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EXPLORING THE IMPACT OF NANOTECHNOLOGY ON ENHANCING ASPHALT MIX PROPERTIES: A COMPREHENSIVE REVIEW

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ABSTRACT

Asphalt is one of the most widely used paving materials globally, known for its exceptional properties, including water resistance, adhesion, durability, and high bonding capacity. However, the significant increase in traffic loads and driving speeds in recent years has resulted in a notable reduction in the service life of asphalt pavement layers, leading to higher maintenance requirements and increased accident risks due to the deteriorating condition of roads. Several studies have shown that the use of advanced nanomaterials can significantly enhance the adhesion properties of asphalt and asphalt mixtures at varying percentages of binder weight. Additionally, it is crucial to consider the environmental impact of nanotechnology to ensure sustainable development. Furthermore, applying these technologies can contribute to improving the quality and durability of asphalt mixes and pavements while also reducing construction and maintenance costs. This research aims to provide a comprehensive review of the latest developments in the use of nanotechnology in asphalt engineering, focusing on improving the performance of asphalt pavements to meet the evolving demands of modern transportation. These developments play a vital role in enhancing the physical and mechanical properties of bitumen and asphalt mixtures, contributing to producing sustainable asphalt that aligns with technological progress and plans. Studies indicate significant benefits in terms of long-term durability. Finally, the research highlights the challenges and practical applications of these technologies, helping practitioners identify the best approaches and methods for future studies.

KEYWORDS: Nanotechnology; Nanomaterials; Modified Bitumen; Asphalt Mixture; Sustainability

استكشاف تأثير تكنولوجيا النانو على تعزيز خصائص خلطات الأسفلت: مراجعة شاملة

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الملخص

يُعتبر الأسفلت من أكثر مواد الرصف استخدامًا على مستوى العالم، حيث يتميز بخصائص استثنائية تشمل مقاومته للماء، وفعاليته في الالتصاق، ومتانتّه، وقدرته العالية على الترابط. ورغم هذه الخصائص، فإن الزيادة الكبيرة في الأحمال المرورية وسرعات القيادة في الآونة الأخيرة قد أسفرت عن تقصير ملحوظ في العمر الافتراضي لطبقات الرصف الأسفلتي، مما أدى إلى ارتفاع متطلبات الصيانة وزيادة مخاطر الحوادث الناتجة عن تدهور حالة الطرق. تشير العديد من الدراسات إلى أن استخدام المواد النانوية المتقدمة يمكن أن يكون له تأثير كبير في تحسين خصائص المواد اللاصقة للأسفلت والمخاليط الإسفلتية بنسب متفاوتة من وزن البيتومين. بالإضافة إلى ذلك، فإن من الضروري أخذ التأثير البيئي لتقنيات النانو في الاعتبار لضمان تحقيق التنمية المستدامة. وعلاوة على ذلك، يمكن لتطبيق هذه التقنيات أن يسهم في تحسين جودة ومتانه المخاليط والأرصفة، فضلاً عن تقليل تكاليف البناء والصيانة. يهدف البحث الحالي إلى تقديم مراجعة شاملة لأحدث التطورات في استخدام تقنيات النانو في مجال هندسة الأسفلت، مع التركيز على تحسين أداء الرصف الأسفلتي بما يتوافق مع المتطلبات المتزايدة للنقل الحديث. تلعب هذه التطورات دورًا حيويًا في تحسين الخصائص الفيزيائية والميكانيكية للبيتومين وخلطات الأسفلت، مما يساهم في إنتاج أسفلت مستدام يتماشى مع التقدم التكنولوجي والخطط المستقبلية. تشير الدراسات إلى فوائد كبيرة من حيث المتانة طويلة الأمد. أخيرًا، يسعى البحث إلى تسليط الضوء على التحديات والتطبيقات العملية لهذه التقنيات، مما يساعد الممارسين على تحديد الاتجاهات والأساليب الأمثل في الدراسات المستقبلية.

الكلمات المفتاحية : تكنولوجيا النانو، مواد نانو، خليط الاسفلت، بيتومين معدل، استدامة.

1. INTRODUCTION

The increasing costs of constructing and maintaining concrete and asphalt pavements call for alternative solutions. The incorporation of nanomaterials with asphalt offers significant economic and performance benefits. This paper examines seven types of nanomaterials, including nano clay and carbon nanotubes, by exploring their production methods, advantages, and applications. It also addresses the challenges associated with using nanomaterials in concrete and asphalt pavements, such as economic concerns, material production issues, and mixing challenges, which are partly due to insufficient research. This study provides a framework to support experimental research aimed at developing new binder materials using nanomaterials, which may potentially enhance the performance of flexible pavements [1].

Nanomaterials offer great potential for improving asphalt performance due to their unique properties. This review highlights how they enhance key characteristics like stiffness, durability, and resistance to aging and UV. Despite some challenges, long-term benefits such as lower maintenance and longer pavement life make them a viable option in road engineering [2]. The asphalt industry is rapidly embracing nanotechnology, outpacing many other sectors due to the significant benefits it offers. Nanomaterials, for instance, can act as modifiers and reinforcements in asphalt, dramatically enhancing its performance. These technologies enable the creation of materials with exceptional stiffness, even at low concentrations. By examining asphalt at the molecular level, researchers can gain a deeper understanding of the interactions between its components, enabling them to develop more durable and high-performance materials.

