Self-Healing Performance of Nanoclay-Modified Asphalt Concrete Wearing Course (AC-WC) Mixtures

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ABSTRACT

The deterioration of AC-WC due to repetitive traffic loading and environmental exposure significantly shortens pavement service life. Enhancing the intrinsic self-healing capability of asphalt mixtures through

nanomaterial modification has emerged as a promising approach to mitigate this issue. This study investigates the self-healing performance of AC-WC mixtures modified with nanoclay derived from locally sourced clay. Nanoclay was produced using a soaking-filtration method and characterized using Scanning Electron Microscopy combined with Energy-Dispersive X-ray spectroscopy (SEM-EDX), confirming nanoscale particle dimensions of approximately 250 nm and a dominant silica and alumina content. Asphalt binders modified with various nanoclay contents were evaluated for penetration, specific gravity, softening point, and ductility. AC-WC Marshall specimens were prepared and tested under three conditions: initial, controlled damaged (approximately 20-25% reduction in stability), and thermally healed (60°C for 24 hours followed by room-temperature conditioning). Self-healing performance was evaluated using a Marshall stability-based Self-Healing Index (SHI), which provides a practical indicator of strength recovery at the mixture scale. The results indicate that nanoclay modification significantly influences the physical and mechanical properties of asphalt mixtures. Nanoclay addition reduced penetration and ductility while increasing specific gravity and softening point, indicating enhanced stiffness and improved resistance to temperature-induced deformation. Self-healing performance improved at moderate nanoclay contents, with the highest SHI value of 0.65 achieved at 4% nanoclay addition, compared to 0.49 for the unmodified mixture. However, higher nanoclay contents reduced healing efficiency due to increased stiffness and particle agglomeration, which restricted molecular diffusion during the healing phase. These findings suggest that nanoclay can enhance both mechanical performance and strength recovery of AC-WC mixtures when applied at an optimal dosage. The use of locally sourced nanoclay further highlights its potential as a sustainable and practical additive for improving pavement durability in conventional engineering applications.

Keywords-nanoclay; self-healing performance; asphalt concrete wearing course; modified asphalt mixtures; pavement durability

I. INTRODUCTION

Flexible pavement systems are widely used due to their constructability, ride quality, and cost efficiency. The AC-WC surface layer is directly subjected to traffic loads and environmental fluctuations, accelerating aging and microcrack initiation, which can evolve into rutting and fatigue damage, thereby reducing service life and increasing maintenance needs [1, 2]. Consequently, research has focused on innovative and sustainable asphalt mixtures that incorporate alternative, environmentally adapted binders and waste-based and locally sourced materials to enhance durability and minimize environmental impacts [2-5]. Temperature fluctuations and environmental exposure significantly influence the mechanistic behavior and durability of asphalt mixtures, affecting stiffness evolution, crack initiation, and long-term performance under traffic loading [6, 7]. Although asphalt exhibits intrinsic self-healing through viscous flow and molecular diffusion during rest periods or at elevated temperatures [8, 9], this capability declines with oxidative aging and increased stiffness, particularly in heavily trafficked pavements [1, 10]. Therefore, enhancing self-healing performance improves durability and extends pavement service life sustainably [11, 12].

In addition to nanomaterial modification, various additives and rejuvenation strategies, including waste-derived oils, polymers, and encapsulated healing agents, have been explored to mitigate moisture damage and enhance the self-healing capability of asphalt binders and mixtures [13-15]. Several methodological approaches have been proposed for evaluating asphalt self-healing performance at both binder and mixture scales [16]. Such strategies have demonstrated the potential to restore binder flexibility and promote crack closure; however, their effectiveness is often dependent on material compatibility, long-term stability, and environmental conditions [17-19]. Similarly, microcapsule-based systems have demonstrated potential for controlled rejuvenator release and crack repair at the microscale [11-13]. Beyond material-based additives, thermally induced self-healing approaches have also been investigated. Induction and microwave-based techniques for enhancing crack closure in asphalt mixtures have been examined [20]. It has been shown that conductive fillers, steel fibers, and metallic additives can significantly improve heating efficiency and strength recovery under electromagnetic activation [17-19, 21]. Despite their effectiveness, these techniques often require specialized equipment, additional conductive materials, and significant energy input, which may limit large-scale field implementation. Further advancements have focused on optimizing induction and microwave parameters to enhance heating efficiency and healing recovery, including the use of industrial by-products and recycled metallic fibers [22-27]. Nanoclay modification enhances the mechanical, rheological, and durability performance of asphalt at both the binder and mixture scales, primarily through improved interfacial interactions, increased stiffness, and modified binder microstructure, which influence crack resistance and healing behavior [4, 28-30]. Nevertheless, excessive nanoclay may induce rigidity and agglomeration, limiting molecular diffusion and healing efficiency [29, 30]. Most studies emphasize binder-level analysis, while mixture-scale self-healing evaluation, particularly for AC-WC, remains limited [31, 32]. Although fracture-based methods such as semicircular bending tests have been proposed to quantify healing performance [16], these approaches often require relatively complex testing setups and advanced equipment [18, 19]. In contrast, the SHI derived from Marshall stability provides a practical, laboratory-accessible indicator for evaluating strength recovery at the mixture scale, although it does not directly capture fracture-based healing mechanisms [7, 10].

