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Performance Evaluation of Asphalt Mixtures Modified with Waste Nano-Barite Powder

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ABSTRACT

This study aimed to explore the potential of utilizing waste nano-barite in enhancing the properties of bitumen and asphalt mixture. The research also examined the effectiveness of waste barite powder as a filler in modifying asphalt mixture behavior. Asphalt mixture samples were prepared through wet mixing with barite modified bitumen and dry mixing with barite filler, followed by testing for Marshall Stability, Cantabro, resilience modulus, and rutting. The findings indicate that the addition of nano-barite to bitumen enhances the properties of bitumen. Furthermore, the performance of asphalt is enhanced by the inclusion of barite in both wet and dry mixing methods, as evidenced by improved Marshall Stability; for example, Marshall Stability in the dry state increases by increasing the barite content to 54.7%. Also, the amount of wear in wet mixing in the amount of 3% filler decreases with increasing barite by about 6%. In addition, the results of statistical analysis show that the improvement of asphalt mixture performance due to the addition of barite in dry, and wet mixing is significant. Utilizing waste nano-barite in bitumen and asphalt mixture improves the performance, sustainability, and energy efficiency. It optimizes raw material usage, reduces environmental impact, and improves cost-effectiveness compared to traditional additives, such as polymers, crumb rubber, or calcium carbonate.

Keywords: Nano-waste barite, Asphalt mixture, Bitumen enhancement, Marshall stability, Resilience modulus.

INTRODUCTION

Road maintenance represents a significant cost for nations, leading to initiatives aimed at enhancing asphalt mixture performance using additives to reduce damage and extend service life. The growing environmental concerns surrounding waste production and the depletion of renewable resources have prompted engineers to incorporate waste materials into pavement construction (Gil, 2022; Li & Tang, 2023). Recent studies have explored the use of recycled crumb rubber (CR) from tires and polyethylene (PE) from plastic waste in bitumen, revealing that CR lowers creep stiffness at low temperatures, thereby reducing cracking risks, while PE enhances hardness at high temperatures. This combined approach has shown marked improvements in the performance of bitumen (Yao et al., 2018). Furthermore, utilizing recycled plastics not only improves the properties of asphalt mixtures, but also lessens landfill contributions and environmental pollution (Nouali et al., 2018).

Additionally, investigations in Australia into polymer-modified hybrid bitumen (PMB) using recycled low-density polyethylene (R-LDPE, sourced from plastic bags) demonstrated its viability as a substitute for virgin polymers, enhancing thermal, chemical, and rheological properties (Joohari & Giustozzi, 2020). The use of this recycled LDPE in hot mix asphalt (HMA) significantly improved rutting resistance (Khan & Marjan, 2023). Furthermore, research on the short-term aging effects of various recycled polymer modifiers has confirmed that such modifications can effectively mitigate aging impacts, indicating their beneficial role under thermal stress conditions during bitumen production (Celauro et al., 2020).

Research indicates that waste plastic polymers present a sustainable and cost-effective approach to enhance asphalt properties, offering combined environmental and economic advantages. A study evaluating the impact of household waste polyethylene terephthalate (PET) on C320 bitumen modification revealed that incorporating 6%-8% of PET optimizes bitumen stiffness and elasticity. Moreover, asphalt mixtures modified with 8% household waste plastic displayed enhanced stability and moisture resistance (Mashaan et al., 2021).

Similarly, investigations into biopolymer-modified asphalt mixture, utilizing high-density polyethylene and pine resin, demonstrated improved performance. This included an increased PG grade, as well as enhanced stability, stiffness, and moisture resistance – performance metrics that meet FAA specifications (Yuniarti et al., 2024). A separate study on polyethylene terephthalate (PET) in ordinary bitumens confirmed that PET-modified bitumen meets necessary requirements and exhibits significant advancements over conventional bitumen (Pasra et al., 2022). Furthermore, nano-material technology has emerged as a cutting-edge additive for improving asphalt mixtures (Wang et al., 2021). Nano-materials, with their high specific surface area, alter the energy and morphology of the material's surface, consequently modifying its physical and chemical properties (Iftikhar et al., 2023). Studies have demonstrated that nano-materials effectively enhance the aging resistance of asphalt mixtures. The integration of nano-materials with polymers has been shown to improve bitumen's rutting resistance, viscosity, and stiffness (Mirsepahi et al., 2020). Carbon nano-particles can also enhance the thermodynamic properties and thermal stability of bitumen (Wang et al., 2020). Additionally, nano-TiO_2/$CaCO_3$ improves the performance and properties of bitumen to an acceptable extent and enhances UV resistance (Wu et al., 2021). Meanwhile, nano-SiO_2 and TiO_2 enhance bitumen's resistance to aging and damage, such as rutting and fatigue (Shafabakhsh et al., 2019), showcasing their potential in modifying the rheological behavior of bitumen. The integration of nano-materials into bitumen represents a frontier in enhancing asphalt performance, leveraging their high specific surface area and reactivity to modify physicochemical properties (Jeffry et al., 2022). Extensive research has established the efficacy of various nano-materials: nano-silica (SiO_2) significantly improves aging resistance and rutting performance (Shafabakhsh et al., 2019), while nano-titania (TiO_2) enhances photocatalytic self-cleaning capabilities, reducing oxidative aging (Wu et al., 2021; Shafabakhsh et al., 2019). Carbon-based nano-particles (e.g. nano-clay, carbon nano-tubes) elevate thermal stability and stiffness (Wang et al., 2020). However, most studies focus on synthetic or virgin nano-materials, with limited exploration of waste-derived nano-additives. While nano-SiO_2 and TiO_2 enhance rutting/fatigue resistance (Sadeghnejad & Shafabakhsh, 2017), their production is often energy-intensive and costly. In contrast, nano-barite ($BaSO_4$), derived from mining waste, offers distinct advantages due to its measurable properties: high density (~4.5 g/cm^3), chemical inertness, and potential to uniquely modify bitumen's viscosity-temperature relationship and radiation shielding—properties scarcely investigated for conventional nano-additives. Critically, prior research lacks comparative analysis of how mineral-derived nano-additives, like barite, perform against widely studied oxides (SiO_2, TiO_2) in terms of filler-bitumen interaction mechanisms, aging kinetics, and environmental footprint. This study addresses this gap by evaluating nano-waste barite not only as a novel modifier, but also by explicitly differentiating its mechanistic contributions from established nano-materials, emphasizing its role in sustainable waste valorization alongside performance enhancement.