Nanomaterials play a crucial role in controlling crack formation, reducing air voids, and enhancing the bonds between the different components of the asphalt mixture. The use of nanomaterials like nano-silica promises to help develop the next generation of asphalt with superior properties. Before the early 1990s, asphalt research was limited, with only a basic understanding of its composition and material properties. However, advances in microscopy and imaging techniques have enabled scientists to study asphalt at much higher resolutions. Furthermore, breakthroughs in other scientific fields have provided new methods to refine existing asphalt models, leading to valuable new insights. The integration of nanotechnology in asphalt research also benefits from advances in disciplines such as colloid science, chemistry, biology, biochemistry, solid-state physics, and materials science [3-5].

Nanomaterials exhibit unique morphological features at the nanoscale, with special properties that arise from their small dimensions [6]. Due to their remarkable mechanical, thermal, barrier, optical, electrical, and magnetic properties, polymer-based nanocomposites have attracted a lot of interest from both academia and industry since the Toyota Research Center developed high-performance polyamide 6/clay nanocomposites [7,8]. Materials science and technology research focuses on materials at many different scales, including macro, micro, and nanoscale. Usually, a dark or black liquid, semiliquid, or solid asphalt is a complex mixture of hydrocarbons with different molecular weights and nonmetallic derivatives. It is frequently utilized as an organic binding substance for corrosion prevention, moisture resistance, and waterproofing. To improve the base asphalt's performance [7,9]. Changes are frequently necessary, especially to enhance characteristics like adhesion, temperature sensitivity, friction, resistance to oxidation and aging, and general durability. Rubbers, polymers, sulfur, metal complexes, fibers, and chemical agents are just a few of the many types of asphalt modifiers that are available [9].

This study investigates the use of nano-white cement (N-WCem) and nano-silica (N-Si) to enhance soil strength for road construction in Egypt, in light of the significant highway network expansion. Traditional stabilizers are replaced with nanomaterials to reduce environmental impact while improving mechanical performance. Various percentages of N-WCem and N-Si were tested, showing continuous improvement in CBR values, especially when both were combined. The findings support the eco-friendly potential of nanotechnology in enhancing subgrade strength under different soaking conditions [10]. This study explored the effect of Nano-Kaolinite on the mechanical performance of warm mix asphalt (WMA), using Evotherm™ as an additive. Nano-Kaolinite was added in varying percentages (2–8%) to enhance durability and strength. Results showed significant improvements in Marshall stability, indirect tensile strength, and compressive strength by 50%, 30%, and 68%, respectively, while reducing Marshall flow and rutting depth. The findings confirm that Nano-Kaolinite enhances the performance and sustainability of WMA, offering economical and environmental benefits [11].

This study investigates the improvement of Egypt's widely distributed kaolin soil using nano-white cement and nano-silica for highway construction applications. Compaction and strength tests showed that nano-white cement reduced workability and dry density but increased moisture content and unconfined compressive strength. Nano-silica alone improved strength up to a 0.9% concentration, after which performance declined. The combination of low-percentage nano-silica with nano-white cement yielded superior strength compared to nano-white cement alone. SEM analysis confirmed enhanced bonding, highlighting the eco-friendly and cost-effective benefits of using nano-additives in soil stabilization [12].

2. FUNDAMENTAL CONCEPTS OF NANOTECHNOLOGY

2.1. Introduction to Nanotechnology

The term "nanomaterial" refers to materials that possess at least one external dimension, such as surface, interface, structure, or feature, at the nanoscale level. The nanoscale is generally defined as having one or more dimensions ranging from 1 to 1000 nanometers, with the most relevant nanomaterials typically falling within the 1 to 100 nm range. The term "nanostructure" refers to engineered materials specifically designed with nanoscale dimensions. Devices with such nanoscale features or heterostructures are increasingly used in the manufacturing of semiconductors, optoelectronics, and quantum conduction devices. Another category of nanostructures includes nanophase materials, which may take the form of superlattices or composite films. These materials are characterized by their high density of interfaces, which contribute to their distinctive properties [13-15].

2.2. Basic Concepts of Nanotechnology in Enhancing Asphalt Mix Properties

Nanotechnology focuses on improving material properties at the nanoscale, using nanomaterials to enhance the performance of key components of asphalt, such as bitumen and aggregates. These materials improve the mechanical, rheological, and physical properties of asphalt, leading to enhanced long-term performance under the challenges of heavy traffic loads and harsh environmental conditions.

Enhancing Mechanical Properties: Nanomaterials improve the mechanical properties of asphalt binders, such as hardness and elasticity, enhancing the asphalt's resistance to deformation, cracking, and deterioration from heavy traffic. For example, nano silica or nano clay can increase strength and flexibility, reducing wear caused by thermal or mechanical interactions [16].

Rheological Properties Improvement: This study examines the effects of adding nano-silica, nano-chitosan, and nano-clay on the physical and rheological properties of asphalt. The results showed significant improvement in the asphalt's rutting resistance, especially at concentrations ranging [17].

Enhanced Resistance to Oxidation and Environmental Damage: Nanomaterials such as graphene and nano silica create a protective barrier, improving asphalt's resistance to environmental factors like UV radiation, moisture, and oxygen. This reduces degradation rates and extends the asphalt's lifespan, lowering the need for frequent maintenance and resurfacing [18].

Improved Distribution and Homogeneity: A challenge with nanomaterials is ensuring their even distribution within the asphalt mix. Advanced techniques, like chemical vapor deposition or nano plasticizers, ensure proper distribution, improving homogeneity and the overall effectiveness of the nanomaterials.

