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Marshall Properties and Rutting Resistance for Asphaltic Mixtures Modified by Nano-Montmorillonite

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ABSTRACT

Rutting is a significant problem in flexible asphalt pavements, causing permanent deformation. Increased traffic, axle load, tire pressure, and hot weather have recently accelerated rutting in flexible pavements. Several researchers have suggested using nanomaterials to improve asphalt pavement and prolong its lifespan. The nano clay chosen for this study is a natural, hydrophilic montmorillonite in its raw form. Consequently, incorporating Nano-montmorillonite (MMT) into asphalt mixtures to improve performance under dynamic loads has gained significant attention. This can help reduce rutting damage and ensure the safety and durability of road surfaces. This study examines the impact of incorporating MMT into hot mix asphalt on the Marshall properties and resistance to rutting. It involved determining the optimal asphalt content using the Marshall design method, as well as the rutting depth for asphalt mixes using wheel tracking tests, for mixtures comprising different MMT percentages (2%, 4%, and 6%) as a percentage of the asphalt binder. The optimal asphalt content was 4.93% for the control mix. The inclusion of 6% MMT increased the Marshall stability the most by 16.79%. Marshall flow decreased when MMT was added. The control mix had a Marshall flow of 3.30 mm, but when using 4% MMT, the flow decreased to 2.81 mm, the most significant reduction. The ideal proportion of MMT was 6%, resulting in a 39.79% reduction in rut depth compared to the control mixture.

Keywords: Rutting, Wheel tracking test, Nano-Montmorillonite, Marshall design method.

1. INTRODUCTION

When road surfaces develop longitudinal depressions in the route of vehicles' wheels, this phenomenon is called rutting. Additionally, it is an essential issue for flexible pavement **(Saleem and Ismael, 2020; Motamedi et al., 2021; Al-Saad and Ismael, 2022; Albayati, 2023).** The most destructive damage to asphalt pavements in Iraq occurs when heavy trucks repeatedly drive over them in scorching weather **(Ismael, 2011; Al-kaissi et al., 2017;**

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Burhan and Ismael, 2019). Rutting is commonly noticed on Iraqi roadways, particularly around checkpoints, posing a substantial risk to the asphalt layers **(Abd and Latief, 2024)**. Rutting is a significant element that can decrease the lifespan of asphalt surfaces **(Malarvizhi, 2015)**. Rutting has the potential to compromise the integrity of flexible (HMA) pavement and pose safety hazards. Enhancing the efficacy of asphalt pavement is essential to minimize or delay surface deformation **(Abd and Qassim, 2017; Taher and Ismael, 2023)**. Rutting is a frequently observed kind of damage in pavements with thick asphalt layers. Pavements subject to elevated pavement temperatures, reduced speed, uphill gradients in hilly regions, and heavy traffic loads are strongly impacted **(Radhakrishnan et al., 2018)**.