Building upon prior research on waste and nano-materials in asphalt mixture enhancement, this study explores the novel application of nano-scale waste barite powder in modifying bitumen and asphalt mixtures. While previous studies have investigated various waste materials and nano-materials to enhance bitumen and asphalt mixture properties, the use of nano-scale waste barite powder remains unexplored. This research investigates the behavior of barite powder-modified bitumen and asphalt mixture samples containing barite filler. Given the widespread distribution of barite mines globally and the environmental challenges posed by accumulating waste and debris, this study aims to repurpose these materials as aggregates (fillers) or bitumen additives in pavements.

MATERIALS AND RESEARCH METHODS

Materials Used

Table 1 summarizes the gradation used. The physical properties of these aggregates were evaluated in accordance with MS-2 standards (Chang & Chien, 2024). The Los Angeles abrasion test indicated a maximum wear of 18%, well within the allowed limits for both the binder course (40%) and topcoat (30%). The flakiness index, tested according to ASTM D4791, was 7.04%, also meeting the required thresholds (30% for binder course and 25% for topcoat, respectively). Fracture percentages were high, with 98% showing one-side fracture and 97% exhibiting breakage on both sides, exceeding the minimum specifications. Water absorption was 1.4% for coarse aggregates and 1.6% for fine aggregates, both below the maximum limits. Specific gravities were determined as 2.667 for coarse aggregates, 2.711 for fine aggregates, and 2.645 for the filler, with the filler exhibiting a water absorption of 2.04%. The bitumen used in this research is AC60-70. In this research, barite powder (Figure 1, 200-20,000 nm scale; wet-grinding method) was used as a filler, and bitumen additive (at the nano-scale), which is based on the results of XRF analysis of the chemical composition of this material, as shown in Table 2. XRF is a quantitative technique for elemental composition analysis in materials. It involves irradiating a pulverized sample with X-rays and measuring the resulting fluorescence. Major elements are quantified as oxides; minor elements are quantified as elements.

Figure 1. Nano-barite powder derived from mining waste (200 -20,000nm)

Table 1. Selected gradation of stone materials

Sieve size	19 mm	12.5 mm	#4	#8	#50	#200
Passing by Weight (Permissible Range)%	100	90-100	44-74	28-58	5-21	2-10
Passing by Weight (This Study)%	100	95	59	43	13	3.6-9

Table 2. XRF analysis results

Chemical Mixture (%)	Component Name	Chemical Formula
11.28	Silica (Sand)	SiO_2
0.82	Alumina	Al_2O_3
0.42	Manganese Oxide	MnO
0.03	Titanium Dioxide	TiO_2
0.01	Calcium Oxide (Quicklime)	CaO
1.86	Magnesium Oxide (Magnesia)	MgO
<0.00	Sodium Oxide	Na_2O
0.04	Potassium Oxide	K_2O
0.08	Phosphorus Pentoxide	P_2O_5
0.02	Barite (Primary Component)	$BaSO_4$
84.08	Sulfur Trioxide	SO_3
1.04	Loss on Ignition (Volatiles/CO_2)	L.O.I.

Research Methodology

This study investigated the effect of waste-derived barite on bitumen properties and asphalt mixture performance. Initially, the properties of bitumen modified with nano-barite were examined. Subsequently, barite powder was incorporated into the asphalt mixture as a filler and evaluated. The experimental procedure is summarized in the research flowchart (Figure 2).

Nano-barite modification necessitates uniform nano-particle dispersion in bitumen. This study employed an ultrasonic mixer to ensure homogeneity. Nano-barite was incorporated at 3%, 5%, and 7% by weight into bitumen heated to 150°C, using an electric mixer at 3000 rpm for 20 minutes. Following modification, standard and advanced bitumen tests, including DSR and FTIR, were conducted on the resulting samples to evaluate their properties.To complete this research, after conducting an examination, and examining the aggregates and bitumens to be used, the optimal bitumen percentage of the mixtures was determined using the Marshall method. Using this optimal percentage of bitumen, the samples needed to perform the Marshall stability test, Resilience modulus, rutting, and Cantabro tests are prepared, and the item is evaluated.

As mentioned, in order to investigate the properties of rheology, the shear modulus, and the shear angle (phase) change were measured at different temperatures, and under dynamic load at different frequencies through the device.

