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Rutting Prediction of Hot Mix Asphalt Mixtures Modified by Nano Silica and Subjected to Aging Process

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Abstract

High-volume traffic with ultra-heavy axle loads combined with extremely hot weather conditions increases the propagation of rutting in flexible pavement road networks. Several studies suggested using nanomaterials in asphalt modification to delay the deterioration of asphalt pavement. The current work aims to improve the resistance of hot mix asphalt (HMA) to rutting by incorporating Nano Silica (NS) in specific concentrations. NS was blended into asphalt mixtures in concentrations of 2, 4, and 6% by weight of the binder. The behavior of asphalt mixtures subjected to aging was investigated at different stages (short-term and long-term aging). The performance characteristics of the asphalt mixtures were evaluated using the Marshall stability, flow, and wheel tracking tests. Field Emission Scanning Electron Microscopy (FESEM) was utilized to understand the microstructure changes of modified asphalt and estimate the dispersion of NS within the asphalt. The results revealed that using NS–asphalt mixtures as a surface layer in paving construction improved pavement performance by increasing stability, volumetric characteristics, and rutting resistance before and after aging. The FESEM images showed adequate dispersion of NS particles in the mixture. Results indicated that adding 4% of NS to asphalt mixtures effectively enhanced the pavement's performance and rutting resistance.

Keywords: Rutting Resistance; Nano Silica (NS); Wheel Tracking Test; Aging; Field Emission Scanning Electron Microscopy (FESEM).

1. Introduction

Rutting deformation significantly affects the structural performance and service life of asphaltic pavements. The characteristics of the pavement material significantly influence its rutting potential. Rutting is the most common permanent deformation of pavement. It is caused by repeated traffic loads that accumulate small, permanent strains in pavement material over time [1, 2]. Rutting may reduce the service life of flexible hot mix asphalt (HMA) pavement and create safety risks. Therefore, enhancing the performance of asphaltic pavements is necessary to prevent or delay surface deformation.

Aging is an inevitable phenomenon affecting the performance of asphalt binders. The aging of asphalt binder begins during the construction of flexible pavements and continues throughout their lives. Two types of aging are generally considered: short-term (ST) and long-term (LT) aging. ST aging occurs when the asphalt is exposed to heat and air during the construction and paving stages. Low-molecular-weight oil components in asphalt binder evaporate during mixing, shipping, laying, and rolling at high temperatures [3]. In contrast, LT aging occurs gradually during the pavements' service lives. The asphalt oxidizes and becomes harder when exposed to oxygen in the air. Binder brittleness and hardness can be affected by oxidation in addition to high temperatures [4].

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Various additives have been used to enhance the behavior and performance of asphalt in various environments [5]. Raof & Ismael (2019) [6] studied the effect of PolyPhosphoric Acid (PPA) on asphalt's resistance to permanent deformation. The results indicated that using PPA to modify asphalt produced higher resistance to rutting than conventional asphalt mixtures. Furthermore, PPA had a higher effect on the rutting resistance of asphalt grades 60–70 than that of asphalt grades 40–50 in recent years, the use of nanomaterials as asphalt modifiers has gained momentum. Researchers successfully changed the properties of binder and asphalt mixtures by adding nanomaterials. Nanomaterials make the asphalt binder stiffer because they have a large surface area and form strong networks in the binder, thus improving resistance to permanent deformation [7].

Nanoclay modification of asphalt cement improved Marshall stability and increased the moisture resistance of asphalt mixtures, as indicated by an increase in the tensile strength ratio (TSR) and index of retained strength (IRS). Adding 4% and 6% nanoclay (MMT) led to a high increase in the IRS and TSR for asphalt cement grades 40-50 and 60-70, respectively [8]. In another study, two types of bitumen binders, grades 40-50 and 60-70, were examined to determine the impact of carbon nanotubes (CNT) on the rutting of asphalt pavement. Bitumen was found to have a higher viscosity, cause a rise in Marshall stability, and improve rutting performance. The 40-50 grade bitumen produced a 61% increase in rutting resistance and a 35% increase in stability at a concentration of 1.5% CNT. In comparison, the 60-70 grade generated similar results for a concentration of 2% CNT [9]. Because of its stability and high surface area, nano silica (NS) is a promising material for developing and producing new multifunctional materials [10]. Additionally, NS has good adhesion and self-healing characteristics. Prior studies established that using nanomaterials improved the chemical and physical properties of asphalt binder, resulting in enhanced asphalt performance [11]. Al-Omari et al. (2021) [12] found that NS-modified mixes perform more effectively at moderate temperatures. Furthermore, increased compaction efforts and lower temperatures improved mixture stiffness while decreasing deformation and rutting potential.

Al-Sabaeei et al. (2020) [13] observed an improvement in the rutting and aging performance of NS-modified asphalt. The aging resistance was rationalized by the NS's exfoliated structure, which serves as a barrier to prevent oxygen from entering the binder matrix and light components from evaporating. Bhat & Mir (2019) [14] showed that NS is a proper additive to enhance asphalt binder resistance to rutting. The rheological properties of the NS-modified asphalt binder indicated an improvement in permanent deformation resistance. Binders modified with NS also exhibit high resistance to oxidative aging and good storage stability at high temperatures.

Chen and Li, 2020 [15], tested the engineering index of nano silica emulsified asphalt. They indicate that the use of nano silica improves stability, permeability, and softening point. Shafabakhsh et al. (2021) [16] examined the influence of nano silica on the occurrence of low-temperature cracks in asphalt mixtures. The results revealed that nano silica has a high potential for improving the low-temperature cracking resistance of asphalt mixtures. Also, the inclusion of 1.2% nano silica enhances the fracture resistance of asphalt mixtures because of the improved adhesion between the binder and aggregates. Ghanoon & Tanzadeh (2019) [17] studied the rutting behavior of NS-modified binders. The multiple stress creep recovery (MSCR) test revealed that the addition of NS may reduce the non-recoverable compliance (Jnr) value, indicating that modified binders had a higher rutting resistance.

