some asphalt plants apply manual labor without dedicated silo installations, resulting in low levels of prevention of air pollution and dust-related work stability. In this study, the author's team aimed to develop a neutralized anti-stripping asphalt concrete material (NASAC) by mixing and extruding slaked lime with a liquid emulsifier additive. The use of pellet-type slaked lime ensures worker safety, prevents air pollution, and simultaneously allows for the incorporation of an anti-stripping agent to enhance the moisture resistance.

2.1.2. Anti-Stripping Technology

Hydrated Lime ($Ca(OH)_2$) is produced by the hydration reaction, where quicklime reacts with water (H_2O), resulting in the release of heat and an increase in volume [39]. The chemical equation for the production of slaked lime is as follows:

$$CaO + H_2O \rightarrow Ca(OH)_2 + 15.6\ \text{kcal/mol}.$$

Slaked lime has a small particle size and a pH value of 11, indicating strong alkalinity. In the production of asphalt mixtures, the addition of slaked lime introduces CaOH+ ions, which combine with SiO− ions on the aggregate surface [40]. This leads to the coating of the aggregate with CaOH+ ions, preventing the degradation of the adhesive strength between the aggregate and the binder caused by moisture. During this process, H+ ions generated during SiO− ion formation and OH− ions produced during CaOH+ ion formation combine to form water, which subsequently evaporates under high-temperature conditions during asphalt mixture production [41,42]. Figure 2 provides a conceptual diagram illustrating the effect of improving the moisture sensitivity through the use of slaked lime.

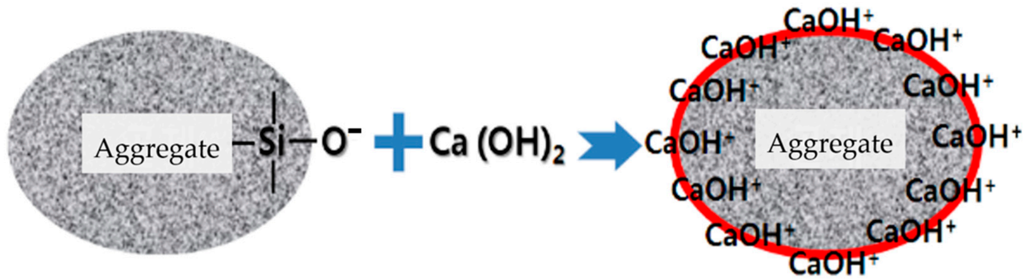


Figure 2. Conceptual diagram of the improvement effect of slaked lime on moisture sensitivity.

2.1.3. Pellet-Type Slaked Lime Stripping Prevention Material

In general, liquid-type anti-stripping agents utilize amine-based or silane-based materials. Various theories have been proposed to explain the mechanism behind their effectiveness in improving moisture sensitivity and preventing the stripping effect [43]. Firstly, due to their molecular structure, these agents exhibit a strong affinity for both the aggregate and the binder [44]. This enhanced affinity facilitates improved adhesion between the aggregate and the binder during the mixture production process. Consequently, the overall bond strength is enhanced. Another theory suggests that the anti-stripping agent acts as a surfactant when mixed with the binder [45]. As the contact angle between the binder and the aggregate is reduced, the bonding area increases, leading to an improved bonding performance [46].

2.1.4. Pellet-Type Stripping Agent for WMA

The commonly used slaked lime poses issues such as dust generation and uneven mixing with the aggregate. Therefore, this research aims to address these problems by developing a pellet-type asphalt concrete mixture (PAC) containing an anti-stripping agent that incorporates slaked lime and a liquid additive for WMA [47].

Asphalt liquid emulsifier additives are typically combined with vegetable oils and mineral oils, such as castor oil, canola oil, soybean oil, corn oil, sunflower seed oil, olive oil, and grapeseed oil [48]. However, when using oil-based liquids for molding slaked lime, the resulting pellets are not structurally stable and easily crumble. To ensure the stability of slaked lime pellets, this study explores the use of waxes with melting points ranging between approximately 60 and 120 °C. Additionally, the goal is to achieve moldability, stability, and economic feasibility by employing oil- and fat-based liquids and amine-based liquid additives. Based on several trial mixes and suggestions from asphalt plant experts, the mixing ratio of the neutralized liquid emulsifier is presented in Table 1.

After analyzing the properties of the liquid emulsifier for WMA, mix 3 was found to contain excellent active ingredients and exhibit stability, as demonstrated in Table 2. The manufacturing process of the pellet-type stripping agent is depicted in Figure 3. In this process, the liquid emulsifier and slaked lime were mixed in a 20:80 ratio and subsequently pelletized using an extruder. Figure 4 showcases one of the produced samples.

Table 1. The mixing ratio of liquid emulsifier.

Component	Mix 1	Mix 2	Mix 3
Wax	8.5 (Carnuba)	8.5 (Castor)	8.5 (Ethylene)
Vegetable oil	3 (soybean)	3 (corn)	3 (olive)
Mineral oil	5.5	5.5	5.5
Surfactants (Fatty acid (C8~C20) amine surfactant)	1.5	3	7
Additive	0.2	0.2	0.2
Water	81.3	79.8	75.8
total	100	100	100

Table 2. Properties of liquid emulsifiers for warm mix asphalt.

	Mix 1	Mix 2	Mix 3
Exterior	Light gray liquid	white liquid	milky liquid
Stability	5 h or less	More than 30 days	7 days or less
Condition	liquid	liquid	liquid
Smell	odorless	odorless	odorless
Active ingredient	18%	20%	24%