Despite extensive research on nanoclay-modified asphalt and self-healing evaluation, there are several important gaps. Most previous studies have focused on binder-scale characterization, while investigations at the asphalt mixture scale, particularly for AC-WC applications, are still limited. In addition, many nanoclay production techniques rely on energy-intensive processes, whereas the potential of low-cost and locally sourced nanoclay materials has not been sufficiently explored. Furthermore, although fracture-based healing evaluation methods provide reliable measurements of healing behavior, they often require specialized equipment and complex testing procedures that are not readily available in conventional pavement laboratories. This study addresses these limitations by integrating locally sourced nanoclay with a practical and reproducible Marshall-based healing assessment framework suitable for conventional laboratory implementation. Based on these considerations, this research investigates the self-healing performance of AC-WC mixtures modified with nanoclay produced from locally sourced clay materials. The objectives of the study are: (1) to produce and characterize nanoclay using a soaking-filtration method; (2) to evaluate the effect of nanoclay addition on the physical properties of asphalt binders; and (3) to assess the self-healing behavior of AC-WC mixtures through Marshall stability recovery and the SHI. The findings are expected to contribute to the development of more durable, sustainable, and practically applicable nanoclay-modified asphalt mixtures for pavement engineering.

II. MATERIALS AND METHODS

A. Materials

A 60/70 penetration-grade asphalt binder, widely used for flexible pavements in tropical regions due to its balanced stiffness and workability, was employed in this study in accordance with national specifications. Coarse and fine aggregates obtained from a local quarry were selected in accordance with AC-WC gradation and mechanical property requirements. Raw clay sourced from a local deposit in Central Java, Indonesia, was processed into nanoclay to reduce cost and environmental impact while maintaining performance [4, 28]. The material was dried, ground, and sieved to ensure purity and uniform particle distribution before modification.

B. Nanoclay Preparation and Characterization

Nanoclay was synthesized using a soaking-filtration method to achieve uniform particle distribution with reduced processing intensity compared to conventional high-energy mechanical milling techniques commonly reported in nanoclay-modified asphalt studies [29, 30]. The clay suspension was agitated, repeatedly filtered, and dried to obtain nanoclay powder. Morphology and elemental composition were characterized using Scanning Electron Microscopy coupled with Energy-Dispersive X-Ray Spectroscopy (SEM-EDX) to assess particle shape, agglomeration, and dominant silica and alumina contents typical of layered silicate minerals such as montmorillonite [29, 30]. Image analysis confirmed nanometer-scale dimensions consistent with previously reported nanoclay-modified asphalt systems. SEM images (Figure 1) reveal an irregular plate-like morphology with nanoscale particle dimensions, characteristic of layered silicate nanoclay structures [29, 30]. The observed morphology indicates effective particle size reduction and dispersion, supporting the suitability of the produced nanoclay for asphalt modification.

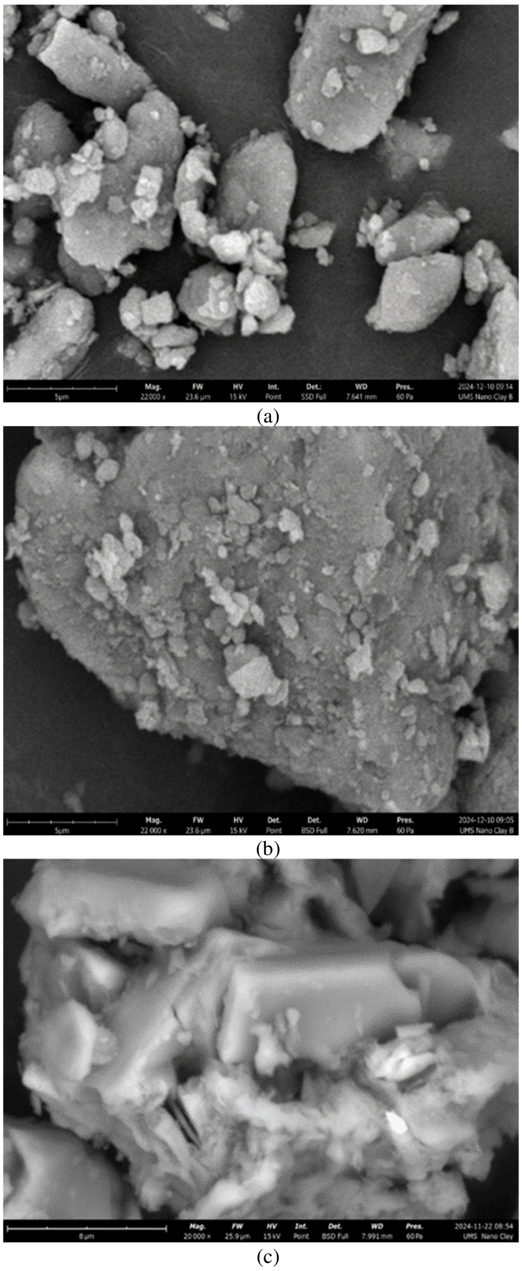
(a)
(b)
(c)

