

The Physical Properties of Modified Bitumen and the Performance of SMA Mixtures with the Inclusion of Cup Lump Natural Rubber

Nurul Farhana Rohayzi¹, Herda Yati Binti Katman^{1*}, Jee Khai Wong¹, Mohd Rasdan Ibrahim², Mohd Fatah Abdul Halim¹, Ahmad Firman Zamzuri¹, Norlailati Shima Mohamad¹, Nor Farhana Mohd Said¹, Noor Aqmal Shakila Kamarudin¹, Khairul Nizam Sulaiman¹

¹*Institute of Energy Infrastructure (IEI) and Department of Civil Engineering, College of Engineering, Universiti Tenaga Nasional (UNITEN), Putrajaya Campus, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia*

²*Center for Transportation Research, Department of Civil Engineering, Faculty of Engineering, Universiti Malaya, 50603 Kuala Lumpur, Malaysia*

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ABSTRACT

Pavement distresses, such as rutting and thermal cracking, adversely affect road performance and service life, highlighting the need for more durable and sustainable methods of binder modification. Although conventional polymer modifiers can enhance performance, their petrochemical origins raise significant environmental concerns. Cup lump natural rubber (CLNR), a renewable resource plentiful in Malaysia, presents a sustainable alternative with potential performance advantages. This study aims to establish the optimal CLNR content for modifying bitumen and to assess the performance of stone mastic asphalt (SMA) mixtures incorporating treated CLNR through both wet and dry mixing methods. CLNR was pre-treated with toluene at a 1:2 ratio to improve dispersion, and bitumen was modified with CLNR at concentrations of 2.5%, 5.0%, and 7.5%. SMA samples were subsequently prepared using a 5% dosage to determine the optimum binder content (OBC). The results demonstrated that CLNR-modified bitumen exhibited a substantial increase in softening point and a reduction in penetration, indicating enhanced rutting resistance and reduced temperature susceptibility. Furthermore, storage stability remained excellent, with temperature differentials below 2.5 °C. The determined OBCs were found to be 5.8% for the dry mix and 5.6% for the wet mix. In conclusion, the incorporation of treated CLNR significantly enhances the performance of both bitumen and SMA mixtures while fostering environmental sustainability, thereby supporting progress in sustainable pavement engineering practices.

^{1*} Corresponding author. *E-mail address:* herda@uniten.edu.my
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INTRODUCTION

Asphalt pavements have been essential in road construction for many years; however, rising traffic volumes and harsh environmental conditions have accelerated their deterioration. Rutting occurs when repeated axle loads cause permanent deformation in the pavement layers, particularly at high temperatures. Fatigue cracking arises from continuous traffic loading that weakens the pavement structure over time, leading to interconnected cracks. In contrast, thermal cracking results from temperature fluctuations, especially low temperatures that force the pavement to contract, causing cracks when its tensile strength is exceeded (Zhai et al., 2020). Premature failures reduce service life and performance, by compromising structural integrity and accelerating deterioration. Rutting alters the wheel path, causing water accumulation and increasing the risk of hydroplaning. Fatigue cracking allows moisture and air to infiltrate lower layers, leading to base weakening and progressive cracking. Thermal cracking creates openings that expand with temperature cycles, facilitating water intrusion and freeze-thaw damage. Together, these defects diminish pavement strength, increase maintenance requirements, and shorten service life, highlighting the need for innovative solutions in pavement engineering.

The increasing prevalence of pavement failures, such as rutting, fatigue, and thermal cracking, highlights the limitations of conventional bitumen. The viscosity, elasticity, and aging resistance of traditional bitumen often fail to meet the demands of modern traffic and climatic conditions. Consequently, there is an urgent need to modify bitumen to improve its mechanical performance, durability, and long-term stability. Among the various modifiers, polymers are preferred due to their superior ability to enhance elasticity and deformation resistance. Polymer-modified bitumen (PMB) increases elasticity through improved elastic recovery and flexibility, allowing for better stress dissipation under repeated loading. For instance, styrene-butadiene-styrene (SBS) modified binders typically demonstrate an elastic recovery exceeding 70%, compared to less than 20% for unmodified versions (Xu et al., 2021). This enhancement helps to delay rutting and fatigue. Furthermore, PMB improves aging resistance by creating a stable polymer network within the bitumen, reducing oxidation and volatilization. Research indicates that SBS modification can reduce the softening point increase after aging by 30% to 50%, indicating slower degradation (Wei et al., 2019). However, reliance on synthetic polymers increases material costs and raises environmental concerns due to their petrochemical origins (Zhai et al., 2020).

Asphalt modifiers can be sourced from synthetic polymers, industrial by-products, or natural bio-based materials. Among these, natural bio-based modifiers have attracted attention for their renewability and low environmental impact. Cup lump natural rubber (CLNR), a coagulated form of natural rubber collected from tapping cups, represents a sustainable and cost-effective option for bitumen modification. With its high polymer content and inherent elasticity, CLNR enhances flexibility, temperature susceptibility, and deformation resistance of asphalt binders. Furthermore, as a low-value by-product of Malaysia's rubber industry, CLNR serves as a locally sourced alternative that reduces reliance on synthetic polymers and supports sustainable practices in pavement engineering. Malaysia exhibits a strong capacity for natural rubber production, having harvested approximately 25,679 tons in June 2025, according to the Department of Statistics Malaysia. Current national stocks of natural rubber exceed 200,000 tons, indicating ample supply. This surplus suggests that utilizing CLNR (a cost-effective, locally sourced natural rubber derivative) can effectively reduce waste and mitigate environmental impacts associated with underutilized stockpiles while promoting sustainable practices (Abdulrahman et al., 2019).

CLNR is a natural and biodegradable product that has a lower environmental impact than synthetic polymers, which are derived from petrochemicals and are non-biodegradable. The production and disposal of synthetic polymer modifiers contribute to greenhouse gas emissions and long-term plastic waste. In contrast, CLNR is renewable, locally sourced, and fully biodegradable, which reduces carbon footprints and minimizes solid waste. These qualities make CLNR a more sustainable option for pavement engineering (Abdulrahman et al., 2019). CLNR presents considerable economic viability by utilizing abundant local resources. According to Department of Statistics Malaysia, Malaysia produces over 25,000

tons of natural rubber monthly, with a significant portion available in low-grade or cup-lump form suitable for industrial use. By employing CLNR as a bitumen modifier, reliance on imported polymer additives can be reduced, thereby supporting domestic industries, and enhancing the local economy. In addition to pavement applications, CLNR is used in products like gloves, footwear, and adhesives, highlighting its versatility. Its properties, including elasticity, tensile strength, and compatibility with bitumen, improve the durability and flexibility of asphalt mixtures, making CLNR a cost-effective and sustainable option for modern road construction (Abdulrahman et al., 2021).