Considering the information mentioned before, utilizing modifiers is essential for enhancing the asphalt concrete properties, improving pavement performance and extending its lifespan **(Badr and Ismael, 2024).** Considerable improvements are dedicated to reducing this distress **(Hamdou et al., 2014).** This improvement is done by Using Nanomaterials, which are defined as materials with a size ranging from 1 nanometer to 100 nanometers or from 10^{-9} to 10^{-7} meters, as stated in European Union Recommendation 2011/696/EU. Nanoclay is the material studied the most for modifying asphalt binders **(Cheraghian et al., 2022; Albayati et al., 2024).** Due to their small dimensions and large surface area, nanoparticles provide specific characteristics as compared to conventional materials **(Yang and Tighe, 2013)**. A combination of materials with varying microscopic properties enhanced its mechanical characteristics **(Hamad and Sarhan, 2021; Hussain et al., 2022)**. Researchers and engineers have long been interested in developing environmentally sustainable asphalt mixtures by adding nano montmorillonite. This approach has been discussed in several studies. In accordance with studies carried out by **(Yu et al., 2007)**, the improvement of high-temperature rutting resistance is a result of the improved viscoelastic characteristics exhibited by the MMT-modified asphalts. **(Jahromi and Khodaii, 2009)** Found that when bitumen is combined with nano clay, its rheological characteristics change, resulting in increased stiffness. Nanoclay also reduces the phase angle and improves bitumen's resistance to aging. The study **(Iskender, 2016)** demonstrated that mixes treated with nano clay at concentrations of 2, 3.5, and 5% exhibited higher rutting resistance when compared to conventional mixes. **(Zahedi and Baharvand, 2017)** discovered that increasing both crumb rubber and nanoclay proportions led to a 1.5 times higher Marshall strength compared to the control sample (10% crumb rubber and 5% nanoclay). This suggests that nanoclay particles filling the gaps between aggregates result in a more tightly packed system modified by bitumen. **(Aljbouri and Albayati, 2023)** evaluated asphalt mixtures containing 3, 5, and 7% nanoclay. Compared to the control mix, 7% nanoclay enhanced Marshall's stability by 58%. The inclusion of nano clay enhanced the volumetric property of VFA, compared to a control mixture, it resulted in an improvement of 7.9%.

(Ismael and Ismael, 2019) Showed that adding MMT to asphalt improved its Marshall properties. Adding 6% of MMT had the highest Marshall stability for the AC(40-50) and AC(60-70), at 11.94 and 10.14 kN, respectively, compared to the control mixture at 9.45 and 7.93 kN. For AC (40-50), the incorporation of MMT (4%) led to the greatest reduction in Marshall flow, at 2.87 mm, compared to the conventional mix at 3.47 mm. Similarly, for AC (60-70), the inclusion of 2% MMT led to the most significant reduction in Marshall flow, at 3.38 mm, compared to the control mix at 3.64 mm. **(Malarvizhi, 2015)** demonstrated that the addition of 5.5% styrene-butadiene-styrene (SBS) and 0.5% nanoclay powder to the asphalt mixture yielded the most favorable outcomes in the conducted tests. This modification effectively enhances the physical and mechanical characteristics of the asphalt binders and mixes. **(de Melo and Trichês, 2017)** work revealed improvements in the asphalt mixture characteristics by incorporating nanoclay. Numerical modelling of a pavement structure verified the beneficial influence of the nanoclay, as the durability of the asphalt surface modified with nanoclay increased in relation to fatigue cracking in comparison to a conventional asphalt surface. **(Boateng et al., 2022)** Found that adding montmorillonite to cold mixes improved stability for all gradation groups at different nanoclay concentrations. The nano clay particles increase the stiffness of the compacted matrix, enhancing adhesion between bitumen and aggregate and possibly increasing friction between particles for improved stability. **(Ezzat et al., 2016)** showed that the inclusion of nanoclay in the mixture resulted in a significant enhancement in the grade of performance of the Dynamic Shear Rheometer (DSR) results. This improvement led to an increased ability to withstand permanent deformation.

Based on the results, **(Khodary, 2015)** determined that the SBS and nCL improve all treated asphalt's penetration and softening point. Modified mixes with 5% SBS and 6% nano clay had three times the tensile strength of untreated mixtures. According to **(Li et al., 2022)**, The anti-aging effects were assessed using rheological and fundamental physical indices, as well as FTIR and AFM markers. The mechanism and sensitivity of the anti-aging process were also investigated. Based on the findings, asphalt binder with 4% MMT shows remarkable anti-aging properties. The study's findings revealed a rise in the softening point and kinematic viscosity and a reduction in binder penetration. The most significant enhancements in the altered binders were achieved with a 6% nanoclay **(El-Shafie et al., 2012)**. The inclusion of Nanoclay resulted in a marginal enhancement of the rheological characteristics of AC at elevated temperatures **(Al-Mistarehi et al., 2023)**.