Fig. 1. SEM micrographs of nanoclay prepared using the soaking-filtration method at different observation areas: (a) first area, (b) second area, and (c) third area.

C. Asphalt Binder Modification and Physical Characterization

Nanoclay-modified binders were produced by incorporating varying nanoclay contents (by binder weight) into heated asphalt under controlled mixing to ensure homogeneous dispersion, with dosages selected to prevent agglomeration [29, 30]. Physical properties, including penetration, specific gravity, softening point, and ductility, were evaluated to determine changes in stiffness, temperature susceptibility, and deformation capacity. The physical properties of the base asphalt binder are summarized in Table I, which confirms that the penetration, specific gravity, softening point, and ductility values of the base asphalt binder satisfy the specification requirements for penetration grade 60/70. This ensures that the initial binder quality is adequate and that subsequent changes in mechanical and self-healing performance can be primarily attributed to nanoclay modification.

TABLE I. PHYSICAL PROPERTIES OF BASE ASPHALT BINDER (PENETRATION GRADE 60/70)

Property	Test method	Specification requirement	Measured value
Penetration at 25 °C (0.1 mm)	[33]	60-70	65
Specific gravity	[34]	≥ 1	1.01
Softening point (°C)	[35]	≥ 48	50
Ductility at 25 °C (cm)	[36]	≥ 100	≥ 140

D. AC-WC Mixture Design and Specimen Preparation

The AC-WC mixture was designed in accordance with national specifications, with aggregate gradation meeting stability and volumetric performance criteria commonly evaluated using the Marshall method [37]. Optimum asphalt content was determined using the Marshall mix design method based on stability, flow, VIM, and VMA criteria. Cylindrical specimens were compacted with standard blows to simulate field conditions. Nanoclay-modified mixtures incorporated the modified binder directly to ensure uniform dispersion. Gradation limits, performance requirements, and nanoclay variations are detailed in Tables II-IV. Table II presents the aggregate gradation within specification limits for AC-WC wearing courses, ensuring proper interlocking, load distribution, and durability. This compliance enables assessing nanoclay effects on Marshall stability and void characteristics. Table III outlines the required performance criteria for conventional and modified AC-WC mixtures, including Marshall stability, flow, VIM, VFA, and VMA. These benchmarks ensure structural integrity and serviceability while enabling performance enhancement through nanoclay modification. Table IV presents the investigated nanoclay dosages, selected to balance mechanical improvements and healing efficiency while minimizing excessive stiffness and agglomeration.

TABLE II. AGGREGATE GRADATION LIMITS FOR AC-WC MIXTURES

Sieve size (mm)	Passing (%) specification
19	100
12.5	90-100
9.5	77-90
4.75	53-69
2.36	33-53
1.18	21-40
0.6	14-30
0.3	9-22
0.15	6-15
0.075	4-9

TABLE III. MIXTURE PERFORMANCE REQUIREMENTS FOR AC-WC

Parameter	Requirement (standard AC-WC)	Requirement (modified AC-WC)
Marshall stability (kg)	≥ 800	≥ 1000
Flow (mm)	2-4	2-4
VFA (%)	≥ 65	≥ 65
VIM (%)	3-5	3-5
VMA (%)	≥ 15	≥ 15

TABLE IV. NANOCLAY CONTENT VARIATIONS IN ASPHALT BINDER

Mixture code	Nanoclay content (% by weight of binder)
NC 0	0
NC 4	4
NC 6	6
NC 8	8