Furthermore, its application aligns with Malaysia's national agenda to increase domestic rubber consumption by a minimum of 10% annually, supporting the country's infrastructure development. In response to emerging challenges, the Malaysian Rubber Board (*Lembaga Getah Malaysia*, LGM) has partnered with the Public Works Department of Malaysia (*Jabatan Kerja Raya*, JKR) to develop advanced rubberized road technologies utilizing CLNR-based additives, particularly the dry-process bituminous cup lump (RRIM CMB). Research indicates that rubberized asphalt mixtures significantly outperform conventional binders, offering increased rutting resistance due to enhanced binder elasticity, improved fatigue life from better stress distribution under repeated loading, and greater resistance to thermal cracking at low temperatures. Laboratory evaluations further confirm superior adhesion between rubber-modified binders and aggregates, reduced temperature susceptibility, and enhanced storage stability. These advancements collectively lead to longer pavement service life, decreased maintenance frequency, and more resilient road surfaces capable of enduring Malaysia's tropical climate and increasing traffic demands.

The optimal dosage of CLNR in asphalt mixtures has not been definitively established, and the comparison between wet and dry mixing methods is limited. Understanding the differences between these methods is crucial, as the mixing technique directly affects CLNR dispersion within the bitumen and the resultant mechanical and rheological properties. In the wet process, CLNR is blended with the binder before combining with aggregates, promoting uniform distribution, and enhancing molecular interactions that improve elasticity, rutting resistance, and longevity. In contrast, the dry process adds CLNR directly to aggregates before applying the binder, which can simplify processing but may result in less uniform coating. Research indicates that the wet method typically provides better binder-modifier compatibility and improved performance under high temperatures and fatigue loading. However, the dry method can still enhance rutting resistance and is easier to implement in the field. A thorough comparison of these methodologies is essential for identifying the most effective approach that balances performance, cost, and practical feasibility, ultimately guiding the design of durable and sustainable rubberized asphalt pavements.

The impact of CLNR on key binder properties such as softening point, penetration, and storage stability has not been fully quantified. Additionally, the relationship between CLNR dosage, mixing method, and binder performance remains unclear. Understanding these factors is essential for optimizing CLNR-modified bitumen formulations, ensuring consistent performance under varying conditions, and guiding practical implementation in asphalt mixtures. The incorporation of CLNR into bitumen poses challenges regarding dispersion, homogeneity, and compatibility. Poor dispersion can create weak zones, while inconsistent homogeneity leads to variability in binder properties. Limited compatibility may cause phase separation during storage, negatively impacting performance. These issues are particularly significant when CLNR is not pre-treated, as untreated CLNR tends to agglomerate, compromising workability, stability, and pavement durability. Comparative evaluations of CLNR-modified binders versus conventional polymer-modified binders are limited. Research suggests that while CLNR improves elasticity and rutting resistance, polymer-modified binders generally offer better high-temperature stiffness and long-term aging resistance. Thus, direct benchmarking is essential to identify optimal performance for specific applications. Addressing these gaps is crucial to optimising the utilisation of CLNR and ensuring its consistent and reliable integration into road pavement systems.

This study is designed to evaluate the physical properties of bitumen modified with varying amounts of CLNR. This study aims to determine the optimal dosage of CLNR and evaluate the performance of stone

mastic asphalt (SMA) mixtures using both dry and wet mixing methods, which are often overlooked in the literature. SMA is chosen for its gap-graded structure, which depends on high binder content for stone-to-stone contact, making it sensitive to binder properties. The inclusion of CLNR enhances elasticity, rutting resistance, and binder-aggregate adhesion, improving the durability and performance of SMA. In contrast, other mixture types, such as dense-graded asphalt, are less affected by binder modifications, resulting in more pronounced benefits of CLNR in SMA.

This research not only advances the understanding of natural rubber-based modifiers but also aligns with national initiatives aimed at fostering environmentally sustainable, durable, and cost-effective pavement technologies. The application of solvent-treated CLNR improves dispersion and compatibility with bitumen, which are crucial for obtaining uniform binder properties and preventing phase separation, while also ensuring consistent elasticity and rutting resistance in modified asphalt. The findings establish optimal CLNR and binder contents for improved pavement performance. This research demonstrates the potential of using Malaysia's cup lump by-product as a modifier for asphalt pavements. This approach reduces reliance on costly imported polymers, promotes environmental sustainability through renewable and biodegradable material, and enhances performance by improving binder elasticity, rutting resistance, and thermal cracking durability. These results provide significant insights for both academic research and practical applications in modern pavement engineering.

Previous investigations into untreated natural rubber in bitumen have revealed issues with dispersion and compatibility that can negatively affect performance. This study employs toluene pretreatment to improve rubber-bitumen interaction, enhance homogeneity, and prevent phase separation, while also introducing innovative approaches to dosage optimization and mixing methods. First, solvent-treated CLNR is systematically evaluated within SMA mixtures, rather than at the binder stage alone, enabling direct linkage between binder modification and mixture performance. Second, the study compares the wet and dry mixing methods using treated CLNR, an area rarely addressed in literature, and determines their respective optimum binder contents. Third, the study seeks to optimize CLNR dosage and binder content for uniform dispersion and compatibility. Homogeneity and interaction are verified through physical tests measuring softening points, penetration, and storage stability, which assess binder consistency, phase separation, and performance efficiency. Finally, by employing locally sourced CLNR and aggregates, the study demonstrates the feasibility of integrating a simple pretreatment method with national sustainability agendas, offering practical value beyond laboratory findings.

EXPERIMENTAL

Materials and methods

Pen 60/70 bitumen, sourced from Asphalt Technology Sdn. Bhd. in Port Klang is commonly used in Malaysian road construction. This grade offers balanced viscosity and temperature susceptibility, ensuring sufficient stiffness for high temperatures while maintaining flexibility to prevent low-temperature cracking. It is also suitable for modification with CLNR. CLNR was collected from rubber plantations in Negeri Sembilan. The rubber was washed with running water, air-dried, and cut into pieces not exceeding 1 cm (Fig. 1) to facilitate mixing and effective filling of aggregate voids. Aggregates were supplied by Kajang Rock Quarry, Kajang, Malaysia, and prepared in accordance with JKR standards. Each sample consisted of 1,100 g of aggregates with 2% Portland cement as filler.



Fig. 1. CLNR after being cut.

Preparation of CLNR-modified bitumen (CLMB)

CLNR was pre-treated by soaking in toluene at a 1:2 (rubber:toluene) ratio for 48 hours at room temperature to enhance homogeneity (Fig. 2). The 1:2 (rubber:toluene) ratio was selected to ensure adequate solvent penetration and swelling of the CLNR particles, thereby promoting homogeneity and dispersion during blending. Lower solvent volumes may restrict CLNR swelling, reducing dispersion and binder-rubber interaction. Conversely, excessive solvent can cause over-swelling of the rubber, leading to phase separation and compromised storage stability. This proportion has also been reported in previous studies (Abdulrahman et al., 2019, 2021; Yu et al., 2018) as effective for enhancing the compatibility of CLNR with bitumen, offering an optimal balance between solvent efficiency, mixing workability, and final binder performance.



Fig. 2. CLNR soaked in toluene.