1. **Filler and Absorption Effects**: Nanomaterials act as fine fillers, efficiently filling voids and pores within the asphalt matrix. This enhances the structural stability of the asphalt, reduces interaction with liquid materials, and improves its overall stability and rigidity [19].
2. **Long-Term Performance**: The inclusion of nanomaterials improves the long-term durability of asphalt. This enhancement helps resist wear and cracking from thermal fluctuations and repetitive mechanical stress, reducing the need for regular maintenance and decreasing the associated environmental and economic costs [17].

2.3. Definition and Scope

Nanotechnology is the process of manipulating matter at a sub-micrometer size to accomplish particular goals, such as altering electrical, mechanical, or optical properties. It also includes the development and use of materials, tools, and systems through nanoscale matter control. The word "nanotechnology" has evolved to refer to this extraordinarily small-scale research and development. Since "nano," which comes from the Greek word for "dwarf," means "dwarf," a nanometer is a "dwarf" meter. To put this into perspective, a human hair's typical diameter is approximately 80,000 nanometers, a human cell measures roughly 10,000 nm, the protein hemoglobin is around 5 nm, and a single atom of ruthenium has a diameter of just 0.2 nm. Nanosystems are composed of molecules that exist at this scale [20-22].

Nanotechnology encompasses the examination and alteration of matter at dimensions between roughly 1 and 100 nanometers, where distinctive phenomena arise that facilitate novel applications. Research and development in this field typically focuses on developing the technologies, instruments, and chemical tools needed for nanotechnology, along with high-resolution imaging techniques to analyze the atomic structures of nanomaterials and biomolecules. It also includes non-fabrication methods, as well as processing, characterization, amplification, and assembly techniques essential for device fabrication. As a result, nanotechnology research has become a specialized subdiscipline within engineering, incorporating the study of nanoscale phenomena and applying them to create new, groundbreaking uses. These efforts often require highly coordinated, multidisciplinary approaches. The theoretical foundations and fabrication processes at the nanoscale are integral to engineering, drawing on a wide range of scientific disciplines, underscoring the importance of interdisciplinary collaboration in overcoming the challenges at this scale [6,23,24].

3. IMPACT OF NANOMATERIAL MODIFICATION ON THE MECHANICAL PROPERTIES OF ASPHALT MIXTURES

Nanotechnology involves the production and material manipulation at the atomic and molecular levels, and nanomaterials possess unique properties that are increasingly being applied in industries such as manufacturing and construction. In road construction, using nanomaterials can enhance the performance and durability of pavement layers. Specifically, in bituminous pavements, various materials and techniques have been developed to reduce fatigue cracking, prevent permanent deformation, and improve the bonding properties of bitumen-aggregate mixtures. Given these advantages, this paper explores the different types of nanomaterials that have been used and studied in road construction, with a particular focus on their application in bituminous mixtures. The paper analyzes the results of studies involving these nanomaterials, including an examination of their types and properties. Finally, it discusses the impact of incorporating different types of nanomaterials at varying concentrations into bituminous mixtures [25-27].

3.1. Carbon Nanotubes

A carbon nanotube (CNT), as shown in **Fig. 1,** is a seamless hollow cylinder with a diameter of around one nanometer that is formed from a graphite sheet that is one atom thick [28]. When initially published, the arc-discharge production and characterization of helical microtubules made of molecular-scale fibers with fullerene-like structures made the initial discovery of CNTs. When compared to other building materials, carbon nanotubes (CNTs) are renowned for their remarkable mechanical qualities. A CNT's tensile strength can reach up to 150 GPa, and its Young's modulus can reach up to 1,000 GPa, depending on the radius of the tube [26]. Multi-walled CNTs (MWCNTs), which are made up of coaxial tubes, and single-walled CNTs (SWCNTs), which are made up of a single tube, are the two primary varieties of CNTs. Although MWCNTs are easier to make and less expensive than SWCNTs, they typically have less stiffness and strength [30].

Only a small number of studies have examined the application of CNTs in bituminous binders and mixes, despite their exceptional qualities. CNTs can greatly enhance the rheological characteristics of asphalt when added to base bitumen in amounts high enough (>1%) [28-30]. In addition to improving the performance of asphalt pavements, adding carbon nanotubes to asphalt mixes at a ratio of 0.001% by weight of bitumen permits a decrease in the thickness of underlying layers, which reduces the need for stone materials [34]. In addition to decreasing vulnerability to oxidative aging, CNTs have been demonstrated to enhance rutting resistance [35,36] and thermal cracking resistance. It is anticipated that these enhancements will benefit bituminous mixture performance in the long run [37].

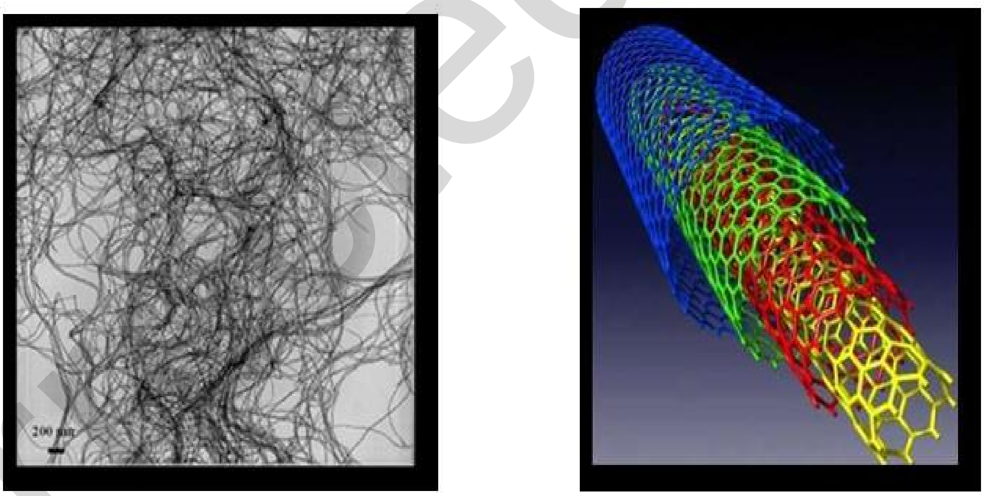

Fig. 1: (a) Carbon Nanotube; (b) hollow carbon tube [34].