E. Self-Healing Test Procedure and Index Evaluation

Self-healing performance was quantified using the SHI, defined as the ratio of recovered to initial Marshall stability [14, 31, 38]. Although the Marshall-based SHI primarily reflects strength recovery rather than fracture resistance, it provides a practical and accessible approach for evaluating mixture-scale healing performance under conventional laboratory conditions [16]. AC-WC specimens were evaluated under initial, damaged, and self-healed conditions following established methodological frameworks involving damage induction, thermal conditioning, and strength recovery evaluation [13, 16, 31]. Baseline stability values were obtained from undamaged specimens before damage induction. For the damaged condition, specimens were subjected to controlled loading until approximately 70%-75% of the initial Marshall stability was reached, representing a moderate damage level associated with microcrack initiation without complete structural failure. The damaged specimens were then conditioned at low temperature to prevent premature healing before testing [13, 14], and Marshall stability tests were conducted to determine residual strength. During the healing phase, damaged specimens were conditioned at 60°C for 24 h to promote binder flow and molecular diffusion. This temperature and duration range is effective for activating asphalt healing without inducing excessive aging [14, 31]. After conditioning, Marshall testing was conducted to assess strength recovery. The SHI, calculated from recovered stability relative to damage-induced loss, was used to quantify mixture-scale healing efficiency [15, 38]. The specimen conditions and procedures are presented in Table V and Figure 2.

TABLE V. SUMMARY OF SPECIMEN CONDITIONS FOR SELF-HEALING EVALUATION

Condition	Description	Purpose
Initial (I)	Undamaged Marshall specimen	Baseline mechanical performance
Damaged (D)	Specimen subjected to controlled damage	Simulate crack initiation
Self-healed (SH)	Damaged specimen after thermal healing	Evaluate strength recovery

Table V defines three evaluation conditions: initial, damaged, and self-healed, representing baseline performance, simulated deterioration, and post-healing recovery, respectively. The overall experimental program is illustrated in the sequence of specimen preparation, controlled damage, thermal healing, and mechanical testing used to quantify self-healing performance through stability recovery.

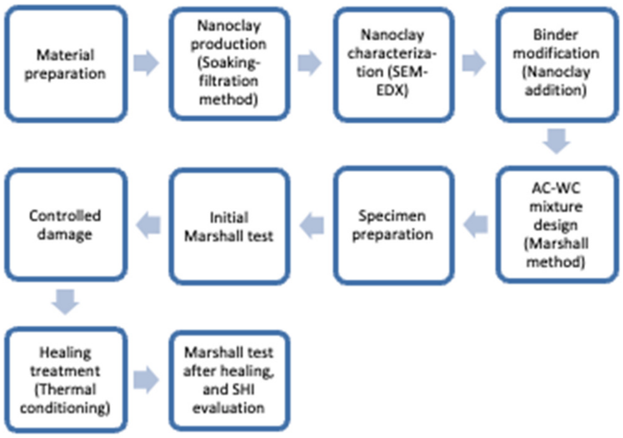

Fig. 2. Experimental program and self-healing test procedure.

III. RESULTS AND DISCUSSION

A. *Characteristics of Produced Nanoclay*

Nanoclay synthesized using the soaking-filtration method exhibited an average particle size of approximately 250 nm, indicating successful production of nanoscale particles. SEM micrographs obtained from different observation areas (Figure 1) revealed predominantly plate-like and irregular layered morphologies characteristic of montmorillonite-type nanoclay. The particles appeared relatively well distributed, with limited agglomeration, suggesting effective exfoliation and separation during the synthesis process. These morphological characteristics are important because they enhance interfacial interaction between the nanoclay and asphalt binder and promote more homogeneous dispersion within the asphalt matrix. Consequently, the produced nanoclay is expected to improve the modification performance of asphalt mixtures, consistent with findings reported in [29, 30]. EDX analysis confirmed that Si and Al were the dominant elements, with a Si/Al ratio characteristic of montmorillonite-type layered silicates. The presence of these polar silicate structures promotes physicochemical interaction with asphalt binder through surface charge effects and interlayer compatibility, thereby enhancing stiffness, thermal stability, and resistance to deformation [29, 30]. Compared with high-energy ball milling, the soaking–filtration method provides a more energy-efficient and scalable approach while maintaining adequate nanoscale dispersion for asphalt reinforcement [29]. From a mechanistic standpoint, the layered structure of nanoclay provides a high specific surface area that promotes strong physico-chemical interactions with asphalt components, particularly polar fractions such as asphaltenes. These interactions improve internal cohesion within the binder matrix and reduce molecular mobility, resulting in increased stiffness and enhanced load-bearing capacity. In addition, the uniform nanoscale dispersion of nanoclay particles facilitates more efficient stress transfer throughout the mixture and contributes to crack-bridging effects at the microstructural level. Together, these mechanisms help improve resistance to crack initiation and crack propagation in asphalt mixtures. Compared with high-energy ball milling, the soaking–filtration method provides a more energy-efficient and scalable approach while maintaining adequate nanoscale dispersion for asphalt reinforcement [29]. The ability to produce uniformly distributed nanoclay with minimal agglomeration is particularly important, as excessive particle clustering may hinder binder mobility and adversely affect healing performance. Therefore, the observed morphology confirms that the produced nanoclay is suitable for achieving a balance between mechanical reinforcement and diffusion-based self-healing mechanisms in asphalt mixtures.