CLNR contents of 2.5%, 5.0%, and 7.5% by weight of bitumen were selected based on previous studies showing that this range effectively balances workability, dispersion, and performance improvements without causing excessive stiffness or processing difficulties. Bitumen was heated to 160–170 °C for 10–15 minutes until liquefied, then mixed using a high-shear Silverson machine (Fig. 3) at 2,000 rpm for 60 minutes. The pre-soaked CLNR gradually incorporated at low rpm, followed by high-shear mixing at 4,000 rpm for 120 minutes while maintaining temperature. The heating temperature of 160–170 °C and duration of 10–15 minutes were selected to ensure the bitumen reached a workable viscosity while minimizing the

risk of thermal degradation. A lower threshold of 160 °C is necessary to liquefy the binder and facilitate effective shear mixing, whereas 170 °C represents the maximum safe limit beyond which oxidation and hardening may occur. Similarly, the 10 to 15-minute range accounts for variations in batch size, ensuring uniform liquefaction without prolonged exposure to heat. These parameters follow established practices in rubber-bitumen modification (Abdulrahman et al., 2019, 2021; Yu et al., 2018).



Fig. 3. The blending and mixing process by using the Silverson machine at the required speed and time.

Binder conventional testing

The penetration test is conducted in accordance with ASTM D5 to assess consistency. Additionally, the softening point test was carried out following ASTM D36 to evaluate thermal behavior at elevated temperatures. The storage stability test was performed per ASTM D7173 to examine separation tendencies of CLMB during heated storage. Softening points of the upper and lower portions were determined according to ASTM D36.

One of the most widely recognized formulas for assessing a binder's susceptibility to temperature variations is the Penetration Index (PI). This index can be determined using the formula presented in Equation 1.

$$PI = \frac{1952 - 500 \log Pen - 20S.P}{50 \log Pen - S.P - 120} \quad (1)$$

where Pen is the penetration value at 25 °C, and S.P is the softening point of the bitumen.

Preparation of CLNR-modified mixture (CLMM)

The SMA mixtures were prepared in accordance with the Marshall procedure, as outlined in ASTM D6926-10. This study involved the preparation of Marshall specimens utilizing two distinct methodologies: the dry mix method (refer to Fig. 4) and the wet mix method (refer to Fig. 5). The preparatory process commenced with oven-drying the aggregates and Ordinary Portland Cement (OPC) at 110 ± 5 °C to constant mass to remove free moisture. Subsequently, the dried aggregates and OPC were preheated to the required mixing temperature of 160–180 °C and maintained for approximately one hour to ensure uniform thermal conditioning prior to binder addition.

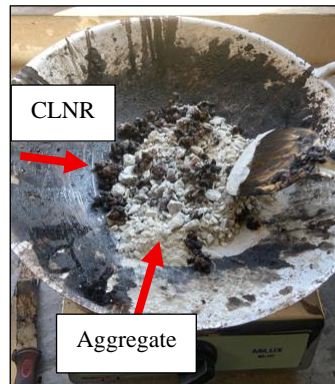


Fig. 4. For the dry mix method, CLNR is heated with aggregate prior to mixing with bitumen.

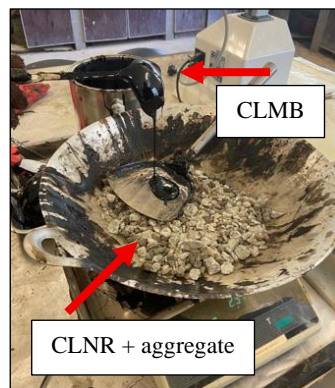


Fig. 5. For the wet mix method, the modified bitumen is added after heating the aggregate.

In the dry mix method, OPC served as the filler in the bituminous mixtures, along with the aggregates and CLNR, which were preheated to 180 °C before blending with bitumen. This procedure ensured that the aggregates were thoroughly coated with bitumen. The mixing temperature of 180 °C conforms to standard practices for conventional bitumen, ensuring adequate fluidity and aggregate coating (ASTM D6926). For CLNR-modified bitumen, this temperature has been experimentally validated to achieve effective rubber dispersion while maintaining the integrity of both the binder and rubber. Different modifiers may require adjustments to the mixing temperature. For the dry mix method, aggregates, OPC, and CLNR were preheated to 180 °C to compensate for the higher viscosity of the CLNR-modified binder. This prevents premature cooling during incorporation and ensures uniform coating.

In contrast, the wet mix method differed only in that, once the OPC and aggregates reached 180 °C, the modified bitumen was incorporated into the mixture. This composite was subsequently mixed to guarantee complete coating of the aggregates with bitumen. Care was taken to ensure that both aggregates and binder were not heated beyond their respective allowable temperature limits, thereby preventing alteration of aggregate properties and minimising binder degradation (Sarnowski et al., 2019). The same pre-heating temperature was adopted to maintain consistency and to guarantee that when the modified binder was introduced, its temperature was not rapidly reduced, thereby avoiding incomplete coating. Thus, the use of 180 °C serves both to facilitate mixing of high-viscosity CLMB and to maintain comparable conditions between dry and wet mixing approaches.

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In the dry mix method, homogeneity is improved by pre-treating CLNR with toluene before drying. This treatment softens the rubber particles, facilitating better interaction with bitumen. As a result, it enhances dispersion, reduces agglomeration, and ensures consistent binder properties. Although dried CLNR tends to regain rigidity, cutting it into ≤ 1 cm pieces allowed better dispersion when heated with aggregates at $180\text{ }^{\circ}\text{C}$, where partial softening of the rubber occurs. During mixing, continuous mechanical stirring ensured the CLNR particles were distributed uniformly throughout the aggregate matrix before binder addition. The dry mix method may not achieve complete molecular-scale dispersion like the wet mix method, but it reflects real-world practices of adding rubber directly to aggregates. While some heterogeneity may reduce binder–rubber interaction and affect performance consistency, research shows that properly pre-treated CLNR can enhance rutting resistance and elasticity. Thus, the dry mix method remains a valuable approach for performance evaluation.

An optimal rubber content of 5% CLNR was selected to balance workability and performance, while the bitumen content varied from 5.0% to 7.0% in 0.5% increments to identify the ideal binder content for stability and mixture durability. Compaction was performed according to the JKR/SPJ/2008-S4 Standard Specification for Road Works, requiring Marshall specimens to receive 50 blows per face for binder-course mixtures (see Fig. 6). Mixing and compaction temperatures were selected to ensure proper fluidity and workability of the binder while preventing degradation of bitumen and rubber. Control specimens followed JKR and ASTM D6926 guidelines, using $160\text{ }^{\circ}\text{C}$ for mixing and $145\text{ }^{\circ}\text{C}$ for compaction. CLNR-modified binders may require slightly higher temperatures for uniform dispersion. Each specimen measured 100 ± 5 mm in diameter and 65 ± 5 mm in height.