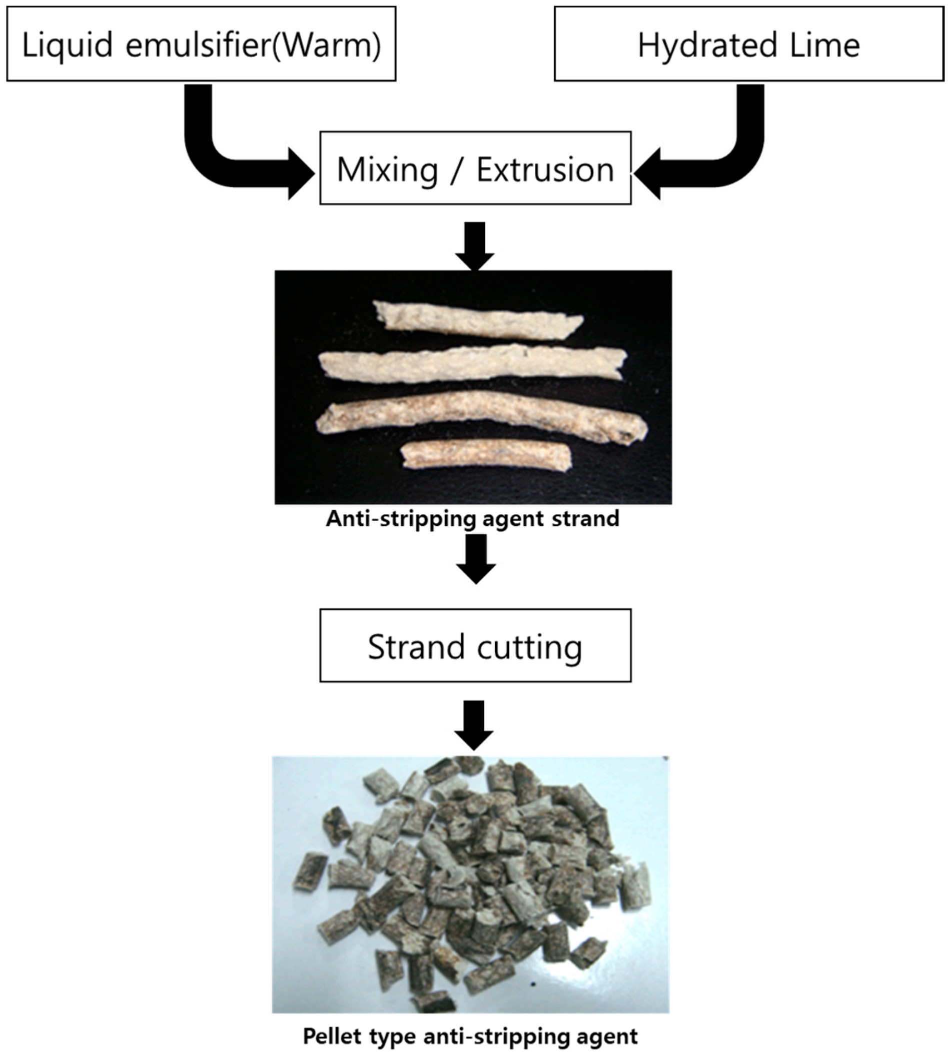


Figure 3. Pellet-type stripping agent manufacturing process diagram for WMA.

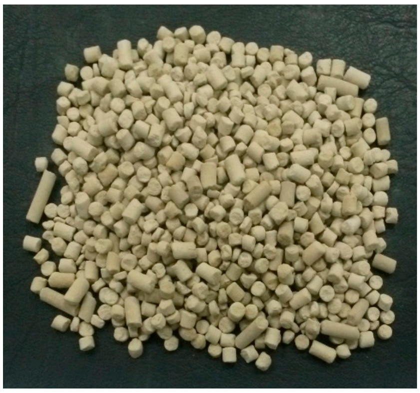


Figure 4. Samples of pellet-type stripping agent for WMA.

2.1.5. Preparation of Modified Asphalt Concrete Mixtures for Performance Tests

Mix Design

A Korean manufacturer provided the fillers and aggregate for the study, and Table 3 presents the essential characteristics of the materials. Previous research and recommendations from relevant investigations suggest that the ideal asphalt binder should constitute 5.6% of the total weight. This study utilized the Superpave method to create specimens. Superpave aims to optimize the strength of asphalt mixtures against rutting, fatigue cracking, and thermal cracking by employing the most effective bitumen pavement techniques. The Superpave Gyratory Compactor (SGC) examines the volume and compaction properties of the materials, and the data collected during compaction can be used to gain insight into the suitability of a specific combination [49].

Table 3. Aggregate and mineral filler properties.

Materials	Properties	Value
Aggregate	Relative apparent density [50]	2.75
	Water absorption [50]	0.178%
	Aggregate crushed value [51]	18.3%
	Los Angeles abrasion value [52]	26.1%
	Flakiness and elongation index [53]	12.6%
Mineral Filler	Relative apparent density [54]	2.28
	Moisture content [54]	0.07%

As shown in Table 4, an asphalt concrete mixture was developed using a 10 mm SMA aggregate type. The inclusion of this material helps prevent binder delamination (desorption) by enhancing the adhesive contact among the aggregates in the standard asphalt mixture. In stone mastic asphalt (SMA), the aggregate bears the entire pressure from vehicle loads, thus reducing the likelihood of binder separation. Table 4 summarizes the particle sizes synthesized in the aggregate during this test.

Table 4. Sieve size gradation.

Sieve Size (mm)	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Gradation	100	100	96.8	63.1	8.9	4.8	3.5	2.8	1.8	0.9

2.2. Laboratory Tests

To assess the fundamental physical properties of the pellet-type anti-stripping agent produced at medium temperatures, fundamental tests were conducted to measure its dispersibility and water resistance.

2.2.1. Dispersion Experiments

The product under development in this study needs to undergo crushing and dispersion using an asphalt production mixer to maintain its shape and alleviate dust-related issues during transportation. Typically, when slaked lime is utilized as an anti-stripping agent, the aggregate mixing time is approximately 5 s. Consequently, in an operational asphalt mixture production plant, the dispersibility of the pellet-type stripping agent was assessed manually after its addition. The experimental findings reveal that the agent was visibly crushed and dispersed into a powdered form.

2.2.2. Moisture Resistance Evaluation

To assess the water resistance of the material, a dynamic immersion test was conducted. The test followed the guidelines outlined in the European Standard EN 12697-11 [55], specifically the 'Determination of the affinity between aggregate and bitumen' test method. The dynamic immersion test (DIT) involves subjecting a sample to rotational motion while immersed in water at a controlled temperature of 25 °C and a speed of 60 revolutions per minute (rpm). Figure 5 provides a visual representation of the dynamic water immersion test.

Figure 5. Dynamic water immersion test.

In this study, a comparative evaluation was conducted to assess the performance of both the slaked lime and the developed materials. The evaluation involved preparing asphalt mixtures by mixing slaked lime and aggregate at various proportions ranging between 0.5% and 2.0% of the total aggregate weight. Table 5 presents the materials utilized and the corresponding test conditions for the dynamic water immersion test.

Table 5. Materials used in dynamic immersion test.