B. *Data Reliability and Statistical Consistency*

To ensure data reliability and repeatability, three replicate specimens were tested for each mixture condition ($n = 3$). The experimental results are presented as mean values with corresponding standard deviations to represent the variability of the measurements. Statistical analyses were conducted to determine the significance of differences among the mixture groups. One-Way Analysis of Variance (ANOVA) was performed at a 95% confidence level ($\alpha = 0.05$) to evaluate whether variations in Marshall stability and SHI caused by different nanoclay contents were statistically significant. Where necessary, pairwise comparisons were further analyzed using t-tests to identify significant differences between individual mixtures. This statistical procedure ensures that the observed changes in mechanical performance and self-healing efficiency are attributable to the effect of nanoclay modification rather than experimental variability. The inclusion of variability indicators and significance testing, therefore, improves the reliability, consistency, and interpretability of the experimental findings.

C. *Physical Properties of Nanoclay-Modified Asphalt Binder*

The physical properties of the asphalt binder before (NC0) and after (NC4-NC10) nanoclay modification are outlined in Table VI. Incorporating nanoclay resulted in a noticeable reduction in penetration values, indicating increased binder stiffness. This behavior is attributed to the layered silicate structure of nanoclay, which restricts molecular mobility within the binder matrix through physical reinforcement and increased surface interaction with asphalt components, particularly the polar fractions [29, 30]. Specific gravity increased slightly with nanoclay addition, reflecting the higher density of mineral-based nanofillers compared to the base binder. In addition, the softening point increased, indicating enhanced resistance to temperature-induced deformation. From a mechanistic perspective, this improvement is associated with the formation of a more structured internal network within the binder, where nanoclay particles act as reinforcing agents that enhance thermal stability and reduce susceptibility to rutting at elevated service temperatures [29].

However, ductility values decreased as nanoclay content increased, indicating a reduction in binder flexibility. This behavior is attributed to the increased stiffness and restricted molecular chain mobility caused by the presence of nanoclay particles, which reduces the ability of the binder to undergo large deformations. Although moderate reductions in ductility may still be acceptable when accompanied by improvements in strength and stability, excessive stiffness can adversely affect crack resistance and self-healing capability. This behavior reflects a significant stiffness–mobility trade-off in nanoclay-modified asphalt systems. Increased stiffness improves load-bearing capacity and resistance to permanent deformation, but it may also restrict molecular diffusion and viscous flow within the binder, which are crucial mechanisms governing the self-healing process. Therefore, careful optimization of nanoclay content is necessary to achieve an appropriate balance between mechanical reinforcement and healing efficiency in asphalt binders and mixtures [29, 30].

TABLE VI. PHYSICAL PROPERTIES OF ASPHALT BINDER MODIFICATION (PENETRATION GRADE 60/70)

Property	NC0	NC4	NC6	NC8	NC10
Penetration at 25 °C (0.1 mm)	65	41.2	39	36.8	34.6
Specific gravity	1.01	1.03	1.04	1.07	1.08
Softening point (°C)	50	51	51	51.5	53
Ductility at 25 °C (cm)	≥ 140	≥140	≥140	112.5	101.5

D. *Marshall Stability Performance of AC-WC Mixtures*

The Marshall stability results for the initial, damaged, and self-healed conditions are presented in Table VII. Under the initial condition, the nanoclay-modified mixtures exhibited higher stability values than the unmodified mixture, indicating improved load-bearing capacity. Among all mixtures, NC 4 showed the highest stability, followed by NC 6 and NC 8, suggesting that moderate nanoclay content provides the most effective reinforcement effect. Mechanistically, the increase in stability can be attributed to the enhanced stiffness of the asphalt binder and improved interfacial bonding between the binder and aggregates due to the nanoscale dispersion of nanoclay particles. The high specific surface area of nanoclay promotes stronger physico-chemical interactions within the asphalt matrix, resulting in more efficient stress transfer and greater resistance to deformation under loading conditions [29, 30]. After controlled damage, all mixtures experienced a decrease in Marshall stability, indicating the formation of internal microcracks and structural deterioration. Nevertheless, the nanoclay-modified mixtures retained higher residual stability than the control mixture, demonstrating improved resistance to crack initiation and propagation. This behavior suggests that nanoclay reinforces the internal structure of the mixture and enhances cohesion at the microstructural level [29, 30]. Among the modified mixtures, NC 4 maintained the highest residual stability after damage. In contrast, mixtures with higher nanoclay contents (NC 6 and NC 8) exhibited a slight reduction in performance. This trend indicates that excessive nanoclay content may increase mixture rigidity and promote particle agglomeration, which can reduce the material’s ability to redistribute stress and accommodate deformation effectively.