The main objective of this study is to evaluate the influence of incorporating nano-montmorillonite (MMT) on the Marshall properties and rutting resistance of the asphalt pavement's wearing course and conduct a comparative analysis with a control mixture utilizing asphalt cement, AC (40-50).

2. MATERIALS USED

The materials chosen for this research were based on their local availability and cost-effectiveness. Asphalt cement (40-50), aggregate (fine and coarse) and filler were utilized. In this work, Nano clay was used as an additive. The material properties were assessed per the specifications outlined by ASTM and **(SCRB R/9, 2003)** standards specifications.

2.1 Asphalt Cement

AC (40-50) is the primary material utilized for pavement construction in Iraq. It came from the refinery of Al-Dora in Baghdad's southern area. **Table 1** displays the physical characteristics of asphalt cement, and all the Results of the asphalt cement examinations conform to **(SCRB R/9, 2003)**.

2.2 Aggregates

The study utilized a coarsely crushed material. The size of coarse aggregate used for the wearing course ranged from 19 mm to 4.75 mm, while the fine aggregate varied in size, ranging from particles less than 4.75 mm to particles larger than 0.075 mm, as per the SCRB requirements **(SCRB R/9, 2003)**. The gradation of the aggregate is presented in **Table 2**. The physical characteristics of fine and coarse aggregate are listed in **Tables 3** and **4.**

Table 1. Physical properties of asphalt cement.

Test	Units	Results	(SCRB R/9, 2003) Specification	ASTM
Penetration	1/10 mm	46	40 – 50	**(ASTM D5, 2013)**
Ductility	cm	160	≥ 100	**(ASTM D113, 2007)**
Softening point	˚C	52	–	**(ASTM D36, 2014)**
Flash Point	˚C	240	232 min.	**(ASTM D92, 2018)**
Specific gravity	-----	1.04	–	**(ASTM, D70, 2018)**
After the Thin-Film- Oven- Test **(ASTM D1754, 1997)**				
Retained Penetration of Original	%	62	55 (Min)	**(ASTM D5, 2013)**
Ductility	cm	81	> 25	**(ASTM D113, 2017)**

Table 2. Selected gradation for wearing course.

Wearing course Sieve Size		Selected Gradation	Specification Limits (SCRB/R9, 2003)
Inch	**mm**		
3/4	19	100	100
1/2	12.5	90-100	95
3/8	9.5	76-90	83
No. 4	4.75	44-74	59
No. 8	2.36	28-58	43
No. 50	0.3	5-21	13
No. 200	0.075	4-10	7

Table 3. The physical characteristics of coarse aggregate.

The test	Test Method	Results	(SCRB R/9, 2003) Requirements
Bulk Specific Gravity	**(ASTM C127, 2015)**	2.59	---
Apparent Specific Gravity	**(ASTM C127, 2015)**	2.607	---
Percent of Water Absorption	**(ASTM, C127, 2015)**	0.56	---
Percent of Wear (Los Angeles's abrasion machine)	**(ASTM C131, 2014)**	14.11	30 Max

Table 4. The physical characteristics of the fine aggregate.

The test	Test Method	Result	SCRB
Bulk Specific Gravity	**(ASTM C128, 2015)**	2.62	---
Apparent Specific Gravity	**(ASTM C128, 2015)**	2.654	---
Percent Water Absorption	**(ASTM C128, 2015)**	0.89	---

2.3 Mineral Filler

The addition of limestone dust as a filler in preparing the asphalt mix was chosen because it is readily available and is comparably cheaper. The asphalt mixture's mineral filler is a crucial component that helps make the asphalt bond stiffer and last longer. A filler is a material that passes through a No. 200 sieve (0.075 mm). **Table 5** shows the physical properties of mineral filler.

Table 5. Physical properties of mineral filler.

