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NANOTECHNOLOGY AND ACHIEVING SUSTAINABILITY OF BITUMEN

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ABSTRACT

Recently, countries around the world have increasingly adopted sustainable development plans, with Egypt being among these nations. As part of these efforts, the production of sustainable bitumen has proven to have a positive impact on enhancing the performance of asphalt mixtures. In this context, nanotechnology was employed to produce bitumen with desirable properties. This study utilized three cost-effective and readily available nanomaterials: nano clay, nano silica, and nano slag. These materials were ground using a ball mill to minimize raw material and grinding costs, and their particle sizes were analyzed using Scanning Electron Microscopy (SEM). Each nanomaterial was tested individually and in combinations of two or more, with proportions ranging from 1% to 5% by weight of asphalt. The findings revealed that the optimal formulation consisted of 2% nano clay and 2% nano silica by weight of asphalt. At this ratio, the penetration value decreased by approximately 16.13%, while the softening point temperature increased by about 14.34%. These changes enhance the asphalt's suitability for hot climates by improving its resistance to high temperatures. Additionally, the kinematic viscosity increased by approximately 20% at the optimal ratio, further contributing to the improved performance of the asphalt mixtures. In conclusion, the study demonstrated that incorporating nanotechnology into asphalt production significantly improves its sustainability and performance, marking a valuable advancement in modern infrastructure development.

KEYWORDS: Sustainability; Nanotechnology; Nanomaterials; Modified Bitumen

التكنولوجيا النانوية وتحقيق استدامة البيتومين

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الملخص

مؤخرًا، اعتمدت العديد من الدول في جميع أنحاء العالم خطط التنمية المستدامة، وكانت مصر من بين هذه الدول. لذلك، فإن إنتاج البيتومين المستدام له تأثير إيجابي على تحسين مخاليط الأسفلت. تم استخدام تكنولوجيا النانو لإنتاج بيتومين بخصائص مرغوبة. في هذه الدراسة، تم استخدام ثلاثة مواد نانوية سهلة الوصول وذات تكلفة منخفضة(نانو طين,نانو سيليكا ونانو خبث)، مع الحفاظ على تكاليف المواد الخام والطحن منخفضة. تم طحن هذه المواد باستخدام مطحنة كروية، وتم قياس أحجام الجسيمات باستخدام المجهر الإلكتروني الماسح (SEM). تم استخدام كل مادة بشكل فردي، بالإضافة إلى استخدامها في تركيبات من مادتين أو أكثر، تتراوح نسبها من ١٪ إلى ٥٪. أظهرت النتائج أن النسبة المثلى كانت ٢٪ من كل من الطين النانوي والسيليكا النانوية من وزن الأسفلت. عند هذه النسبة، انخفضت قيمة الاختراق بحوالي ١٦,١٣٪، وارتفعت درجة حرارة نقطة الانصهار بحوالي ١٤,٣٤٪. إن تقليص قيمة الاختراق وزيادة درجة حرارة نقطة الانصهار يجعل الأسفلت أكثر ملاءمة للبيئات الحارة، مما يعزز مقاومة مخاليط الأسفلت لدرجات الحرارة المرتفعة. كما أظهرت النتائج أن هذه النسبة زادت اللزوجة الحركية بحوالي ٢٠٪. من خلال هذه الاختبارات، تم التوصل إلى أنه يمكن جعل الأسفلت أكثر استدامة باستخدام تكنولوجيا النانو، مما يمثل تقدمًا كبيرًا في وقتنا الحالي.

الكلمات المفتاحية : الإستدامة ، النانو تكنولوجى ، مواد النانو، البيتومين المعدل.