	Conventional Slaked Lime AC Mixture					Newly Developed AC Mixture
	0%	**0.5%**	**1.0%**	**1.5%**	**2.0%**	**1.0%**
Mixing temperature (°C)			155 °C			135 °C
Aggregate (g)	510	507.4	504.9	502.3	499.8	504.9
Anti-stripping agent (g)	-	2.6	5.1	7.7	10.2	5.1
Asphalt (g)			16			16

2.2.3. Tensile Strength Ratio (TSR)

There are various methodologies available for assessing the moisture sensitivity of asphalt mixtures, AASHTO T 283 [56] being the most commonly employed method thus far. This test, also known as the tensile strength ratio (TSR) test, involves measuring the ratio of indirect tensile strength before and after exposure to water treatment. In this study, a water immersion test was conducted, wherein the specimens were immersed in water at a temperature of 60 ± 1 °C for a duration of 24 ± 1 h, followed by immersion in a water bath at 25 ± 1 °C for 2 ± 0.5 h. LHMA and PWMA were comparatively evaluated using this method.

2.2.4. Hamburg Wheel Tracking Test

TSR is the most common test method for moisture sensitivity evaluation, but it is unable to represent field commonality. Accordingly, the Hamburg wheel tracking test, which can simultaneously evaluate moisture sensitivity and plastic deformation, is emerging as an alternative. The Hamburg wheel-tracking test is specified in AASHTO T 324 [57]. It is a test method to measure the amount of settlement by immersing a specimen at a high temperature (50 °C) using a Hamburg wheel tracking tester of 12 and repeatedly loading a wheel load of 705 ± 4.5 N.

The TSR test is commonly used to evaluate moisture sensitivity. However, it is important to note that this test method may not accurately represent real-world conditions. As an alternative, the Hamburg wheel tracking test has gained prominence as it allows for the evaluation of both moisture sensitivity and plastic deformation simultaneously.

The Hamburg wheel tracking test, specified in AASHTO T 324 [57], involves immersing a specimen at a high temperature (50 °C) using a Hamburg wheel tracking tester with a load of 705 ± 4.5 N. The settlement of the specimen is measured by repeatedly subjecting it to wheel loading. To assess the moisture sensitivity of the mixture, the rut depth is analyzed at 20,000 iterations using the graph shown in Figure 6. According to regulations, a mixture exhibiting more than 10,000 passes and less than 20 mm of settlement in 20,000 iterations is considered to possess excellent water resistance. It is worth noting that a later occurrence of rutting indicates a higher degree of moisture sensitivity for the mixture.

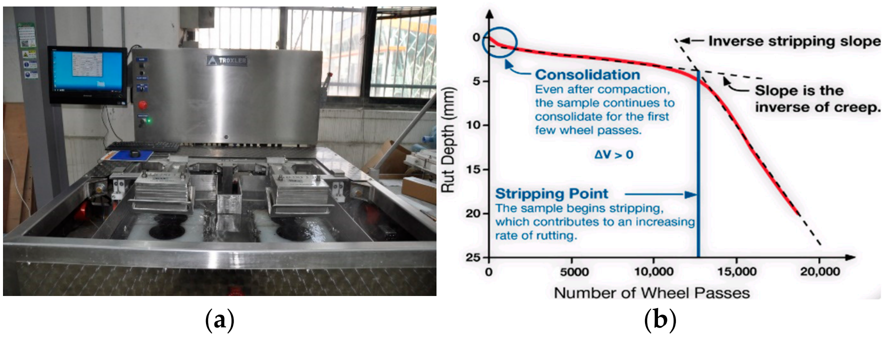


Figure 6. (**a**) Hamburg wheel tracking tester; (**b**) Hamburg wheel tracking test result analysis method.

2.2.5. Cantabro Test

The Cantabro test is a widely used method to evaluate the resistance of asphalt mixtures against aggregate detachment. In this test, an asphalt mixture specimen is subjected to a Los Angeles abrasion tester at a controlled temperature of (20 ± 1) °C. The specimen is rotated for 300 cycles, with a rotation speed ranging between 30 and 33 revolutions per minute. The mass of the specimen before and after the test is measured to calculate the loss rate, which indicates the degree of aggregate detachment. The Cantabro loss rate test, conducted at a temperature of 20 °C, adheres to the test method specified in KS F 2492 [58].

2.2.6. Dynamic Modulus Test

Test methods for asphalt mixtures commonly analyze the relationship between deformation and applied load. This correlation is typically quantified as the elastic modulus or stiffness, which characterizes the linear relationship between load and deformation. In materials exhibiting elastic behavior, the stiffness remains constant, resulting in a linear load–deformation relationship. However, non-linear behavior is observed when the stiffness varies based on the loading conditions and duration. Asphalt mixtures fall into the category of viscoelastic materials due to their rapid property changes in response to varying loads and temperatures. Consequently, the behavior of asphalt mixtures under repeated loading conditions was investigated, and the outcomes are illustrated in Figure 7. The graph distinguishes between elastic, plastic, viscoelastic, and viscoplastic regions to depict the varying response of the material.

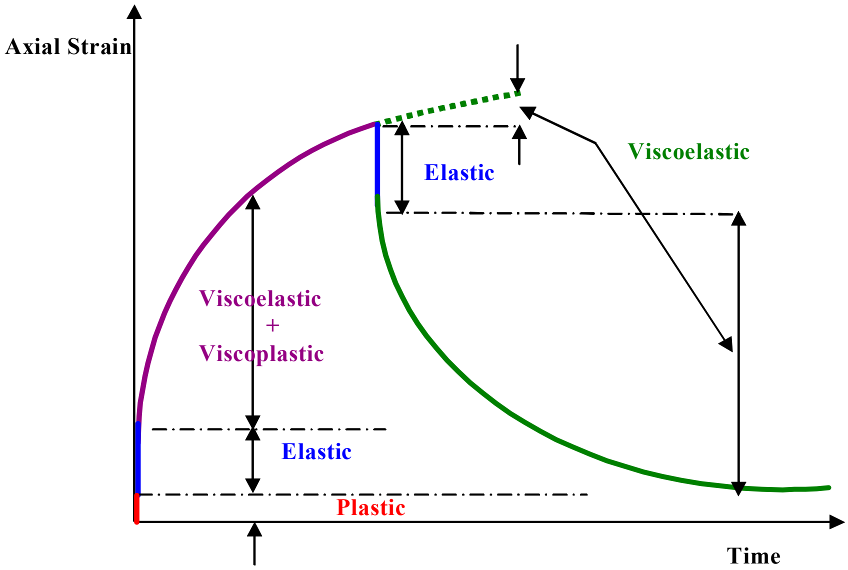


Figure 7. Deformation characteristics of mixtures under repeated loading.

