

Improving The Mechanical Performance of High Modulus Asphalt Mixtures Using Nanoclay

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ABSTRACT

This study investigated the effect of nanoclay (NC) additives on the mechanical performance of high modulus asphalt mixtures (EME). The research studied NC at four different binder weight percentages (0 %, 2 %, 4 %, 6 %) through Marshall stability tests and indirect tensile strength (ITS) and resilient modulus (M_R) evaluations at 5 °C, 25 °C and 40 °C. The results showed substantial improvements across all performance indicators. The Marshall stability increased by 20.7 % when NC reached 6% but flow values decreased by 18.2 % for NC values between 4 % and 6 % because of enhanced permanent deformation resistance. The ITS values showed a 16.5 % increase which demonstrated better tensile strength performance. The M_R values showed significant growth at all test temperatures which reached 55 % at 5 °C and 66.7 % at 25 °C and 64.6 % at 40 °C. The material demonstrated better elastic recovery through these tests, which were conducted at different thermal conditions. The mixture containing 6 % NC reached a richness modulus (K) value exceeding 3.4, which fulfilled the EME2 classification requirements. Statistical analysis (ANOVA) and mechanical evaluation identified 4% NC as the optimal dosage, as it achieved the maximum Marshall stiffness (6.18 kN/mm), while further increases to 6 % did not yield statistically significant improvements. The research shows nanoclay acts as an effective modifier that enhances both structural and mechanical properties of EME mixtures.

Keywords: High modulus asphalt (EME), Nanoclay, Indirect tensile strength, Resilient modulus, Richness modulus.

1. INTRODUCTION

The rising need for long-lasting and environmentally friendly pavement systems on busy highways has led to the creation of advanced asphalt technologies including High Modulus Asphalt Concrete (HMAC) which is known as Enrobés à Module Élevé (EME) (Chen et al., 2020). The French developed EME mixtures during the 1970s as a material which combines dense grading with high stiffness and abundant binder content to achieve better structural strength and minimize layer heights (Corté, 2001; Delorme et al., 2007). The research team

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developed these mixtures, which multiple countries, including the United Kingdom, China and Latvia, now use for construction purposes. The research team in Iraq conducted experimental studies using domestic materials and modified construction methods to test these mixtures (Kadhim et al., 2018; Li et al., 2017; Zhu et al., 2020).

Scientists continue to develop EME mixtures because they aim to improve their stiffness, rutting, and fatigue resistance through modification techniques. The research incorporates three main components, which include polymer-modified binders and reclaimed asphalt pavement (RAP) and industrial by-products to achieve better workability and cost-effectiveness, and enhanced resistance against different loading types and environmental factors (Izaks et al., 2022; Wang et al., 2017; Zaumanis et al., 2020). The development of nanotechnology has brought forward new methods to enhance asphalt through modification. Research shows nano-silica and nano-calcium carbonate nanomaterials improve asphalt binder performance through enhanced stiffness and temperature stability and extended fatigue life (Oda et al., 2020; Taherkhani and Tajdini, 2019). The research identifies NC as the most suitable material because it possesses a big surface area and long dimensions and intercalation properties which enable strong bonding with bitumen molecules (Golestani et al., 2015; Hussain et al., 2022).

Although numerous studies have explored the impact of NC on conventional Hot Mix Asphalt (HMA) mixtures, such investigations on high modulus asphalt mixtures like EME remain limited (Ameri et al., 2017). Research conducted by (Aljbouri and Albayati, 2023) demonstrated that NC addition to traditional HMA results in better Marshall stability and moisture resistance and indirect tensile strength performance. The current research lacks a complete investigation of nanoclay effects on EME mixture performance characteristics which creates an important knowledge deficit. In Iraq, the French LPC design procedure has been partially adopted, but due to the unavailability of specialized French testing equipment (e.g., the LCPC Wheel Tracker and French Gyratory Compactor) (Albayati and Lateif, 2017; Kadhim et al., 2018), required to create a modified mix design through accessible equipment and volumetric methods and mechanical tests, including Marshall stability and indirect tensile strength (ITS) and resilient modulus (M_R).

The scientific community lacks sufficient research about nanoclay applications in high modulus asphalt mixtures (EME) because these materials show increasing demand for constructing durable pavements that handle heavy traffic loads. This gap underscores the importance of the present study, which systematically evaluates the mechanical and volumetric properties of EME modified with nanoclay. Methodologically, this research adapts the French EME design criteria to locally available Iraqi materials and laboratory conditions

2. MATERIALS AND METHOD

This section provides an overview of the selected materials and analyzes where they were sourced from.

2.1 Asphalt Cement

This study used bitumen 20/30 penetration grade. The Daura refinery, located in Baghdad serves as the primary source for this binder material. The experimental results for binder testing are listed in **Table 1**.



Table 1. Asphalt Binder Properties

Property	Unit	Results	EN-12591 Specification
Penetration (25 °C, 100 g, 5 sec)	0.1 mm	21	20-30
Ductility (25 °C, 5 cm/min)	cm	31	---
Softening Point (Ring& Ball)	°C	62	55-63
Flash point (Cleveland open Cup)	°C	295	240 (Min.)
Specific Gravity @ 25 °C	---	1.052	---
After conducting the Thin-Film Oven Test (ASTM D 1754)			
Retained Penetration (% of original)	%	78	55 (Min.)
Ductility (25 °C, 5 cm/min)	cm	25	---

2.2 Aggregates: Fine and Coarse

The fine and coarse aggregates sourced from Badrah quarry were utilized. The coarse aggregate for the binder course ranged in sieve diameters between (19 mm) to (4.75 mm), whereas the fine aggregate size varied between (4.75 mm) to (0.075 mm) sieve. **Table 2** displays several physical characteristics of both fine and coarse aggregates. The gradation curve was initially plotted based on the EME 0/14 as specified by (Sanders and Nunn, 2005). Subsequently, the passing percentages corresponding to standard ASTM sieve sizes were determined by projecting from the constructed gradation curve, in order to align with the available U.S. sieving system used in the laboratory. **Fig. 1** illustrates the gradation of aggregates.