Test	Result
Bulk Specific Gravity	2.69
Passing No.200, %	98

2.4 Nano-Montmorillonite (MMT)

The Nanomaterial used for this research is Nano clay (NC), shown in **Fig. 1**, which is also referred to as montmorillonite MMT K(10) in local and commercial contexts. Sigma-Aldrich obtained it from the United States and manufactured it as a nono-clay.

Figure 1. Nano-montmorillonite.

Table 6 illustrates the physical properties of Nano clay powder as outlined by **(Karkush et al., 2020)**. The particle size of MMT was analyzed using a laser instrument to determine if it had achieved the nanoscale. The test referred to is called Atomic Force Microscopy (AFM) analysis. This test is used to get images with a resolution close to the atomic level, allowing for the measurement of surface topography. This test can measure the degree of surface roughness in samples**.**

Table 6. The physical properties of MMT.

Property	Result
Type of Mineralization	Montmorillonite
Density, g/cm^3	0.5-0.7
Special surface area, m^2 /g	220-270
Electrical conductivity, µS/cm	25
Ion exchange coefficient	48
Color	Pale yellow
The empty gap between the rats (Å)	60
Humidity, %	1-2

Figs. 2 and **3** display the particle size and morphology of Nanoclay when subjected to laser analysis. The analysis revealed that the mean diameter of the particle size was 21.51nm, which satisfies the criteria for nanometer-scale measurements.