3.2. Nano clay

Clay can be transformed into nanosized materials known as nanomaterials, which are categorized into forms such as nanofibers, nanoplatelets, nanofillers, and nanocomposites. Various types of nano-clay products have been studied, including montmorillonite, synthetic phyllosilicates, saponite, sepiolite, attapulgite, and halloysite. Although a large number of natural nano-clays exist, only a few have shown significant potential for advanced materials applications, such as thermoplastic composites, elastomer reinforcement, and asphalt. These clays can create hybrid structures that improve characteristics, including tensile strength, modulus, elongation, and wear resistance. The performance of asphalt mixtures has been enhanced by the notable efficacy of halloysite nanotubes as pore formers [38-40].

Modifying clay is a crucial step in improving its dispersibility, achieving the desired compounding properties, and ensuring a strong, stable final product. It is also essential to manage the environmental impact of natural clays, especially given the growing focus on sustainability. Compounding technology is the most widely used and developed method for modifying clay, enabling the creation of nanoscale clay materials that can enhance or even surpass the functionality and performance of their larger counterparts. The unique behaviors and characteristics of nano-clays, such as their small size and high aspect ratio, have garnered significant attention from researchers across various industrial sectors. As interest in these materials continues to grow, the scientific community remains focused on exploring and developing the full potential of nano-clay technologies [40-43].

3.3. Nano silica

Nano silica is a very useful substance that is widely available on Earth and is essential to many different companies, such as those that produce foam silica, colloidal silica, and silica gels. Because of its potential in cutting-edge industries like medicine and medication delivery, micro-silica particles—especially in their nanoparticle form-have attracted a lot of attention. Amorphous silica nanoparticles, often known as nanotubes, have attracted a lot of attention in scientific studies because of their special qualities and their uses in a variety of fields [44].

In industrial applications, silica nanoparticles are widely used to reinforce elastomers, enhance rheological properties, and enhance the effectiveness of bitumen and asphalt mixtures. Silica nanocomposites are particularly valued for their low production costs combined with high-performance characteristics, making them an attractive option for a variety of applications. Their versatility and cost-effectiveness have led to increasing use across industries ranging from construction to automotive and beyond [45].

Fig. 2. When asphalt-based adhesives are mixed with nano silica, it causes a slight decrease in viscosity, which suggests that the manufacturing process benefits from lower processing temperatures and reduced energy consumption. Despite this reduction in viscosity, the modified asphalt maintains or even improves its recovery ability compared to the unmodified asphalt. Importantly, the low-temperature behavior and stress relaxation properties of nano-silica-modified asphalt remain similar to those of unmodified asphalt. The addition of nano-silica does not hurt these essential characteristics [46].

Additionally, the adhesive and asphalt combinations' anti-aging, crack-resistant, and general durability are enhanced by the use of nano-silica. Additionally, asphalt that has been treated with nano silica has much-improved anti-shedding and decay resistance. But it's crucial to remember that adding nano-silica does not affect the asphalt mixtures' low-temperature bonding qualities or performance, guaranteeing that these crucial features stay the same [47].

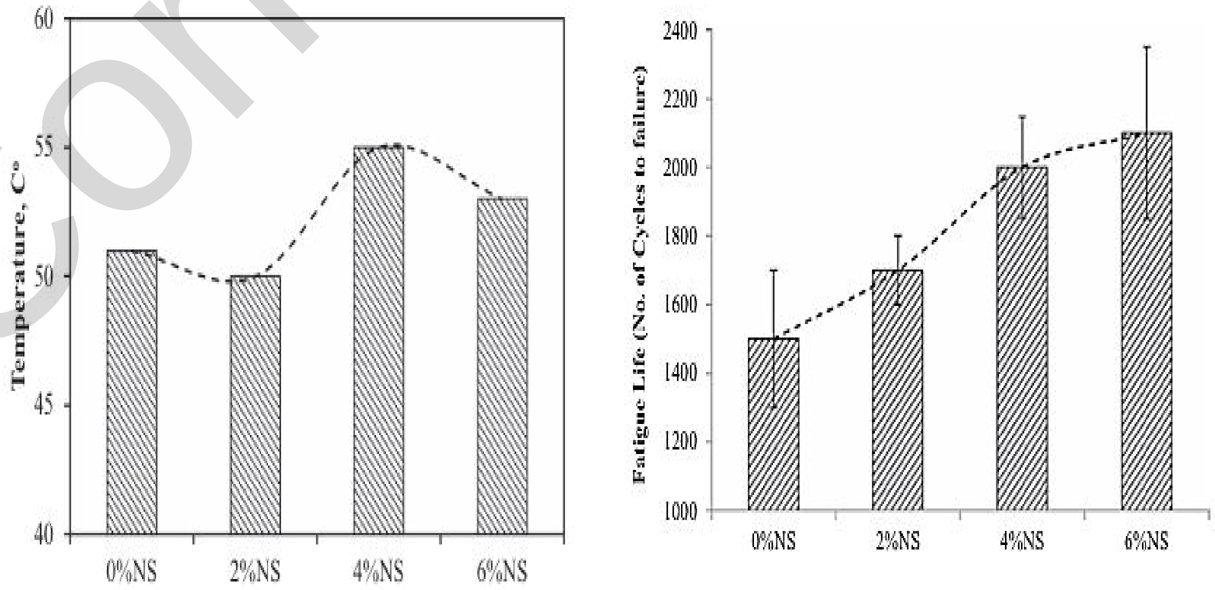

Fig. 2: [a] Softening point values at different concentrations of NS, [b] Fatigue life of compacted mixtures [48].