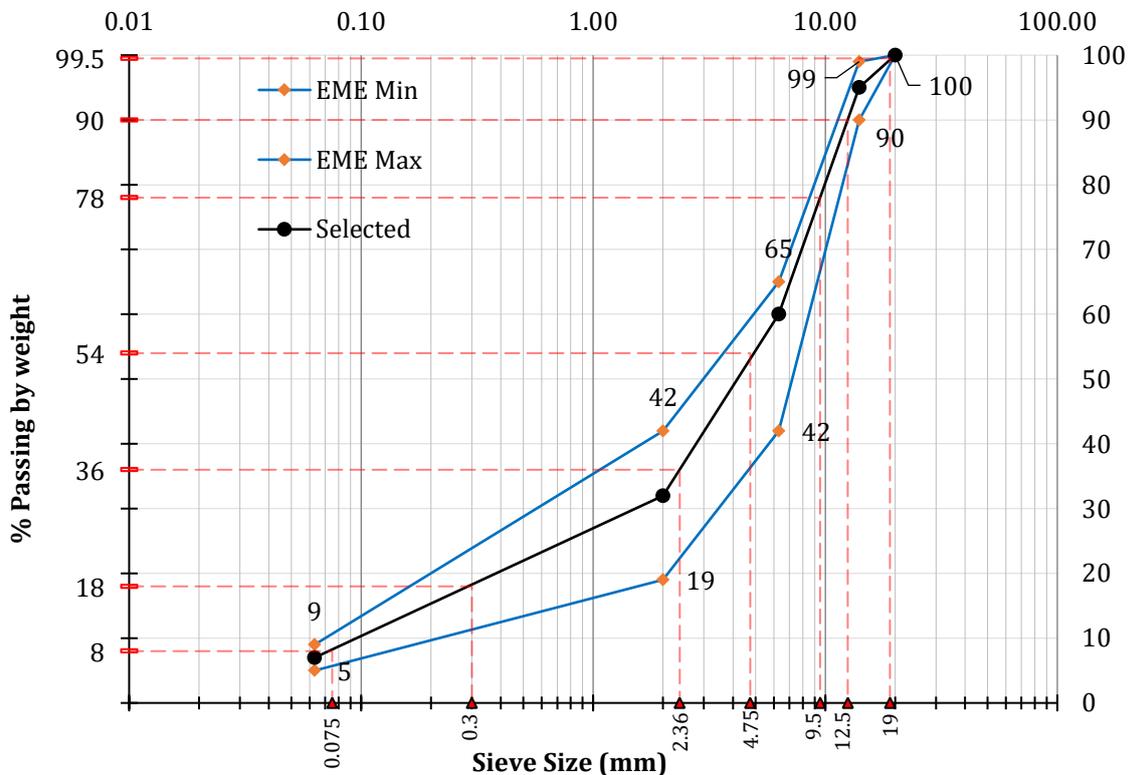


Figure 1. Aggregate gradation for binder course compared with ASTM sieves

Table 2. Aggregate Properties.

Property	ASTM Standard	Results	SCRB Limits
Coarse Aggregate			
Bulk Specific Gravity	(ASTM C128)	2.62	---
Water Absorption %	(ASTM C127)	0.55	---
Los Angeles Abrasion%	(ASTM C131)	17.8	30 Max
Fine Aggregate			
Bulk Specific Gravity	(ASTM C128)	2.632	---
Water Absorption %	(ASTM C127)	0.79	---

2.3 Mineral Filler

This research adopted limestone dust as its filler material because of its availability and affordability. The filler enhances the asphalt binder's rigidity and long-term performance. The material exists as a fine powder that will pass through a No. 200 sieve with a 0.075 mm opening.

2.4 Nanoclay (NC)

The nanoclay used in this study is a high-purity powder commercialized as Blocktone 22A. Its chemical composition consists of Aluminum Silicate Hydrate with the chemical formula $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$ and is identified by CAS Number 1332-58-7. The material is characterized by excellent thermal stability, with a decomposition temperature of 269 °C, making it suitable for high-temperature asphalt mixing processes. The NC powder is shown in Fig. 2. its morphology and particle size distribution were characterized using Atomic Force Microscopy (AFM), as presented in Figs. 3 and 4. The AFM analysis showed that the material achieved nanoscale dimensions because the average particle diameter measured 49.67 nm. A high-shear mechanical mixer was operated at 4000 rpm for 45 minutes when NC was added to the neat bitumen to prevent potential nanoparticle agglomeration (Golestani et al., 2015).