Bala et al. (2020) [18] investigated the effect of nano silica and binder content on the performance of asphalt mixtures, finding that increasing the concentration of nano silica increased Marshall stability, fatigue life, and indirect tensile strength. On the other hand, the Marshall flow and mineral aggregate voids decreased. Fini et al. (2016) [19] demonstrated that adding NS to asphalt binders increased their resistance to rutting, enhancing the asphalt binder's storage modulus, elasticity, and aging resistance. The primary purpose of this study is to assess the effect of NS on the Marshall properties and rutting resistance of bitumen modified with NS by using a penetration grade 40-50 asphalt cement at different aging condition (Unaged, short-term, and long-term aging). The rheological properties of NS-modified asphalt at high temperatures before and after aging were examined to explore whether they were suitable for high temperature pavement application.

2. Materials and Sample Preparation

The laboratory work included asphalt binder conventional tests for virgin and modified asphalt cement. Asphalt concrete specimens were made for the Marshall test to find the optimum asphalt and Marshall properties. Such as stability and flow values. Moreover, the AASHTO R 30 standard procedure was utilized to simulate the mixtures' aging. In order to measure the rut depth, slab specimens were prepared by roller compactor. The wheel tracking test has been performed at two test temperatures (45 and 55 °C) to simulate the local high ambient climate. Figure 1 is the flowchart of the methodology opted for the present study.

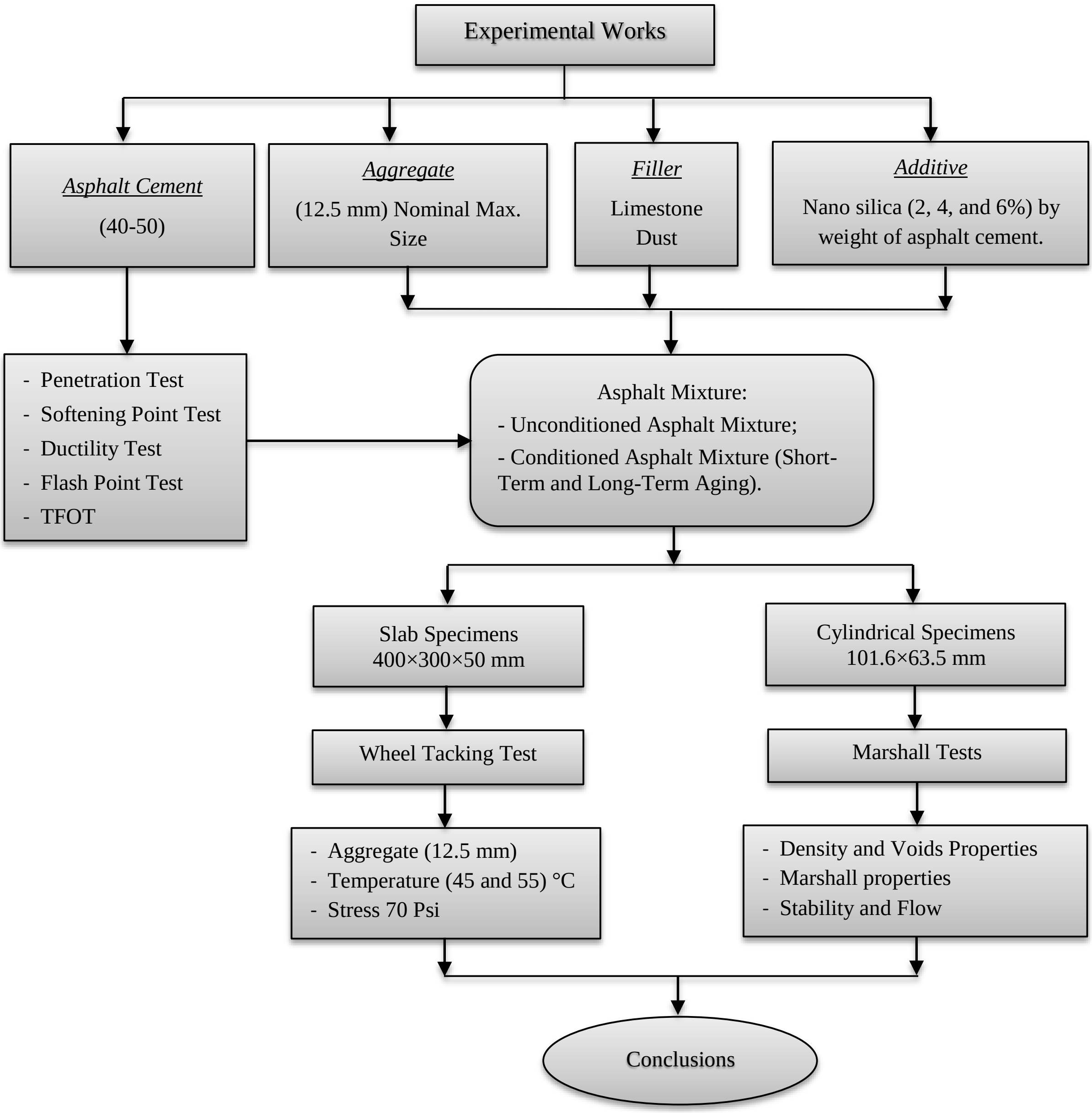


Figure 1. Flow Chart for Work Program

2.1. Asphalt Cement

This study used an AC (40-50) asphalt binder delivered from the Al-Daurah refinery. The test results conform to the requirements specified by the Iraqi State Corporation for Roads and Bridges (SCRB R/9, 2003) [20].

2.2. Fine and Coarse Aggregates

Coarse crushed aggregate was used in this research and supplied from Al-Obaidi Mix Plant. For the asphalt wearing course, the coarse aggregate's size varied between 19 mm and 4.75 mm sieve sizes. The fine aggregate had particle size between No. 4 and No. 200, according to the SCRB specifications. The physical properties of fine and coarse aggregate are reported in Table 1.

2.3. Mineral Filler

Limestone dust was used to prepare an asphalt concrete mixture for this study; it was purchased from an Iraqi lime plant in Karbala. The filler is a non-plastic material that passes through a 0.075 mm sieve opening.