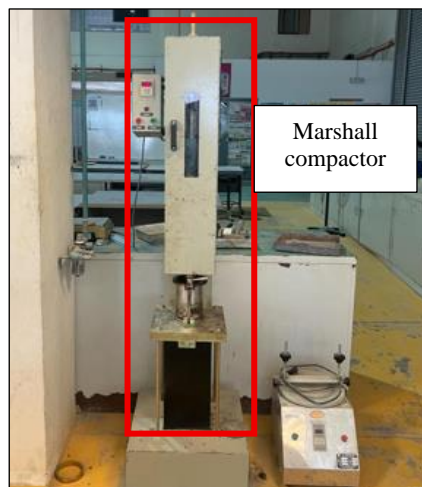


Fig. 6. The Marshall compactor.

Determination of OBC

The optimum binder content (OBC) was determined in accordance with the Marshall Mix Design procedure (ASTM D6926 and ASTM D1559). For each rubber content level, SMA specimens were prepared with binder contents ranging from 5.0% to 7.0% in 0.5% increments by weight of aggregates. Three replicates were produced per binder content to ensure consistency. After compaction and curing, specimens were tested for bulk specific gravity (ASTM D2726) and maximum theoretical specific gravity (ASTM D2041). These values were used to calculate air voids (V_a), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB). Marshall stability and flow were also determined in accordance with

ASTM D1559. The following criteria were considered in selecting the OBC following the JKR Standard Specification for Road Works:

- (i) Peak of the curve taken from the stability graph.
- (ii) Flow equals 3 mm from the flow graph.
- (iii) Peak of the curve taken from the bulk specific gravity graph.
- (iv) VIM equals to 3.5% from the VIM graph.

The OBC was chosen as the binder content that satisfied the above requirements simultaneously. When more than one binder content met the criteria, the value closest to 4% air voids with the highest stability was selected. Based on this procedure, the OBC was determined as 5.8% for the dry mix method and 5.6% for the wet mix method.

RESULTS AND DISCUSSION

Physical properties of modified bitumen

Penetration test

Fig. 7 illustrates that the addition of CLNR at lower concentrations initially reduces the penetration value, which then increases at higher concentrations. Specifically, the 5% CLNR concentration yielded the lowest penetration value of 6.68 mm, followed by 2.5% CLNR at 6.85 mm. The penetration value of 6.0–7.0 mm corresponds well with a 60/70 penetration grade binder. In contrast, the 7.5% CLNR concentration recorded a higher penetration value than the base bitumen, at 10.98 mm. Penetration levels decreased by 8.9% at a 2.5% concentration of CLNR and by 11.1% at a 5% concentration, while 10% concentration resulted in a 46% increase. The 5% concentration proved to be the most effective modification. This variability is due to moderate CLNR concentrations enhancing stiffness and the binder-rubber interaction, whereas excessive rubber can reduce compatibility, cause particle agglomeration, and trap the binder, leading to increased penetration and softer behavior.

This reduction in penetration values indicates increased hardness of the modified bitumen, as CLNR contributes to binder stiffening. The swelling of rubber particles in the bitumen forms a stronger matrix. During blending, CLNR absorbs lighter oils from the bitumen, causing further swelling and establishing a gel-like structure at the bitumen-rubber interface (Albuaymi et al., 2023). The decrease in penetration indicates an increased asphaltene content and reduced maltene content, resulting in greater binder stiffness. This enhancement improves rutting resistance and high-temperature performance of the asphalt mixture, potentially extending pavement service life by reducing permanent deformation under traffic loading (Bahruddin et al., 2020).

Research by Hazoor Ansari et al. (2022) revealed a 14% improvement in penetration resistance. Similarly, Azahar et al. (2021, 2019b) reported a 20% decrease in penetration values. Bahruddin et al. (2020) observed a 16.38% reduction in penetration with 5% and 4% of CLNR used, respectively. Abdulrahman et al. (2019) noted that increasing CLNR content further reduced penetration values. Albuaymi et al. (2023) found significant increases in base bitumen hardness due to CLNR modification, as indicated by lower penetration values. Additionally, Mustafa Kamal et al. (2020) documented a 10% decrease in penetration following CLNR addition.

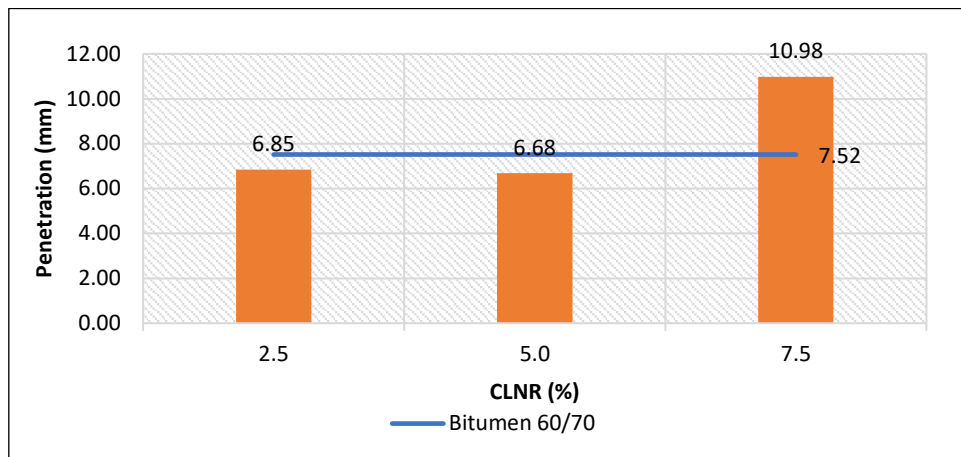


Fig. 7. Penetration of varied rubber content.

Softening point test

Fig. 8 presents the impact of adding CLNR on the softening point value of bitumen. The results indicate a reduction in the softening point relative to the control sample, with the exception of the sample with 5% CLNR. The softening points of the samples were determined as follows: 48.07 °C for 2.5% CLNR, 46.50 °C for 7.5% CLNR, and a slight increase to 48.67 °C for 5% CLNR. This data indicates that a moderate addition of CLNR (5%) enhances binder stiffness and high-temperature resistance, while an excessive amount (7.5%) can compromise binder cohesion and lower the softening point. Higher softening points indicate lower temperature susceptibility and better resistance to rutting. The 2.5% and 5% CLNR samples fell within the acceptable range of 48–56 °C for 60/70 penetration grade bitumen, demonstrating satisfactory high-temperature performance. However, the 7.5% CLNR sample fell below this specification, indicating that excessive rubber can reduce high-temperature stability and pavement durability.

These findings indicate that incorporating 5% CLNR optimally balances binder stiffness, elasticity, rutting resistance, and temperature susceptibility. This enhancement improves the asphalt mixture's resilience to traffic loads and thermal stresses, reducing deformation and cracking, and ultimately extending pavement service life. The slight increase in the softening point signifies improved hardness and stiffness of the binder, essential for effective pavement performance. Enhanced stiffness boosts rutting resistance under heavy traffic and high temperatures, while sufficient hardness maintains structural integrity, resulting in a longer service life and reduced maintenance needs (Ghfar et al., 2022).