Table VII displays the Marshall stability values of AC-WC mixtures under different conditions. To ensure reliability, the reported values represent the mean results of replicate specimens, with observed variability within an acceptable range. As illustrated in Figure 3, nanoclay-modified mixtures exhibit higher initial and recovered stability compared to the control mixture. The improvement is most pronounced at moderate nanoclay content (NC 4), confirming that an optimal dosage exists where mechanical reinforcement is maximized without inducing excessive stiffness. Beyond this level, the marginal decrease in stability indicates a transition from beneficial reinforcement to stiffness-dominated behavior, which may adversely affect both damage resistance and healing potential.

TABLE VII. MARSHALL STABILITY RESULTS OF AC-WC MIXTURES UNDER DIFFERENT CONDITIONS

Mixture code	Initial Stability (IS) (kg)	Damaged Stability (DS) (kg)	Self-Healed Stability (SHS) (kg)
NC 0	1136	1079	1107
NC 4	1521	1225	1417
NC 6	1510	1084	1332
NC 8	1415	1061	1231

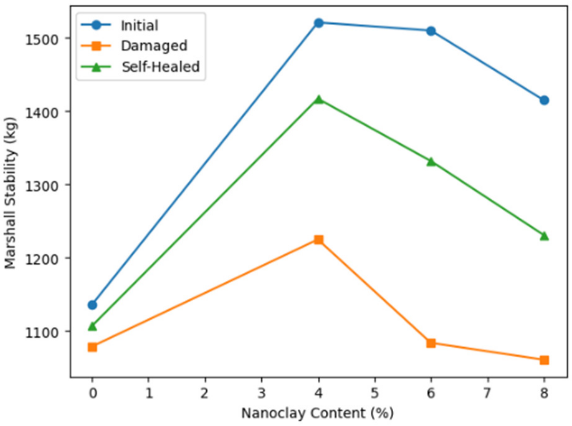

Fig. 3. Marshall stability of AC-WC mixtures with different nanoclay content.

E. *Self-Healing Performance and SHI*

Self-healing performance, quantified using the SHI, varied significantly with nanoclay content after the healing process. The calculated SHI values indicate that nanoclay addition enhances healing efficiency at moderate contents, while excessive dosages reduce recovery capability. The unmodified AC-WC mixture exhibited a relatively low SHI (0.49), reflecting limited intrinsic healing capability. The NC 4 mixture exhibited the highest SHI value (0.65), indicating a tendency toward improved healing performance at moderate nanoclay content. The results indicate a trend toward an optimal nanoclay content, at which the balance between mechanical reinforcement and healing capability is enhanced. This behavior reflects a stiffness-mobility interaction within the asphalt matrix. From a mechanistic perspective, the enhancement can be attributed to the high specific surface area of nanoclay, which improves interfacial interaction and facilitates stress redistribution. In addition, nanoscale dispersion promotes localized binder flow and diffusion across crack interfaces, which are key mechanisms governing the self-healing behavior in asphalt materials [8, 9]. The interaction between thermal activation and mechanical recovery has been highlighted in asphalt systems [39]. During the healing phase, elevated temperature enhances binder mobility, enabling viscous flow and molecular diffusion that contribute to crack-face re-bonding. The presence of well-dispersed nanoclay particles further supports this process by improving heat distribution and maintaining structural integrity during recovery.

However, at higher nanoclay contents (NC 6 and NC 8), SHI values decreased despite the relatively high initial stability. An SHI of NC 8 (0.48) is comparable to or slightly lower than that of the control mixture, indicating that excessive nanoclay content may negate the benefits of mechanical reinforcement in terms of healing performance. This behavior highlights a significant stiffness-mobility trade-off. While increased stiffness enhances load-bearing capacity, it also restricts molecular mobility, reduces viscous flow, and limits diffusion across crack interfaces, thereby hindering the healing process. Furthermore, excessive nanoclay content may promote particle agglomeration, leading to heterogeneous dispersion within the binder matrix. Such agglomeration can act as stress concentration points and reduce the effectiveness of stress relaxation, ultimately decreasing healing efficiency [38]. This explains the observed decline in SHI at higher nanoclay dosages despite improved stiffness properties.