3.4. Nano Slag

Nanoslag, with its smaller particle size, offers better reinforcement for the asphalt matrix, enhancing its overall performance. Given its higher cost, it is valuable to study the potential benefits of Nanoslag to optimize its usage and decrease the cost of mixture preparation. The use of Nanoslag is advantageous for the road construction industry because it has been demonstrated to enhance asphalt mixtures' mechanical qualities, particularly in enhancing rutting performance and water stability. This study mainly examines how different doses of Nanoslag affect asphalt mixes' fatigue behavior and performance at high and low temperatures. The impact of granite and limestone fillers is not the focus of this research. By replacing traditional fillers with different amounts of Nanoslag, the study aims to examine changes in high-temperature performance, resistance to cracking at low temperatures, and the ability of mixtures of asphalt to resist fatigue deformation and damage [49,50]. The Regional Center for Mycology and Biotechnology at Al-Azhar University used a Transmission Electron Microscope (TEM) as shown in **Fig. 3**.

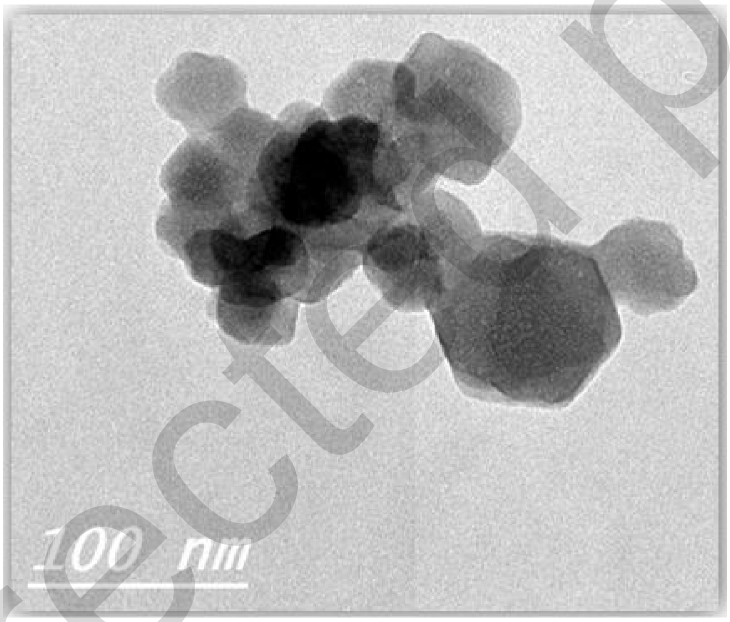

Fig. 3: TEM Image of Nano-Slag [52].

To examine the microstructure of Nanoslag to comprehend its form. The TEM images provided a clear view of the particle sizes collected from the microstructure. The grinding method, however, did not affect the sphericity of the particles or the chemical composition and their respective percentages. Despite this, the grinding process was found to significantly reduce the particle sizes, as confirmed by the Scanning Electron Microscope (SEM) images, which further illustrated the reduction in particle size [51].

4. IMPACT OF THE ASPHALT BINDER'S NANOMATERIALS MODIFICATION

After being altered with nano-silica, the binder showed a greater melting temperature, increased viscosity, and decreased permeability. According to Dynamic Shear Rheometer (DSR) testing, the modified binders exhibited a decrease in phase angle and an increase in complex modulus. These findings suggested that fatigue resistance was improved by nano-silica changes. Since organically modified montmorillonite clay can encourage well-dispersed structures in the binder, most research focuses on this type of clay.

Similarly, nano-clay-modified binders also showed a higher melting point, increased viscosity, and decreased permeability. Rheological, they showed a lower phase angle and a higher complex shear modulus. Raw nano-clay in a hydrated state may form interconnected structures, although some studies have reported improved performance with untreated raw clay. The final performance of the binder is greatly influenced by the type of nano-clay that is utilized. Even when the same base binder is used, studies with different types of nano-clay have yielded varied results, though similar trends are often observed [53]. **Table 1** provides earlier research on asphalt binder enhancement.

Table 1: Research on the additive properties of nanomaterials.

Type of Modification	Tests	Enhancement	Reference
2, 4, 6, 7 and 8% Nanoslag	Marshall stability, indirect tensile strength, compressive strength, and Marshall flow	increased by 41%, 69%, and 45% respectively decreased by 17%	51
4%and 6% NS by wt. of binder	Rutting, aging, and fatigue cracking, dynamic modulus, and flow number	A substantial enhancement has been found	54
2 and 4% Montmorillonite Nano clay by wt. of binder	Rotational viscosity, the dynamic shear complex modulus, was	Improved	55
NS	Anti-aging resistance, rutting fatigue cracking	Enhanced	56
2, 4, and 8% micro silica MS by wt. of binder	Asphalt aging index The aging index	Decreased by up to 4% Negatively affects after 8% MS	57
7% Optimum NS	Penetration Viscosity	Decrease by 7.13% Increased by 8.33%	58
7.0% NS	Penetration viscosity Marshall Stability flow Stiffness ITS rutting resistance	Reduction Increased Increase of 25% Reduction Increased Increase of 40%	59
MS or SF	Psenetration viscosity Marshall Stability Marshall Stiffness	Decreased Increased Increased Decreased	60
1,2 and 3% (NS, NC)WITH 5%SBS	Stability and flow Rutting	Improved indicated	61
3%NC AND 5%SBS	Marshall Stability Marshall flow Rutting	Increased by 12.9% Decreased by7.6% Decreased by42.9%	62
1,2and3% (NS, NC) WITH	Penetration	Decreased	63