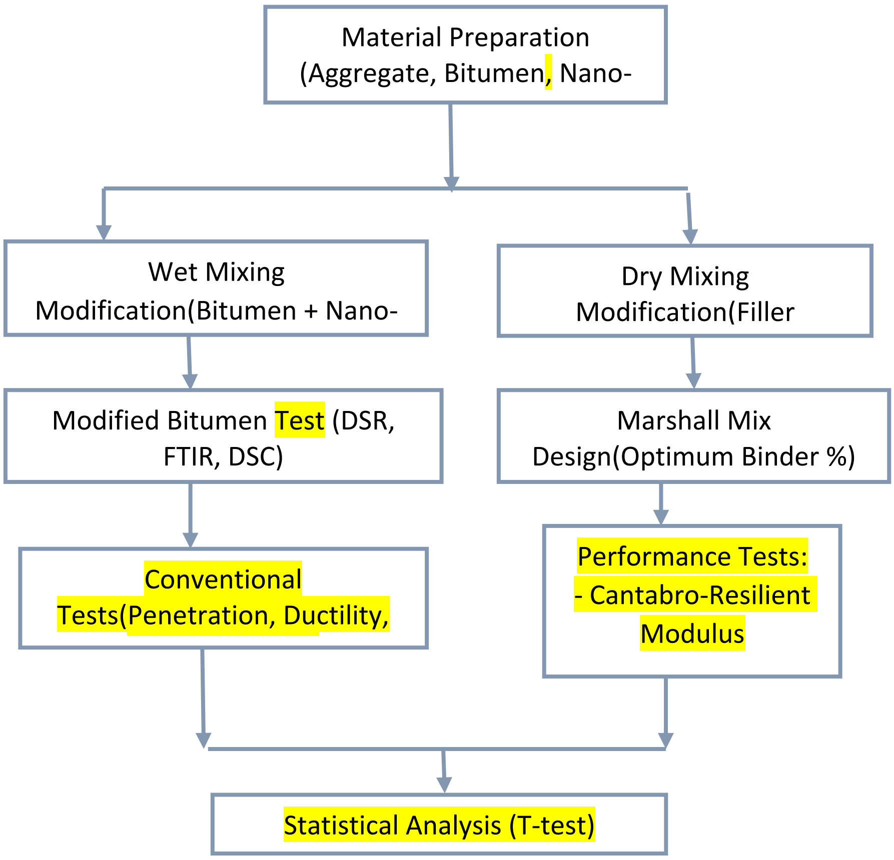


Figure 2. Research methodology flowchart for performance evaluation of asphalt mixtures modified with waste nano-barite powder

Infrared spectroscopy is also based on the absorption of radiation, and the study of vibrational mutations of molecules, and ions of polyatoms. This method is used as a powerful, and developed method for determining the structure, and measurement of chemical species. This method is also mainly used to identify organic compounds, because the spectra of these compounds are usually complex, and have a large number of maximum and minimum peaks that can be used for comparative purposes. In this method, by irradiating an electromagnetic beam to the molecule at infrared wavelengths, part of this energy (at specific wavelengths) is used to vibrate the bonds, and this reduction in energy causes an absorption peak in the FTIR spectrum of the sample. These absorption peaks can be as unique as a fingerprint for each specific molecule, and prove the presence of that substance in the composition under study (Khan, 2025).

The Marshall stability/flow ratio (Marshall quotient) is a key parameter in the Marshall test (ASTM D1559-89, 2001), representing the ratio of stability to flow. It evaluates asphalt concrete's resistance to rutting and permanent deformation. Higher values indicate stiffer, more deformation-resistant mixtures. In this study, Marshall samples with varying barite filler percentages were tested to determine this ratio. Additionally, asphalt mixtures underwent resilient modulus testing using a universal testing machine (UTM-14) under two loading modes: semi-sinusoidal (peak load: 2800 N, load duration: 250ms, pulses: 5) and rectangular. The resilient modulus was calculated using Equation (1), assuming a Poisson's ratio of 0.5 (AASHTO TP31, 1996).

$$M_r=\frac{P(\mu+0.27)}{T\times\Delta h} \quad (1)$$

P: Maximum load (N)
μ: Poisson's ratio (= 0.5)
T: Sample length (mm)
Δh: Horizontal displacement (mm).

Rut testing was performed using a Universal Testing Machine (UTM-14, 14-ton capacity). For this test, the standard jaws were replaced with specialized rut test jaws, and specimens were loaded according to Figure 5. In this study, Cantabro test was used to evaluate the abrasion resistance of asphalt mix. The test involves testing Marshall samples inside the Los Angeles apparatus (without metal pellets) at 300 rpm, at 30 to 34°C at 18 to 25°C (Lim et al., 2024). In Cantabro method, the weight loss percentage of the samples obtained from Eqn. (2) should not be more than 20%.

$$P = 100(\frac{P1-P2}{P1}) \quad (2)$$

P: Wear percentage
P_1: Sample initial weight
P_2: Weight after wear.

RESULTS AND DISCUSSION

Bitumen-Barite Composite Performance Analysis

Laboratory testing using a Dynamic Shear Rheometer (DSR) was conducted to analyze the rheological properties of bitumen samples, including shear modulus and phase angle changes under varying temperatures and dynamic loads. G^* indicates the material's total resistance to deformation, while δ reflects the relative balance between viscous behavior and elastic behavior. This testing is critical for evaluating asphalt binder performance under traffic loading conditions, particularly for determining rutting resistance and fatigue cracking potential in accordance with superpave specifications (AASHTO T315). The study assessed both unmodified bitumen and samples modified with nano-barite.As summarized in Table 3, nano-barite modification significantly enhanced the complex modulus (G^*). This indicated improved resistance to permanent deformation (rutting). Higher G^* values and lower phase angles (δ) suggested superior rutting stability. The complex modulus of nano-barite-modified bitumen was notably higher than that of pure bitumen, demonstrating increased resistance to rutting and asphalt mixture deterioration. This improvement was attributed to a 22%-35% increase in viscosity from nano-material addition, which strengthened the bitumen's resistance to shear forces (Shabaani et al., 2019).

Table 3. DSR test for samples containing nano-barite(NB) powder (G * / Sinδ)

Temperature (ºC)	**46**	**52**	**58**	**64**	**70**	**76**	**82**
Bitumen	15	4.4	2.2	0.95	0.45	0.07	0.02
Bitu + 3%NB	19.22	8.66	2.03	0.97	0.47	0.24	012
Bittu+ 5% NB	6.34	14.95	0.41	0.35	0.09	0.003	0.006
Bitu+7% NB	4.59	2.28	1.001	0.500	0.23	0.002	0.004

Infrared spectroscopy was employed as a powerful analytical method for structural characterization and chemical species identification Figure 3 presents the FTIR spectrum of the bitumen-barite composite. Consistent with Ramaswamy et al.'s (2020) findings, barite exhibited two characteristic peaks: a band at 700-800 cm⁻¹ corresponding to out-of-plane bending vibrations of SO_4^{2-} ions, and a band at 1000–1200 cm⁻¹ associated with asymmetric stretching vibrations of the SO_4^{2-} group in barite.