This enhancement in stiffness is associated with increased molecular weight, which contributes to greater resistance within the asphalt matrix. Furthermore, the rise in softening point indicates that the modified bitumen, characterized by an increase in asphaltene content and a decrease in maltene content, correlates with a reduced penetration value due to elevated viscosity (Bahruddin et al., 2020). The increase in the softening point indicates that the binder can withstand higher temperatures before softening, reflecting improved viscosity and cohesion. This enhanced temperature resistance reduces rutting and permanent deformation under heavy traffic and high temperatures, thereby improving structural stability and extending the pavement's service life.

The findings of this study are consistent with those of prior research. Ghfar et al. (2022) reported a 32% increase in the softening point, while Hazoor Ansari et al. (2022) documented an increase ranging from 11% to 24% in softening with rising concentrations of CLNR. Furthermore, both Azahar et al. (2019, 2021) observed an 8% increase in softening point values. These results corroborate the studies conducted by Abdulrahman et al. (2019) and Albuaymi et al. (2023) which indicated that the incorporation of CLNR

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leads to elevated softening point values. Additionally, Mustafa Kamal et al. (2020) reported an 11% increase in softening point values associated with the inclusion of CLNR.

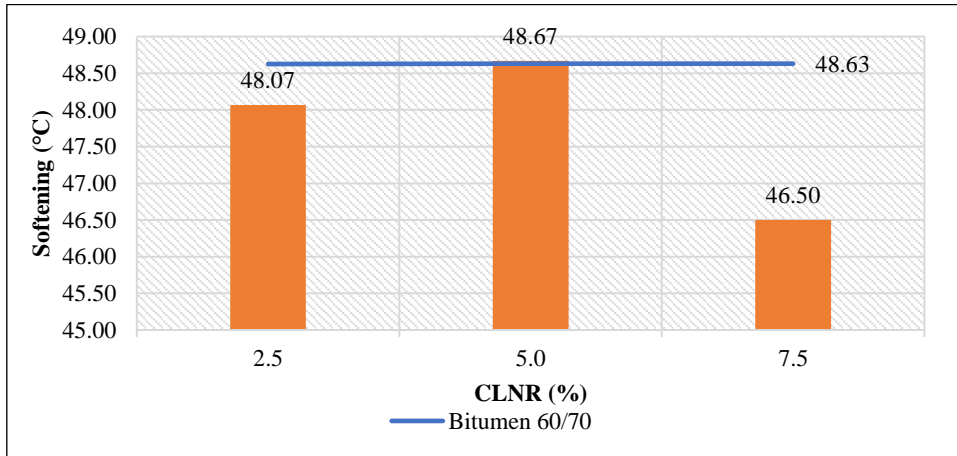


Fig. 8. Softening of varied rubber content.

Storage stability test

The modified rubber demonstrates stability and homogeneity when its storage stability meets the required specification of maintaining a temperature differential of less than 2.5 °C between the upper and lower samples after exposure to high-temperature conditions. As illustrated in Fig. 9, the incorporation of 5% CLNR achieves optimal performance, satisfying the criteria for storage stability. At 7.5% CLNR, a significant difference in softening points between the upper and lower sections indicates inadequate storage stability. Excess rubber can cause incomplete dispersion and phase separation, leading to inconsistent binder properties that may compromise pavement performance. This separation highlights the incompatibility between CLNR and bitumen. Excessive rubber leads to poor dispersion, resulting in settling and distinct layering that reduces uniformity and weakens the binder-rubber interaction, ultimately compromising the performance and durability of the asphalt mixture (Azahar et al., 2021).

Within modified bitumen at elevated storage temperatures, rubber particles are uniformly distributed throughout a low-viscosity bitumen matrix, causing the material to function as a suspension. Due to the disparity in densities between asphalt and CLNR, the rubber particles tend to settle at the bottom of the container. The mixture, although initially dispersed, is not homogeneous. Density variations cause CLNR particles to settle, leading to non-uniform binder properties and potential performance variability. Qian et al. (2019) have observed a prevailing consensus that the viscosity of binders is inversely correlated with the settling velocity of the rubber.

The dispersion of rubber particles is adversely affected by the competition between asphaltenes and polymers for the lighter components of asphalt. In addition, insufficient resin content may lead to the precipitation of asphaltenes from the oily fractions, thereby exacerbating the degree of phase separation in modified asphalt (Qian et al., 2019). CLNR's high molecular weight improves homogeneity by enhancing interaction with bitumen molecules. This reduces particle mobility and agglomeration during mixing, leading to a more uniform dispersion and better binder consistency and mixture performance. Research conducted by Azahar et al. (2021) and Salehfard et al. (2017) highlighted that the molecular weight of the polymeric chains is comparable to that of asphaltenes, resulting in a competitive interaction for the solvency of the maltene fraction. A failure in achieving sufficient solvency or an imbalance among the components may precipitate phase separation. Inadequate solvency or an imbalance between the binder and rubber

diminishes compatibility, causing rubber particles to settle or float, which results in phase separation and inconsistencies in binder properties. Additionally, variations in solubility parameters and densities between rubber and bitumen contribute to this phenomenon (Salehfard et al., 2017). Overall, the incorporation of CLNR modifies the adhesion properties of bitumen, thereby strengthening the bond with aggregates and reducing the incidence of stripping (Azahar et al., 2019b).

The findings presented in this study are consistent with previous research, confirming the stability of binders when maintained at elevated temperatures (Abdulrahman et al., 2019; Azahar et al., 2021; Hazoor Ansari et al., 2022; Azahar et al., 2019). According to the work of Abdulrahman et al. (2019), the difference in softening point temperature between the top and bottom sections of the modified sample, upon the incorporation of CLNR, is minimal and remains within the acceptable limits set by ASTM specifications. This finding is consistent with the results reported by previous studies (Abdulrahman et al., 2019).

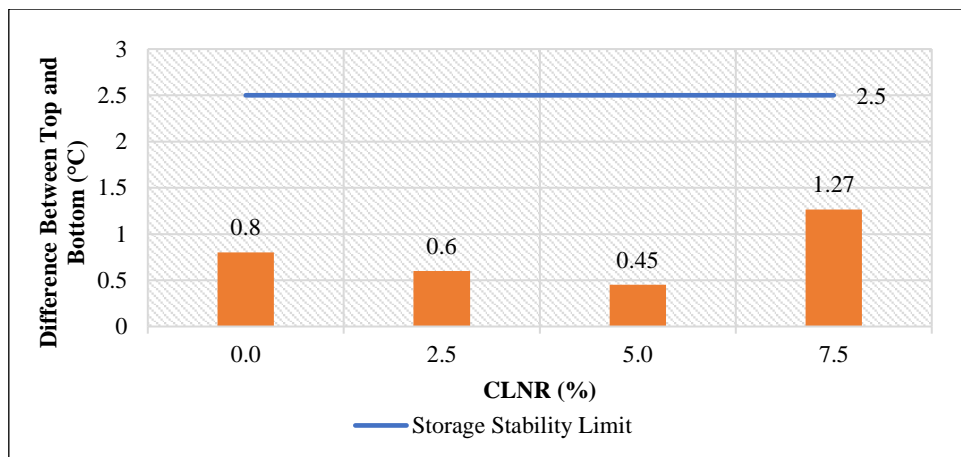


Fig. 9. Storage stability of varied rubber content.