Figure 2. The image of Nanoclay powder

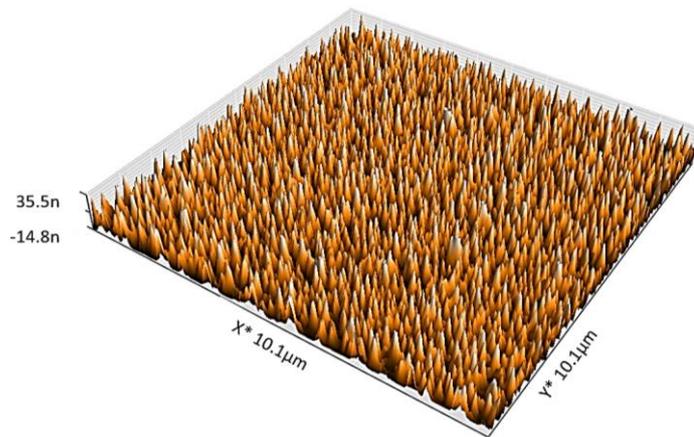


Figure 3. Characterization particle morphology of NC by AFM

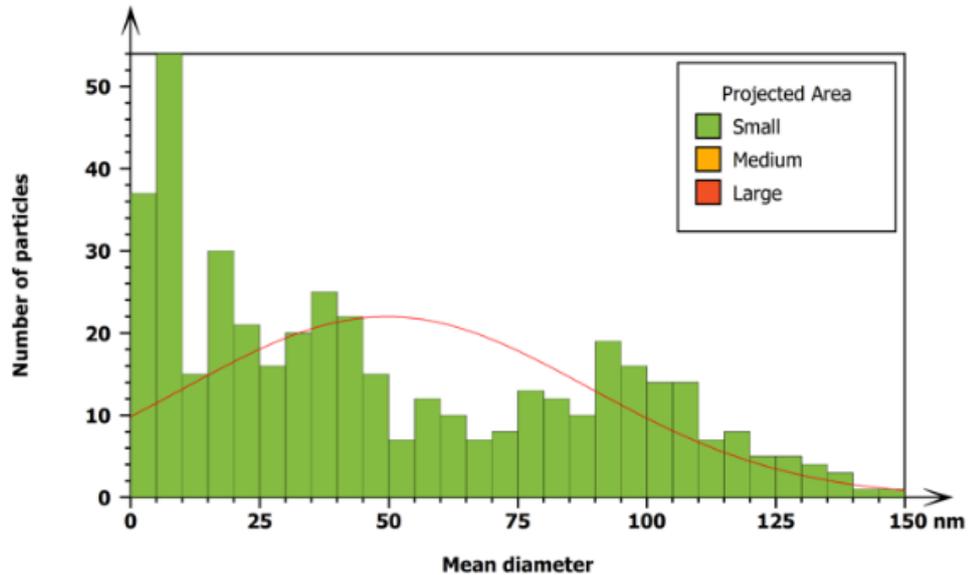


Figure 4. NC Particle Size Distribution.

2.5 Marshall Test

The asphalt binder was preheated to 155 ± 5 °C before the addition of (NC) at concentrations of 2 %, 4 %, and 6 % by binder weight. Mixing was performed using a high-shear mechanical mixer operating at 4000 rpm for 45 minutes on a heated surface to ensure proper dispersion (Aljbouri and Albayati, 2024; Li et al., 2017). The evaluation EME mixture required trial blends with asphalt content percentages ranging from 4% to 6% by total mix weight. Three replicate specimens represented each percentage level in this study. The samples underwent cooling to room temperature for about 24 hours after compaction before undergoing testing. Marshall testing analyzed stability and flow, along with bulk density and air void content, according to ASTM D6927 standards (Mohammed et al., 2024). The Asphalt Institute established 4% air void as the standard target for determining (OAC) (Al-Attar and Ismael, 2025). The aggregate blend had a nominal maximum size of 19.0 mm (binder course), and 6% limestone dust by aggregate weight was added as mineral filler. The laboratory testing for Marshall, ITS and Resilient modulus is illustrated in Fig. 5.



2.6 Indirect Tensile Strength Test

The Indirect Tensile Strength (ITS) test was conducted in accordance with ASTM D6931 to evaluate the tensile cracking resistance of asphalt mixtures. Cylindrical specimens (100 mm diameter, 63.5 ± 2.5 mm height) were conditioned at 25 °C for at least two hours prior to testing (Yousif et al., 2024). Each sample was loaded along its vertical axis at a deformation rate of 50 mm/min using a universal testing machine until failure. The ITS value (kPa) was determined from the peak load using Eq. (1).

$$ITS = \frac{2000 P}{\pi.t.d} \quad (1)$$

where t is the specimen thickness (mm), and D is the diameter (mm).

2.7 Resilient Modulus (M_R) Test

The test was conducted in accordance with ASTM D4123 to evaluate the response of asphalt mixtures under repeated load conditions. Cylindrical specimens with a diameter of 101.6 mm and a height of 63.5 mm were prepared using the same compaction procedure as Marshall specimens. The testing process required all samples to undergo four hours of temperature conditioning at their target test points, which included 5 °C, 25 °C and 40 °C. The test was carried out using the indirect tensile configuration, in which a repeated haversine load pulse was applied vertically along the specimen's diametric axis. The load duration was set to 0.1 seconds, followed by a rest period of 0.9 seconds. A repeated axial load was applied to simulate traffic loading, and horizontal deformations were recorded using linear variable differential transformers (LVDTs), and M_R was calculated accordingly (Taherkhani, 2016).

2.8 Richness Modulus (K)

The richness modulus (K), adopted in the LPC Bituminous Mixtures Design Guide, is a parameter that reflects the conventional thickness of the asphalt binder film coating the aggregate particles. The parameter is widely used in the classification of High Modulus Asphalt Concrete (HMAC/EME), where values of $K \approx 2.5-3.3$ correspond to EME1 mixtures suitable for medium traffic, and $K \geq 3.4$ define EME2 mixtures designed for very heavy traffic conditions. The richness modulus was calculated according to the LPC technical guide using the following general relationship in Eq. (2)

$$TL = K \times \alpha \times \sqrt[5]{\Sigma} \quad (2)$$

where:

TL is the minimum binder content (% by aggregate mass),

K is the richness modulus,

α is the correction coefficient that accounts for the density of the aggregates,

Σ is the specific surface area of the aggregate blend, expressed in m^2/kg , determined from the aggregate gradation. The value of α was determined from the effective specific gravity of aggregates (Gse), while Σ was computed based on the particle size distribution, considering the relative proportions of coarse particles (>6.3 mm), medium particles (0.25–6.3 mm), and fines (<0.063 mm). Based on these parameters, the richness modulus (K) was calculated for

each mixture using its actual binder content and aggregate gradation. The calculated values were later used to evaluate whether the mixtures satisfy the requirements of EME1 or EME2 classification according to the LPC specifications.

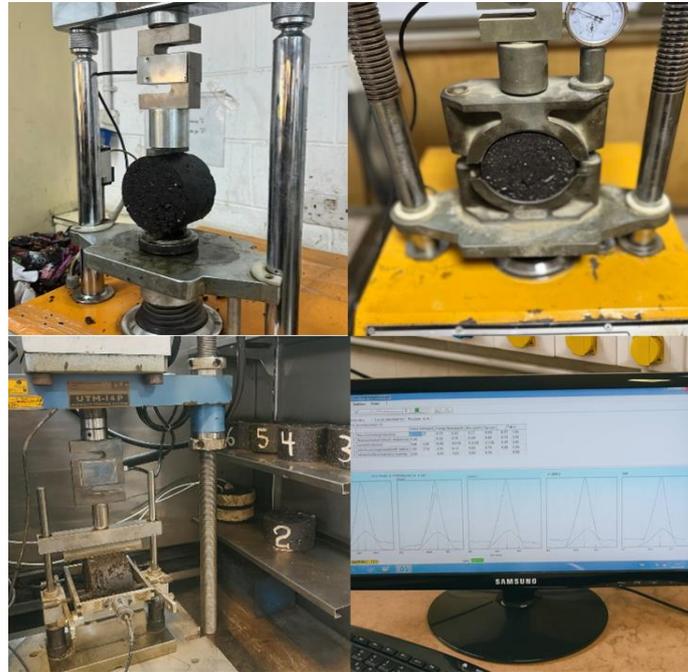


Figure 5. Laboratory testing of specimens

2.9 Statistical Analysis

A two-way factorial ANOVA was conducted on resilient modulus (M_R) for the HMAC. Fixed factors were NC content (0%, 2%, 4%, 6%) and test temperature (5 °C, 25 °C, 40 °C). Model residuals were checked for normality and homogeneity of variances; significance level was set at $\alpha = 0.05$. Post-hoc pairwise comparisons were performed using Tukey's HSD to compare NC levels within each temperature and temperatures within each NC level. All analyses were performed in IBM SPSS Statistics (v26) (Montgomery and Runger, 2011).