1. INTRODUCTION

Nanotechnology has recently emerged as an innovative and impactful approach in the materials industry, with nanomaterials being widely utilized worldwide. The Scientific Board on Emerging and Newly Identified Health Risks defines nanomaterials as substances with dimensions—or internal structures—of 100 nanometers or less. These materials exhibit unique properties at this nanoscale that distinguish them from their larger-scale counterparts [1]. Numerous studies have evaluated the impact of nanomaterial modifications on the performance of asphalt mixtures. Three types of nanoparticles—zero-valent iron, silica, and bentonite nano clay—were incorporated into a 35/50 penetration grade asphalt. In all modifications, the nanoparticles were used at a concentration of 4% of the total mass of the modified binder. The results indicated that these nano modifications significantly enhanced performance, with nano silica showing a notable improvement in stiffness and resistance to permanent deformation [2,3]. Bitumen has long been used as a binder in highway and runway construction due to its excellent viscoelastic properties[1]. Bitumen is an organic mixture composed of various chemical compounds. Its physical and chemical properties and structure can change when exposed to heat, oxygen, and ultraviolet (UV) rays in a process known as aging [4].

Nano-silica has a large surface area, increasing particle collisions frequency. This higher collision rate enhances the particles' reactivity and chemical activity, potentially leading to greater instability[5]. Asphalt properties can be enhanced with various modifiers, including polymers, rubbers, metals, fibers, chemical agents, and sulfur. In recent years, nanomaterials have gained popularity in the engineering of highway pavements and research as a cutting-edge modifier for bitumen [6]. Nanotechnology has found applications in various fields, including pavement engineering, where it is used to introduce new devices, materials, and systems at the molecular level. While many researchers have investigated the use of nanomaterials in Portland cement, their application in asphalt pavements has gained attention more recently. In recent years, there has been a growing effort to enhance asphalt materials by incorporating nanomaterials in both cementing asphalt and emulsions. A variety of nanomaterials, such as nano silica, nano clay, nano-hydrated lime, polymerized powders, nano-sized plastic powders, nanotubes, and nanofibers, have been or are expected to be utilized in asphalt modification [7].

The study investigated the impact of nano silica on the chemical bonding and rheological properties of asphalt. The results showed that while the viscosity of the modified asphalt with nano silica decreased slightly, there was a significant increase in the dynamic modulus of the modified asphalt mixture. Additionally, the rut depth of the modified asphalt mixture was significantly reduced [8].

The rutting resistance of Hot Mix Asphalt (HMA) specimens containing nano TiO_2 was evaluated using the Hamburg Wheel Track Device (HWTD). Nano TiO_2 was added at various concentrations (1.5%, 3.5%, 5.5%, and 9%) to enhance the properties of a 60–70 asphalt binder. The results indicated that nano TiO_2-modified binders improved both the rheological and physical properties of unaged and aged asphalt binders. Furthermore, the modification significantly increased the rutting resistance of the asphalt mixtures. Statistical analysis confirmed that nano TiO_2 significantly enhanced most of the tested properties of the base asphalt binder. However, the incorporation of nano TiO_2 had an insignificant effect on the stiffness and the Jnr Nanotechnology is also applied in concrete mixtures, driving the development and utilization of nanoscale scientific concepts and nanofiber materials. Research has shown that nanofibrous cement-based materials can effectively address minor damage, while also limiting the changes in strains, temperatures, and stresses within joints and structural components [10] .Common clays are naturally occurring minerals, and their composition can vary significantly. Most clays are alumina-silicates with a layered structure, consisting of sheets made up of silica (SiO_4) tetrahedra connected to alumina (AlO_6) octahedra in various configurations. The properties of nanocomposites are largely influenced by the chemistry of the organic cations and polymer chains, as well as by the methods used to disperse and incorporate the clay within the nanocomposite [11]. Efforts have been made to enhance the technical characteristics of asphalt mixtures by incorporating carbon nanotubes into bitumen. The research examined the Marshall parameters for hot mix asphalt modified with 0.1%, 0.5%, and 1% carbon nanotubes, comparing them with conventional asphalt mixtures. Among the methods of incorporating carbon nanotubes, the dry process was chosen as the most practical for this study. The results indicated that increasing the amount of carbon nanotubes improved the properties of asphalt concrete. Specifically, the sample with 0.01% carbon nanotubes by weight of bitumen demonstrated the best performance. This sample showed a 32.53% increase in Marshall Stability and a 44.71% improvement in the Marshall Ratio compared to the control sample. Additionally, it exhibited an 8.4% reduction in Marshall Flow and a 0.68% decrease in specific gravity, all of which were still within acceptable regulatory limits. Although the initial cost of the samples with 0.005% and 0.01% carbon nanotubes was higher than that of the control sample, the overall cost may be lower. This is because the modified mix, due to its improved strength, requires a thinner underlying layer compared to the control mix, potentially reducing total expenses [12].