Table 1. Fine and Coarse aggregate physical properties

Property	ASTM [21]	Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity	C-127 & C-128	2.58	2.63
Water Absorption %	C-127 & C-128	0.57	0.731
Los Angeles Abrasion %	C-131	15.26	-

2.4. Nano Silica (NS)

Nano silica is an inorganic substance primarily derived from silica precursors. NS can be utilized as a binder modifier to enhance the performance of asphalt mixtures owing to its uniquely large surface area, good dispersion ability, high stability, and chemical purity [22]. A high-dispersion powdered form of hydrophobic NS particles provided by US Research Nanomaterials; Inc. was used. Figure 2 presents the NS particles employed in this study. Tables 2 and 3 illustrate the characteristics of NS.

Figure 2. Nano silica

Table 2. Analysis of Nano silica

SiO_2	Ca	Ti	Fe	Na
> 99%	< 70 ppm	< 120 ppm	< 20 ppm	< 50 ppm

Table 3. Properties of Nano silica

Particle Size	True Density	Surface Area	Bulk Density	Purity
20-30 nm	2.4 g/cm^3	180-600 m^2/g	< 0.10 g/cm^3	+99%

2.5. Aggregate Gradation Selection

The Iraqi standards specifications (SCRB/R9, 2003) states that for the wearing course, the nominal maximum size of aggregate is 12.5 mm. Figure 3 illustrates the aggregate gradation that was utilized.

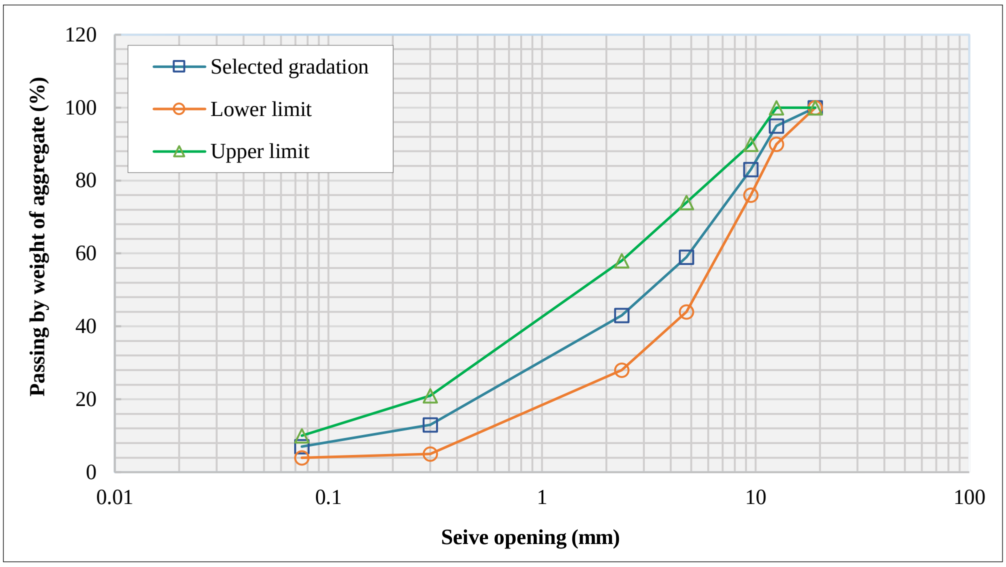


Figure 3. Design aggregate gradation

2.6. Preparation of the Asphalt Mixtures

A high shear mixer was used to blend the NS with the asphalt binder. The asphalt binder was heated to 163 °C to form a uniform liquid, then blended with NS at concentrations of 2, 4, and 6% by weight of binder, respectively. NS was added gradually to reach the desired level while the mixer rotated at 500 rpm to promote the uniform dispersion of

NS particles. After 10 minutes, mixing speeds were increased to 3000 rpm for an hour [23]. As the concentration of NS increased, the temperature was increased to further enable the uniform dispersion of NS particles within the binder. Using five asphalt contents (4, 4.5, 5, 5.5, and 6% by weight of total mixture), three specimens were manufactured for each of the five contents to determine the optimum asphalt content for the HMA. Similar sets of specimens were prepared using asphalt modified with 2, 4, and 6% NS. The same procedure was applied to establish the optimum asphalt content for the modified mixtures.

The AASHTO R 30-02 [24] standard procedure was utilized to simulate the mixtures' aging. The asphalt mixture underwent short-term (ST) aging, a process simulating the mixing and compaction stages of construction. After mixing, the asphalt mixture was placed in a forced-draft oven for 4 h ± 5 min at a compaction temperature of 135 °C, stirring hourly to maintain uniform conditioning. Next, the mixture was removed from the oven and compacted before testing. Long-term (LT) aging replicates the aging that occurs throughout the asphalt's service life. After the short-term aging simulation, LT aging was performed by exposing the compacted mixture to a temperature of 85 ± 3 °C for 120 ± 0.5 h.

2.7. Conventional Physical Properties Tests

Penetration at 25 °C, ductility at 25 °C, and softening point temperature were measured on modified and control asphalt binder specimens. To analyze the effect of ST aging on modified asphalt binder, the specimens were subjected to the thin-film oven (TFO) aging procedure for 5 h at 163 °C (ASTM D 1754 [25]). The NS-modified asphalt's aging resistance was calculated using the penetration aging index to characterize the increase in asphalt hardness after aging, as specified in Equation 1:

$$\text{Penetration aging Index} = \frac{\text{Aged result test value}}{\text{Unaged result test value}} \tag{1}$$

A lower aging index value indicates a reduced susceptibility to aging. The penetration index (PI) was utilized to calculate the temperature susceptibility of the modified binder, as shown in Equation 2:

$$\text{PI} = \frac{1952 - 500 \times \log(\text{Pen } 25) - 20 \times \text{SP}}{50 \times \log(\text{Pen } 25) - \text{SP} - 120} \tag{2}$$

where Pen 25 is the penetration depth at 25 °C and SP is the softening point temperature.

2.8. Wheel Tracking Test

A simulation test was conducted to evaluate the rut depth of NS-modified asphalt mixtures using a wheel-tracking device. Heavy axle loads and high-volume traffic were simulated by repeatedly rolling a small, loaded wheel across HMA slabs under various aging conditions. This test measured rut depth at 45 °C and 55 °C by applying a stress level of 70 psi (483 kPa) to rectangular slabs during 5000 cycles, as presented in Figure 4.