3. RESULTS AND DISCUSSION

3.1 Marshall Test

3.1.1 Optimum Asphalt Content

In this study, the Optimum Asphalt Content (OAC) was determined as the binder content corresponding to 4.0% air voids in the compacted mixture. The point needs to meet all essential requirements, which include VMA and VFA values and stability and flow measurements according to MS-2 guidelines (Albayati and Qadir-Ismael, 2024). Marshall mix design results revealed a steady increase in (OAC) with increasing NC content, rising from 4.90 % at 0 % NC to 5.08 %, 5.23 %, and 5.48 % at 2 %, 4 %, and 6 % NC, respectively. The high viscosity of asphalt binder with NC addition leads to increased asphalt requirements for proper coating and complete aggregate coverage. The small size of NC particles and their large surface area cause them to absorb more binder, which leads to higher asphalt consumption (Dai et al., 2023).



3.1.2 Marshall stability

Marshall stability showed a clear and progressive increase with the inclusion of NC. The control mixture showed a stability of 14.92 kN, but the addition of 2 % NC increased it to 16.26 kN (+8.9 %), and 4 % NC increased it to 17.20 kN (+15.2 %), and 6 % NC increased it to 18.02 kN (+20.7 %). This enhancement is attributed to the interaction between the asphalt matrix and the layered silicates of the NC. The light molecular weight components of bitumen enter the silicate layers to create two types of structures, which enhance the binder matrix strength through intercalation and exfoliation. The process increases asphalt viscosity while it enhances its internal friction, which results in better mechanical strength. (Merusi et al., 2014; Yang et al., 2021). The results are consistent with previous studies by (Hassan and Ismael, 2025). These results are presented in summary form in **Table 3**.

Table 3. Marshall Mix Design Properties.

Mixture	OAC (%)	Marshall Stability (kN)	Flow (mm)	Bulk Density (gm/cm ³)	Air Voids (%)	Voids in Mineral Aggregate (%)	Voids Filled with Asphalt (%)	Marshall Stiffness (kN/mm)
No.1 0% NC	4.90	14.92	3.40	2.382	4	13.90	71.18	4.39
No.2 2% NC	5.08	16.26	3.13	2.377	4	14.02	71.38	5.19
No.3 4% NC	5.23	17.20	2.78	2.370	4	14.34	72.20	6.18
No.4 6% NC	5.48	18.02	3.08	2.362	4	14.87	72.98	5.85

3.1.3 Bulk Density

The bulk density showed a minor decrease when NC content levels rose. The density values changed as follows when NC dosage increased from 0 % to 2 %: the density decreased to 2.377 g/cm³ (-0.21 %), then to 2.370 g/cm³ (-0.50 %) at 4 % NC and finally to 2.362 g/cm³ (-0.84 %) at 6% NC. The specific behavior emerges because of the increasing optimum asphalt content in NC-containing mixtures. The air void content remained at 4 % while additional asphalt displaced heavier aggregate particles, which resulted in a decrease of mass per unit volume. The bulk density of the mixture decreased slightly because asphalt has a lower specific gravity than mineral aggregates. The results of the bulk density comply with (Iskender, 2016).

3.1.4 Marshall Flow

Flow values exhibited a decreasing pattern with increased NC up to 4 %, dropping from 3.40 mm in the control to 3.13 mm and 2.78 mm at 2 % and 4 % NC, respectively. The high surface area of NC particles (Aljbouri and Albayati, 2023) leads to increased internal cohesion and stiffness of the mixture, which results in reduced deformation. The flow rate increased to 3.60 mm when the NC reached 6% because the asphalt content reached its optimal point. The flow values remained at acceptable levels because NC achieved successful plastic deformation reduction, but the increased binder content and particle clustering could lead to slightly better flow rates. **Fig. 6** illustrates the effect of varying NC percentages on Marshall stability, flow, and OAC.



3.1.5 Marshall Stiffness

Marshall stiffness, defined as the ratio of Marshall stability to flow, provides a complementary assessment of the mixture's resistance to deformation under load (Esfahani and Jahromi, 2020; Esa et al., 2024). Marshall stiffness, calculated as the ratio of stability to flow. It increased from 4.39 kN/mm in the control mixture to 5.19 kN/mm (+18.2 %) at 2 % NC, peaked at 6.18 kN/mm (+40.7 %) at 4 % NC, then slightly declined to 5.85 kN/mm at 6 % NC. This peak at 4 % NC represents the most effective mechanical synergy between stability and flow, providing maximum resistance to deformation. Beyond this concentration, the higher asphalt content required for the 6 % NC mixture leads to increased flow, resulting in the observed decline in stiffness. Fig. 7 Marshall stiffness values (kN/mm) for asphalt mixtures modified with different NC contents.

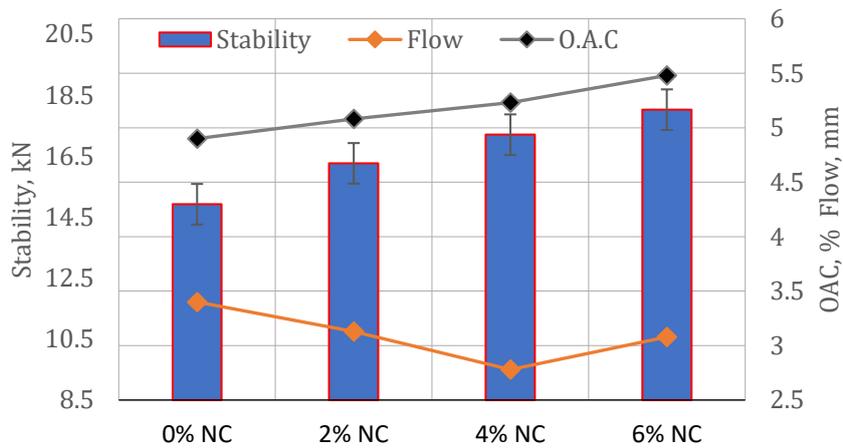


Figure 6. Influence of varying NC dosages on Marshall stability, flow, and (OAC).