To assess the characteristics of the linear viscoelastic material employed in this study, a dynamic elastic modulus test was conducted. The experimental setup employed the MTS 810 instrument, as depicted in Figure 8. The test was executed in compliance with the AASHTO TP 62 protocol [59]. The dynamic elastic modulus test encompassed a range of load cycles at frequencies of 20, 10, 5, 1, 0.5, and 0.1 Hz, as well as temperatures of 5, 20, 40, and 54 °C. The applied load level was adjusted to yield a total strain within the range of 50 to 75 μs.

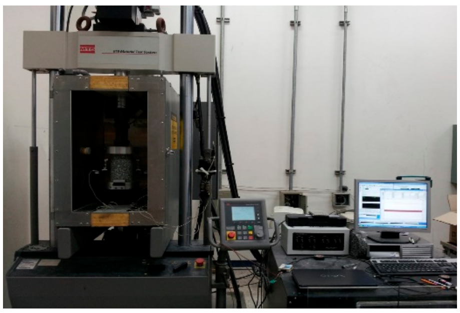


Figure 8. MTS 810.

2.2.7. Fatigue Crack Resistance Evaluation

Fatigue cracking, accompanied by permanent deformation, represents a prominent failure mode in asphalt pavements. These fatigue cracks result from the combined effects of cyclic and temperature-induced loads, which exhibit significant variability. Under repeated loading, the formation of microcracks progressing into observable macrocracks on the pavement surface is a well-established phenomenon. Recent research findings have also highlighted the potential for crack propagation from the top to the bottom layers under specific conditions [60,61].

In this study, the fatigue crack resistance of each asphalt mixture was evaluated through a direct tensile fatigue test. Specifically, a controlled crosshead cyclic testing approach was employed. This method applies repeated strains to the specimens using the equipment's crosshead until failure occurs at a temperature of 20 °C, utilizing a 10 Hz haversine loading cycle. Figure 9 provides a visual representation of the direct tensile fatigue test. The direct tensile fatigue test offers a valuable means of examining the fatigue crack resistance of the asphalt mixtures investigated. By subjecting the specimens to controlled strain cycles, the test facilitates the assessment of their ability to withstand repeated loading conditions, which closely mimic real-world scenarios. The results obtained from this test will contribute to a comprehensive understanding of the fatigue performance of the asphalt mixtures, aiding in the development of more durable and reliable pavement designs. The fracture point of the specimen was identified using the method proposed by Reese [62], whereby the rapid change in phase angle served as the criterion for determination.

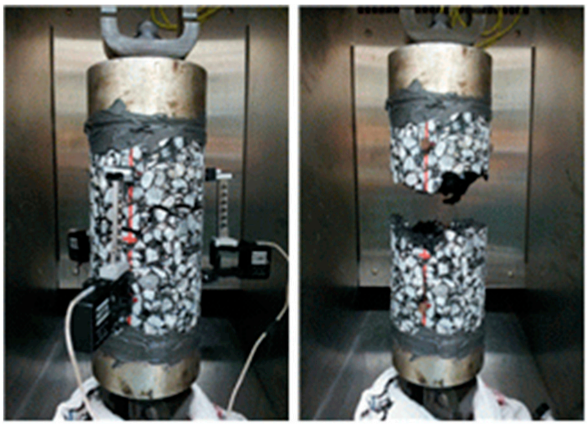


Figure 9. Direct tension cyclic fatigue test.

3. Results and Discussions

3.1. Moisture Resistance Evaluation

The results of the dynamic water immersion test are presented in Figures 10 and 11. Notably, Figure 10 demonstrates that the cover retention rate exhibited an upward trend with an increase in the slaked lime content. Furthermore, it was observed that the utilization of slaked lime and the developed materials at a minimum of 1% content meets the quality standard for the dynamic immersion test (DIT), which requires a minimum of 50% cover retention.

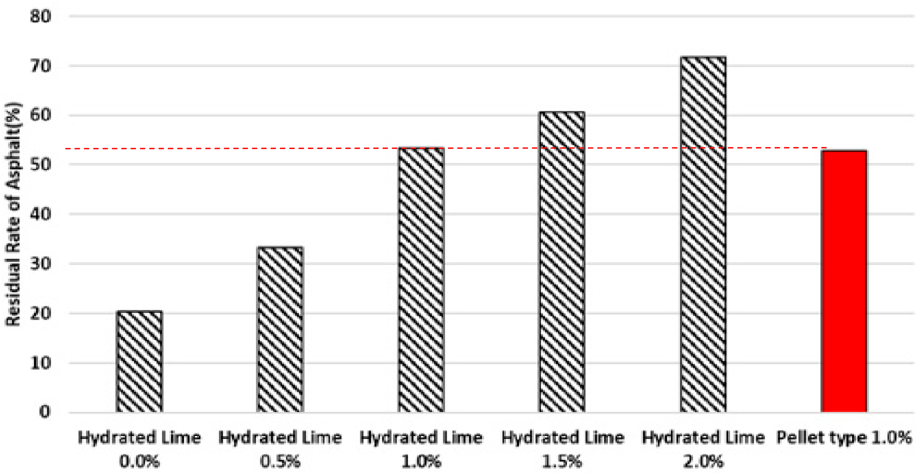


Figure 10. Results of dynamic water immersion test.

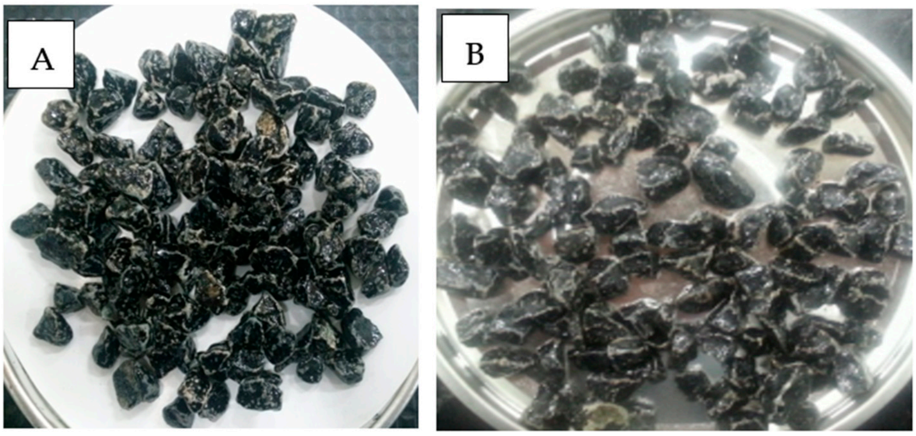


Figure 11. Photo after dynamic water immersion test. (**A**) Hydrated lime 1%, (**B**) Pellet type 1%.