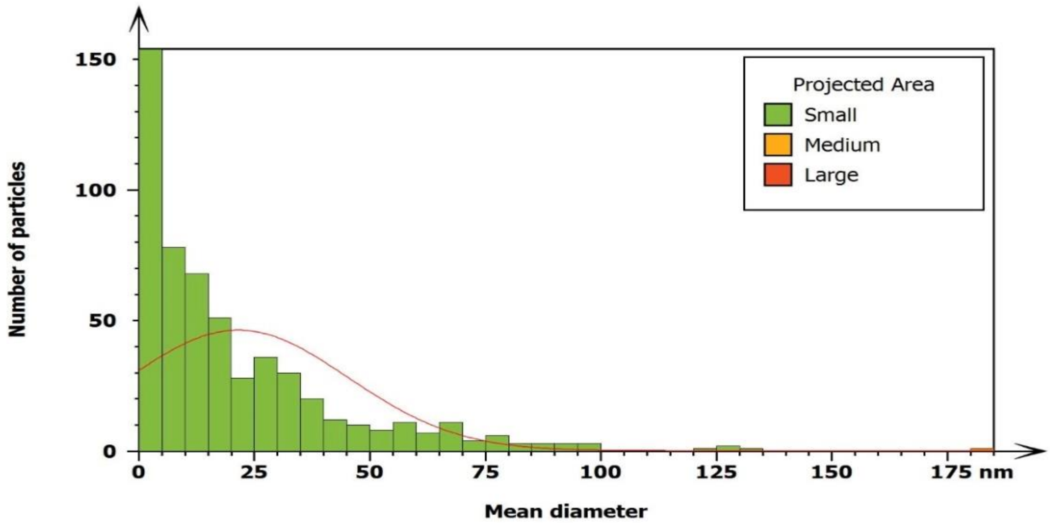

Figure 2. The average MMT particle diameter

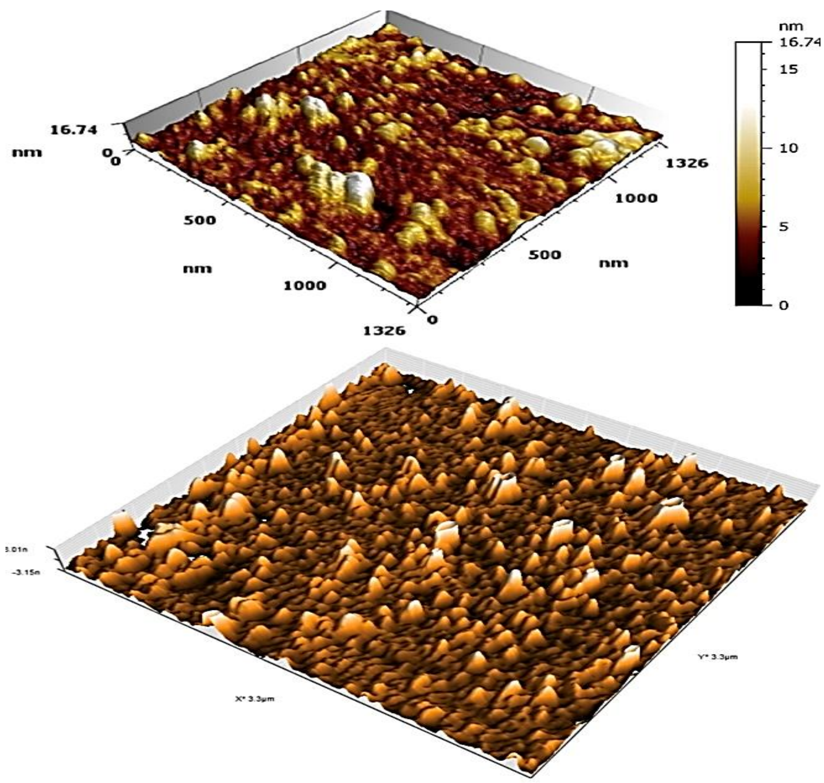

Figure 3. The morphology of the particle size of MMT.

2.4.1. X-ray Fluorescence (XRF) Test

An X-ray fluorescence examination was performed to ascertain the chemical structure of MMT and MMT's chemical structure and characteristics. **Table 7** shows its chemical components.

Table 7. The MMT's chemical components.

Symbol	Element	Concentration %
Na_2O	Sodium	0.30
MgO	Magnesium	2.893
Al_2O_3	Aluminum	15.94
SiO_2	Silicon	49.78
K_2O	Potassium	0.62
CaO	Calcium	2.34
TiO_2	Titanium	0.35
Fe_2O_3	Iron	5.26

3. EXPERIMENTAL METHODOLOGY

3.1 Marshall Test

The asphalt was heated until it reached 163 °C as the upper limit for (40-50) penetration grade, and subsequently, the asphalt was mixed with MMT at various weight percentages (2, 4, and 6%). The blending procedure occurred on a heated plate at a speed of blending of around 3000 (rpm) for 45 minutes. Subsequently, to determine the optimal asphalt composition for the HMA, five different amounts of asphalt by weight of the whole mix were tested: 4, 4.5, 5, 5.5, and 6%. For each asphalt percentage, three specimens were created. The specimens were subjected to a variety of Marshall tests, including flow, stability, and density-void analysis, to identify the optimal composition of asphalt. The experiments were performed using a 12.5 mm aggregate nominal maximum size and mineral filler composed of 7% limestone dust based on the weight of the whole aggregate. The mean value was calculated for each set, composed of three specimens for each asphalt percentage. The same method was repeated for all MMT-modified sample percentages. The test of Marshall for asphalt mix design, as determined by (**ASTM D6927, 2015)**, was utilized as a fundamental test. The cylindrical specimens, measuring 4 × 2.5 inches, were made by thoroughly mixing and compacting them with 75 blows on each face. A total of 1200 gm of asphalt mixture was prepared, with differing ratios of MMT (2, 4, and 6%) by weight of asphalt binder. The objective was to determine the optimal asphalt content and Marshall characteristics. **Fig. 4** illustrates the specimens of Marshall prepared.

Figure 4. Test of Marshall.