The study examined the effect of Carbon Nanotubes (CNT) on asphalt binder. The results indicated that the incorporation of CNT as an additive led to improvements in the rheological properties of the asphalt binder [13]. The study examined the impact of nano clay on the properties of bitumen modified with Styrene-Butadiene-Styrene (SBS). The results showed that as the percentage of nano clay increased, the penetration of bitumen decreased, while the softening point increased [14]. The study examined the impact of nano clay on the properties and rheological characterization of asphalt binders. The results indicated that as the percentage of nano clay increased, both the viscosity and softening point of the asphalt binder also increased [15]. The study suggested using calcium oxide (CaO) to enhance the properties of bitumen and asphalt mixtures. The results indicated that CaO nanoparticles improved the penetration properties of bitumen, leading to a 28.9% decrease in penetration value. Additionally, the softening point increased with higher percentages of nano CaO, specifically rising by 24.5% when 5% nano CaO was added to the bitumen [16]. Previous research has explored the use of various nanomaterials in bitumen and asphalt mixtures, but a deeper understanding of their effects on bitumen's physical and rheological properties is still needed. This study focuses on modifying bitumen with nano clay, nano silica, and nano slag. Nano silica and nano clay will be added at concentrations ranging from 1% to 5%, based on findings from previous studies and economic considerations. The modified bitumen will be evaluated through penetration tests, softening point measurements, and kinematic viscosity assessments. The results will be compared to those of unmodified bitumen to assess the impact of the nanomaterials. Additionally, silica fume will be blended with virgin bitumen at proportions of 2%, 4%, and 8% by weight of bitumen. The findings showed that the silica fume-modified binder exhibited lower sensitivity to temperature and greater resistance to aging effects compared to the unmodified virgin binder [17]. The results showed significant improvements in the physical and rheological properties, temperature susceptibility, and rutting resistance of asphalt modified with high levels of NSF.

Additionally, the NSF additive significantly reduced the acceleration of short-term aging compared to NS [18]. An additional laboratory study was conducted to evaluate the performance properties of the corresponding asphalt mixtures, focusing on resilient modulus, indirect tensile strength, fracture energy, moisture susceptibility, and fatigue life. The results indicated that the incorporation of NS material positively influenced various properties of both the asphalt binder and mixture. This enhancement suggests that NS-modified asphalt can be used in the construction of more durable pavements, thereby reducing life-cycle costs [19]. The modified binders with 30%, 40%, and 50% NSF were selected to prepare NSF-modified mixtures. The results revealed that asphalt mixtures with 30%, 40%, and 50% NSF-modified binders exhibited greater resistance to moisture damage, rutting, and fatigue cracking compared to the control mixture. The innovation of this research lies in the ability to produce a modified asphalt mixture using only two-thirds of the amount of bitumen, while still achieving superior performance compared to the control mixture [20].

2. MATERIAL CHARACTERIZATION

2.1. Bitumen

Suez Petroleum's virgin 60/70 penetration grade bitumen was chosen as the basis binder. The bitumen was tested at the General Authority of Roads and Bridges's laboratory. Its physical values are shown in **Table 1**.

