Pakistan Journal of Scientific Research
Multidisciplinary & Peer Reviewed
Volume: 5, Number: 1, Pages: 20-28, Year:2025

Article

Nano Silica-Modified Asphalt: Enhancing Resistance to Rutting, Cracking, and Moisture Damage

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Submitted: 07-02-2025**, Revised:** 13-05-2025, **Accepted:** 25-05-2025

Abstract

Road infrastructure durability with extended lifespan through asphalt pavement determines its potential for sustainable development. The asphalt material experiences different types of damage throughout its existence. However, fatigue cracking is combined with rutting and moisture damage, which create major pavement failures that demand ongoing maintenance efforts. The exploration of Nano Silica (NS) nanomaterial modification of asphalt represents an emerging technique to bolster the mechanical and rheological capabilities. Nano Silica shows promise as an improving agent for asphalt binders because of its tiny particles and expansive surface area, which enhances stiffness and aging resistance while boosting rutting resistance. This study investigates the effect of Nano Silica on the physical properties of asphalt mixtures. Laboratory tests such as penetration and softening point while also evaluating ductility and Marshall Stability were conducted on traditional mixtures and mixtures that included NS modification. The evaluation of Asphalt performance enhancement required the addition of Nano Silica from 1% to 5% to identify the most effective amount. Lab results confirm that Nano Silica addition results in asphalt mixtures with higher stiffness levels, better thermal stability, and stronger permanent deformation resistance. Adding NS enhances the adhesive qualities between aggregate particles and asphalt binders, thus minimizing their susceptibility to moisture damage. Research determined the best NS addition level by weighing the mixture's performance outcomes against its ability to be easily worked. Research results confirm that Nano Silica is a successful modifier for improving asphalt pavement mechanical strength and service life capabilities. This research proves that nanotechnology investigations in pavement engineering can be valuable by examining asphalt mixture development for long-term usage in busy road networks.

Keywords: Nano Silica; asphalt mixture; pavement performance; rutting resistance; moisture damage.

1. Introduction

Road construction extensively utilizes the material known as asphalt because it provides outstanding mechanical characteristics alongside affordable operations and straightforward upkeep systems [1]. Asphalt pavements experience four primary degradation forms, including rutting fatigue cracking, thermal cracking, and moisture-induced damage, which shorten their operational existence [5]. Time-damaged asphalt pavements experience structural weakening due to environmental conditions, traffic load, and chronological deterioration. Research shows several enhancement techniques exist for asphalt performance by adding polymer fibers and nanomaterials [3]. In recent years, nanotechnology has risen in prominence because it enhances mechanical properties and rheological behavior and extends the durability of asphalt mixtures [2]. Research indicates that Nano Silica is an effective asphalt binder modifier thanks to its high surface area and strong bonding capabilities, making it an amorphous silicon dioxide form [4]. NS additives lead to asphalt improvements that increase its resistance at high temperatures, decrease its permanent deformation, and enhance its fatigue lifetime. NS improves the bond between asphalt and aggregates and lowers the amount of stripping and susceptibility to moisture damage [7]. Laboratory examinations show that asphalt modified with NS demonstrates superior resistance to aging and superior protection from oxidation, resulting in extended pavement service life. NS modification effectiveness depends heavily on temperature, dispersion method, optimized dosage, and particle size [9]. Youths need to solve two issues with NS implementation: achieving equal distribution within pavement components and finding the best NS dose for performance improvements [8]. Additional research needs to occur before NS implementation can be utilized adequately in pavement engineering practice. A laboratory experiment investigates NS effects on physical and rheological traits of asphalt mixture by performing penetration tests with additional softening points and viscosity and Marshall Stability tests [10]. Research outcomes from this investigation will generate stronger, sustainable asphalt pavement solutions that could be utilized in heavy traffic roads along with harsh environmental conditions.

2. Materials and Methods

This study utilizes asphalt binder and aggregates with nano silica as its materials. The used asphalt binder follows the standards of 70# penetration-grade asphalt, which remains a standard material for road building. Crushed stone with sand and mineral filler creates asphalt aggregates that meet the quality specifications of asphalt mixtures. The commercial provider supplies Nano Silica as an amorphous ultrafine silicon dioxide powder with high surface area properties to boost asphalt binder properties. The properties of the asphalt binder used in this study are summarized in Table I:

Table I: Properties of asphalt binder.