3.2 Wheel Tracking Test

The wheel-tracking equipment emulated the resistance to rutting in the asphalt mixtures by applying repeated loads through a moving wheel across a sample. At the National Center for Construction Laboratories and Research / Baghdad laboratory (NCCLR), a Dyna compactor, which conforms to EN 12697-22 requirements, was employed to compress the loose asphalt mixture and create a slab of 30×40×5 cm. The rut depth at a temperature of 55 °C was recorded in this test. A 70-psi stress level (483 kPa) was applied to rectangular slabs for 10000 cycles (20000 passes). The slabs were extracted from the molds after 24 hours of cooling at room temperatur. **Fig. 5** displays the roller compactor used in this investigation, whereas **Fig. 6** illustrates the compaction and testing of slab specimens.

Figure 5. Roller compactor device.

Figure 6. Samples of slabs used in wheel tracking test.

4. RESULTS AND DISCUSSION

4.1 Marshall Test

The test results of Marshall's test for combinations containing MMT, with varying quantities, are presented in **Table 8** and **Fig. 7**. The test findings in **Table 7** match the **(SCRB/R9, 2003)** specification limits. The optimal amount of asphalt was raised due to the increased amount

of MMT, as shown in **Fig. 7**. Compared to the control mixture, 2, 4, and 6% of MMT to asphalt cement increased by 4.46%, 6.90%, and 8.72%, respectively.
Adding MMT to the asphalt resulted in a denser mixture due to the increased surface area, leading to a rise in bulk density. The bulk density rose by 0.58, 1.02, and 1.11% with the addition of 2, 4, and 6% MMT, respectively.
All of the mixtures exhibited superior stability in comparison to the control mixture. A maximum Marshall stability of 11.48 kN was reported when 6% MMT was added to the asphalt cement AC (40-50), compared to the control mixture with a Marshall stability of 9.83 kN. The inclusion of MMT also reduced Marshall flow; the largest decrease was observed at 4% of MMT, where Marshall flow dropped to 2.81 mm as compared to 3.30 mm for the control mixture.

Table 8. Results of the test of Marshall.

MMT, %	O.A.C, %	Stability, kN	Flow, mm	VMA, %	AV, %
0	4.93	9.83	3.30	16.48	4.91
2	5.15	10.1	3.34	16.77	3.62
4	5.27	11.03	2.81	16.85	3.42
6	5.36	11.48	3.44	15.82	3.57
(SCRB/R9, 2003) Limits	4-6	8 Min	2-4	14 Min	3-5

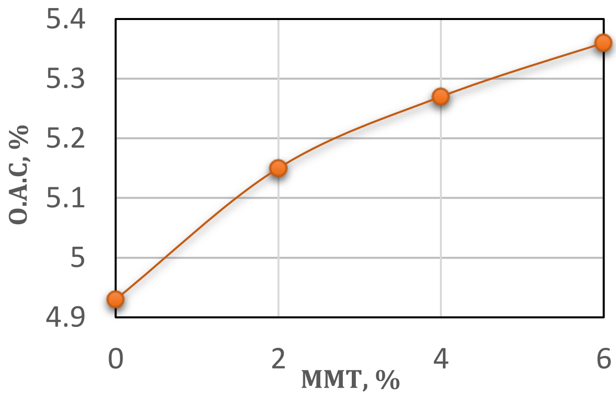

Figure 7. Effect of MMT on O.A.C.

4.2 Wheel Tracking Test

Eight slabs measuring 40×30×5 cm were produced and subjected to testing at a temperature of 55° C. The testing involved utilizing a moving wheel load of 70 psi for a total of 10,000 cycles, equivalent to 20,000 passes. **Table 9** and **Fig. 8** present the ultimate rutting depth after 10,000 cycles. The control mix demonstrated more excellent permanent deformation resistance than all combinations, including different proportions of MMT.

Table 9. A summary of the test data for wheel tracking.

MMT, %	Rutting depth, mm	Percentage change, %
0	12.19	-
2	9.53	-21.82
4	8.31	-31.82
6	7.34	-39.79

* Negative signal (-) indicates a decrease in rut depth.

The mixture with a 2% MMT content exhibited the most remarkable rutting depth, measuring 9.53 mm; in comparison to the control mixture, the depth of rutting was measured to be 12.19 mm. The lowest rutting depth was observed when 6% MMT was added.