Table1: Physical & mechanical characteristics of the bitumen

Tests	Penetration (0.1 mm)	Softening point (ºc)	Flashpoint (ºc)	Kinematic viscosity (cst)
AASHTO NO.	T-49	T-53	T-48	T-201
Results for bitumen	62	47.4	268	446
Specification Limits	60-70	45-55	+250	+320

2.2. Modifiers

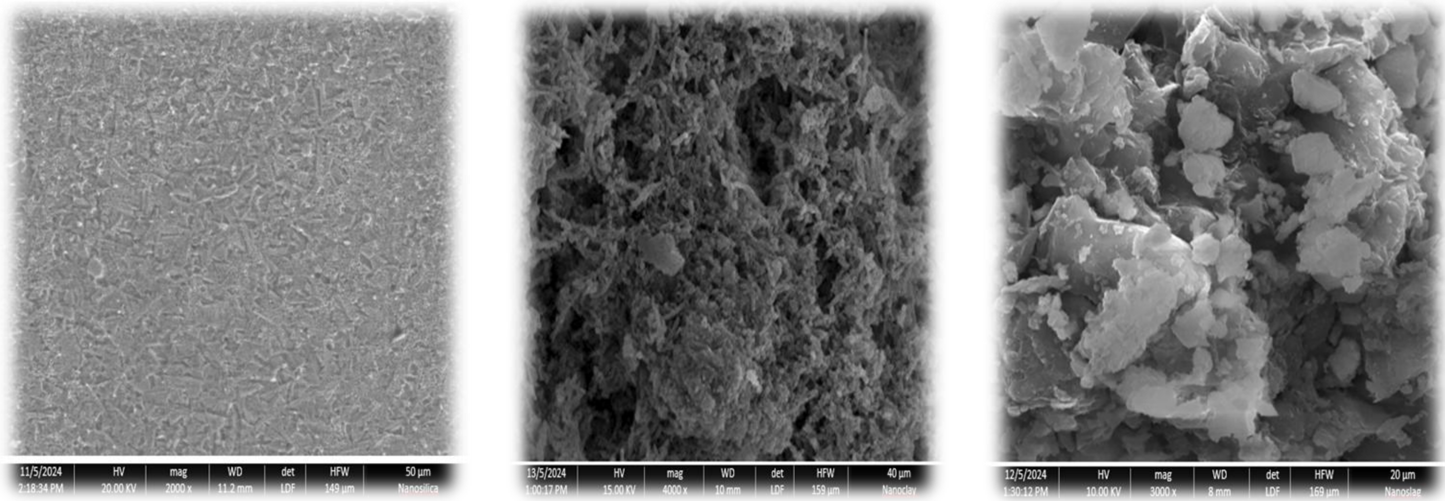
In this study, different nanomaterials were used as modifiers for bitumen. These materials were ground using a Standard Ball Mill Machine, as shown in **Fig.1**, with a grinding ratio of 1:10, resulting in nanometer-sized materials: nano clay, nano silica, and nano slag, as illustrated in **Fig.2**. To ensure nanometer size, scanning was conducted on the three materials at the Institute for Mineral Studies using scanning-electron-microscope (SEM), shown in **Fig. 3**. The scans revealed that the nanomaterials have particle sizes ranging from 20 to 70 nanometers, as depicted in **Fig. 4**. **Table 2** also details the chemical and physical characteristics of the three materials.

Fig. 1: Standard Ball Mill Machine

(a) Nano-Clay Powder (b) Nano-Silica Powder (c) Nano-Slag Powder

Fig. 2: Nanomaterial's powder

Fig. 3: Scanning electron microscopy (SEM)



(a) Nano silica (b) Nano clay (c) Nanoslag

Fig. 4: SEM images for the nanomaterial's modifiers

Table 2: Chemical Analysis of Nano Materials

Chemical Composition	Nanosilica%	Nanoclay%	Nanoslag%
Silica (SiO_2)	92.7	51.23	**12.45**
Alumina Oxides (Al_2O_3)	7.45	19.73	**8.68**
Ferric Oxides (Fe_2O_3)	0.075	5.70	**3.15**
Calcium Oxides (CaO)	0.07	1.83	**32.42**
Magnesium Oxides (MgO)	0.24	3.42	**10.29**
Sodium Oxides (Na_2O)	0.03	0.93	**0.87**
Potassium Oxides (K_2O)	**0.05**	**0.82**	**0.11**

2. Modified Bitumen Preparation

The asphalt content was heated to 135°C ± 5°C to produce the modified bitumen. Then, different percentages of nano-slag (1.5%, 2%, 3%, and 5%) by weight of bitumen were added to produce the modified bitumen. The base bitumen was mixed with the nano materials using a high-speed shear mixer at a shear speed of 2000 rpm for one hour. The control sample and the modified asphalt binders were prepared as outlined in **Table 3.**