Property	Unit	Value
Penetration (25°C)	0.1mm	67.3
Ductility (15°C)	cm	22.8
Softening Point	°C	48.8
Wax Content	%	1.8
Flash Point	°C	328
Solubility	%	≥99.9
Density (25°C)	g/cm³	1.036

2.1 Nano Silica

Nano Silica is a nanomaterial with high surface area and strong bonding properties, which helps improve the stiffness and durability of asphalt mixtures. Three different types of hydrophobic Nano Silica were used in this study, shown in Table II.

Table II. Different types of Nano Silica

Type	BET (m^2/g)	Particle Size (nm)	Loss on Drying (%)	SiO_2 Content (%)
Silica	130 ± 25	12	≤1.5	≥99.8
OCS-Silica	110 ± 20	16	≤0.5	≥99.8
SOC-Silica	100 ± 25	14	≤0.5	≥99.8
SCA-Silica	125 ± 20	12	≤0.5	≥99.8

2.2 Sample Preparation

The evaluation of modified asphalt physical characteristics required the addition of different Nano Silica amounts (1%, 3%, and 5% based on asphalt weight) to the asphalt binder. The mixture preparation required continuous stirring at 4000 RPM with temperature-controlled heating of asphalt binder at 140°C for 60 minutes to achieve Nano Silica dispersion. Research teams used the modified asphalt to prepare asphalt mixtures by following the Marshall mix design process.

The researchers compacted each measured Nano Silica amount using standard Marshall hammer procedures. Several tests examined prepared specimens' physical and mechanical properties through penetration, softening point, ductility, and Marshall Stability measurements. Achieving assessment results was possible through tests that determined asphalt mixtures' performance in high-temperature deformation situations and their resistance to moisture damage. The collected test results determined the best amount of Nano Silica between workability and performance levels needed for actual field implementation.

Nano Silica alters asphalt mixtures to increase their stiffness, along with projected durability and minimal reduction in flexibility. The study about NS effects on asphalt performance supports the development of durable pavement solutions requiring minimal maintenance.

3. Experimental Procedure

3.1 Testing Methods

A comprehensive series of laboratory tests were conducted to evaluate the effects of Nano Silica on the mechanical and physical properties of asphalt mixtures. These tests followed standard procedures and specifications to ensure consistency and reliability of results. The key tests performed are described below:

- Penetration Test (ASTM D5): This test measures the hardness of asphalt by determining the depth (in tenths of a millimeter) that a standard needle penetrates under a 100g load at 25°C for 5 seconds. Lower penetration values indicate a more rigid and more resistant binder.
- Softening Point Test (ASTM D36) determines the temperature at which asphalt softens sufficiently to allow a steel ball to sink through a specified distance in a ring of bitumen. A higher softening point indicates better resistance to high-temperature deformation.
- Ductility Test (ASTM D113): The ductility of asphalt is measured by stretching a standard specimen at a specified rate and temperature until it breaks. The elongation (in cm) is recorded, and higher values indicate better flexibility and resistance to cracking.
- Marshall Stability and Flow Test (ASTM D6927): The Marshall Stability test measures the maximum load the asphalt specimen can withstand before failure. At the same time,

the flow value indicates the deformation corresponding to the peak load. Higher stability values represent stronger mixtures, whereas moderate flow values suggest good workability and flexibility.

- Dynamic Shear Rheometer (DSR) Test (AASHTO T315): The DSR test evaluates the viscoelastic properties of asphalt by applying oscillatory shear stress. It measures complex modulus (G*) and phase angle (δ), providing insights into the stiffness and resistance to rutting at high temperatures.
- Moisture Susceptibility Test (ASTM D4867): The resistance of asphalt mixtures to moisture-induced damage was assessed using the tensile strength ratio (TSR). Higher TSR values indicate better resistance to stripping and moisture damage.