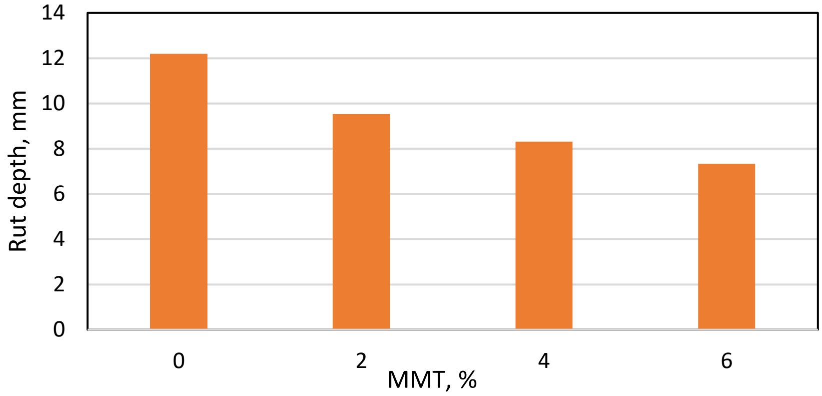

Figure 8. Rutting depth (mm) results @ 10000 cycles.

4.3 Dynamic Stability

Dynamic stability is a widely used measurement for assessing the susceptibility of an asphalt mixture to rutting. The measurement is determined by the number of cycles that result in a permanent deformation of 1 mm during the final 25% of the one-hour testing period. The investigation involved a lengthy experimental period, during which Eq. (1) was employed to compute the dynamic stability according to **(Ismael et al., 2022)**.

$$DS = \frac{C_{10000} - C_{7500}}{RD_{10000} - RD_{7500}} \quad (1)$$

where:
DS = Dynamic Stability (cycle/mm), C_{10000} = Cycles 10000, C_{7500} = Cycles 7500, RD_{10000} = Rut depth at the cycles 10000, and RD_{7500} = Rut depth at the cycles 7500.
Fig. 9 illustrates the relation between rut depth, dynamic stability, and the content of MMT. The wheel tracking test results indicated that the modified asphalt mixes with MMT exhibited greater dynamic stability values than the conventional mixture.

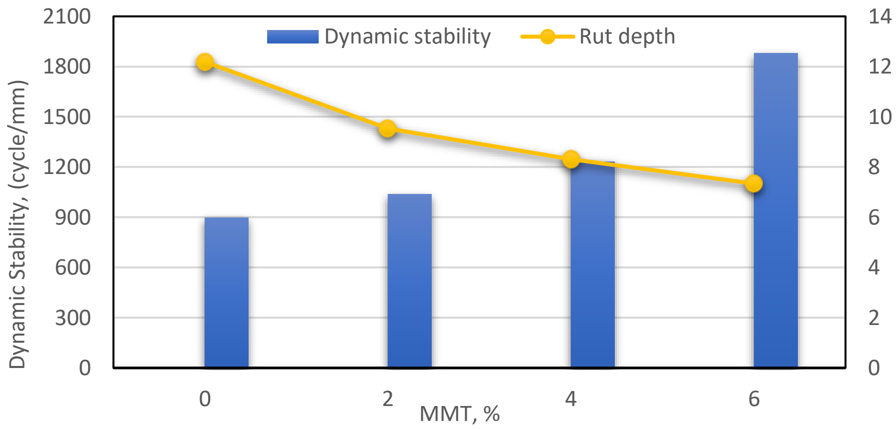

Figure 9. Relation between Rut depth, dynamic stability, and MMT content.