Figure 4. Wheel tracking test

Prepared NS-modified slabs were classified into three conditions: unaged (UN), short-term aged (ST), and long-term aged (LT). The specimens were compacted according to British Standard EN 12697– 33 using the Dyna-Compact Pneumatic Roller Compactor at the National Center for Construction Laboratories and Research / Baghdad laboratory (NCCLR). This modern device compresses asphalt mixture slabs of 300×400 mm, 25 to 100 mm thick, under controlled conditions that simulate in-situ compaction. After 24 hours, the slabs were left to cool at room temperature and, subsequently, removed from the molds. Figure 5 shows the roller compactor utilized in this study, while Figure 6 illustrates a set of specimens subjected to the wheel tracking test.

Figure 5. Roller Compacter machine at NCCLR

Figure 6. Slab specimens for Wheel tracking test

The UN slabs were tested immediately after mixing and compacting without undergoing any aging procedure. After mixing the ST aged specimens on the stove, the loose specimens were placed in the laboratory oven at a temperature of 135°C for 4 hours to simulate short-term aging. The mix was subsequently poured into a mold, and the mold was placed in the device for compacting [24].

For LT specimens, the loose samples first underwent a short-term aging procedure at 135°C for 4 hours after mixing. The specimens were then directly poured into a mold, which was placed in the device for compacting. Next, the compacted slabs were placed in a laboratory oven at 85 °C for five days (120 h) to simulate the long-term aging process, as shown in Figure 7. After five days, the LT slabs were removed from the oven and left to cool at room temperature.

Figure 7. Set of specimens in the oven for LT aging

2.9. Microstructural Analysis

Field Emission Scanning Electron Microscopy (FESEM) was used to verify that the NS particles were dispersed evenly in the asphalt. The microstructures of base asphalt and NS-modified asphalt were compared using the FESEM-generated images. After mixing NS with asphalt at the three prescribed concentrations (2, 4, and 6%), a slice of each mixture was used for testing. The Zeiss Emission Scanning Electron Microscope (FESEM) in Iran was employed to characterize the distribution and morphology of NS in asphalt binder and asphalt mixture.

3. Results

3.1. Conventional Physical Properties Tests

Various physical properties for aged and unaged modified binders are presented in Table 4.

Table 4. Conventional properties for NS-modified binders

NS Content (% by wt. of Asphalt)	Aging Condition	Penetration (25 ^{0}C, 100 gm, and 5 sec)	Penetration Aging Index	Softening Point (Ring and Ball)	Ductility, (25 ^{0}C and 5 cm/minute)	PI
0%	Unaged	44	0.93	51	168	-1.234
	TFOT	41				
2%	Unaged	42	0.90	53	157	-0.869
	TFOT	38				
4%	Unaged	37	0.84	55	145	-0.697
	TFOT	31				
6%	Unaged	26	0.81	59	131	-0.591
	TFOT	21				

The results obtained for NS-modified binders clearly indicate that mixing affected the modified binder's stiffness. The penetration depth recorded reductions of 5, 16, and 41% with the addition of 2, 4, and 6% of NS, respectively. Therefore, NS-modified asphalt is more resistant and harder than unmodified asphalt. Furthermore, NS-modified TFO-aged asphalt samples presented a continuous decrease in penetration depth with increasing NS concentration. The decrease in the binder's aging index indicates that the addition of NS decreases the oxidation process in the binder, hence increasing the binder's resistance to aging.

The softening point value is inversely correlated with the penetration value — the softening point of NS-modified asphalt is considerably higher than that of the control asphalt binder. Asphalt with a higher softening point is less susceptible to temperature variations. At high temperatures, mixtures containing NS-modified asphalt exhibit a higher resistance to permanent deformation and rutting.

The addition of NS significantly reduced the ductility of NS-modified asphalt. The dispersion of NS in a virgin binder decreases the ability of the binder to elongate. This could explain the measured reduction in ductility. The higher PI values of NS-modified asphalt show that these binders are more temperature-resistant and elastic [26]. This is a significant finding, as high temperatures cause rutting, a common type of pavement distress seen throughout the road network in Iraq [27]. The results obtained are in agreement with other studies' outcomes [13, 28].

3.2. Marshall Test

Since volumetric properties affect durability, they are essential for estimating pavement performance and service life. With the addition of NS, the optimal asphalt content increased from 4.92% in an unmodified binder to 5.21, 5.3, and 5.5% with the addition of 2, 4, and 6% of NS, respectively. Table 5 shows that, for unaged conditions, adding NS enhances the characteristics of the mixture by increasing its bulk density and Marshall stability and decreasing its flow while maintaining the other properties within limits prescribed by the Iraqi SCRB (2003) [20].

Table 5. Marshall Test Results for Unaged Asphalt mixtures

NS Content (%) by wt. of Asphalt	O.A.C. (%) by wt. of Total Mix	Stability (kN)	Flow (mm)	Bulk Density (gm/cm^3)	Air Voids (%)	V.M.A (%)	V.F.A (%)
0%	4.92	10.32	3.48	2.305	4.52	16.83	73.17
2%	5.21	11.58	3.31	2.313	4.14	16.79	75.32
4%	5.3	12.17	2.97	2.316	3.94	16.76	76.50
6%	5.5	13.74	3.26	2.32	3.69	16.80	78.01

The increases in the viscosity, softening point temperature, and bulk density of asphalt led to an increase in Marshall stability as the percentages of NS increased up to 6%. Results indicate that the maximum stability of the NS-modified mixture improved by 33.1%. The Marshall flow was reduced by 4.9% and 14.7% with the addition of 2% and 4% of NS, respectively. For 6% of NS, the Marshall flow was higher than for 2% and 4% of NS but remained 6.3% lower than the control mixture's flow. However, Hasaninia & Haddadi (2018) [29] showed that the Marshall stability and flow increase with the concentration of NS. In our study, the measured decrease in flow may be attributed to a different process of gradation and densification that increased stability but decreased flow. The air voids percentage is related to the asphalt mixture's durability. Due to the high surface area of the NS particles added to the asphalt cement and the increase in the asphalt mixture's bulk density, the percentage of air voids recorded low values compared to the control mixture.

Figure 8 illustrates the effect of aging on the Marshall stability. With increasing NS content, the Marshall stability increased initially, then declined. NS particles disperse and are absorbed by the asphalt binder's ingredients, making the asphalt stiffer and more resistant to aging, hence increasing its stability. For the aged samples, the Marshall flow was reduced with the addition of 2%, 4%, and 6% NS despite the increase in asphalt content, as seen in Figure 9.