Determination of optimum rubber content

The 2.5% and 5.0% concentrations of CRNR showed performance index (PI) values of -0.95 and -0.86, respectively. The 7.5% concentration falling outside the normal range of -1.0 to 0 for 60/70 penetration grade bitumen. This indicates that excessive rubber can increase temperature susceptibility beyond acceptable limits. This suggests that the 2.5% CLNR demonstrates greater susceptibility to temperature variations compared to the 5.0% CLNR. In summary, incorporating CLNR at both 2.5% and 5.0% levels results in a notable enhancement of bitumen performance by enhancing binder stiffness, rutting resistance, and high-temperature performance, thereby improving overall asphalt performance. The research findings indicate that a 5.0% CLNR delivers more consistent and stable outcomes, with a PI closer to zero and within the acceptable range for 60/70 penetration grade bitumen. This formulation maintains adequate stiffness at high temperatures to resist rutting while ensuring flexibility at lower temperatures to reduce cracking.

In contrast, the 2.5% CLNR demonstrates increased sensitivity to temperature variations due to its lower PI, while the 7.5% CLNR exceeds the normal range, indicating potential phase separation or reduced compatibility. Thus, the 5.0% CLNR is recommended for its uniform rheological properties, predictable performance under varying thermal conditions, and enhanced durability, making it the optimal choice for rubber content.

Marshall properties of rubberised bituminous samples

The OBC was established by the SMA mix requirements as outlined by the JKR. For this study, a rubber content of 5% CLNR has been utilised, based on the optimal rubber content determined in prior research. The binder content analysed spans from 5% to 7%, with increments of 0.5%, adhering to the design bitumen content specified by JKR. The mean optimum bitumen content is derived by averaging four distinct values: the peak identified from the stability curve, a flow measurement of 3 mm from the flow graph, the peak from the bulk specific gravity graph, and VIM recorded at 3.5% from the VIM graph. Given that the flow and VIM values surpass the thresholds of 3 mm and 3.5%, respectively, the OBC is determined by ensuring compliance with the JKR/SPJ/2008-S4 Standard, specifically in reference to Table 4.7.5 for SMA Mix Requirements (Jabatan Kerja Raya Malaysia [JKR], 2008).

Control samples

Table 1 presents a summary of the mixture properties for the control sample OBC. The OBC of the control sample was established at 5.90%. The density was measured at 2.32 mg/m³, with voids filled with bitumen recorded at 72.75%. The VIM for the control sample was documented at 4.93%. According to the JKR standard, the acceptable range for VIM in SMA mixes is between 3% and 5%; thus, the VIM obtained for the control sample adheres to this requirement. Moreover, the VMA for the control sample was assessed at 18.11%. The JKR standard specifies a minimum requirement for VMA at 17%, indicating that the VMA for the control sample also complies with established standards. The Marshall stability and flow values for the control sample were recorded at 14935 N and 3.87 mm, respectively. The JKR standard mandates a minimum stability value of 6200 N and specifies that flow should fall within the range of 2–4 mm. It can therefore be concluded that both the Marshall stability and flow values of the control sample at OBC meet the JKR standard requirements. Finally, the MQ of the control sample was recorded at 3.86 kN/mm.

Table 1. The mixture properties of control sample at OBC

OBC	Density (mg/m ³)	VFB (%)	VIM (%)	VMA (%)	Flow (mm)	Stability (N)	MQ (kN/mm)
5.90	2.32	72.75	4.93	18.11	3.87	14935	3.86

The OBC identified in this study is consistent with the findings reported by Hainin et al. (2013), who recorded an OBC of 6% for control samples of SMA20 bituminous mixtures. Similarly, Akbulut & Gurer (2022) documented an OBC of 6.22% for SMA mixtures, while Fernandes et al. (2019) indicated an OBC of 5.8% bitumen content. Furthermore, lower OBC values of 5.5% and 5.4% were observed by Tai Nguyen & Nhan Tran (2018) and Mashaan et al. (2014), respectively. Variations in aggregate gradation, bitumen grade, and modifier type lead to differences in OBC, which affect binder demand and workability. Collectively, these previous studies support the conclusion that the OBC of 5.9% determined in the present study is acceptable and falls within the established range. Hainin et al. (2013) specifically noted the OBC of 6% for SMA20 control samples utilizing PG76 bitumen. The parameters measured in this study, including flow, air voids, mixture density (MA), and stability values (3.6 mm, 4.9%, 17.8%, and 15810 N, respectively), correlate with the findings of previous research. However, a notable discrepancy exists concerning the resilient modulus; Hainin et al. (2013) reported a resilient modulus of 1930 MPa. In contrast, Akbulut & Gurer (2022) established a stability value of 1551.6 kg (15221 N), alongside a VFB of 78%, a flow measurement of 3.7 mm, and a VMA of 16.2%, which are consistent with the outcomes of the current study.

Dry mix samples

Table 2 presents a summary of the properties of a mixture containing 5% CLNR, produced using the dry mix method at the OBC. The OBC was determined to be 5.80 with the incorporation of 5% CLNR. The addition of CLNR leads to a reduction in the OBC. The application of the dry mix method resulted in a 1.69% decrease in the OBC value. This process partially fills voids and coats surfaces before the binder is

added, thereby minimizing the bitumen needed for adequate aggregate coverage and ensuring optimal mixture workability. The density of the dry CLMM was recorded at 2.32 mg/m³, which is consistent with the control sample. The volumetric VFB was measured at 72.25%, reflecting a slight reduction of 0.69% compared to the control sample. The VIM was recorded at 4.99%, representing an increase of 1.22% over the control sample, yet this value remains within the acceptable parameters established by JKR. The VMA was observed at 17.96%, which is 0.83% lower than the control sample but satisfies JKR's minimum requirements. The stability value was noted at 17060 N, indicating a 14.23% increase relative to the control sample, thus complying with JKR's minimum standards. The flow value was recorded at 3.72 mm, which is 3.88% lower than the control sample but still falls within the allowable range specified by JKR. Finally, the MQ was determined to be 4.59 kN/mm, representing an 18.91% increase over the control sample.

Table 2. The mixture properties of 5 % CLNR through the dry mix method at OBC

OBC	Density (mg/m ³)	VFB (%)	VIM (%)	VMA (%)	Flow (mm)	Stability (N)	MQ (kN/mm)
5.80	2.32	72.25	4.99	17.96	3.72	17060	4.59

The OBC of the SMA20 bituminous mixture, incorporating 5% CLNR through the dry mix method, has been established at 5.8% bitumen content. Currently, there exists a paucity of studies investigating the application of CLNR with SMA20 aggregate gradation and comparing the wet and dry mix methodologies. Nonetheless, analogous results from other types of rubber, such as crumb rubber and natural rubber latex, may serve as a reference for assessing the dependency of the obtained results. These materials exhibit similar effects on binder stiffness, temperature sensitivity, and optimal binder content, allowing for an assessment of the impact of rubber type, dosage, and mixing method on performance trends. Generally, the OBC for 5% rubber content is reported to range between 5.5% and 6.6% bitumen content. Evaluation of fatigue life of CRM-reinforced SMA and its relationship to dynamic stiffness (Azahar et al., 2019; Mashaan et al., 2014; Suwanto et al., 2023). For example, Azahar et al. (2019) documented OBC values of 5.5% and 5.6% with 5% CLNR in their research. Consequently, it can be concluded that the OBC of 5.8% achieved in this study is acceptable and consistent with previous investigations.