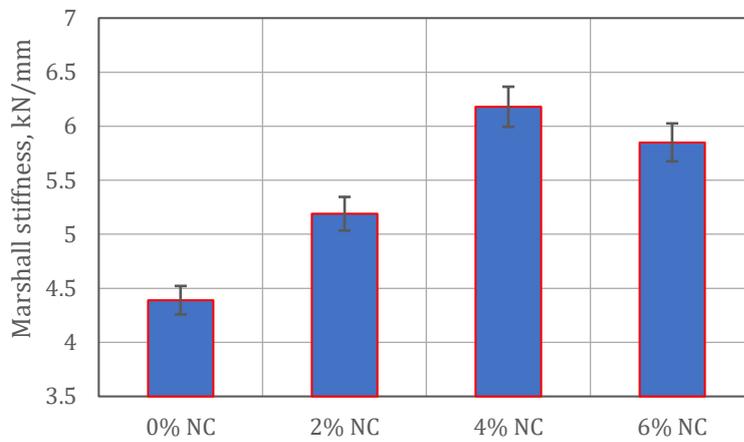


Figure 7. Marshall stiffness versus NC content

3.1.6 Voids in Mineral Aggregate VMA and Voids Filled with Asphalt VFA

The values of VMA and VFA followed a specific pattern as asphalt content levels rose. Higher NC content is associated with a slight increase in Voids in Mineral Aggregate VMA values, primarily due to the rise in optimum asphalt content (OAC). The 4 % air void requirement demands additional binder application, which results in increased binder volume that expands the intergranular voids slightly. The VFA values demonstrated a gradual increase when the asphalt content rose, which produced improved void space coverage. The addition



of this mixture component will enhance both mixture durability and moisture resistance because VFA values must reach particular thresholds to reduce permeability and establish correct binder film thickness (Brown et al., 2009), which aligns with the design approach of this study.

3.2 Indirect Tensile Strength

The Indirect Tensile Strength (ITS) test results showed that tensile resistance increased with each addition of NC. The control mixture (0 % NC) showed an average ITS of 1367 kPa, but the values rose to 1440 kPa (+5.3 %), 1526 kPa (+11.6 %) and 1593 kPa (+16.5 %) when NC content reached 2 %, 4 % and 6 %, respectively. This improvement is primarily attributed to the layered structure and high surface area of NC particles (Ramadhansyah et al., 2020). Similar enhancements in ITS due to NC incorporation were also reported by (Ameri et al., 2016). The variation in tensile strength with different NC contents is illustrated in Fig. 8.

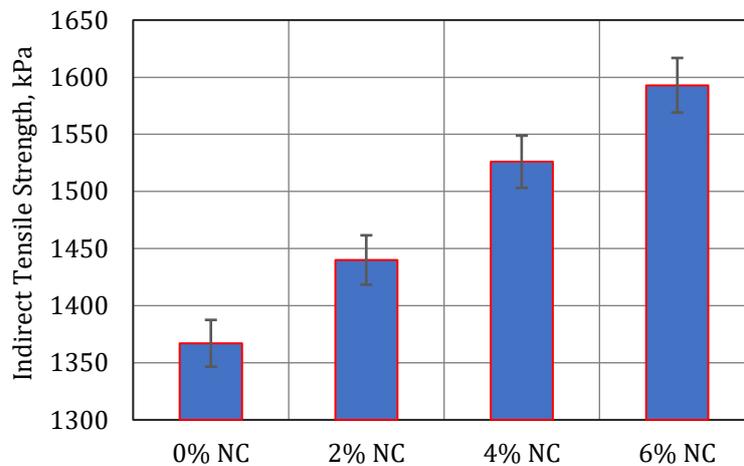


Figure 8. Indirect Tensile Strength versus NC content.

3.3 Resilient Modulus

The researchers measured resilient modulus (M_R) values for asphalt mixtures with 0% NC and 2 % NC and 4 % NC and 6 % NC at 5 °C and 25 °C and 40 °C as shown in Fig. 9.

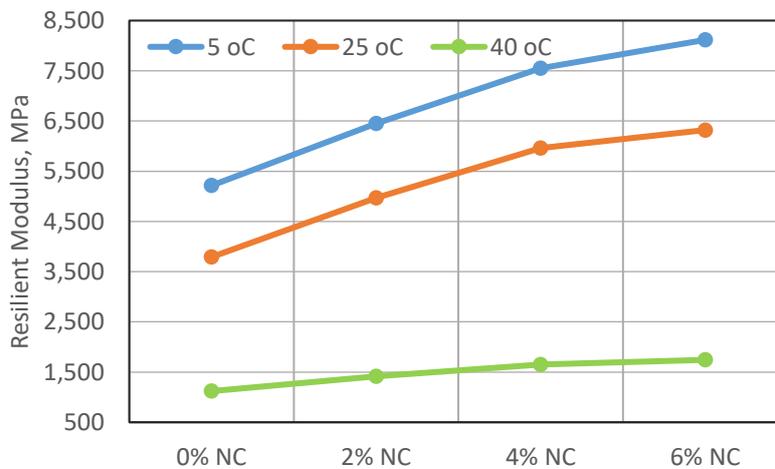


Figure 9. Variation of resilient modulus with NC content.



The test results show that M_R values increase with rising NC percentages at all evaluated temperatures because NC acts as a reinforcing agent for asphalt mixtures. The M_R values at 25 °C showed a progressive increase from 3,791 MPa for the control mixture to 4,971 MPa (+31.1 %), 5,962 MPa (+57.3 %) and 6,320 MPa (+66.7 %) when NC was added at 2 %, 4 % and 6 %, respectively. The testing results at 5 °C showed that M_R values increased from 5,215 MPa at 0 % NC to 8,116 MPa at 6 % NC, which shows that the material becomes stiffer when exposed to cold temperatures, thus reducing its risk of thermal cracking. The M_R values of all mixtures decreased at 40 °C because the binder became soft, but NC addition still resulted in a substantial increase from 1,121 MPa (0 % NC) to 1,743 MPa (6 % NC), which showed improved resistance to high temperatures and permanent deformation.