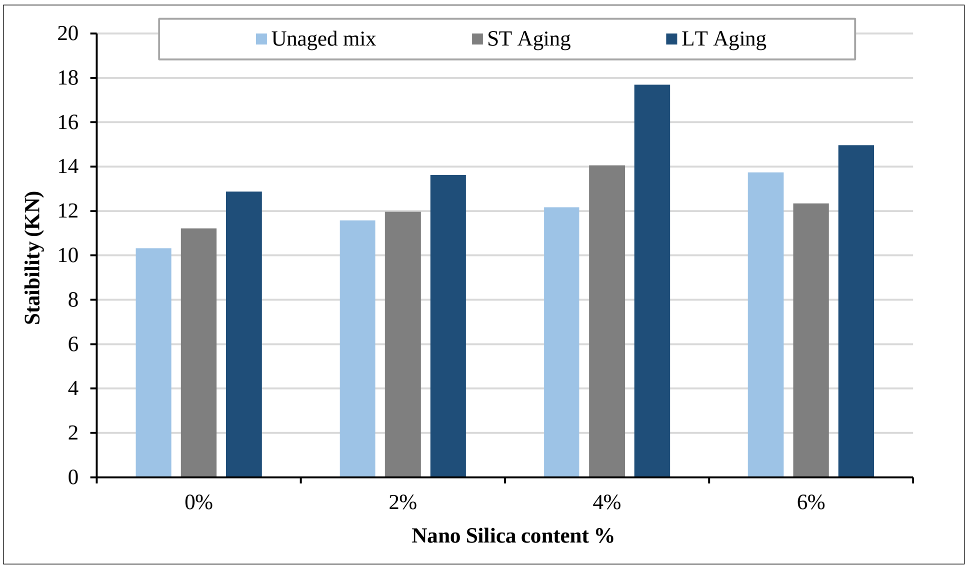


Figure 8. Effect of NS and aging on Marshall Stability

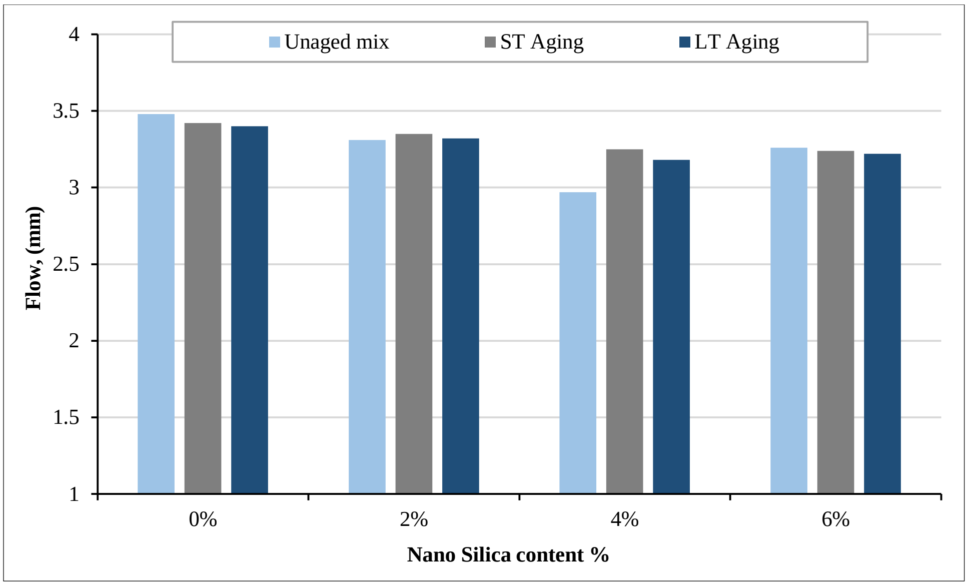


Figure 9. Effect of NS and aging on Marshall Flow

Figure 10 clearly indicates that the air void percentage increases with aging. Adding NS to bitumen reduced the air voids percentage of the asphalt mixture. Asphalt binders lose volatile components through oxidation and volatilization as they age, causing a decrease in volume and an increase in viscosity. As a result, the weight of the mixture is reduced. Adding NS to bitumen increases the bulk-specific gravity of aged mixtures, as shown in Figure 11.