5%SBS	Softening point	Increased	
2% NS+SBS	Physical properties	Improved	64
2% carbon Nano powders	Penetration, ductility, viscosity, and softening point	Increased	65
3,5 and 7% (NS)	Penetration Softening point	Decreased Increased	66
3,5and7% (NC)	Penetration Softening point	Increased Decreased	
1,3,5, and 7% NS	Flow Permanent deformation	Increased Decreased	67
Nanocomposite +SBS	Rutting	Deacresed	68

5. RESEARCH OBJECTIVES

This research will investigate whether nanotechnology can address the HMA problems by identifying and understanding the reinforcement effects of several well-preferred nanomaterials that enhance various asphalt mix properties to meet the demand for sustainable and durable HMA. This study is also expected to minimize the utilization of modified and more expensive materials by harnessing the potential of cost-effective nano-fillers like nano-clay, nano-silica, and nano-titania, considering the benefits of using nano-fillers with corresponding HMA properties that promise to optimize the proportion of fillers for excellent performance. The study suggests a thorough analysis of the most advanced techniques available for comparison analysis, and it also highlights the need for the latest findings in this promising research avenue of diversified nanotechnology applications on HMA [69-71].

6. BENEFITS OF NANOTECHNOLOGY IN ASPHALT MIXTURES

Nanotechnology is expected to deliver benefits in two key ways: enhancing the cost-effectiveness, durability, and efficiency of existing products and processes, and enabling the creation of completely new products. When applied to bitumen and asphalt mixtures, Nanotechnology offers the following specific advantages [68].

- Improve polymer-modified asphalt's storage stability and resistance to UV aging and degradation.
- Lessen vulnerability to moisture when exposed to de-icing agents, water, and snow.
- Asphalt mixtures function better at low temperatures.
- Increase the asphalt pavements' lifetime and resilience.
- Reduce manufacturing and maintenance costs and energy use.
- Minimize the need for ongoing maintenance and repairs.

7. COST-BENEFIT ANALYSIS: ECONOMIC IMPLICATIONS OF NANOMATERIALS IN ASPHALT PAVEMENTS

The integration of nanomaterials into asphalt pavements necessitates a comprehensive cost-benefit analysis to ensure their practical and economic viability. Despite the proven advantages of nanomaterials in enhancing pavement performance, such as improved durability, resistance to deformation, and extended service life, their application is often challenged by high initial costs. These include the elevated prices of nanomaterials compared to conventional additives, as well as additional expenses related to processing and uniform dispersion within asphalt mixtures.

However, the economic outlook can be significantly improved through the utilization of low-cost, locally available materials that can be converted into nanomaterials using simple mechanical methods, such as grinding. Materials such as natural clay, silica, steel slag, and ceramic waste have demonstrated great potential as effective nano-modifiers when processed into nanoscale particles. These alternatives not only offer substantial cost savings but also contribute positively to sustainability by recycling industrial by-products.

Although production and application processes may still require careful handling and technical consideration, the long-term performance benefits, including reduced maintenance costs and enhanced pavement lifespan, can outweigh the initial investment. Therefore, policymakers and engineers must weigh these factors carefully when evaluating the feasibility of adopting nanotechnology in pavement infrastructure.

Fig. 4 and **Table 2** present a comparative overview of the cost implications and performance gains associated with various nanomaterials in asphalt modification, addressing a current gap in the literature regarding the economic dimension of nanomaterial use in this field.

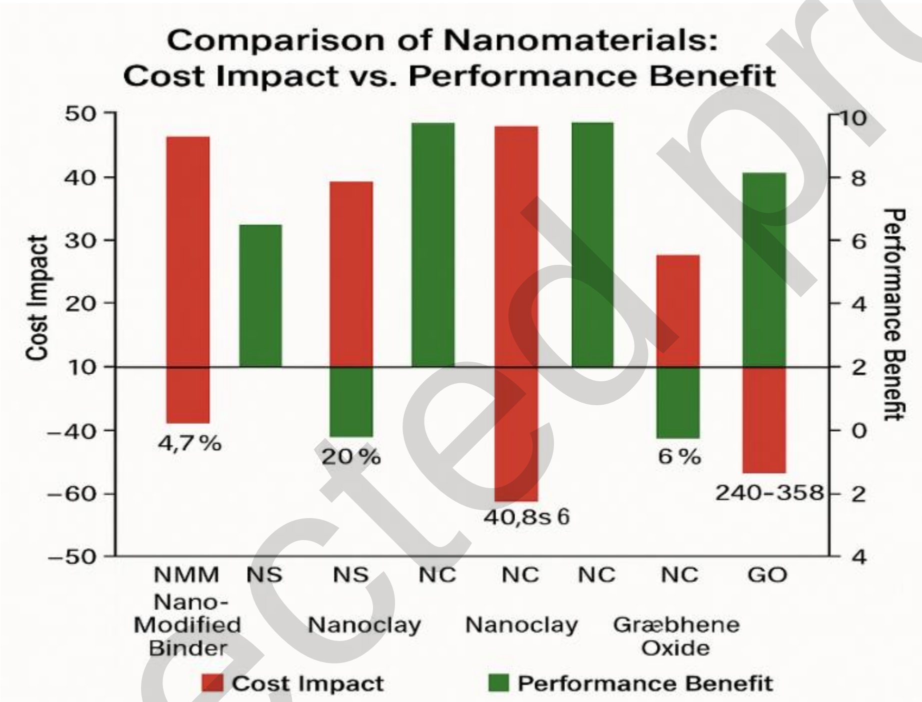

Fig. 4: Comparison of nanomaterials: cost impact vs. performance benefit

Table 2: Cost Impact and Performance Benefits of Various Nanomaterials in Asphalt Mixtures