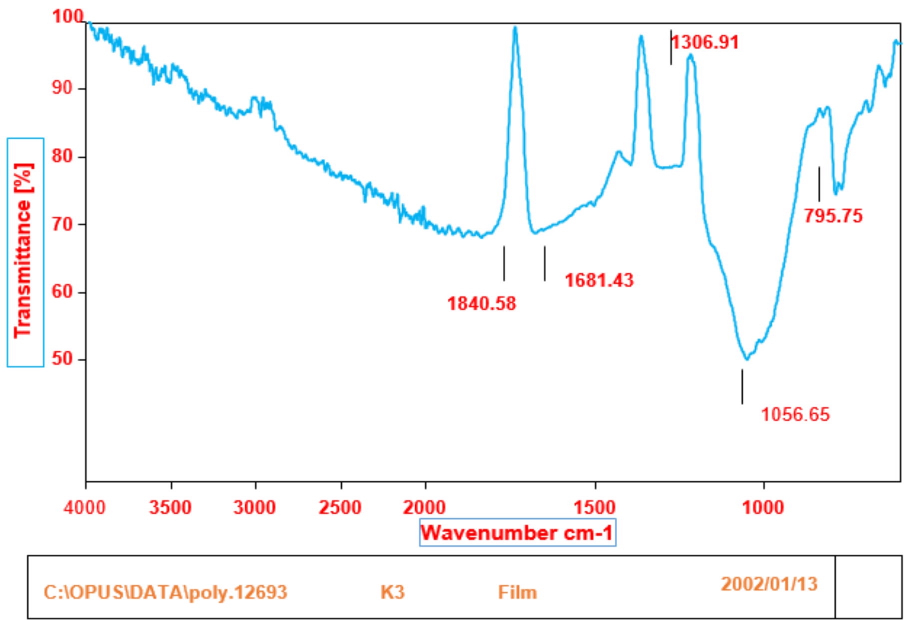


Figure 3. FTIR spectrum of bitumen-barite sample

The characteristic sulfate peaks (700–800 cm⁻¹ and 1000–1200 cm⁻¹) confirmed barite's presence as $BaSO_4$. Additional peaks at 1132 cm⁻¹ (C–O stretching), 1453 cm⁻¹ (C–H bending), and 1732 cm⁻¹ (C=O stretching) correspond to functional groups inherent to bitumen, consistent with documented spectra (Imanbayev et al., 2017). Javidparvar et al. (2020) associated C–O vibrations with coating stability in bituminous composites, while Javidparvar et al. (2019) linked C–H and C=O groups to key material properties. The coexistence of barite-specific and bitumen-specific peaks in the FTIR spectrum substantiates successful composite formation.

Barite-modified Asphalt Mixture Performance

This study determined the optimal bitumen content using the Marshall method according to the AASHTO T 245 standard. Diagrams illustrating Marshall stability, flow, specific gravity, and void characteristics of compacted samples were prepared for various bitumen percentages. The average air void (VA) content was found to be 4%. Values of maximum theoretical specific gravity (Gmm) helped identify the optimal bitumen content. For filler contents of three percent (3%), six percent (6%), and nine percent (9%), the optimal bitumen contents were 5.5%, 4.9%, and 4.5%, respectively (Tan et al., 2022). Subsequently, main asphalt mixture samples were prepared for testing. These were divided into two series. Barite was used as a filler at industry-standard concentrations of 3%, 6%, and 9% by weight of the aggregate.

Wet mixing: Barite nano-particles were mixed with bitumen at concentrations of 3%, 5%, and 7% by weight of the bitumen before combining with the aggregate.

Results obtained from Marshall test are recorded in Table 4. The Marshall stability-to-flow ratio (often simply called the Marshall ratio), a key parameter for assessing moisture susceptibility (stripping) and resistance to permanent deformation, was also evaluated.

Table 4. Results obtained from Marshall test of samples containing ordinary (limestone powder) filler, and barite

Filler percentage (%)	Marshall ratio		Flow(mm)		Marshall Stability (kN)	
	Barite	Limestone filler	Barite	Limestone filler	Barite	Limestone filler
3	452.6	268.83	2.89	4.0	13.08	11.76
6	528.84	277.5	3.26	4.4	17.24	12.21
9	700.29	388.41	3.33	4.66	24.09	18.00

Results indicated that samples containing barite filler exhibited a higher Marshall stability-to-flow ratio (Marshall ratio) and lower flow rate compared to those with limestone filler. This suggested improved bitumen-aggregate mixing efficiency. Consequently, barite samples demonstrated higher Marshall stability, indicating increased mix rigidity and resistance to deformation. Cantabro abrasion loss test results (Figure 4) showed decreased wear (lower mass loss) with increasing barite filler percentage. Rutting tests, conducted before and after aging (Figure 5), revealed that rut depth increased with higher filler percentages; however, this increase was less pronounced in mixtures containing barite. Figure 5a demonstrated that barite enhanced asphalt concrete performance against rutting compared to limestone. Aging significantly increased the strain under rutting load in limestone samples (Figure 5b), whereas barite exhibited a more beneficial role in improving rutting resistance, reducing the strain increase caused by aging, as shown in Table 5.