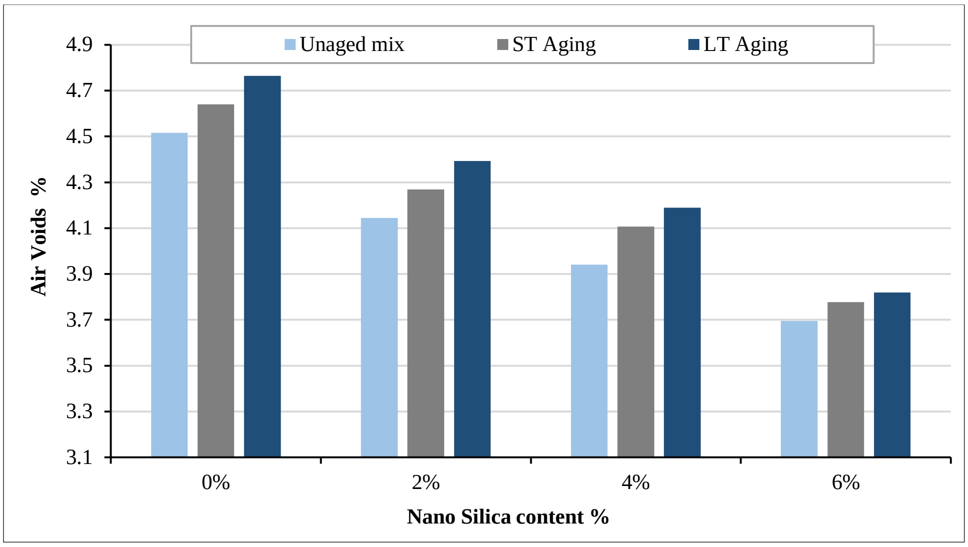


Figure 10. Effect of NS and aging on Air Voids

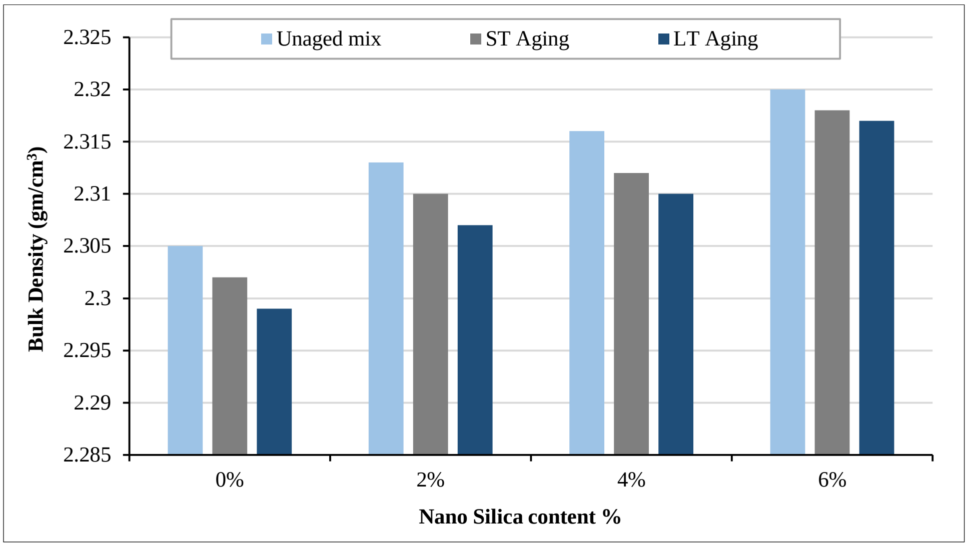


Figure 11. Effect of NS and aging on Bulk Density

The results of the aged samples showed that the 9VMA and the VFA were decreased with addition of 2 %, 4 % and 6 % of NS for different aging conditions. The effect of NS on VMA% and VFA% are shown in Figures 12 and 13 respectively.

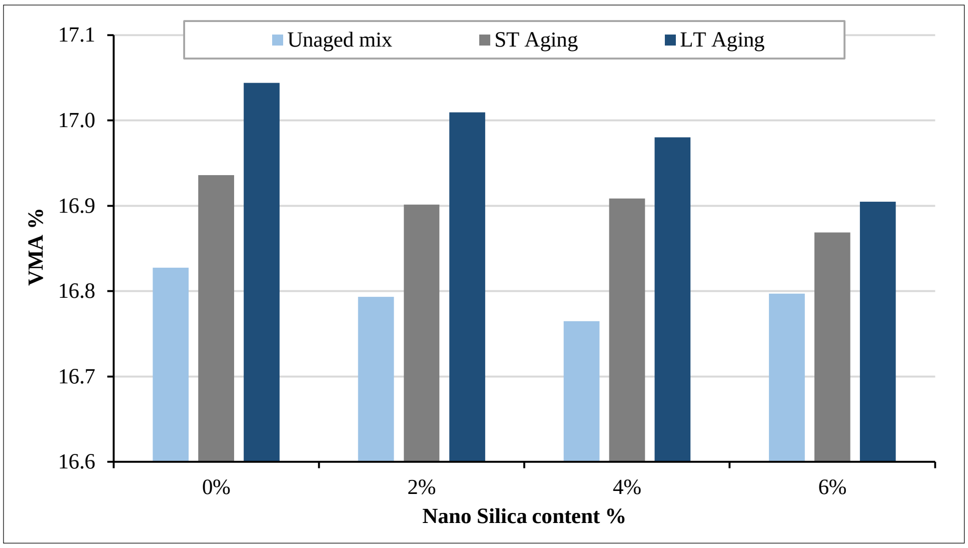


Figure 12. Effect of NS and aging on voids in mineral aggregate

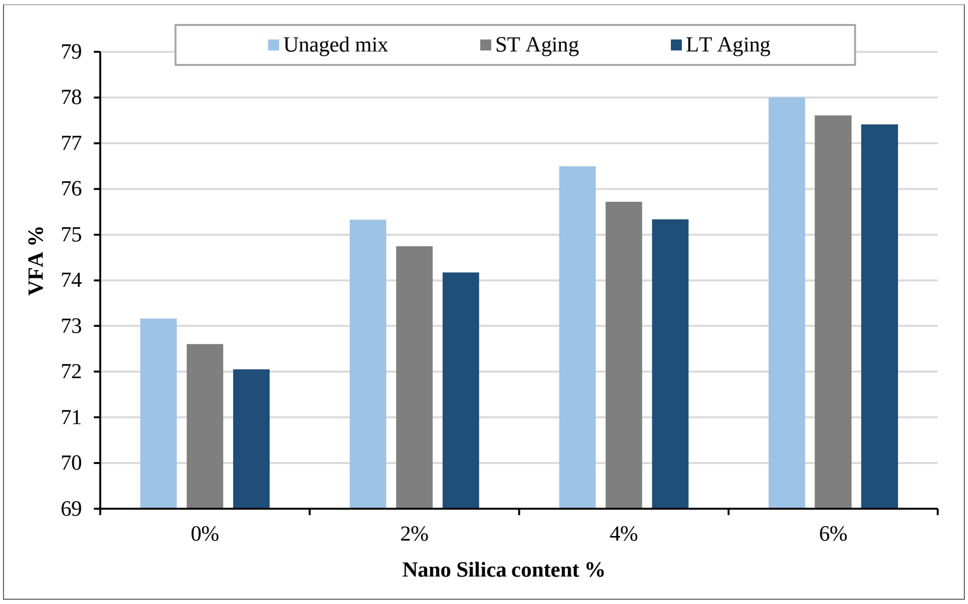


Figure 13. Effect of NS and aging on voids filled with asphalt

3.3. Wheel Tracking Test

Wheel tracking tests were conducted by applying a pressure of 70 psi at 45 ˚C and 55 ˚C on specimens containing various concentrations of NS (0, 2, 4, and 6%) and for three aging conditions: unaged, ST aging, and LT aging. In general, the rutting pattern observed at 70 psi is identical for both temperatures. Rutting decreases with aging, and the rut depth on NS-modified specimens is lower than that on control specimens. This clearly indicates a superior performance for NS-modified specimens at high temperatures. This trend can be seen in Figures 14 and 15, which summarize the maximum rut values obtained for all hot asphalt mixtures. The lowest rut values were achieved for a 6% unaged NS-modified mixture with only 2.4 mm and 3.1 mm at 45 ˚C and 55 ˚C, respectively.