Nanomaterial	Estimated Cost Impact	Key Performance Improvements	Reference
NMM (Nano-Modified Binder)	Approx. 4.7% increase in binder cost	Enhances Marshall stability, rutting resistance, and cracking resistance (CTindex)	73
Nanosilica (NS)	Up to 43% increase in total cost per ton of asphalt mixture	Improves resilient modulus and permanent deformation resistance	74
Nanosilica (NS)	20% increase in cost per ton of modified binder	Enhances the aging resistance of asphalt	75
Nanoclay (NC)	Fivefold increase in cost for a 5 cm asphalt layer (27 €/m² vs. 5 €/m² for conventional mix)	Enhances fatigue life and elastic behavior of asphalt concrete	76

Carbon Nanotubes (CNT)	Reduces overall construction costs by approximately. 40% due to decreased pavement thickness	Significantly improves fatigue resistance of hot mix asphalt	77
Nanoclay (NC)	Cost-benefit ratio < 1 at 6% dosage; provides efficient performance improvement relative to cost	Simultaneously enhances rutting and fatigue resistance	78
Nanoclay (NC)	Reduces binder cost by 22–33% compared to polymer-modified alternatives	Increases surface free energy and improves adhesive bonding	79
Graphene Oxide (GO)	Estimated cost: $240–358 per ton of asphalt mixture (at 1.5% by binder weight)	Improves fatigue and rutting performance	80
Nanosilica (NS)	Cost increase from 6.8 €/m² to 21 €/m² for 5 cm asphalt layer with 3% nanosilica	Enhances mechanical properties and moisture damage resistance	81

8. MECHANISMS OF NANOMATERIALS IN ASPHALT PAVEMENTS

Nanotechnology primarily focuses on materials at the nanoscale, while civil engineering infrastructure and road pavements deal with the macroscopic scale. A key question that often arises is how changes at the nanoscale can affect macroscopic properties and behavior. Nanomaterials possess unique characteristics, such as high functional density, increased sensitivity, distinct surface effects, large surface area, high strain resistance, and catalytic activity. Through a comprehensive review of existing literature, it is generally agreed that nanomaterials can enhance the physical, rheological, and mechanical properties of asphalt binders and mixtures. The specific mechanism and degree of improvement depend on the type of nanomaterial used and its compatibility with the asphalt binder. Researchers continue to study and optimize the incorporation of nanomaterials to achieve the desired improvements in asphalt binder properties. This section will provide a detailed explanation of the various mechanisms that contribute to these improvements in **Fig. 5** [82].

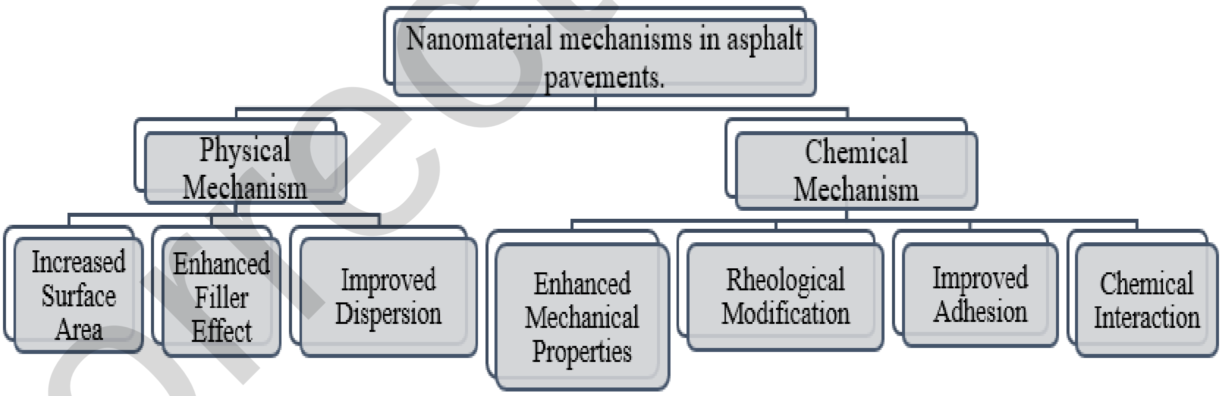

Fig.5. Nanomaterial mechanisms in asphalt pavements.

• **Increased Surface Area:** Nanomaterials possess a remarkably high surface area due to their small particle size. When integrated into asphalt binders, they form a network of fine particles that further increases the overall surface area. This enhanced surface area boosts the interaction between the nanomaterials and the binder, resulting in improved performance [83].

• **Enhanced Filler Effect:** The high surface area and small particle size of nanomaterials serve as fillers, effectively filling the gaps and voids in the asphalt matrix in a way that traditional macro-scale fillers cannot match [84].

• **Improved Dispersion:** Achieving uniform dispersion of nanomaterials within the asphalt binder is essential. Proper dispersion ensures that the nanomaterials are evenly distributed, resulting in consistent enhancements in the binder's properties [85].