Table 3. bitumen samples

Binder type	Sample code	Description
Unmodified bitumen	Control	(Control).
(Modified bitumen) +Nano Clay.	NC5	Control +5%NC
(Modified bitumen) + Nano Silica.	NS5	Control +5%NS
(Modified bitumen) + Nano slag.	NSg3	Control +3%NSg
(Modified bitumen) + Nano Clay and Nano Silica	NC2NS1	Control +(2%NC+1%NS)
(Modified bitumen) + Nano Clay and Nano Silica	NC2NS2	Control +(2%NC+2%NS)
(Modified bitumen)+ Nano Clay, Nano Silica, and Nano slag.	NC2NS2NSg2	Control +(2%NC+2%NS+2%NSg)

4. RESULTS AND DISCUSSION

4.1 Penetration Test

A penetration test was managed to examine the impact of different nanomaterials on the penetration grade of bitumen. Three modified bitumen samples were prepared for each type of addition to measuring the distance the standard needle penetrates the bitumen sample at 25°C. The results indicate that adding a blend of nano-silica and nano-clay to bitumen reduces penetration value. The penetration value decreases from 62 for unmodified bitumen to 52 with the addition of 2% of both materials combined, meaning this addition reduces the penetration value by approximately 16.13%. This reduction is preferred in high-temperature areas, and this percentage was optimal compared to other additions. Improved penetration can increase the hardness of bitumen, which may boost the strength of asphalt mixtures against rutting. However, this added hardness could also make the bitumen more cracked and prone to fatigue under heavy loads. Nonetheless, the level of hardness enhancement was not sufficient to cause significant brittleness, making the increased hardness a beneficial characteristic of bitumen. **Fig. 5** shows the Penetration apparatus. **Fig. 6** shows the results of the penetration test.

Fig. 5: Penetration apparatus

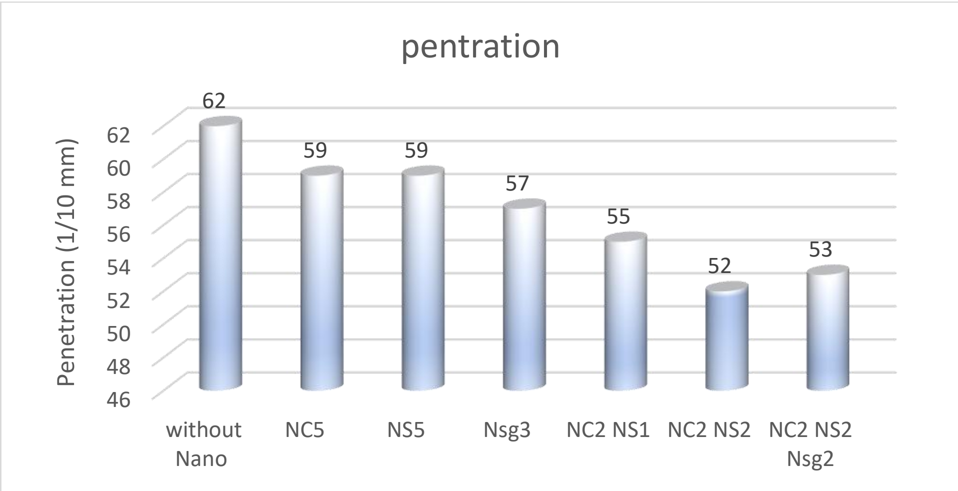


Fig. 6: Results of Penetration Test.

4.2 Softening Point

In the softening point test for bitumen modified with nanomaterials**. Fig. 7** shows the apparatus for the bitumen softening point test, the outcomes, as figured in **Fig. 8**, show that adding nanomaterials increases the softening point of the bitumen. This suggests better resistance to high temperatures in asphalt mixtures. The results show that the softening point increased by 14.34% with 2% each of nano silica and nano clay, making the combination the optimal ratio compared to other additions for achieving the highest softening point. Improving the softening point can decrease the thermal sensitivity of the bitumen. Consequently, a rise in the softening point can decrease changes in bitumen specifications due to heat fluctuations, as the modified bitumen's sensitivity to temperature variations is reduced. The modified bitumen could be utilized in areas with high annual temperatures or regions with heavy traffic.