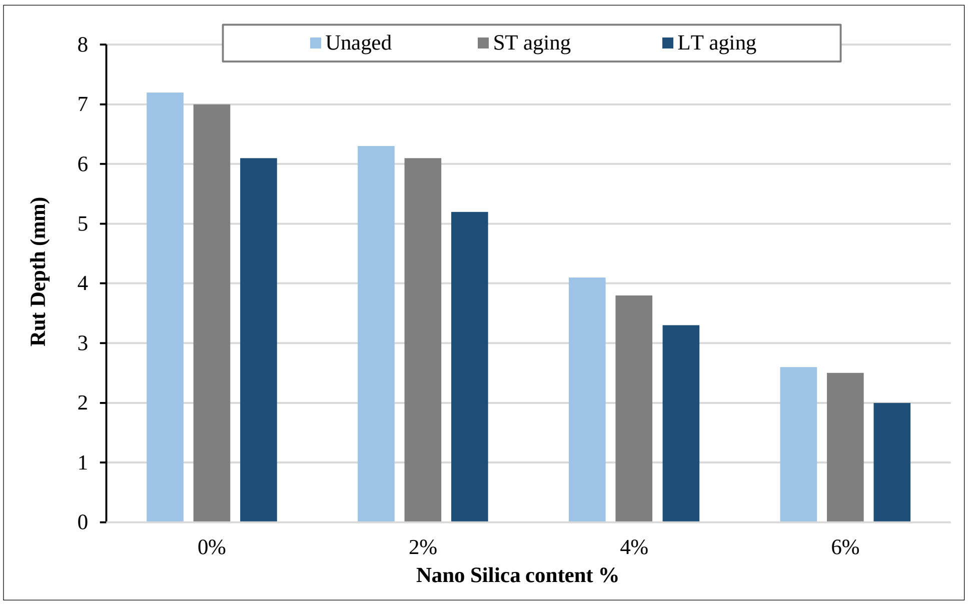


Figure 14. The effect of NS on rutting depth for (45 ˚C, 70 psi, 5000 cycles)

Figure 14 details rutting reduction values obtained at 45 ˚C and 70 psi. Adding 2, 4, and 6% NS decreased the rut depth of unaged modified specimens by 12.5, 43.06, and 63.89%, respectively. For ST-aged specimens, the rut depth decreased by 12.86, 45.71, and 64.29% with the addition of 2%, 4%, and 6% NS, respectively. For LT-aged specimens, the rut depth decreased by 14.75%, 45.9%, and 67.21%, with concentrations of 2, 4, and 6% NS, respectively. Rutting reduction values at 55 ˚C and 70 psi are presented in Figure 15. Adding 2, 4, and 6% NS decreased the rut depth of unaged modified specimens by 9.89%, 43.96%, and 62.64%, respectively. For ST-aged specimens, the rut depth decreased by 11.49, 43.68, and 63.22% for concentrations of 2, 4, and 6% NS, respectively. While for LT-aged specimens, the rut depth decreased by 12.49, 44.71, and 67.06%, with the addition of 2, 4, and 6% NS, respectively.

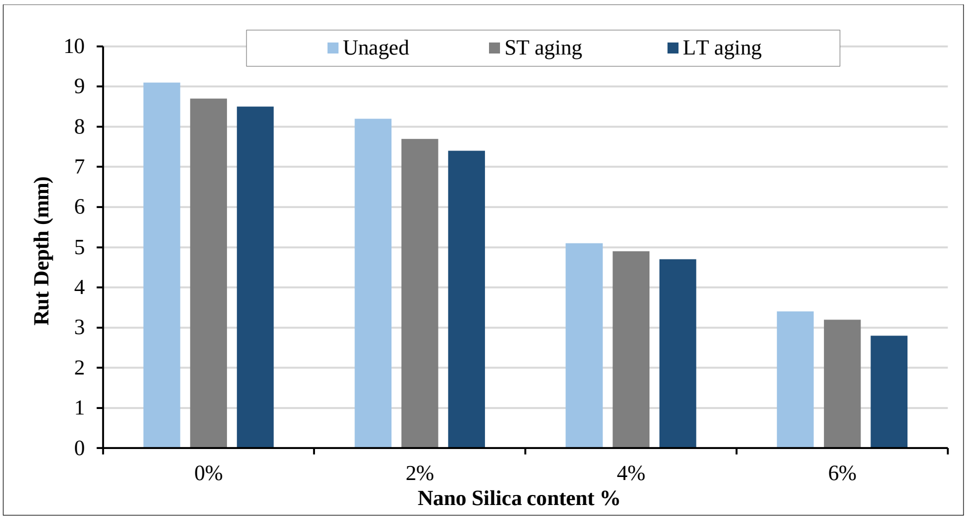
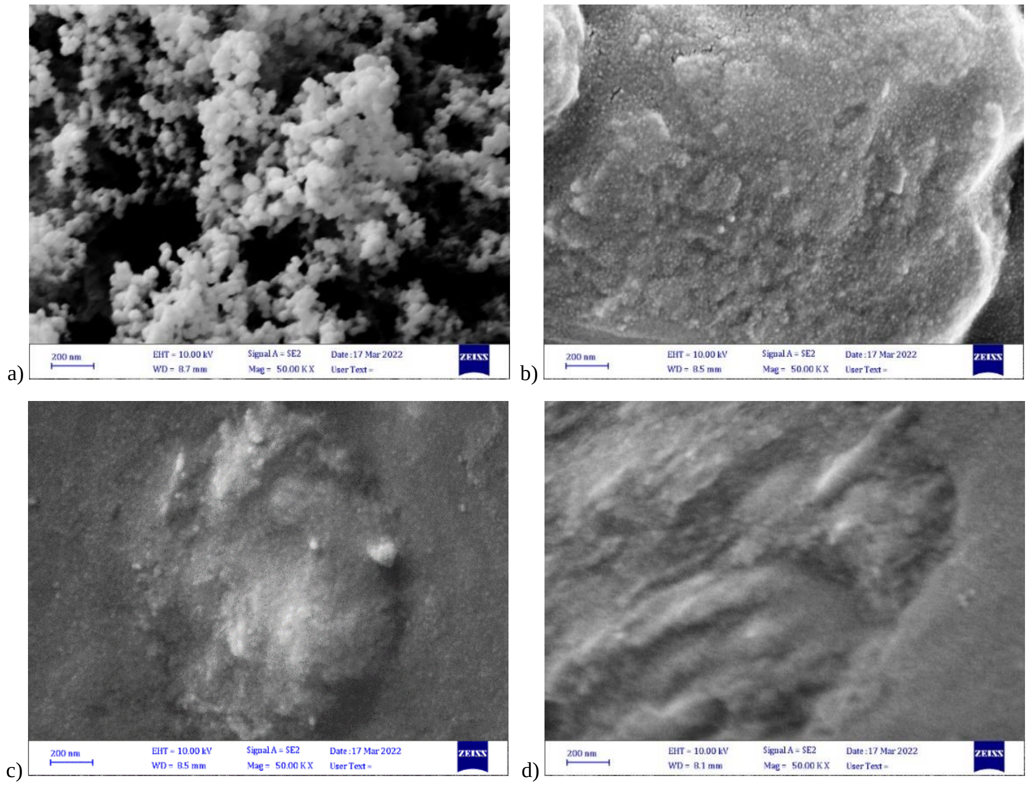