3.2. Performance Test of Modified Asphalt Concrete Mixture

In this study, the performance of two asphalt mixtures, namely Slaked Lime Hot Mix Asphalt (LHMA) and Pellet-Type Anti-Stripping Warm Mix Asphalt (PWMA), was compared and evaluated. Both mixtures were prepared with a lime content of 1% to meet the standard requirements for dynamic water immersion.

3.2.1. Tensile Strength Ratio (TSR)

The application of the water immersion test method with controlled temperature conditions allows for a comprehensive evaluation of the LHMA and PWMA samples. By subjecting the specimens to an initial hot water immersion, followed by a subsequent immersion in a water bath at a lower temperature, the potential impact of temperature differentials on the moisture sensitivity was taken into account.

The test results, as depicted in Figure 12, indicated that both types of asphalt mixtures satisfied the quality standard for asphalt mixtures (TSR $\geq$ 0.80) as both mixtures reach the TSR value of approximately 83%. The satisfactory performance of both LHMA and PWMA in meeting the asphalt mixture quality standard (TSR $\geq$ 0.80) highlights their effectiveness in resisting moisture-induced damage. This indicates that both asphalt mixtures possess a high level of resistance to the detrimental effects of water infiltration.

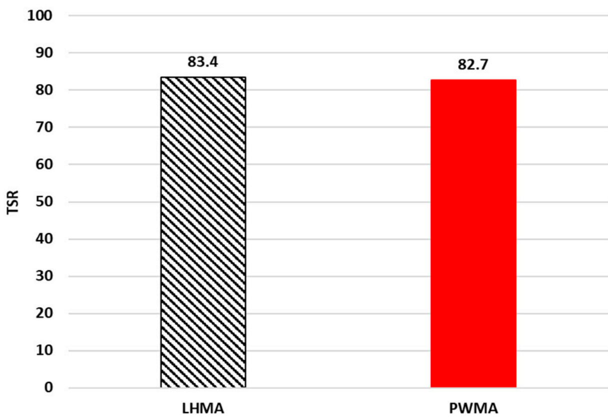


Figure 12. Moisture resistance test (TSR) results.

The comparability of LHMA and PWMA in terms of their TSR values suggests that the Pellet-Type Anti-Stripping Warm Mix Asphalt (PWMA) can serve as a viable alternative to the conventional Slaked Lime Hot Mix Asphalt (LHMA) in terms of its moisture resistance. This finding opens up the possibility of utilizing PWMA as a sustainable and effective option for asphalt pavement construction, contributing to improved longevity and durability under varying environmental conditions.

3.2.2. Hamburg Wheel Tracking Test

Figure 13 presents a graphical representation of the results obtained from the Hamburg wheel tracking test. For the general asphalt mixture (HMA), settlements of up to 20 mm were observed in approximately 13,481 cycles, with stripping occurring around 10,550 cycles. In the case of the PWMA, a settlement of 20 mm was observed at approximately 16,500 cycles, and stripping was observed around 13,900 cycles. Finally, in the case of the LHMA, a settlement of 20 mm was noted at roughly 19,650 cycles, while stripping was observed around 13,650 cycles.

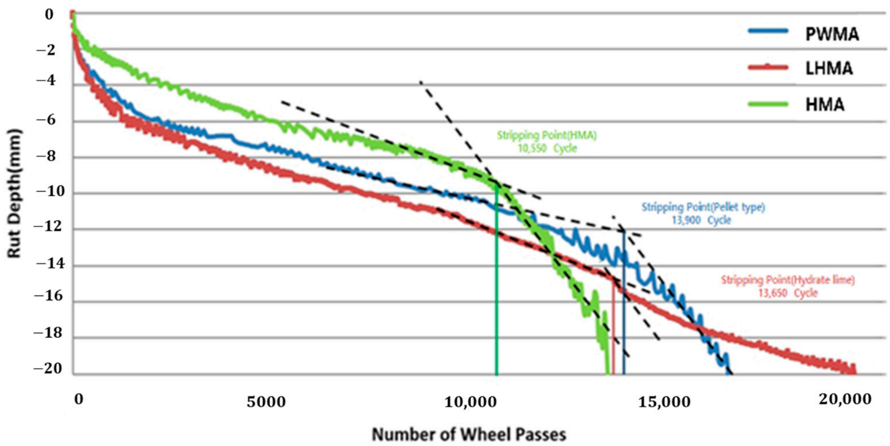
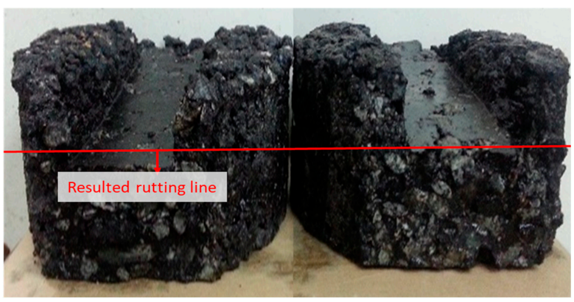


Figure 13. Hamburg wheel tracking test results.

These findings from the Hamburg wheel tracking test provide valuable insights into the performance of the different asphalt mixtures in relation to moisture sensitivity. The results indicate that the general HMA exhibited the highest occurrence of settlements and stripping, followed by the polymer-modified asphalt (PWMA) and the lightweight asphalt mixture (LHMA). Such results have implications for engineering and construction practices. The higher number of settlements and stripping in conventional HMA suggests a greater vulnerability to moisture-induced damage. This indicates the need for additional measures, such as improved moisture resistance additives or modified mixture designs, to enhance the performance of HMA in wet conditions.

On the other hand, PWMA and LHMA demonstrated relatively lower occurrences of settlements and stripping, suggesting improved moisture resistance compared to HMA. Although the PWMA mixture did not outperform the LHMA in the case of the 20 mm settlement, the slightly higher stripping resistance shows the potential application of the proposed method. These findings could guide the selection of asphalt mixtures for specific applications, prioritizing those with enhanced moisture sensitivity properties in regions prone to high moisture exposure.

In Figure 14, the post-testing condition of the specimens is depicted, providing a visual representation of the observed changes.



(**A**) (**B**)

Figure 14. Specimen after Hamburg wheel tracking test ((**A**) LHMA; (**B**) PWMA).