3.4 Richness Modulus Evaluation

The richness modulus (K) was calculated for all mixtures according to the LPC technical guide using the binder content and aggregate gradation. The obtained values are presented in **Table 4**.

Table 4. Richness Modulus (K) of Mixtures With NC.

Nanoclay content (%)	0 %	2 %	4 %	6 %
K value	3.02	3.16	3.34	3.48

As shown in **Table 4**, the control mixture (0 % NC) and those containing up to 4 % NC exhibit K values within the EME1 classification range ($K \approx 2.5-3.3$). In contrast, the mixture with 6% NC reached a value of 3.48, exceeding the minimum threshold for EME2 classification ($K \geq 3.4$). This indicates that NC incorporation not only improves the mechanical performance of the mixtures but also upgrades their structural classification according to LPC standards.

3.5 Statistical Results for Resilient Modulus (M_R)

Two-way ANOVA (Type III sums of squares) showed highly significant main effects of NC content and temperature, as well as a significant NC \times Temperature interaction **Table 5**. These results confirm that the observed increases in M_R are systematic rather than random.

Table 5. Two-way ANOVA (Type III) for M_R

Source	df	F	p-value	ηp^2
NC	3	174.836	1.94×10^{-16}	0.956
Temperature	2	463.571	6.66×10^{-20}	0.975
NC \times Temperature	6	30.938	3.69×10^{-10}	0.886

As shown in **Table 5**, the two-way ANOVA demonstrated highly significant effects of both NC content ($\eta p^2 = 0.956$) and temperature ($\eta p^2 = 0.975$) on resilient modulus (M_R), along with a strong NC \times Temperature interaction ($\eta p^2 = 0.886$, $p < 0.001$). M_R values increased consistently with higher NC levels at all test temperatures, while they decreased as temperature rose (5 °C > 25 °C > 40 °C). The analysis of interactions showed that NC performance depended on temperature because the biggest relative improvement occurred at 25 °C (+66.7% at 6% NC compared with the control) yet significant benefits were still achieved at 5 °C and 40 °C.

The Post-hoc Tukey HSD tests ($\alpha = 0.05$) confirmed the ANOVA findings. All NC concentrations showed significant differences at 5 °C, while no statistically significant



difference was observed between the 4% and 6% NC dosages at 25 °C and 40 °C ($p > 0.05$). Although the 6% NC mixture exhibited slightly higher absolute M_R values, the performance gain beyond 4% was statistically marginal, indicating a clear performance plateau. This statistical behavior explains why 4% NC was identified as the optimal dosage, achieving maximum enhancement of elastic properties under service temperatures without requiring higher NC content.

The observed statistical plateau in M_R values can be explained through three distinct mechanistic stages of nanoclay modification:

- (2 % NC): At this initial dosage, NC particles act as a reinforcing filler, increasing binder viscosity and stability through intercalation with bitumen molecules.
- (4 % NC): This represents the optimal mechanical synergy where exfoliated structures reach maximum efficiency, resulting in a substantial increase in M_R from 6,452 to 7,548 MPa at 25 °C.
- (6 % NC): Beyond the 4% threshold, the high surface area of NC requires additional asphalt (OAC) for coating. This extra binder introduces a 'lubrication effect' that counteracts the stiffening potential.

4. STUDY LIMITATIONS

The research investigates nanoclay-modified EME mixtures through laboratory tests, which evaluate their mechanical and volumetric behavior. The research study does not evaluate performance characteristics, which include fatigue resistance and moisture damage, and long-term aging and are considered beyond the scope of this research. Workability and field compaction behavior were not assessed. Future studies are recommended to verify these aspects and to validate the laboratory findings. Although the use of NC does drive up initial construction costs, it extends pavement life and reduces thickness suggests long-term economic benefits. Therefore, upcoming studies should perform a cost analysis evaluation.

5. CONCLUSIONS

This study investigated the effect of NC additives at dosages of 0 %, 2 %, 4 %, and 6 % by binder weight on the mechanical and volumetric properties of (EME). The laboratory test results enable us to make the following conclusions:

- The addition of NC resulted in a progressive enhancement of Marshall stability because the stability increased by 20.7% when using 6% NC compared to the control sample. The Flow values decreased by up to 4% NC, which showed better resistance to deformation but the 6% NC sample showed a minor increase because of its higher asphalt content.
- The Marshall stiffness achieved its peak value at 4% NC concentration, which resulted in the possible strength to flexibility ratio.
- The indirect tensile strength (ITS) increased progressively with higher NC content, reaching a 16.5 % improvement at 6 % NC, suggesting stronger binder–aggregate bonding and improved resistance to tensile-induced cracking.
- The test results showed that M_R values rose substantially at all testing temperatures, with 55 %, 66.7 %, and 64.6 % increases at 5 °C, 25 °C, and 40 °C, respectively. The research results demonstrated that the material developed elastic properties, which improved its ability to recover loads after it experienced temperature changes.
- The K values from calculations increased with NC addition until the 6% NC mixture reached $K \geq 3.4$, which qualifies it for the EME2 classification.



- The statistical evaluation showed that the M_R enhancements reached a highly significant level ($p < 0.001$) while post-hoc tests established 4% NC as the best dosage because additional increases at 6% did not produce significant improvements.

NOMENCLATURE

Symbol	Description	Symbol	Description
NC	Nanoclay	K	Richness Modulus
EME	High Modulus Asphalt Mixture	SCRB	State Corporation for Roads and Bridges
ITS	Indirect Tensile Strength	VMA	Voids in the mineral aggregate
M_R	Resilient Modulus	VFA	Voids Filled with Asphalt

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Credit Authorship Contribution Statement

Madyan Al-Attar: Conceptualization, Laboratory experiments, Data analysis, Writing – original draft. Mohammed Ismael: Conceptualization, Supervision, Methodology guidance, Review and editing.