Wet mix samples

The OBC for the SMA20 mixture with 5% CLNR using the wet mix method was established at 5.6%. This finding is consistent with prior research, including Hainin et al. (2013), who reported an OBC of 6.0% for SMA20 mixtures with PG76 bitumen, and Akbulut & Güner (2022), who found an OBC of 5.8% for rubber-modified SMA mixtures. These results confirm compliance with established binder requirements for optimal mixture performance. Table 3 provides a summary of the properties of the mixture containing 5% CLNR produced by the wet mix method at the OBC. The data reveal that the incorporation of CLNR through this method results in a further decline in the OBC value owing to its improvement in binder-rubber compatibility and coating efficiency, leading to a decreased binder requirement for adequate workability. Several factors influence OBC, such as aggregate gradation, filler content, binder viscosity, rubber dosage, and the chosen mixing method. Specifically, the wet mix method led to a 3.45% reduction when compared to the dry CLMM and a 5.08% decrease relative to the control sample.

The density of the wet CLMM was recorded at 2.33 mg/m³, reflecting an increase of 0.43% compared to both the dry CLMM and the control sample. The VFB was measured at 71.72%, which is 0.73% lower than the dry CLMM and 1.42% lower than the control sample. The VIM was recorded at 4.95%, exhibiting a decrease of 0.8% compared to the dry CLMM; however, it was 0.41% higher than the control sample, remaining within the standards set by the JKR. The VMA was documented at 17.52%, reflecting reductions of 2.45% and 3.26% from the dry CLMM and control sample, respectively, while still satisfying the minimum JKR requirements. The stability value was observed at 16242 N, representing a decrease of 4.79% when compared to the dry CLMM, yet an increase of 8.75% over the control sample, thus meeting the

minimum standard established by JKR. The stability differences between the two mixing methods are due to their respective processes.

In the dry mix method, rubber is added directly to the aggregates, enhancing interlock and resulting in slightly higher stability. Conversely, the wet mix method blends rubber with bitumen before combining it with aggregates, which improves coating uniformity but may reduce interlock and lead to lower stability. These variations are influenced by differences in compaction, binder distribution, and rubber-bitumen interactions. The flow value was recorded at 3.93 mm, exhibiting increases of 5.65% and 1.55% in comparison to the dry CLMM and control sample, respectively, while remaining within the allowable limits defined by JKR. Finally, the MQ was measured at 4.14 kN/mm, which is 9.80% lower than the dry CLMM but 7.25% higher than the control sample.

Table 3. The mixture properties of 5 % CLNR through the wet mix method at OBC

OBC	Density (mg/m ³)	VFB (%)	VIM (%)	VMA (%)	Flow (mm)	Stability (N)	MQ (kN/mm)
5.6	2.33	71.72	4.95	17.52	3.93	16242	4.14

Summary

The findings from the CLMM indicate that both the inclusion of CLNR and the choice of mixing method, wet or dry, have a significant impact on the properties of asphalt mixtures. The incorporation of CLNR leads to an increase in VIM, with the dry mix method resulting in higher VIM values compared to the wet mix method. In the dry mix approach, CLNR is added directly to the aggregates before the introduction of bitumen, which limits the interaction between rubber particles and binder. This often results in uneven rubber dispersion, localized bitumen absorption, and reduced binder effectiveness in coating the aggregates, contributing to a higher VIM. Conversely, in the wet mix method, CLNR is pre-blended with the bitumen, allowing for complete swelling and uniform integration of the rubber into the binder. This promotes better aggregate coating and results in lower VIM values.

The increase in VIM can also be attributed to the swelling behaviour of CLNR particles, which absorb a portion of the bitumen and create additional voids between aggregates. From a pavement performance perspective, maintaining adequate air voids is crucial, as they enable proper densification under traffic loading during the early service life of the pavement. Effective densification reduces future settlement, enhances aggregate interlock, and ensures even load distribution, thereby minimizing rutting, cracking, and premature deformation, ultimately improving pavement durability. Air void content is critical in determining the bleeding characteristics of asphalt mixtures. Low air voids can result in binder flushing, where excess bitumen rises to the surface and creates a slick layer prone to rutting. Conversely, high air voids reduce the binder's ability to cover the aggregates, compromising cohesion and increasing susceptibility to cracking under traffic and thermal stresses. Insufficient binder also impairs the coating and bonding of aggregates, leading to decreased tensile strength and flexibility, which accelerates fatigue and thermal cracking in the pavement. Therefore, the observed VIM behaviour emphasizes the importance of selecting an appropriate mixing method and rubber content to achieve an optimal balance between durability and structural integrity.

The inclusion of CLNR in asphalt mixtures results in a decrease in VMA. This reduction is primarily attributed to the elastic and viscous properties of CLNR, which enhance aggregate packing and compaction efficiency. When pre-treated, CLNR tends to soften and effectively fill the voids between aggregate particles, leading to a denser, more cohesive mixture with reduced air spaces, thereby lowering the overall VMA. The difference in VMA between dry and wet CLMM is closely related to the mixing technique and how CLNR is distributed throughout the asphalt matrix. In the dry mix method, CLNR is added directly to the aggregates before the introduction of bitumen. This results in less uniform interaction, where rubber particles may behave similarly to fine aggregates, contributing to a more open mix structure. Consequently, dry CLMM typically exhibits a higher VMA than the wet-mixed counterpart. In contrast, the wet mix

method involves pre-blending CLNR with bitumen, which allows the rubber to swell uniformly and integrate smoothly with the binder phase. Improved aggregate coating and tighter packing lead to a reduction in VMA, enhancing load transfer and mixture stiffness, which increases resistance to rutting and deformation under traffic. Additionally, optimized binder dispersion and compatibility in the wet mix reduce voids, minimizing moisture infiltration and cracking risks. Together, these factors contribute to a more durable pavement with enhanced structural integrity and a longer service life.

VMA is a critical parameter in asphalt mixture design, as it ensures sufficient space for air voids and an adequate amount of binder to maintain mixture durability. Maintaining the minimum VMA requirements, as specified by the JKR, is essential to achieve long-term pavement performance. When binder content is insufficient, the bitumen film cannot adequately coat the aggregates, leaving some surfaces exposed. This exposure allows water to penetrate the thin binder layer, weakening the bond between the binder and aggregates. This process, known as stripping, results in aggregate detachment under traffic loads, creating voids and reducing interlock. Over time, repeated wetting and loading accelerate micro-cracking and pothole formation, ultimately compromising the strength and service life of the pavement. Conversely, excessive binder content, often associated with high VMA and poor void control, may lead to bleeding and rutting under traffic loads. In this study, although CLNR inclusion led to a reduction in VMA, all values remained within the acceptable limits set by JKR, confirming the structural soundness of the mixtures.