3.3. Plastic Deformation Resistance Evaluation

The wheel tracking test is a laboratory-based method designed to simulate the continuous load exerted by vehicular traffic and assess the resistance of asphalt mixtures to permanent deformation. This test was conducted in accordance with the specifications outlined in KS F 2374 (wheel tracking test method of asphalt mixture). It is important to note that a higher dynamic stability value corresponds to superior resistance against permanent deformation. For this particular study, two distinct types of asphalt mixture specimens were meticulously prepared, and subsequent measurements were taken to determine the deformation rate (RD, mm/min) and dynamic stability (DS, times/mm).

The obtained test results are visually depicted in Figure 15. Notably, the deformation rate exhibited a similar trend for both asphalt mixtures, indicating comparable susceptibility to deformation under the applied loading conditions. Conversely, the dynamic stability of the PWMA demonstrated an approximately 6% increase when compared to that of the LHMA. For example, the DS value of the proposed mixture obtained the DS of 1514 cycle/mm, while this value for the latter mixture is 1428 cycle/mm. The condition of the specimen after the test is illustrated in Figure 16, providing a visual representation of the observed outcomes. The improved dynamic stability observed in the PWMA signifies its enhanced ability to withstand permanent deformation when subjected to repeated loading, thus rendering it suitable for application in areas where durability and long-term performance are of paramount importance, such as high-traffic zones or regions experiencing elevated temperatures. On the other hand, the relatively lower dynamic stability exhibited by the LHMA suggests its potential limitations in environments characterized by repetitive loading, necessitating careful consideration during pavement design and material selection processes.

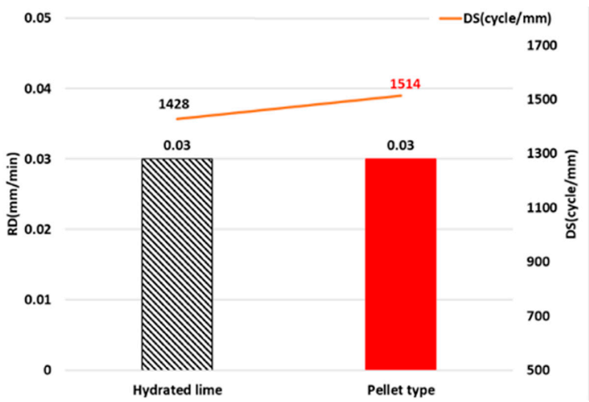


Figure 15. Wheel tracking test results.

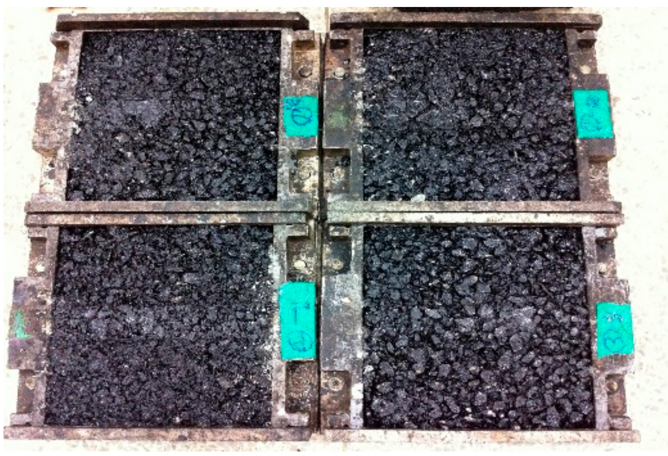


Figure 16. Specimen after wheel tracking test.

3.4. Evaluation of Aggregate Detachment Resistance/Cantablo Test

The test results are presented in Figure 17. Both the lightweight asphalt mixture (LHMA) and the polymer-modified asphalt (PWMA) exhibited results that were superior to the loss rate standard of 20% or less. Figure 18 visually depicts the condition of the specimen after the Cantabro test.

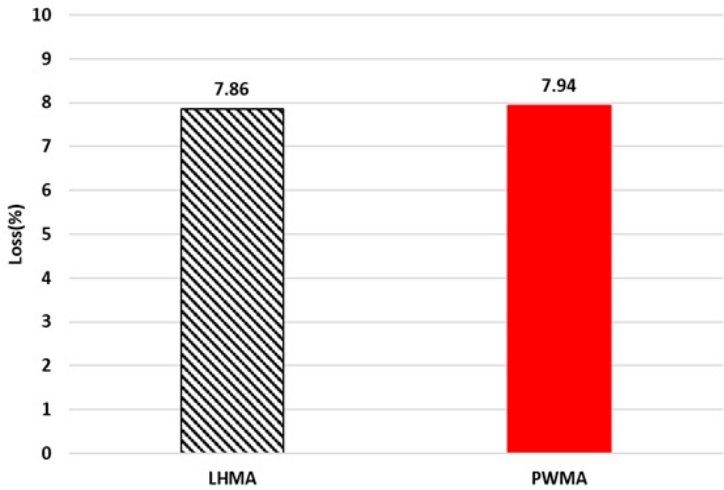


Figure 17. Cantabro test results.

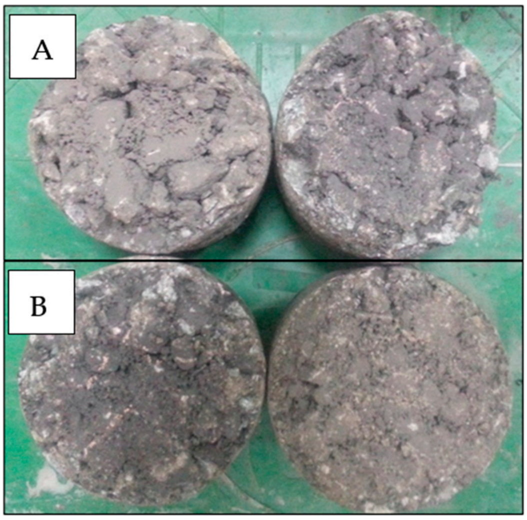


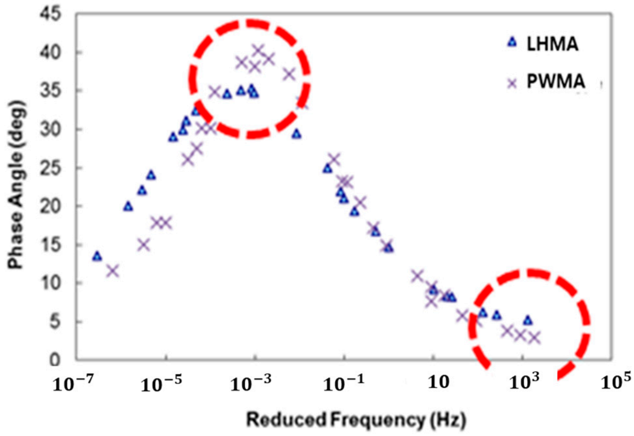
Figure 18. Specimens after the Cantabro test ((**A**) LHMA, (**B**) PWMA).