Declaration of Competing Interest

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

REFERENCES

- Al-Attar, M., and Ismael, M., 2025. Mechanical performance and predictive modeling of hot mix asphalt modified with nanoclay. *Civil and Environmental Engineering*. <https://doi.org/10.2478/cee-2026-0030>.
- Albayati, A.H., and Lateif, R. H., 2017. Evaluating the performance of high modulus asphalt concrete mixture for base course in Iraq. *Journal of Engineering*, 23(6), pp. 14–33. <https://doi.org/10.31026/j.eng.2017.06.02>
- Albayati, N., and Ismael, M.Q., 2024. Rutting performance of asphalt mixtures containing treated RCA and reinforced by carbon fibers. *AiBi Revista de Investigación, Administración e Ingeniería*, 12 (1), pp. 18–28.
- Aljbouri, H.J., and Albayati, A.H., 2023. Effect of nanomaterials on the durability of hot mix asphalt. *Transportation Engineering*, 11. <https://doi.org/10.1016/j.treng.2023.100165>.
- Aljbouri, H.J., and Albayati, A.H., 2024. The effect of nano-hydrated lime on the durability of hot mix asphalt. *Journal of Engineering*, 30, pp. 143–158. <https://doi.org/10.31026/j.eng.2024.03.10>.
- Aljbouri, R.Q. and Albayati, A.H., 2023. Investigating the effect of nanomaterials on the Marshall properties and durability of warm mix asphalt. *Cogent Engineering*, 10(2), P. 2269640. <https://doi.org/10.1080/23311916.2023.2269640>.



- Ameri, M., Mohammadi, R., Vamegh, M., and Molayem, M., 2017. Evaluation the effects of nanoclay on permanent deformation behavior of stone mastic asphalt mixtures. *Constr Build Mater*, 156, pp. 107–113. <https://doi.org/10.1016/j.conbuildmat.2017.07.055>.
- Ameri, M., Nobakht, S., Bemana, K., Vamegh, M., and Rooholamini, H., 2016. Effects of nanoclay on hot mix asphalt performance. *Pet Sci Technol*, 34, pp. 747–753. <https://doi.org/10.1080/10916466.2016.1164714>.
- Brown, E.R., Kandhal, P.S., Roberts, F.L., Kim, Y.R., Lee, D.Y. and Kennedy, T.W., 2009. *Hot mix asphalt materials, mixture design, and construction*. 3rd ed. Lanham, MD: National Asphalt Pavement Association Research and Education Foundation.
- Chen, Y., Wang, H., Xu, S., and You, Z., 2020. High modulus asphalt concrete: A state-of-the-art review. *Constr Build Mater*, 237. <https://doi.org/10.1016/j.conbuildmat.2019.117653>.
- Corté, J.F., 2001. Development and uses of hard grade asphalt and of high modulus asphalt mixes in France, in: 80th TRB Annual Meeting, Session 436: Perpetual Bituminous Pavements, Part 1. *Transportation Research Board*, Washington, USA, pp. 12–31.
- Dai, Y., Liang, W., Ye, D., Xie, S., Sang, Y. and Li, D., 2023. Modification effects of nanosilica on asphalt binders: A review. *Nanotechnology Reviews*, 12(1), P. 20230138. <https://doi.org/10.1515/ntrev-2023-0138>.
- Delorme J., Roche C., and Wendling L., 2007. *LPC Bituminous Mixtures Design Guide*. France.
- Douglas C. Montgomery, George C. Runger, 2011. *Applied Statistics and Probability for Engineers*, 5th ed. John Wiley & Sons, Inc., United States of America.
- Esa, N.Y., Azahar, W.N.A.W., Kasim, N., and Basri, N.K., 2024. Comparison of the mechanical performance of dense grading and porous grading mixture utilized with crumb rubber modified binder. *IJUM Engineering Journal*, 25 (1), pp. 128–141. <https://doi.org/10.31436/iiumej.v25i1.2969>
- Esfahani, M.A., and Jahromi, M.N., 2020. Optimum parafibre length according to mechanical properties in hot mix asphalt. *Road Materials and Pavement Design*, 21(3), pp. 683-700. <https://doi.org/10.1080/14680629.2018.1527240>.
- Golestani, B., Nam, B.H., Nejad, F.M., and Fallah, S., 2015. Nanoclay application to asphalt concrete: Characterization of polymer and linear nanocomposite-modified asphalt binder and mixture. *Construction and Building Materials*, 91, pp. 32-38. <https://doi.org/10.1016/j.conbuildmat.2015.05.019>.
- Hassan, F.S., and Ismael, M.Q., 2025. Marshall properties and rutting resistance for asphaltic mixtures modified by nano-montmorillonite. *Journal of Engineering* 31 (2), pp. 19–33. <https://doi.org/10.31026/j.eng.2025.02.02>.
- Hussain, W.A.M., Abdulrasool, A.T., and Kadhim, Y.N., 2022. Using nanoclay hydrophilic bentonite as a filler to enhance the mechanical properties of asphalt. *Journal of Applied Engineering Science*, 20 (1), pp. 300–304. <https://doi.org/10.5937/jaes0-35111>.
- Iskender, E., 2016. Evaluation of mechanical properties of nano-clay modified asphalt mixtures. *Measurement (Lond)*, 93, pp. 359–371. <https://doi.org/10.1016/j.measurement.2016.07.045>
- Izaks, R., Rathore, M., Haritonovs, V., and Zaumanis, M., 2022. Performance properties of high modulus asphalt concrete containing high reclaimed asphalt content and polymer modified binder.



International Journal of Pavement Engineering 23, pp. 2255–2264.
<https://doi.org/10.1080/10298436.2020.1850721>.

Kadhim, H.A., Al-Humeidawi, B.H., and Medhloom, M.K., 2018. Production of high modulus asphalt concrete with high rutting resistance. *ARPN Journal of Engineering and Applied Sciences* (13), pp. 4204–4217.

Li, P., Zheng, M., Wang, F., Che, F., Li, H., Ma, Q., and Wang, Y., 2017. Laboratory performance evaluation of high modulus asphalt concrete modified with different additives. *Advances in Materials Science and Engineering*, 2017(1), P. 7236153. <https://doi.org/10.1155/2017/7236153>.