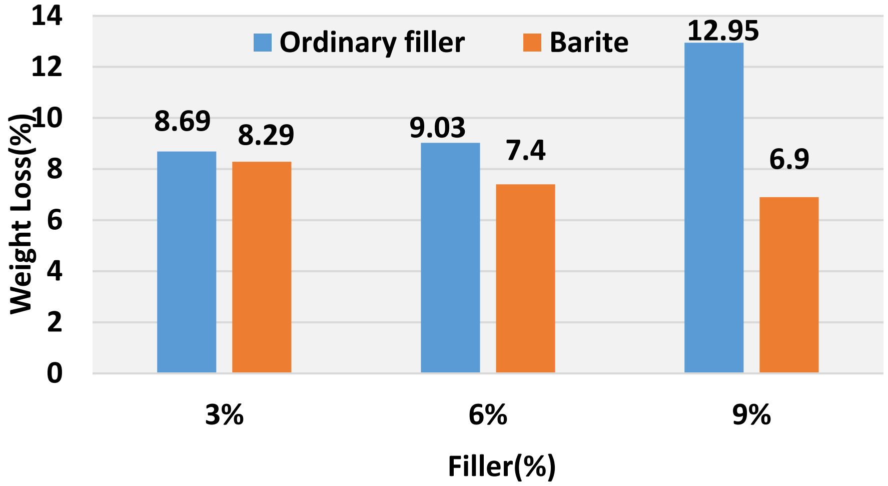
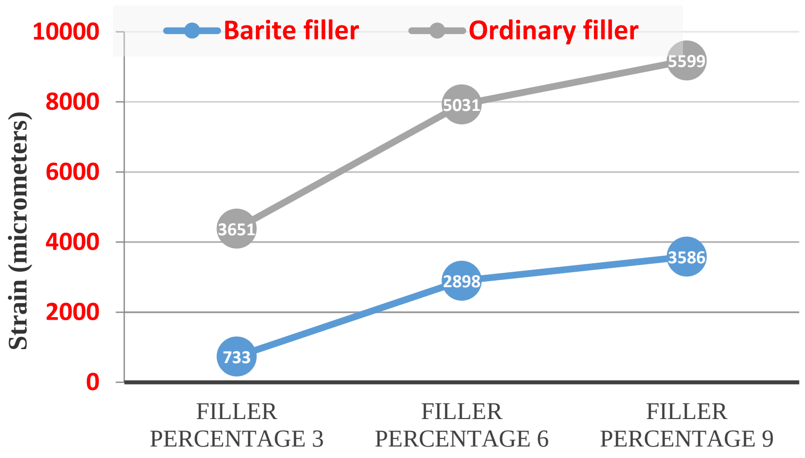


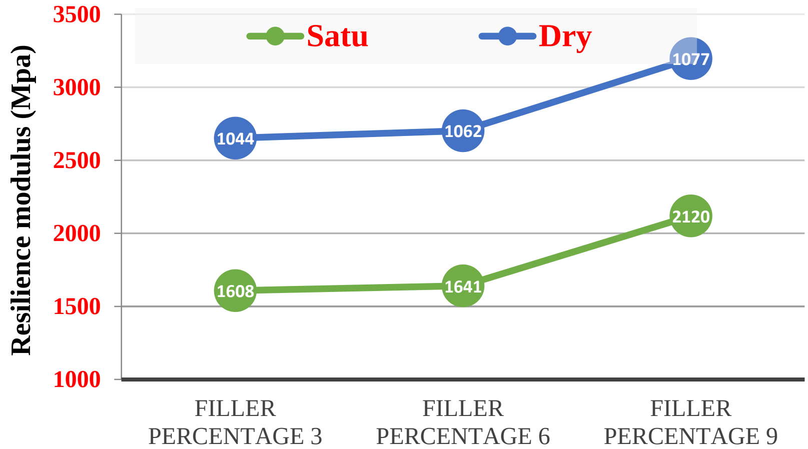
Figure 4. Cantabro test results for barite and limestone samples

Table 5. Results of rutting test under semi-sinusoidal load

Filler Content (%)	9%	6%	3%	Filler Type
Before Aging				
	5599	5031	3651	Limestone
	3586	2898	733	Barite
After Aging				
	7269	6802	6427	Limestone
	6221	4801	4237	Barite



5A) Before aging



5B) After aging

Figure 5. Rutting of specimens under semi-sinusoidal loadingm A) Before aging, B) After aging

Performance Analysis of Wet-mixed Asphalt

After making Marshall samples in the wet mixing design, the results related to the strength and wear resistance of the samples were obtained. The Marshall stability diagram was drawn according to Figure 6.

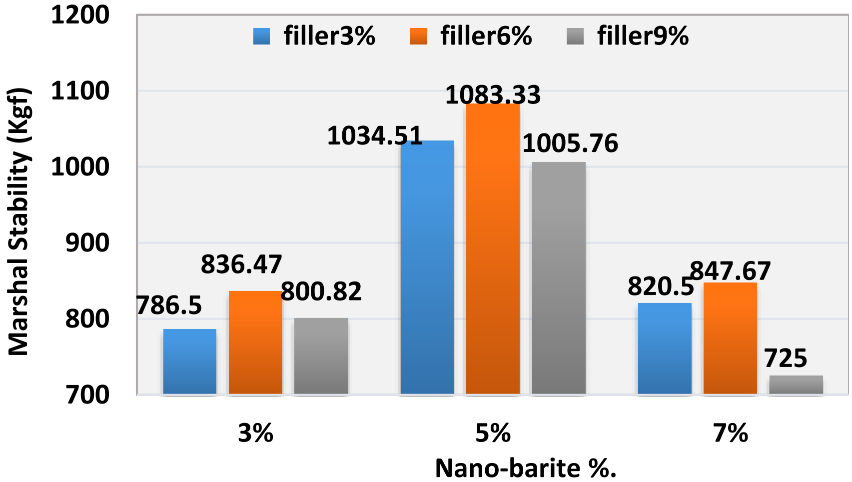
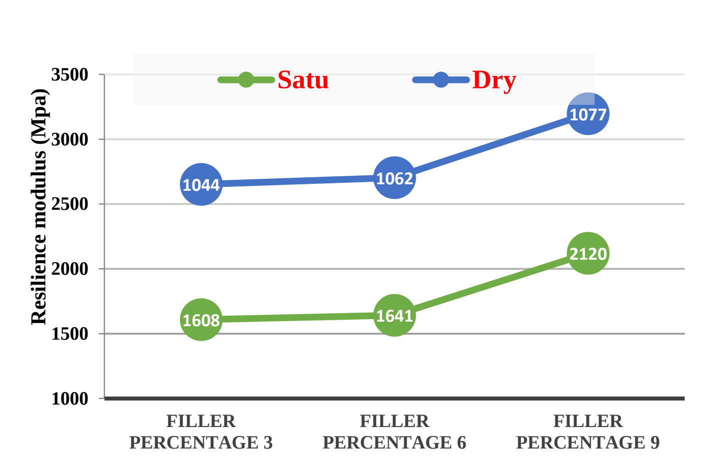