3.2 Sample Preparation and Testing Conditions

Experimental samples of Nano Silica-modified asphalt mixtures received different NS proportions in amounts totalling 1% to 5% by weight of the asphalt. The experimental procedures for sample preparation accompanied testing activities as follows:

1. The high-shear mixer at 4000 RPM operated for 60 minutes, combined 140°C hot asphalt binder with Nano Silica to achieve complete particle dispersion.
2. Cylindrical asphalt specimens were formed by compacting a mixture of modified asphalt with aggregates using a standard Marshall hammer.
3. The testing specimens underwent defined laboratory aging procedures before testing as a technique to duplicate field-aged specimens.
4. The testing process included subjecting prepared samples to penetration, softening point, ductility, rheological tests, and Marshall Stability tests following standard test methods.
5. Tests delivered complete information about Nano Silica's impact on asphalt performance, enabling researchers to find the best dosage rates for durable pavements.

4. Results

4.1 Penetration and Softening Point

Tests confirmed that Nano Silica addition decreased the penetration depth of asphalt, indicating that it enhances asphalt material hardness and stiffness. The modified asphalt resisted high-temperature deformation because the softening point increased with Nano Silica content. Table III displays the obtained results.

Table III. Obtained results of Nano Silica

Nano Silica Content (%)	**Penetration (0.1 mm)**	**Softening point (°C)**
0% (Control)	67.3	48.8
1%	62.5	50.2
3%	58.7	52.1
5%	55.4	54.3

These results indicate that higher Nano Silica content results in stiffer asphalt, improving its resistance to permanent deformation at high temperatures, as shown in Figure 1.

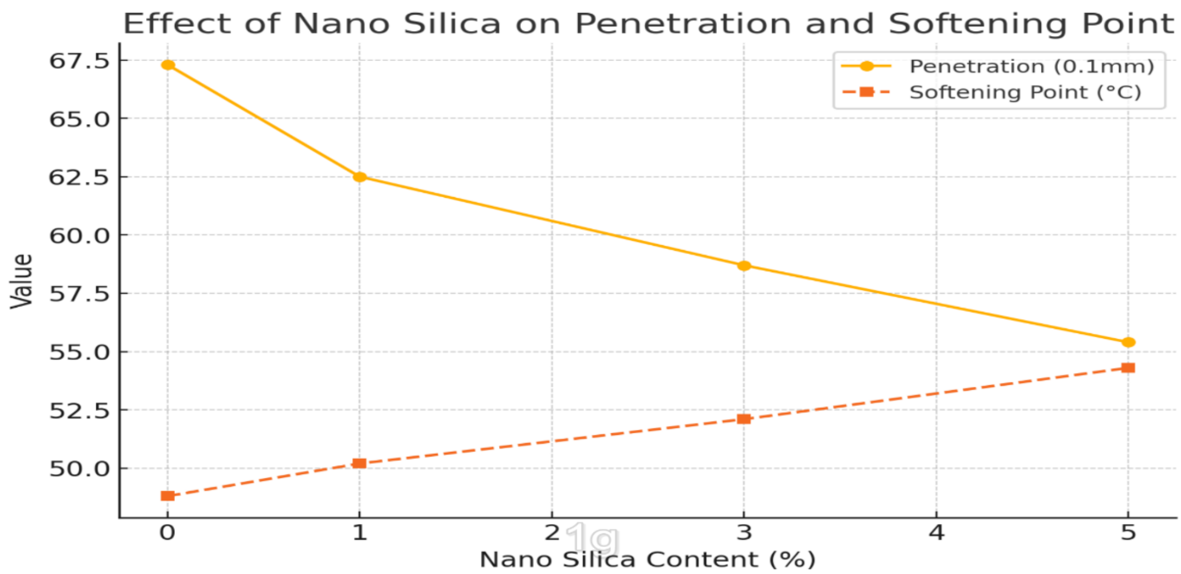

Figure 1. Effect of Nano Silica on Penetration and Softening Point

4.2 Marshall Stability and Flow

Asphalt mixture stability increased substantially when Nano Silica was added based on results from the Marshall Stability test. The maximum stability value occurred at a 3% Nano Silica ratio, but further addition led to lower stability levels due to increased stiffness. Table IV contains the summary of experimental data.