The results indicate that both the LHMA and PWMA displayed favorable performances, with loss rates below the specified threshold of 20%, and both mixtures share the equivalent resistance during the simulated damage condition. This suggests that these mixtures possess a robust capacity to retain their aggregate structure and minimize aggregate detachment under the applied test conditions. The implications of these results extend to the realm of engineering and construction practices. Asphalt mixtures with low loss rates, as demonstrated by the LHMA and PWMA in this study, are deemed suitable for applications where long-term durability and resistance to aggregate detachment are critical factors. This is particularly relevant for porous asphalt mixtures, where maintaining the integrity of the aggregate structure is essential for its optimal performance and permeability.

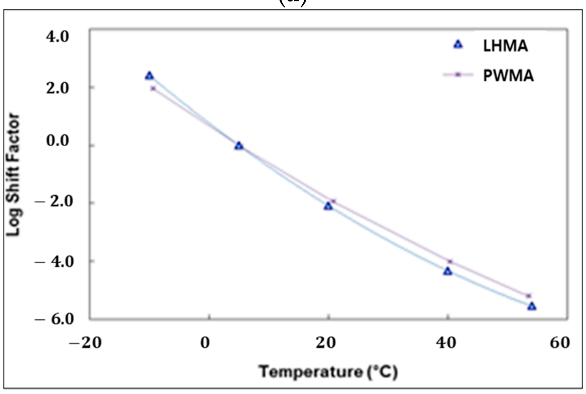
3.5. Dynamic Modulus Test Results

The master curve analysis was performed using the experimental data of the dynamic modulus of elasticity for PWMA and LHMA, and the results are presented in Figure 19.

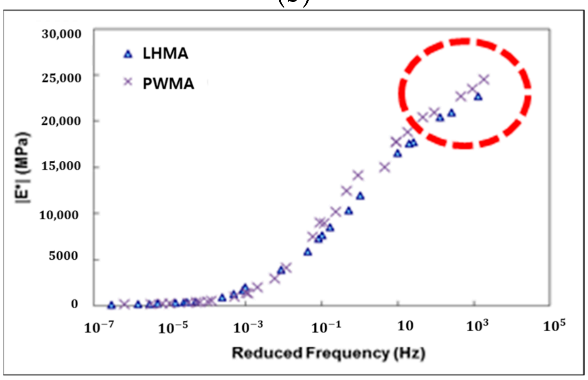
Upon examination, both PWMA and LHMA exhibited similar behavior characteristics in terms of the modulus of elasticity with respect to temperature and load cycle. However, notable differences were observed in the high-temperature range (slow load frequency region), where PWMA displayed a slightly higher modulus of elasticity compared to LHMA. For example, at the reduced frequency of 10^{-3}, the phase angle of the PWMA is around 35°, while this value for the LHMA is nearly 40°, resulting in the difference of 12.5%. This indicates that PWMA exhibits superior resistance to plastic deformation. Additionally, at high load cycles, PWMA also demonstrated a slightly higher modulus of elasticity than LHMA, suggesting a potential reduction in its susceptibility to low temperature-induced cracking. For instance, at the loading frequency of 10^3, the gap between both conditions is around 3°, indicating the notable elasticity behavior of the PWMA mixture in this condition.



(**a**)

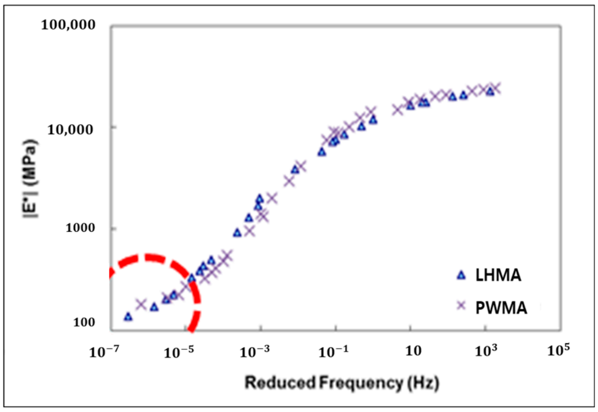


(**b**)



(**c**)

Figure 19. *Cont.*



(**d**)

Figure 19. Master curve. (**a**) Phase angle; (**b**) Shift Factor; (**c**) Master curve (semi-log); (**d**) Master curve (log-log).

As shown in Figure 19c, the higher modulus of elasticity observed in PWMA indicates its enhanced ability to resist plastic deformation under high-temperature conditions. This makes PWMA particularly suitable for applications where durability and resistance to permanent deformation are crucial factors. On the other hand, the slightly higher modulus of elasticity at high load cycles suggests that PWMA may offer improved resistance against temperature-induced cracking, a vital consideration for asphalt pavements subjected to heavy traffic and fluctuating environmental conditions.

However, it is important to note that the observed differences between PWMA and LHMA in terms of the modulus of elasticity are relatively small. Further investigation is warranted to assess the practical significance of these differences in real-world scenarios. Evaluating the long-term performance of both mixtures under field conditions would provide valuable insights into their actual behavior and assist in making informed decisions regarding material selection and pavement design. Moreover, the mechanisms underlying the observed differences in the modulus of elasticity between PWMA and LHMA warrant further exploration. Investigating the composition and properties of the asphalt binders, as well as the interaction between the binders and aggregates, may help elucidate the factors contributing to the variations in the material behavior. Additionally, considering the effect of aging and long-term exposure on the dynamic modulus of elasticity would contribute to a more comprehensive understanding of the performance of these asphalt mixtures over time.

3.6. Fatigue Crack Resistance Results

The fracture point of the specimen was identified using the method proposed by Reese (1997), whereby the rapid change in phase angle served as the criterion for determination. Figure 20 illustrates the dynamic variations in the elastic coefficient and phase angle as a function of the number of applied loads. Typically, as the number of loads increases, the dynamic elastic coefficient exhibits a gradual decline, while the phase angle demonstrates a corresponding increase. Subsequently, upon the application of a constant load, a sharp reduction in the phase angle occurs, signifying specimen damage.