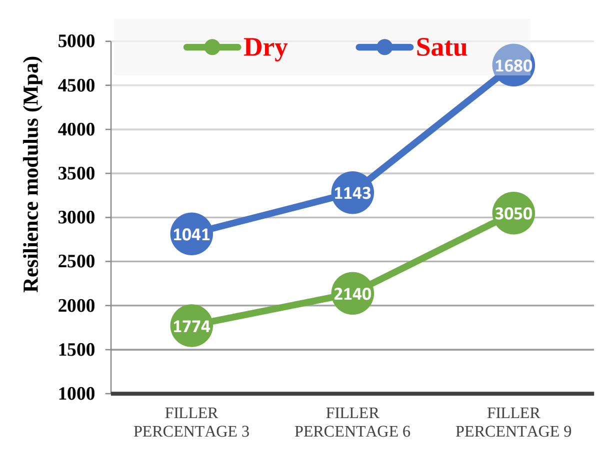
Figure 6. Marshall ratio results in wet nano-barite mixing conditions

Results indicated that increasing the nano-barite percentage in bitumen and filler content initially raised the Marshall stability-to-flow ratio (Marshall ratio), followed by a decline. Optimal performance occurred with modified bitumen containing five percent (5%) nano-barite and six percent (6%) filler, yielding the highest Marshall ratio. Overall, nano-barite modification improved the Marshall ratio compared to samples with ordinary bitumen in dry mixing. For example, samples with three percent (3%) limestone filler and unmodified bitumen had a Marshall ratio of 268.83, whereas wet-mixed samples with 3%, 5%, and 7% nano-barite yielded ratios of 786.5, 836.47, and 828.00, respectively. This improvement enhanced asphalt mixture hardness and deformation resistance due to the strengthened bond between bitumen particles facilitated by nano-material addition.

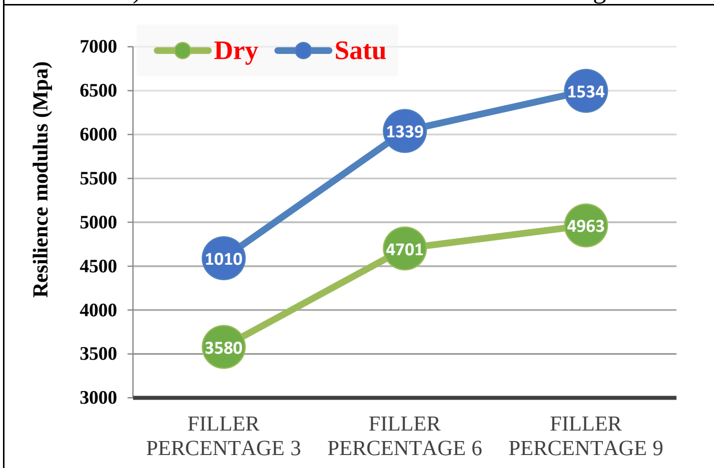
Furthermore, Cantabro test results (Figure 7) showed that wear rates initially decreased with increased barite modification before rising again. Los Angeles (LA) abrasion values remained within allowable limits (below 20%), underscoring nano-barite's positive impact on bitumen behavior and wear resistance. Enhanced adhesion and strength from nano-barite contributed to improved performance and reduced wear of the resulting asphalt concrete. Figure 7 also presents the resilience modulus test results for asphalt mixture samples made with modified bitumen and 3%, 6%, and 9% fillers, tested under semi-sinusoidal and rectangular loading modes. Recent studies indicated that nano-material integration significantly enhances the mechanical properties and durability of asphalt mixtures, contributing to improved performance and longevity (Chen et al., 2023).



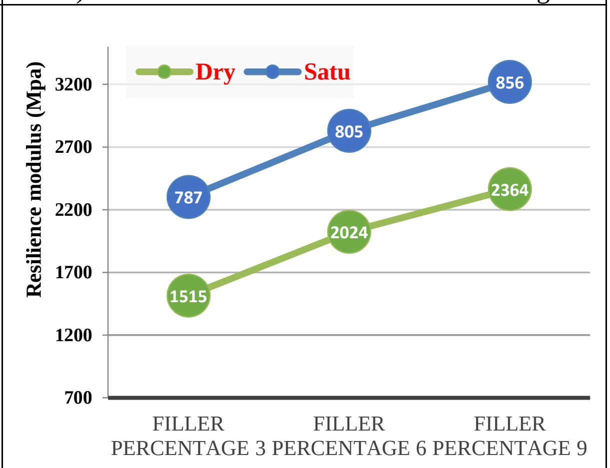
A) 3% Nona-barite in semi-sinusoidal loading