5. CONCLUSIONS

Asphalt pavement rutting is a significant problem for road users and authorities. Therefore, this is considered a research gap that must be solved. The asphalt was modified with nano-Montmorillonite (MMT) to increase its resistance against rutting. This study examines the impact of using MMT on Marshall properties and rutting resistance of HMA. The main conclusions drawn from the findings obtained through this research are:

- The addition of MMT at ratios of 2, 4, and 6% enhanced the asphalt mixture's Marshall properties. The highest Marshall stability was recorded when 6% MMT was added, which was increased by 16.79%. The addition of MMT reduced Marshall flow by 14.84% at 4% of MMT.
- The volumetric property of VFA improved due to MMT addition. The best improvement compared to the Control mixture was achieved by using 4% MMT, resulting in improvements of 13.53%.
- The specimens subjected to modification exhibited an enhanced resistance to rutting. Specifically, at 55°C, the rut depth in specimens containing 6% MMT decreased by 39.79%. An increase in dynamic stability was observed across all combinations incorporating varying percentages of MMT compared to the control mixtures. Notably, the composition containing 6% MMT demonstrated the highest dynamic stability with a value of 1880 cycles/mm, as opposed to the control mixture, which registered 896 cycles/mm.
- Compared to the previous studies, the analysis of the data collected in this study verified the positive impact of MMT on the ability to resist rutting.

NOMENCLATURES

Symbol	Description	Symbol	Description
AC (40-50)	Asphalt cement with a penetration grade of (40-50)	O.A.C	Optimal asphalt content
ASTM	American Society for Testing and Materials	SCRB	State Corporation for Roads and Bridges
AV	Air voids	VMA	Voids in mineral aggregate
MMT	Montmorillonite	VTM	Voids in Marshall specimen

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Credit Authorship Contribution Statement

Farah Salam Hassan: Writing – review & editing, Writing – original draft, Validation, and Methodology. Mohammed Q. Ismael: Methodology, review & 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.

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خصائص مارشال ومقاومة التخدد للخلطات الاسفلتية المعدلة بالنانو–مونتموريلونايت

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الخلاصة

يمثل التخدد مشكلة كبيرة في الأرصفة الأسفلتية المرنة، مما يؤدي الى التشوه الدائم.ان زيادة حركة المرور، الحمل على المحور ، ضغط الاطارات والطقس الحار يؤدي الى تسارع حدوث التخدد في الارصفة المرنة. قد اقترحت بحوث مختلفة استخدام المواد النانوية لغرض تعزيز رصف الاسفلت وتمديد عمره. تم اعتماد مادة الطين النانوي الطبيعية والمحبة للماء بشكلها الخام (المونتموريلونايت) في هذه الدراسة. وتبحث هذه الدراسة تأثير اضافة المنوتموريلونايت الى خليط الاسفلت الساخن على خواص مارشال ومقاومة التخدد. وتتضمن تحديد محتوى الاسفلت الامثل باستخدام طريقة مارشال للتصميم، بالإضافة الى ذلك، تحديد عمق التخدد للخلطة الاسفلتية باستخدام فحص تتبع مسار العجلة، للخلطات التي تتألف من نسب مختلفة من المونتموريلونايت (2, 4, و6٪) كنسبة من وزن السمنت الاسفلتي. وقد اظهرت النتائج ان المحتوى الامثل للأسفلت هو 4.93٪. وقد أدى اضافة 6٪ من المونتموريلونايت الى زيادة ثباتية مارشال بنسبة 16.79٪. انخفض تدفق مارشال عند اضافة المونتموريلونايت. حيث كان تدفق مارشال للخلطة الاساسية يبلغ 3.30 مم، ولكن عند استخدام 4٪ من المونتموريلونايت، انخفض التدفق الى 2.81 مم. كانت النسبة المثالية للمونتموريلونايت هي 6٪، مما أدى الى تقليل عمق التخدد، حيث قل بنسبة 39.79٪ بالمقارنة مع الخلطة الأساسية.

الكلمات المفتاحية: التخدد، فحص مسار العجلة، النانو–مونتموريلونايت، طريقة تصميم مارشال.