Figure 21 presents the results of the fatigue crack resistance test, with the initial stress and strain established based on the load applications. The test outcomes depicted in the test reveal that PWMA exhibits a remarkable increase of approximately 2500 load cycles, at the same initial strain rate (250 μs), compared to LHMA. Consequently, PWMA demonstrates superior fatigue resistance in comparison to LHMA. This indicates that PWMA possesses commendable resistance to fatigue-induced cracking, making it a promising candidate for pavement applications. However, it is crucial to note that pavement damage arises from a multitude of factors. Therefore, a comprehensive assessment incorporating diverse indoor commonality evaluations, rigorous test construction, and meticulous monitoring is imperative to validate these findings. Nonetheless, it is important to acknowledge that the evaluation of pavement durability involves a holistic perspective, encompassing numerous factors that contribute to pavement deterioration. Therefore, it is crucial to conduct thorough verification assessments by considering various indoor commonality evaluations, test construction approaches, and ongoing monitoring protocols.

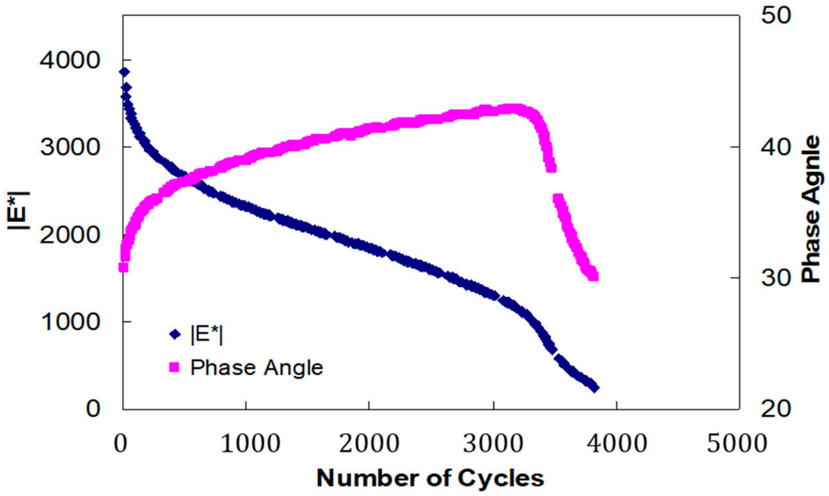


Figure 20. Dynamic modulus of elasticity and phase angle change according to load.

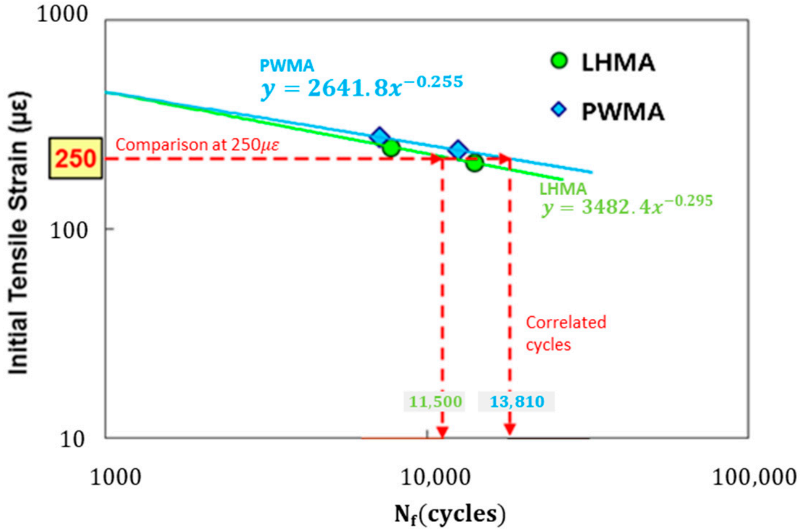


Figure 21. Evaluation of fatigue crack resistance.

4. Conclusions

This study aimed to develop a pellet-type stripping inhibitor for WMA road pavement applications that can effectively withstand the extreme environmental conditions resulting from climate change. In order to enhance the water resistance of asphalt pavement and reduce production temperatures, a pellet-type stripping inhibitor incorporating amine-based and wax-based liquid additives was developed. The developed pellet-type stripping inhibitor was incorporated into the asphalt mixture (PWMA), and its water resistance and resistance to plastic deformation were assessed. The research objectives and key findings obtained through this study are summarized as follows:

- The material demonstrated satisfactory dispersibility test results when applied in plant settings, addressing the issue of dust generation by maintaining its shape during production and transportation.

- Considering the performance of the asphalt mixture (PWMA), the experimental results revealed that the PWMA met the quality standards and exhibited a comparable performance to the heated asphalt mixture (LHMA) that utilized slaked lime as a stripping inhibitor. Both LHMA and PWMA satisfy the quality standard for asphalt mixtures (TSR $\geq$ 0.80), with an approximately 83% TSR value achieved for both mixtures.
- As found in the rutting resistance test (Hamburg wheel tracking test), PWMA and LHMA had fewer settlements and stripping than HMA as these mixtures required 16,500 and 19,650 cycles to reach 20 mm settlement, respectively, compared to that of the control mix (13,481 cycles), indicating better moisture resistance. Although LHMA performed better than PWMA in terms of the 20 mm settlement, the slightly higher stripping resistance found in the PWMA mixture suggests the potential use of the proposed method.
- In regard to the Cantabro test, both LHMA and PWMA exhibit favorable performances with loss rates below the specified threshold of 20%, indicating their capacity to retain the aggregate structure and minimize detachment under the test conditions.
- PWMA demonstrates a 12.5% lower phase angle (35°) compared to LHMA (40°) at a reduced frequency of 10^{-3}, indicating superior resistance to plastic deformation. Additionally, at high load cycles, PWMA exhibits a slightly higher modulus of elasticity than LHMA, suggesting its reduced susceptibility to low-temperature-induced cracking.
- Notably, the fatigue crack resistance test demonstrated that PWMA exhibited an extended fatigue life, with failure occurring at more than 20% compared to LHMA.
- The application of the pellet-type stripping inhibitor, as developed in this study, offers various advantages. It not only prolongs the lifespan of pavement structures, but also reduces the production temperature of the asphalt mixture by more than 20 °C. This reduction contributes to lowering greenhouse gas emissions and petroleum energy consumption, making the pellet-type inhibitor a viable and environmentally friendly option for pavement applications. The findings suggest that the developed material can significantly contribute to sustainable road construction practices.
- Overall, the developed material shows great promise as an eco-friendly and sustainable solution for road pavement applications. Future research should focus on field trials and real-world implementation to further validate the performance and practicality of this innovative stripping inhibitor for WMA.

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