Table IV. Summary of experimental data

Nano Silica Content (%)	Marshall Stability (kN)	Flow (mm)
0% (Control)	12.4	3.2
1%	14.6	3.0
3%	17.2	2.8
5%	16.5	2.5

The increase in Marshall Stability suggests improved load-bearing capacity. At the same time, the decrease in flow values indicates increased stiffness, as shown in Figure 2.

4.3 Ductility and Moisture Susceptibility

Test results for ductility demonstrated that increased content of Nano Silica caused asphalt materials to become less flexible. The ductility test demonstrated that every specimen met the required flexibility standards. Evaluation of moisture susceptibility showed improved water resistance through Nano Silica modification because the tensile strength ratio (TSR) values increased, as shown in Table V.

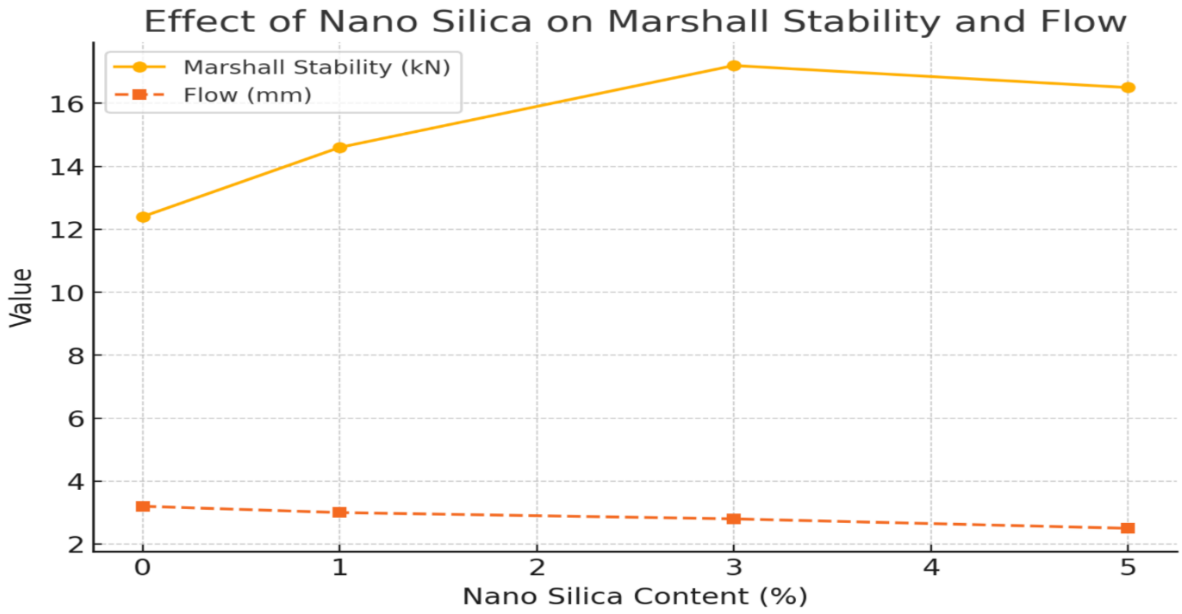

Figure 2. Effect of Nano Silica on Marshall Stability and Flow

Table V. Test result for ductility.

Nano Silica Content (%)	Ductility (cm)	Tensile Strength Ratio (TSR)
0% (Control)	22.8	78.5%
1%	20.6	82.3%
3%	18.4	86.7%
5%	16.9	88.2%

These results indicate that while ductility decreases with increased stiffness, the asphalt becomes more resistant to moisture-induced damage, as shown in Figure 3.