TABLE VIII. SHI OF NANOCLAY-MODIFIED AC-WC MIXTURES

Mixture Code	IS (kg)	DS (kg)	SHS (kg)	SHI
NC 0	1136	1079	1107	0.49
NC 4	1521	1225	1417	0.65
NC 6	1510	1084	1332	0.58
NC 8	1415	1061	1231	0.48

Table VIII depicts the SHI values of nanoclay-modified AC-WC mixtures. The reported SHI values represent the mean of replicate specimens, with relatively consistent trends observed across mixtures. The results indicate a clear tendency toward an optimal nanoclay content, at which the balance between mechanical reinforcement and healing capability is enhanced. Although the Marshall-based SHI does not directly capture fracture behavior, it provides a practical and reproducible indicator of strength recovery at the mixture scale. Compared to fracture-based methods such as semicircular bending or fatigue-rest-recovery tests, the Marshall-based approach offers a simpler and more accessible alternative for laboratory evaluation, particularly in conventional pavement testing environments. Figure 4 illustrates the variation of SHI with nanoclay content. The SHI increases up to 4% nanoclay content, indicating enhanced healing efficiency, and decreases at higher contents due to increased stiffness and reduced binder mobility. The non-linear trend confirms that nanoclay modification must be carefully optimized to achieve an effective balance between structural performance and self-healing capability.

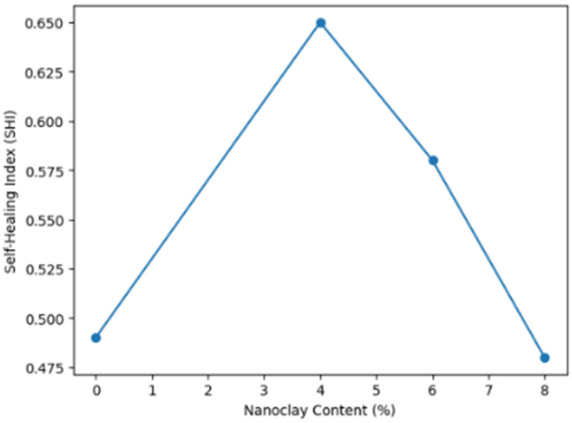

Fig. 4. Variation of SHI of AC-WC mixtures.

F. Discussion on Optimum Nanoclay Content

The results demonstrate the existence of an optimal nanoclay content that balances mechanical reinforcement and self-healing capability in AC-WC mixtures. Among the investigated mixtures, the NC 4 composition achieved the most favorable combination of stability enhancement and healing efficiency, indicating that an equilibrium between stiffness and molecular mobility is essential for optimal performance. Moderate nanoclay addition improves the internal structure of the asphalt matrix by increasing interfacial bonding, enhancing stress distribution, and promoting crack-bridging effects at the microscale. At the same time, sufficient binder mobility is maintained, allowing viscous flow and molecular diffusion across crack interfaces, which are substantial for self-healing. Similar nanofiller-induced improvements in healing efficiency have also been reported in carbon nanotube-modified asphalt systems, highlighting the role of nanoscale reinforcement in facilitating mechanical recovery [38].

However, excessive nanoclay content leads to a stiffness-dominated response, where increased rigidity restricts molecular diffusion and prolongs relaxation time, thereby reducing healing efficiency. In addition, particle agglomeration at higher dosages may create localized stress concentrations and hinder uniform stress redistribution. This behavior explains the observed decline in SHI at higher nanoclay contents and confirms that maximizing nanofiller content does not necessarily result in optimal performance. These findings are consistent with [29, 30], emphasizing the importance of optimizing nanoclay dosage to avoid adverse effects on flexibility and crack recovery.

Furthermore, healing efficiency is highly influenced by material aging and conditioning conditions, as these factors directly affect binder viscosity and molecular diffusion capability. As the binder ages, its stiffness increases, reducing its ability to flow and diffuse across crack interfaces during the healing process. Consequently, the self-healing capability of the asphalt mixture decreases, emphasizing the importance of maintaining a balance between stiffness enhancement and sufficient molecular mobility [28]. From a practical point of view, the use of locally sourced nanoclay provides a sustainable and cost-effective alternative to commercially manufactured nanomaterials. Combined with a simplified evaluation method, such as the Marshall-based SHI, the proposed approach offers a practical and feasible framework for assessing self-healing performance in conventional pavement laboratories. Although the Marshall-based method does not directly represent fracture mechanics behavior, it provides a reliable and accessible indicator of strength recovery that can support engineering evaluation and decision-making, particularly in laboratories with limited resources [14, 38]. Overall, the findings indicate that the performance of nanoclay-modified asphalt mixtures is governed by the balance between stiffness enhancement and molecular mobility. Therefore, the nanoclay content must be carefully optimized to achieve both improved mechanical durability and effective self-healing capability.