Figure 15. The effect of NS on rutting depth for (55 ˚C, 70 psi, 5000 cycles)

These results demonstrate that adding NS improves the asphalt's high-temperature performance by increasing its resistance to rutting. The rutting reduction results varied with the aging conditions and concentrations of NS. In addition, the highest reductions in rut depth were achieved on 6% NS-modified mixtures for all three aging conditions and both temperatures. This proves that 6% NS can maintain the rutting resistance of HMA for various aging conditions. These results may be attributable to the high surface area, good dispersion ability, and excellent stability of NS particles. When dispersed in asphalt binder, NS particles create a new structure that absorbs and transfers load more efficiently, hence boosting rutting resistance. The wheel tracking test results obtained in this study exhibit a good level of agreement with previously published research outcomes [14, 17, 19, 30].

3.4. Microstructural Analysis

FESEM images of NS-modified asphalt helped estimate the NS dispersion within the asphalt and understand the microstructure changes of modified asphalt. Figure 16 shows FESEM images of unmodified and NS-modified binders. As illustrated in Figures 16-b to 16-e the nanoparticles were uniformly distributed throughout the binder, this could be related to the high surface area and good dispersion ability of NS particles. Moreover, the surface of the NS-modified binder was rougher than that of unmodified asphalt, indicating a difference in surface properties. This alteration in the material's microstructure increases asphalt adhesion, which leads to the enhanced performance of NS-modified binders. This study's microstructural analysis findings agree with those obtained by Nazari et al. (2018) [31]. Finally, as shown in Figure 15(f), improved bonding properties between aggregates and binder may be achieved due to microstructural modifications, with the formation of a dense framework structure in the NS-modified asphalt mixture.



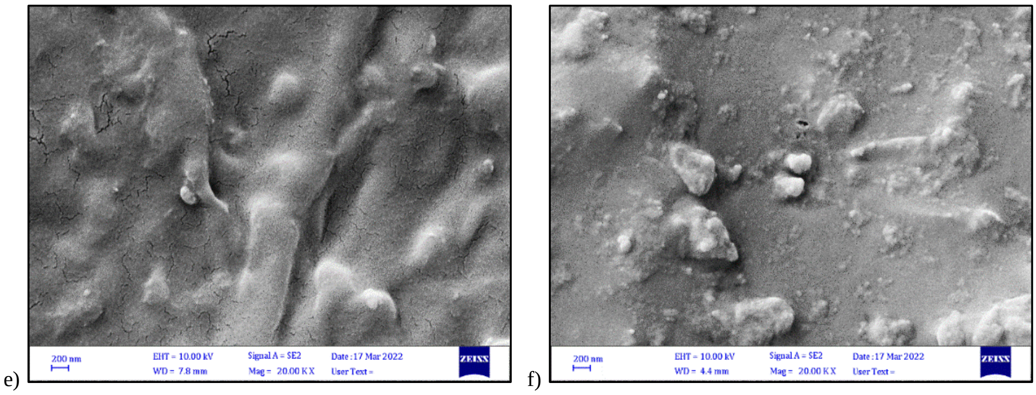


Figure 16. FE-SEM images for the NS and NS modified binders (a) Nano Silica, (b) Control binder, (c) 2% NS-modified binder, (d) 4% NS-modified binder, (e) 6% NS-modified binder, (f) 4% NS modified mixture

4. Conclusions

This research work investigated the performance of asphalt mixtures modified with NS. The following conclusions were reached:

- Adding NS to HMA caused a significant improvement in stiffness and consistency under various aging conditions compared to unmodified asphalt, thus enhancing the HMA's resistance to rutting;
- The addition of 6% NS increased Marshall stability by 33.1% in an unaged specimen. When aging was considered, adding 4% NS increased Marshall stability by 25.3% and 37.5% for short-term and long-term aging, respectively. The NS-modified asphalt mixtures had lower flow rates than the control mixture;
- The microstructure of NS-modified asphalt differed from that of the control asphalt binder. Moreover, observations indicated a uniform distribution of NS particles in the binder matrix;
- The modified specimens displayed a higher resistance to rutting at higher test temperatures. The rut depth in 6% NS-modified specimens decreased by 63.89% at 45 °C and 62.64% at 55 °C. The rut depth displayed an identical trend on short-term and long-term aged specimens, both types of aging improving the binder's resistance to rutting;
- Regarding pavement performance and resistance to rutting at higher in-service temperatures under different aging conditions, adding 4% NS to the asphalt binder produced the optimal increase in service life and quality of asphalt.

5. Declarations

5.1. Author Contributions

M.Q.I. and Z.K.T. contributed to the design and implementation of the research, to the analysis of the Results, and to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

This research was funded by the Department of Civil Engineering, College of Engineering, University of Baghdad.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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