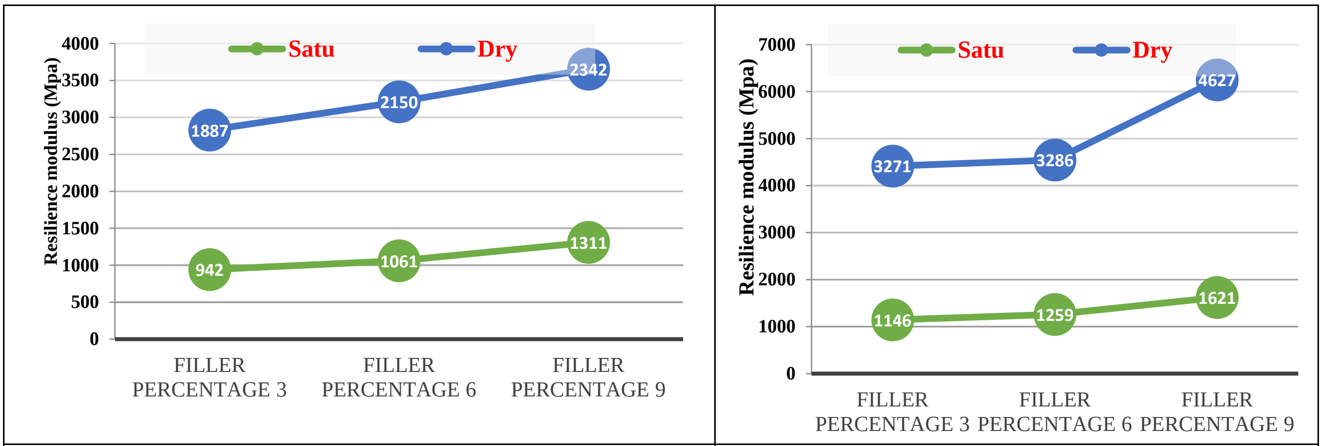
B) 5% Nona-barite in semi-sinusoidal loading



C) 7% Nona-barite in semi-sinusoidal loading



D)3% Nona-barite in rectangular loading



E) 5% Nona-barite in rectangular loading | F) 7% Nona-barite in rectangular loading

Figure 7. Resilience modulus of modified bitumen asphalt mixtures with barite filler (3%, 5%, 7%) under semi-sinusoidal (0.1 Hz, 25°C) and rectangular (0.5 Hz, 40°C) loading
Sub-figures color-coded by filler content: blue (Dry), green (Satu.).

Figure 7 indicates that the resilience modulus increased in samples made with modified bitumen, suggesting higher hardness and improved material adhesion due to chemical interactions between barite and bitumen. Dynamic creep test results (Figure 7) showed that rutting generally increased with higher nano-barite percentages in the bitumen; however, within each nano-barite percentage, rutting decreased as filler content increased. For instance, with three percent (3%) nano-barite, micro-strain values for samples containing three percent (3%), six percent (6%), and nine percent (9%) filler were 1738, 3669, and 5599 micrometers (µm), respectively, reflecting a performance increase of 111% from 3% to 6% filler and a performance increase of 53% from 6% to 9% filler (Figure 7a). Samples modified with 3% nano-barite exhibited more effective rutting performance. Comparing wet mixing results with those of dry mixing, wet-mixed samples using bitumen modified with 3% nano-barite demonstrated reduced rutting. Creep reduction percentages for these wet-mixed samples *versus* dry-mixed samples using ordinary bitumen were 48%, 72%, and 1.01% across the tested conditions. After aging (Figure 7b), samples containing 3% nano-barite had lower creep, attributed to enhanced adhesion between bitumen and aggregate.

Performance Evaluation

Statistical analysis, utilizing SPSS24 software, was conducted to evaluate the performance of asphalt mixtures modified with waste nano-barite powder in dry mixing mode. Paired samples T-tests were performed to compare mixtures containing ordinary filler and barite across various performance parameters, In Table 6, the results of the statistical tests are presented. The significance level was set at 0.05. Significant differences were observed between barite and ordinary filler in Marshall ratio (barite mean = 248.996, ordinary filler mean = 64.087), and wear (barite mean = 2.6933, ordinary filler mean = 2.97130). Furthermore, statistically significant differences were noted in dry resilience under semi-sinusoidal loading (barite mean = -1765.66, ordinary filler mean = 765.97), saturation under semi-sinusoidal loading (barite mean = -1006.66, ordinary filler mean = 1141.64), dry resilience under rectangular loading (barite mean = -293.66, ordinary filler mean = 894.29), and saturation under rectangular loading (barite mean = -504.66, ordinary filler mean = 723.519). Additional T-test results indicated significant differences for Marshall barite ratios at 3% (mean = 807.93), 5% (mean = 1041.2), and 7% (mean = 797.723), as well as wear at 3% (mean = 6.37), 5% (mean = 5.0199), and 7% (mean = 4.7951). Significant differences were also found for modulus of dry resilience and sinus saturation (mean = 48.86.3) and resilience modulus of dry and saturated rectangular solidity (mean = 4547.66). All reported differences were statistically significant.

The statistically significant differences ($p<0.05$) in Table 6 demonstrate barite's substantial engineering impact *versus* ordinary filler. Marshall ratios (248.996 *vs.* 64.087) indicate that barite mixtures withstand over 3.8× higher loading before deformation – a critical enhancement for heavy-traffic pavements. Lower wear values (2.6933 *vs*. 2.97130) confirm barite's superior resistance to surface degradation, directly reducing maintenance frequency. Negative values of resilience moduli are unexpected and require verification of sign convention, but suggest fundamentally distinct deformation behavior under load. Crucially, extreme t-values (e.g. -6.73 for Marshall ratio) and near-zero p-values confirm that these differences are not random variations, but reflect practically meaningful improvements in rutting resistance and durability. These outcomes validate barite's functional superiority across key performance metrics.