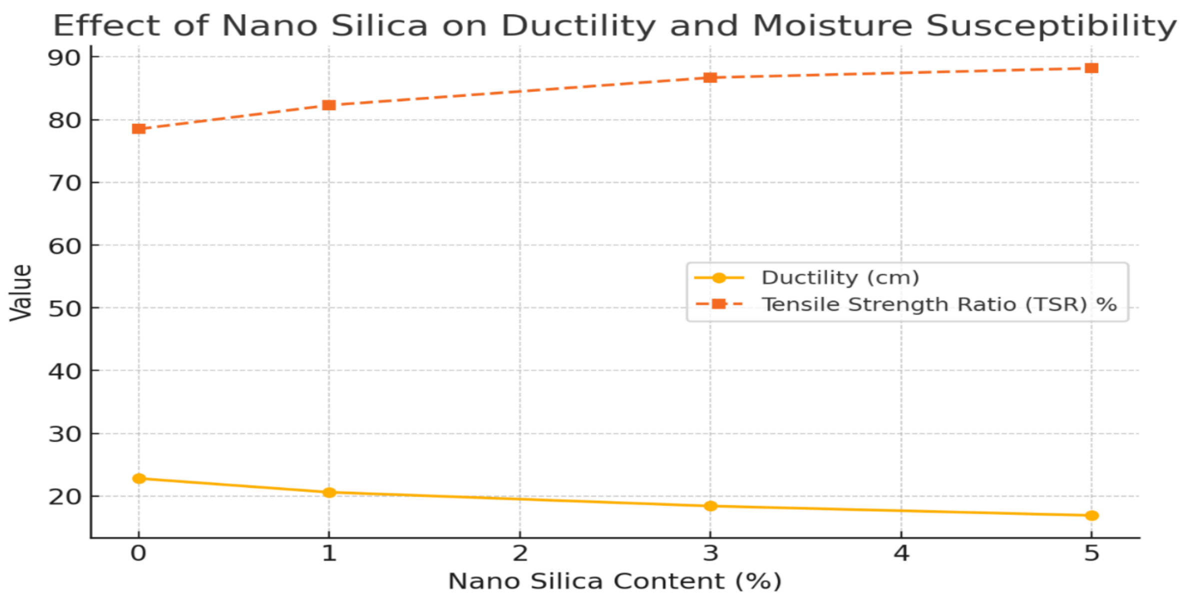

Figure 3. Effect of Nano Silica on Ductility and Moisture Susceptibility

4.4 Rheological Performance

DSR results displayed higher complex moduli (G*) values during tests with rising Nano Silica concentrations, strengthening stiffness, and rutting resistance properties. An improvement in elastic response and a reduction in permanent deformation became evident since the phase angle (δ) decreased, as shown in Table VI.

Table VI. DSR results

Nano Silica Content (%)	Complex Modulus (G*) (Pa)	Phase Angle (δ) (°)
0% (Control)	8200	85
1%	9300	81
3%	11200	77
5%	10750	74

These findings confirm that Nano Silica enhances the high-temperature performance of asphalt by increasing stiffness and elasticity, as shown in Figure 4.