G. Implications for Pavement Engineering Practice

The enhanced self-healing performance of nanoclay-modified AC-WC mixtures demonstrates strong potential for improving pavement durability and reducing life-cycle maintenance costs. The ability of these mixtures to recover mechanical strength after damage suggests that crack propagation can be delayed during the early stages of pavement deterioration, thereby extending service life and postponing major rehabilitation activities. The findings further indicate that nanoclay modification can be incorporated into conventional asphalt mixture design without requiring substantial changes to existing construction practices. In particular, the optimum nanoclay content identified in this study (4%) provides a practical reference for achieving a balance between stiffness enhancement and healing efficiency in wearing course applications. However, the results also highlight the importance of dosage optimization. Excessive nanoclay content may increase mixture stiffness while reducing healing capability. Therefore, careful control of material proportioning, mixing procedures, and quality assurance is essential to ensure consistent field performance. From a sustainability perspective, the use of locally sourced nanoclay offers a cost-effective and environmentally friendly alternative to commercially engineered nanomaterials. Utilizing locally available resources can reduce transportation demand, lower material costs, and support more sustainable pavement engineering practices. Furthermore, the use of a Marshall-based SHI provides a practical and accessible framework for evaluating healing performance in conventional laboratory settings. This is particularly beneficial for agencies and institutions with limited access to advanced fracture-testing equipment, enabling broader implementation of self-healing assessment in routine pavement evaluation. Integrating nanoclay modification and practical healing evaluation methods contributes to the development of durable, sustainable, and low-maintenance pavement systems.

IV. CONCLUSIONS

This study investigated the self-healing performance of AC-WC mixtures modified with nanoclay produced from locally sourced clay materials. The experimental results demonstrated a structure–property–healing relationship in nanoclay-modified asphalt mixtures. Nanoclay synthesized through the soaking-filtration method successfully produced nanoscale layered silicate particles with an average size of approximately 250 nm. SEM-EDX analysis confirmed the dominance of Si and Al elements, indicating the presence of layered silicate minerals compatible with the asphalt binder matrix. The incorporation of nanoclay significantly influenced the physical and mechanical properties of the asphalt binder and mixtures, since it reduced penetration and ductility while increasing the softening point, indicating enhanced stiffness and improved thermal resistance. At the mixture scale, these modifications contributed to higher Marshall stability, improved resistance to damage, and greater recovery of mechanical strength after the healing process. The self-healing performance of the mixtures exhibited a dosage-dependent trend governed by the interaction between stiffness and molecular mobility. The mixture containing 4% nanoclay achieved the highest SHI value (0.65), indicating improved healing performance compared to the control mixture (0.49). This improvement is associated with enhanced interfacial interaction, better stress redistribution, and diffusion-related healing mechanisms within the asphalt matrix. However, higher nanoclay contents reduced healing efficiency due to increased rigidity, restricted molecular mobility, and possible particle agglomeration. These findings indicate that nanoclay dosage must be carefully optimized to achieve a balance between mechanical reinforcement and healing capability, as increasing nanofiller content does not necessarily result in improved healing performance.

It should also be noted that the Marshall-based SHI used in this study primarily reflects strength recovery rather than fracture-based healing behavior. Therefore, the results should be interpreted as a practical indicator of mixture-scale healing performance under controlled laboratory conditions. Nevertheless, the proposed evaluation approach provides a simpler and more accessible alternative to fracture-based methods commonly requiring specialized equipment and advanced testing procedures. Unlike many previous studies that mainly focused on binder-level characterization or relied on fracture-based testing methods, this research demonstrates a laboratory-accessible approach for evaluating self-healing performance at the AC-WC mixture scale using Marshall-based stability recovery. The findings further extend current knowledge by establishing a clear relationship between nanoclay structure, asphalt mixture properties, and healing behavior, while emphasizing the importance of balancing stiffness enhancement and molecular mobility. Overall, the study provides a practical and scalable contribution toward the development of sustainable pavement engineering applications using locally available nanomaterials.

DECLARATION OF COMPETING INTERESTS

The authors declare that there are no known financial interests, personal relationships, or competing interests that could have appeared to influence the work reported in this paper.

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DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

AI USE AND DECLARATION OF GENERATIVE AI USE

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language refinement and sentence restructuring. After using this service, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the published article.

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