Table 6. Statistical comparison of asphalt mixture properties with barite and ordinary fillers

Property	**Filler Type**	**Mean**	**Std. Dev.**	**t-value**	**df**	
Marshall Ratio	Barite	249.00	*N/A*	-6.73	2	0.021
Marshall Ratio	Ordinary	64.09	*N/A*			
Wear	Barite	2.69	*N/A*	2.00	2	0.029
Wear	Ordinary	2.97	*N/A*			
Dry Resilience (Semi-sinusoidal)	Barite	-1765.66	*N/A*	-3.99	2	0.044
Dry Resilience (Semi- sinusoidal)	Ordinary	765.97	*N/A*			
Saturation (Semi- sinusoidal)	Barite	-1006.66	*N/A*	-1.53	2	0.026
Saturation (Semi- sinusoidal)	Ordinary	1141.64	*N/A*			
Dry Resilience (Rectangular)	Barite	-293.66	*N/A*	-0.57	2	0.038
Dry Resilience (Rectangular)	Ordinary	894.29	*N/A*			
Saturation (Rectangular)	Barite	-504.66	*N/A*	-1.21	2	0.035
Saturation (Rectangular)	Ordinary	723.52	*N/A*			
Marshall Ratio 3% Barite	Barite	807.93	25.73	54.38	2	<0.001
Marshall Ratio 5% Barite	Barite	1041.20	39.22	45.99	2	<0.001
Marshall Ratio 7% Barite	Barite	797.72	64.43	21.44	2	0.002
Wear 3% Barite	Barite	6.37	0.87	12.70	2	0.006
Wear 5% Barite	Barite	5.02	0.37	28.24	2	0.001
Wear 7% Barite	Barite	4.80	1.03	12.38	2	0.006
Modulus of Dry Resilience, and Sinus Saturation	Barite	4886.30	989.39	8.55	2	0.013
N/A: Not applicable; standard deviation is omitted for filler-type comparisons (Barite vs. Ordinary) as these values represent category means without replicated measurements of identical mixtures.						

For filler-type comparisons (barite *vs*. ordinary), statistical analysis used mean values derived from grouped data (e.g. all barite mixes *vs*. all ordinary mixes; hence standard deviation (Std. Dev.) was not applicable (N/A) as these represent category means rather than replicated measurements of identical mixtures. Conversely, for barite dosage variations (3%, 5%, 7%), Std. Dev. values reflect sample replicates and are fully reported. The t-tests for filler-type comparisons appropriately used category means (n=2 independent groups, df=2). Degrees of freedom (df) were set at 2 for all t-tests, based on comparisons between two independent filler categories (barite *vs*. ordinary). Negative resilience values warrant re-verification of sign conventions in raw data. The revised table separates filler-type comparisons (with N/A Std. Dev.) and barite dosage effects (with valid Std. Dev.) to eliminate ambiguity.

Utilizing waste nano-barite in asphalt mixtures delivers synergistic economic and environmental advantages by transforming mining residues into high-value pavement enhancers. Sourcing barite from waste streams not only eliminates raw material costs associated with virgin polymers or industrial nano-materials (e.g. SiO_2, TiO_2), but also circumvents landfill disposal expenses and associated ecological burdens, directly supporting circular economy principles. Critically, the documented performance enhancements—including a 54.7% increase in Marshall stability, ~6% reduction in abrasion loss, and superior rutting resistance—translate to extended pavement service life. This durability directly reduces long-term resource consumption by diminishing the frequency of rehabilitation activities, thereby lowering cumulative energy use and emissions over the infrastructure lifecycle. Furthermore, the improved moisture resistance (evident in Cantabro results) diminishes water-induced damage, curtailing the need for resource-intensive repairs. Thus, the environmental merit of nano-barite extends beyond waste diversion: it creates a cascade effect where enhanced mechanical properties inherently promote sustainability through conserved materials, reduced maintenance interventions, and minimized carbon footprint. This dual benefit paradigm—where performance and environmental gains are intrinsically linked—distinguishes waste-sourced nano-barite from conventional modifiers and establishes its holistic value proposition for eco-efficient infrastructure.

CONCLUSIONS

This study examined the influence of nano-barite on bitumen and asphalt mixes *via* wet and dry methods, evaluating properties, like resilience, rutting, Marshall stability, and Los Angeles wear. The key conclusions are:

- Nano-barite effectively enhanced the bitumen composites, as demonstrated by increased $G^*/\sin\delta$ values in DSR tests, indicating improved rutting resistance (high-temperature performance).
- Samples with 5% nano-barite modified bitumen demonstrated outstanding Marshall ratios, peaking at 1034.1 with 3% filler.
- In dry mixing, wear percentage decreased with more barite, unlike standard fillers. Wear declined from 8.29% to 6.9% with increasing barite content, highlighting its reinforcing effect.
- -The wear test results showed a general decrease with higher barite content, with a non-monotonic anomaly at 3% concentration. Contrary to the monotonic trend, 3% barite samples exhibited higher wear than 5% and 7% barite samples. This deviation may be attributed to subo-ptimal nano-particle dispersion at lower concentrations.
- Wet mixing with nano-barite consistently reduced wear below that of base bitumen and standard filler. Exceptions occurred only with a specific mix of 7% nano-barite bitumen and 9% filler, which resulted in slightly elevated wear.
- Nano-barite modification positively affects asphalt mixture characteristics, enhancing Marshall stability and wear resistance. The findings highlight the advantage of wet mixing in achieving superior performance characteristics, reaching Marshall Ratio of 1034.1 with 5% nano-barite content.

This study demonstrates the innovative use of waste nano-barite to enhance asphalt concrete performance. Nano-barite significantly improves Marshall Stability and wear resistance in both wet and dry mixes. Wet mixing with 5% nano-barite achieved exceptional Marshall ratios, suggesting superior performance for pavements in hot climates, optimizing sustainability and cost-effectiveness.

Nomenclature

DSR	Dynamic shear rheometer
FTIR	Fourier transform infrared
ITS	Indirect tensile strength
*G**	Complex shear modulus
Mr	Resilience modulus
s_i	Tensile strength
δ	Phase angle

Declarations

- The authors confirm that there are no relevant financial or non-financial interests to report.
- There are no competing interests related to the content of this article that the authors wish to declare.
- All authors affirm that they have no connections or involvement with any organizations or entities that possess financial or non-financial interests in the topics or materials discussed in this manuscript.
- The authors have no financial stakes or proprietary interests in any of the materials referenced in this article.

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Conflict of Interests

The authors affirm that there is no known or potential conflict of interests regarding the research, authorship, or publication of this article.

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