Li, R., Xiao, F., Amir Khanian, S., You, Z., and Huang, J., 2017. Developments of nano materials and technologies on asphalt materials—A review. *Construction and building materials*, 143, pp. 633–648. <https://doi.org/10.1016/j.conbuildmat.2017.03.158>.

Merusi, F., Giuliani, F., Filippi, S., Polacco, G., 2014. A model combining structure and properties of a 160/220 bituminous binder modified with polymer/clay nanocomposites. A rheological and morphological study. *Mater Struct* 47, pp. 819–838. <https://doi.org/10.1617/s11527-013-0096-3>

Mohammed, F.A., Latief, R.H., and Albayati, A.H., 2024. Assessment of traditional asphalt mixture performance using natural asphalt from sulfur springs. *Journal of Engineering*, 30(01), pp. 54–73. <https://doi.org/10.31026/j.eng.2024.01.04>.

Oda, A.W., El-Desouky, A., Mahdy, H. and Moussa, O.M., 2020, December. Effects of asphalt modification by Nanosilica and Nanoclay on asphalt binder and hot mix asphalt properties. In *IOP Conference Series: Materials Science and Engineering*, 974(1), P. 012003. IOP Publishing. <https://doi.org/10.1088/1757-899X/974/1/012003>.

Ramadhansyah, P.J., Masri, K.A., Norhidayah, A.H., Hainin, M.R., Muhammad Naquiuddin, M.W., Haryati, Y., Satar, M.K.I.M. and Juraidah, A., 2020, January. Nanoparticle in asphalt binder: A state-of-the-art review. In *IOP Conference Series: Materials Science and Engineering*, 712(1), P. 012023. IOP Publishing. <https://doi.org/10.1088/1757-899X/712/1/012023>.

Sanders, P.J., and Nunn, M., 2005. The application of Enrobé à Module Élevé in flexible pavements Prepared for Quarry Products Association, Refined Bitumen Association and Highways Agency.

Taherkhani, H., 2016. Investigating the effects of nanoclay and nylon fibers on the mechanical properties of asphalt concrete. *Civil Engineering Infrastructures Journal* 49, pp. 235–249. <https://doi.org/10.7508/cej.2016.02.004>.

Taherkhani, H., and Tajdini, M., 2019. Comparing the effects of nano-silica and hydrated lime on the properties of asphalt concrete. *Constr Build Mater* 218, pp. 308–315. <https://doi.org/10.1016/J.CONBUILDMAT.2019.05.116>.

Wang, C., Wang, H., Zhao, L., and Cao, D., 2017. Experimental study on rheological characteristics and performance of high modulus asphalt binder with different modifiers. *Constr Build Mater* 155, pp. 26–36. <https://doi.org/10.1016/j.conbuildmat.2017.08.058>.

Yang, X., Shen, A., Guo, Y., Wu, H., and Wang, H., 2021. A review of nano layered silicate technologies applied to asphalt materials. *Road Materials and Pavement Design* 22, pp. 1708–1733. <https://doi.org/10.1080/14680629.2020.1713199>.

Yousif, M.A., Zghair, H.H., and Alsaeedi, F., 2024. Optimal design of mechanical performances of asphalt mixtures comprising nano-clay additives. *Open Engineering*, 14 (1). <https://doi.org/10.1515/eng-2022-0586>.



Zaumanis, M., Arrigada, M., and Poulidakos, L.D., 2020. 100% recycled high-modulus asphalt concrete mixture design and validation using vehicle simulator. *Constr Build Mater* 260. <https://doi.org/10.1016/j.conbuildmat.2020.119891>.

Zhu, J., Ma, T., Fan, J., Fang, Z., Chen, T., and Zhou, Y., 2020. Experimental study of high modulus asphalt mixture containing reclaimed asphalt pavement. *J. Clean Prod* 263. <https://doi.org/10.1016/j.jclepro.2020.121447>.

تحسين الأداء الميكانيكي للخلطات الإسفلتية الجساءة الصلابة باستخدام النانوكلي

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الخلاصة

تتناول هذه الدراسة تأثير إضافة مادة النانوكلي (NC) على الأداء الميكانيكي للخلطات الإسفلتية عالية الجساءة (EME). تم تقييم تأثير النانوكلي عند أربع نسب وزنية مختلفة من الاسفلت (0%، 2%، 4%، 6%) على ثبات مارشال، ومقاومة الشد غير المباشر (ITS)، ومعامل الرجوعية (MR) عند درجات حرارة 5 °م، و 25 °م، و 40 °م. أظهرت النتائج تحسناً ملحوظاً في جميع مؤشرات الأداء؛ إذ ازدادت قيمة ثبات مارشال بنسبة 20.7% عند إضافة 6% من النانوكلي، في حين انخفضت قيم التدفق بنسبة 18.2% عند نسب 4% و 6% نتيجة لتحسين مقاومة التشوه الدائم. كما أظهرت نتائج اختبار الشد غير المباشر زيادة بنسبة 16.5%، مما يشير إلى تحسن في مقاومة الشد للخلطة. وأظهرت قيم معامل الرجوعية ارتفاعاً واضحاً في جميع درجات الحرارة المختبرة، حيث بلغت الزيادة 55% عند 5 °م، و 66.7% عند 25 °م، و 64.6% عند 40 °م. وأثبتت المادة قدرة محسنة على الاسترجاع المرن ضمن الظروف الحرارية المختلفة. كما حققت الخلطة التي تحتوي على 6% من النانوكلي قيمة معامل التواء (K) تجاوزت 3.4، وهو ما يتوافق مع متطلبات تصنيف EME2. أظهر التحليل الإحصائي (ANOVA) والتقييم الميكانيكي أن نسبة 4% من النانوكلي هي الجرعة المثلى، حيث حققت أقصى قيمة لصلابة مارشال (6.18 كيلو نيوتن/ملم)، في حين لم تودّ الزيادة إلى 6% إلى تحسينات معنوية إحصائية. تؤكد نتائج هذه الدراسة أن النانوكلي يُعدّ معدّلاً فعّالاً يُحسّن الخصائص الميكانيكية والبنوية لخلطات EME.

الكلمات المفتاحية: الخلطة الإسفلتية عالية الجساءة (EME)، النانوكلي، مقاومة الشد غير المباشر، معامل الرجوعية، معامل التواء.