Furthermore, the inclusion of CLNR leads to an increase in Marshall stability, with dry CLMM exhibiting higher stability values compared to wet CLMM. In the dry mix method, rubber particles are introduced directly to the hot aggregates before the bitumen is added. This early contact allows the rubber to partially soften and interact with the aggregate surface, enhancing mechanical interlocking and contributing to improved load distribution. During dry mixing, the swelling of CLNR fills micro-voids between aggregates, enhancing particle contact and reducing internal gaps. This improved packing increases cohesion between aggregates and the binder, resulting in a denser mixture. As a result, load transfer is optimized, permanent deformation is minimized, rutting resistance is improved, and the pavement's service life is extended. This improved aggregate-rubber bonding strengthens the structural framework of the mixture, increasing its resistance to deformation and enhancing load-bearing capacity, as evidenced by higher Marshall stability values. Additionally, the dry mix method may promote better adhesion between rubber particles and the binder, further improving the strength and durability of the asphalt mixture.

From the Marshall stability test, it can be inferred that the strength of the adhesive bond between the binder, rubber, and aggregates plays a crucial role in regulating the failure mechanism. Enhanced adhesion and interlocking increase the mixture's ability to withstand applied loads, thereby delaying failure and enhancing overall stability.

Moreover, the flow values of the CLMM vary depending on the mixing method. When using the wet mix method, the flow value of the wet CLMM samples was higher than that of the control samples. In contrast, the flow value of the dry CLMM samples was lower than that of the control samples when using the dry mix method. In the wet mix method, CLNR is pre-blended with the bitumen, forming a more elastic and cohesive binder phase. This modified binder exhibits increased viscosity and flexibility, resulting in higher flow values due to its ability to deform more easily under loading. The thicker binder film enhances deformability and may act as a cushion between aggregate particles, thereby reducing interlocking and contributing to increased plastic deformation during the Marshall test.

Conversely, in the dry mix method, CLNR is added directly to the hot aggregates before the binder is introduced. This can lead to localized binder absorption by the rubber particles, reducing the effective binder available to coat and lubricate the aggregates. Consequently, this results in a stiffer mixture, with lower flow values, increased internal friction, and improved aggregate interlock. Such characteristics are typical when the binder content is either limited or absorbed by modifiers, such as CLNR. Despite these differences, all flow values remain within the acceptable limits specified by JKR. Low flow values indicate

a stiffer mixture, often due to insufficient binder to lubricate aggregate particles. Without an adequate binder, aggregates cannot move or deform under load, limiting flow during Marshall testing. Therefore, determining the OBC and ensuring flow remains within standard ranges is crucial for maintaining workability, cohesion, and crack resistance, ultimately enhancing pavement durability. On the other hand, high flow values, often caused by excessive binder, can result in aggregate particles “floating” within the mix, thereby reducing aggregate interlocking and structural integrity.

The inclusion of CLNR leads to an increase in the Marshall Quotient (MQ), with the dry-mixed CLMM recording a higher MQ than the wet-mixed counterpart. MQ, defined as the ratio of Marshall stability to flow value, is commonly used to assess a mixture’s resistance to creep deformation. It serves as an indicator of the stiffness and long-term rutting resistance of asphalt mixtures. A higher MQ value is desirable, as it reflects a stiffer mixture capable of carrying applied loads while resisting deformation under repeated traffic. The dry-mixed CLMM exhibits superior MQ values due to stronger aggregate interlock and improved adhesive bonding between CLNR particles and bitumen-coated aggregates. This enhanced interaction results in a more rigid structure with a higher stiffness modulus, contributing to better rutting resistance. In contrast, the wet-mixed CLMM, although showing improved stability compared to the control, demonstrates higher flow values. This is attributed to the elastic and deformable characteristics of the rubberized binder, which increase the mixture’s flexibility but slightly reduce the MQ despite improved overall stability.

CONCLUSION

This study evaluated the effects of CLNR on the physical and mechanical properties of bitumen and SMA mixtures. Tests on bitumen modified with 2.5%, 5.0%, and 7.5% CLNR indicated that CLNR significantly enhanced binder performance, improving the softening point, reducing penetration value, and increasing storage stability. The 5.0% CLNR concentration demonstrated the most consistent results and was selected as the optimal content for further evaluation.

Subsequent bituminous mixtures were prepared using this optimal dosage via both dry and wet mixing methods. Results showed that the dry mix CLMM achieved higher VIM, VMA, Marshall stability, and MQ, while exhibiting a slightly lower flow value compared to the wet mix CLMM. These findings suggest that the dry mix method more effectively enhances mixture stiffness, internal friction, and deformation resistance.

In conclusion, the incorporation of 5% CLNR significantly improves the physical properties of bitumen and the performance of SMA mixtures. The dry mix method offers superior enhancements, making it suitable for applications where high stiffness and rutting resistance are desired, making it particularly suitable for hot-climate regions or pavements exposed to high traffic loads, where elevated temperatures increase the risk of permanent deformation. This study highlights the potential of CLNR as a sustainable and cost-effective modifier for asphalt pavement construction in rubber-producing countries such as Malaysia.

A few recommendations for future development are stated below to increase the utilisation of rubber in bitumen modification.

- (i) The use of CLNR is currently limited. Future research should examine its effectiveness in modified bitumen, with and without additives, through laboratory experiments, field assessments, and chemical analyses (e.g., FTIR, DSC, SEM) to enhance understanding of molecular interactions and long-term performance of CLNR-modified binders.

- (ii) The performance of CLNR-modified bituminous mixtures requires further investigation, particularly regarding rutting and fatigue resistance. Future research should include mechanical tests such as resilient modulus, dynamic creep stiffness, and indirect tensile strength to evaluate their structural behavior under traffic loads and temperature variations.
- (iii) The performance of bituminous mixtures of CLNR by the wet and dry mix method needs to be done for further understanding of its differences in mixing methods with variations of CLNR content.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: study conception and design: Nurul Farhana Rohayzi, Herda Yati Binti Katman, Jee Khai Wong, Mohd Rasdan Ibrahim; data collection: Nurul Farhana Rohayzi, Mohd Fatah Abdul Halim, Ahmad Firman Zamzuri, Norlailati Shima Mohamad, Nor Farhana Mohd Said, Noor Aqmal Shakila Kamarudin, Khairul Nizam Sulaiman; analysis and interpretation of results: Nurul Farhana Rohayzi, Herda Yati Binti Katman; draft manuscript preparation: Nurul Farhana Rohayzi, Herda Yati Binti Katman. All authors reviewed the results and approved the final version of the manuscript.

DATA AVAILABILITY/ SUPPLEMENTARY MATERIALS

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Tenaga Nasional.

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