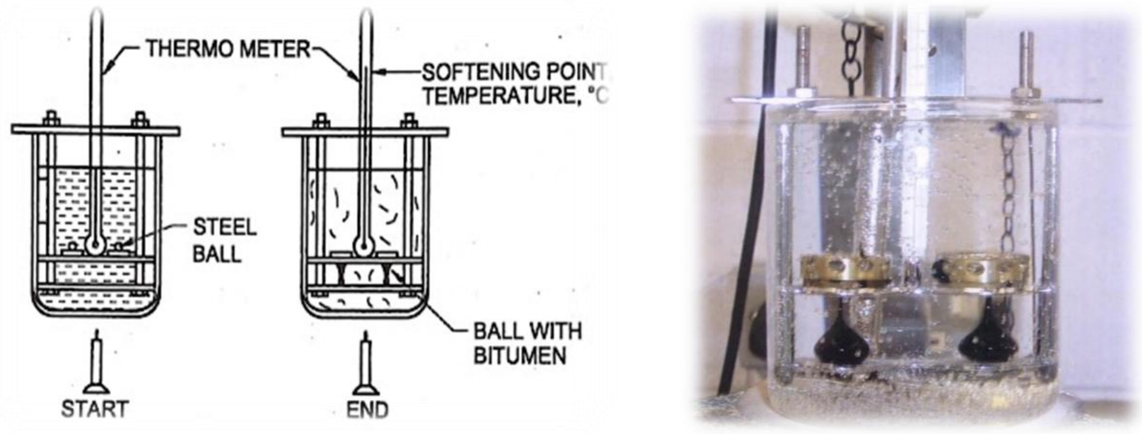


Fig. 7: Softenig point test machine

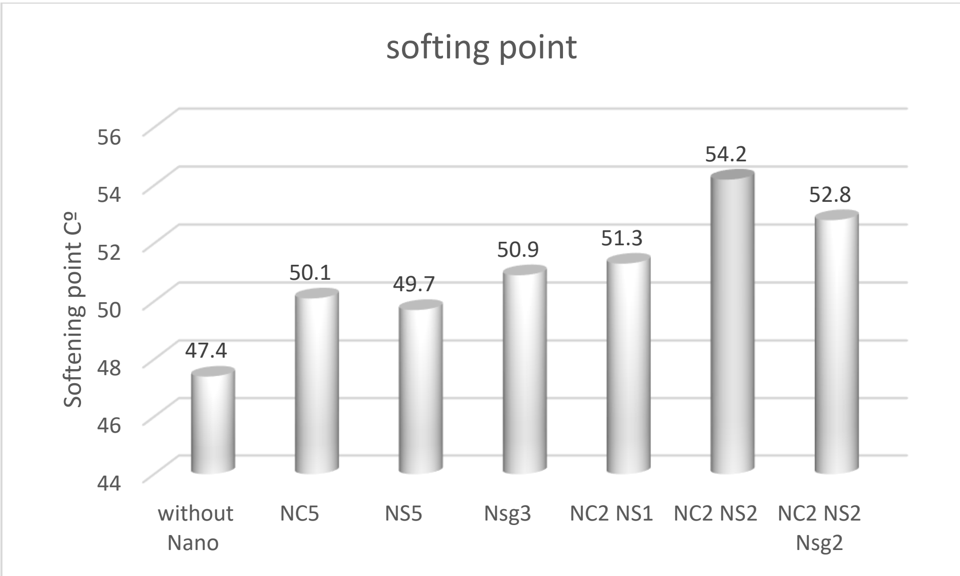


Fig. 8: Softening Point Test Results

4.3 Kinematic Viscosity

The kinematic viscosity test was performed as shown in **Fig.9** at 135°C to evaluate the effect of nanomaterials on bitumen viscosity. The results showed that adding 2% of both nano clay and nano-silica together led to a 20% increase in kinematic viscosity, making this ratio the optimal one compared to the other tested combinations, as shown in **Fig.10.**