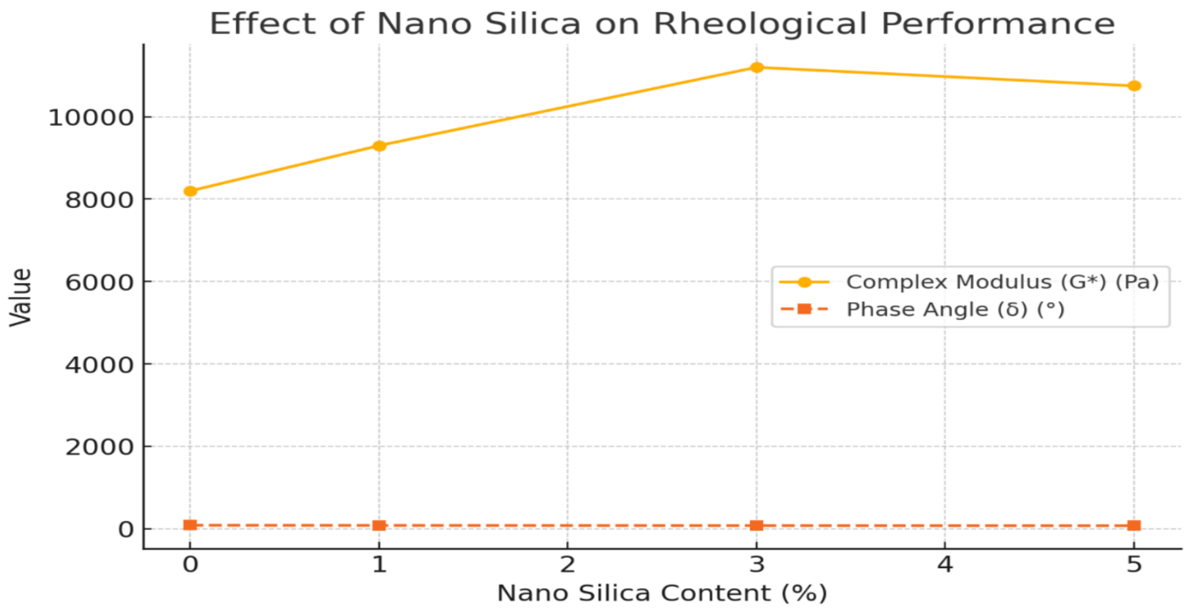

Figure 4. Effect of Nano Silica on Rheological Performance.

At the optimal dosage of 3%, Nano Silica proved to be an effective enhancer for asphalt, making it more durable and deformation-resistant.

4. Conclusions

A research project analyzed how Nano Silica affects asphalt mixture properties at the physical and mechanical levels. Experimental data allows researchers to make these statements:

1. The penetration test analysis shows that Nano Silica addition promotes asphalt stiffness, thus diminishing its vulnerability to permanent deformation.
2. The addition of Nano Silica raises asphalt softening points, which leads to better resistance to thermal deformation and high-temperature flow.

3. The highest stability occurs when testing the mixtures with 3% Nano Silica content according to the Marshall Stability test, resulting in improved load-bearing properties.
4. The results from ductility tests show that asphalt material flexibility decreases as Nano Silica proportions increase. Nevertheless, every tested sample fulfilled the acceptable ductility standards.
5. According to the tensile strength ratio (TSR) analysis, Nano Silica boosts asphalt moisture resistance, thus protecting asphalt from destructive water exposure.
6. Rutting resistance improves with a Rise in complex modulus (G*) according to data from Dynamic Shear Rheometer (DSR) testing.
7. Laboratory tests show that Nano Silica functions as an excellent asphalt mixer modifier to strengthen asphalt mixtures mechanically and in terms of durability. The laboratory experiments revealed that 3% of nano silica represented the ideal dosage since it provided excellent workability and the best performance outcomes. Long-term testing and field observations of Nano Silica-modified asphalt should be studied to establish its practical uses in constructing roads.

Recommendations

The study findings lead to the following suggestions:

1. The research demonstrates that adding 3% Nano Silica maximizes results in improved mechanical properties while maintaining workability. Researchers should test this 3% Nano Silica concentration when analyzing changing weather and traffic flow patterns.
2. Field testing of NS-modified asphalt mixtures should be conducted following laboratory benefits demonstration to evaluate their long-term aging performance, durability, and maintenance needs.
3. The rheological behavior of NS-modified asphalt requires testing with Multiple Stress Creep Recovery (MSCR) and Frequency Sweep evaluation methods to determine how NS-modified asphalt behaves under different stress conditions.
4. A thorough economic review of Nano Silica should exist to demonstrate its financial benefit during large-scale road construction. Moreover, the assessment of NS production's environmental effects and application processes must be conducted.
5. Future research must concentrate on developing improved mixing techniques because they directly affect the uniform distribution of Nano Silica in asphalt binders while avoiding agglomeration that reduces performance capabilities.
6. Seeking future investigation will study Nano Silica interactions with asphalt modifiers such as polymers and fibers to develop superior performing hybrid asphalt mixtures.
7. Using NS leads to increased moisture resistance. However, additional testing of combining NS with anti-stripping agents would lead to better durability of asphalt pavements exposed to wet weather conditions.

Author Contributions: Conceptualization, R.S., M.S., and U.A.; methodology, S.Q.; software, U.A.; validation, R.S., S.Q. and U.A.; formal analysis, S.Q.; investigation, R.S.; resources, U.A.; R.S.; writing—original draft preparation, U.A. and M.S.; writing—review and editing, S.Q. and M.S.; visualization, M.S. and S.Q.; supervision, R.S.; project administration, M.S. and R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.
Data Availability Statement: Data is available on reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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