Fig. 9: Viscosity test machine

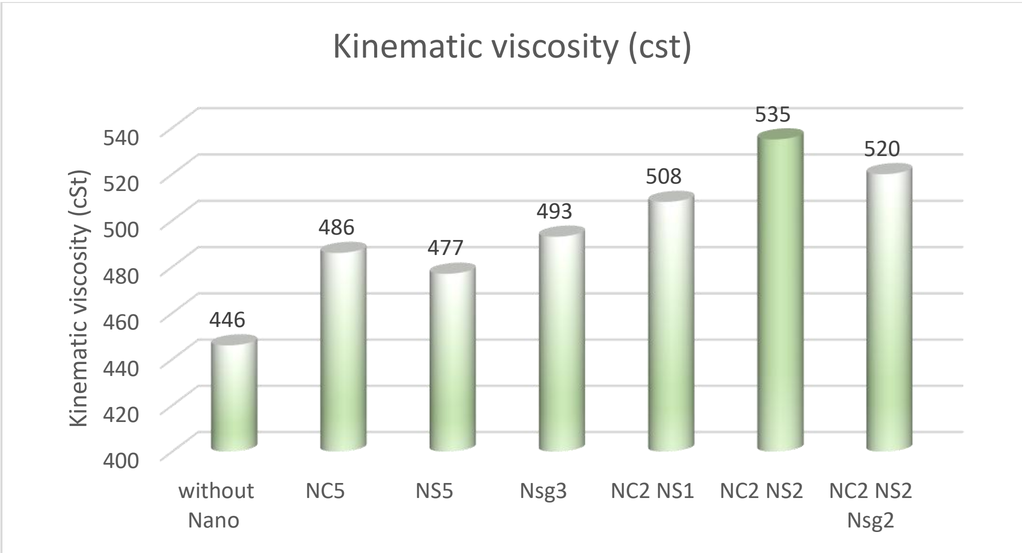


Fig. 10: Kinematic Viscosity Test Results

The decrease in penetration value, increase in softening point, and increase in viscosity reflect an improvement in the bitumen's resistance to deformation under hot conditions. This indicates that the modified bitumen can retain its shape, strength, and mechanical properties in environments exposed to high temperatures, reducing issues such as rutting. Additionally, it can withstand large volumes of traffic movement. The optimal ratio determined (2% nano-silica and nano-clay) provides a good balance between enhancing stiffness without causing excessive brittleness, thereby improving the performance of the modified bitumen compared to other additives.

CONCLUSIONS

This study compares the effects of incorporating various percentages of nanomaterials, including nano-slag, nano-clay, and nano-silica, into bitumen to enhance its mechanical, physical, and chemical properties. Using these materials in bitumen is crucial for achieving substantial environmental and economic benefits and plays a key role in promoting sustainability.

The usage of nanomaterials significantly affects asphalt properties. Results indicate that using a blend of nanomaterials as an asphalt modifier can greatly improve properties to withstand high temperatures and heavy traffic loads. The findings show that the optimal ratio is 2% for each nano-clay and nano-silica based on the heaviness of asphalt. At this ratio, the penetration value decreased by about 16.13%, and the softening point temperature rose by approximately 14.34%. The reduced penetration value and increased softening point temperature make the asphalt more suitable for hot environments, and the asphalt mixtures become more resistant to high temperatures. The results also showed that this ratio increased the kinematic viscosity by about 20%.

It is recommended that the performance of bitumen in asphalt mixtures be examined when modified with various nanomaterials. Additionally, skid resistance should be evaluated to understand the impact of nano-silica, nano-slag, and nano-clay on the surface roughness of asphalt mixtures.

Using other Nano materials (Carbon Nanotubes, Nano Cement, Nano Rubbers, etc) with different percentages to modify bitumen and asphalt mix; and study their effects on bitumen and asphalt mix properties.

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