• **Enhanced Mechanical Properties:** The incorporation of nanomaterials can enhance the mechanical properties of both asphalt binders and mixtures, including increased strength, stiffness, and resistance to deformation, ultimately contributing to more durable and longer-lasting pavements [86]

• **Rheological Modification:** Nanomaterials can modify the rheological properties of asphalt binders, enhancing their resistance to deformation at high temperatures and reducing brittleness at low temperatures. This results in improved performance across a wide range of environmental conditions. This improvement is demonstrated by enhanced elasticity, better temperature susceptibility, and increased resistance to rutting and cracking observed in modified asphalt binders [87, 88]

• **Improved Adhesion:** Nanomaterials can improve the adhesion between the asphalt binder and aggregate particles, leading to stronger cohesion and increased resistance to moisture-induced damage, such as stripping [89].

• **Chemical Interaction:** It was found that the incorporation of nanoparticles into the bitumen matrix significantly influences the molecular reorganization, as evidenced by changes in the infrared spectra. **Fig.6.** illustrates that this interaction promotes the formation of a new polyaromatic structural system. Consequently, the physical, chemical, and rheological properties of the bitumen are notably enhanced [90].

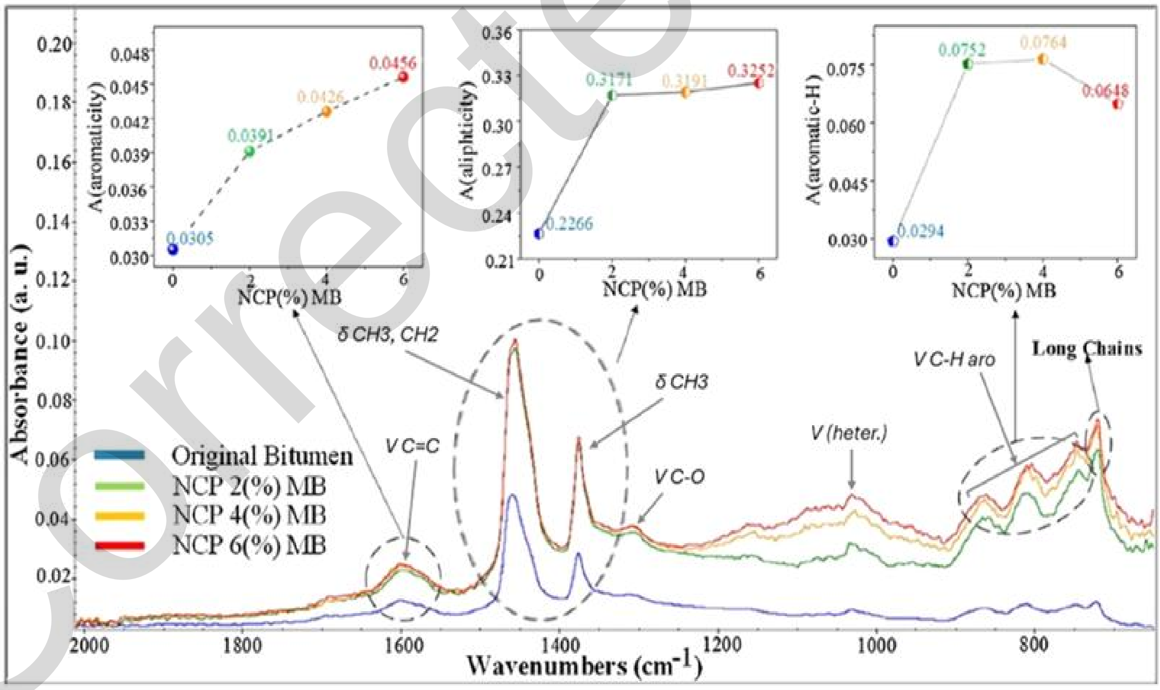

Fig.6. Fourier Transform Infrared (FTIR) spectra of unmodified and nano-modified bitumen [90].

CONCLUSIONS

This review comprehensively addresses the application of modified nanomaterials in asphalt paving. Both theoretical and experimental studies have demonstrated that incorporating nanomaterials into asphalt represents an innovative approach in civil engineering and holds significant promise for revolutionizing the construction and maintenance of asphalt pavements. The review provides a thorough examination of the broad range of research literature, highlighting the diverse applications of nanomaterials and their profound impact on the performance of asphalt materials. The integration of nanomaterials into asphalt has resulted in notable improvements in several fundamental properties, including mechanical characteristics such as stiffness, strength, and flexibility, as well as resistance to degradation modes such as rutting, cracking, and moisture damage. These enhancements can be attributed to mechanisms such as nanoparticle dispersion, interfacial bonding, and barrier effects, all of which contribute to the observed improvements in asphalt performance.

The results lead to the following conclusions:

Adding nano-silica to asphalt mixtures significantly enhances key properties, including fatigue resistance, moisture damage resistance, Marshall stability, indirect tensile strength, stiffness modulus, and reduced permanent deformation. Research shows that nano-silica concentrations typically range from 1% to 7%, with improvements generally increasing as the dosage rises. However, higher dosages may become costly, so the economic feasibility of using larger amounts should be carefully considered.

The type of nano clay used affects asphalt performance, with factors like surface area, particle size, and treatment type playing a key role. Modifying nano clay improves fatigue resistance, stability, and moisture resistance. Dosages range from 1% to 7%, with higher dosages often improving performance. However, some organically modified nano clays show peak performance at lower dosages (2%). Since modified nano clays are more expensive, optimization is needed to balance performance and cost.

Nano slag enhances asphalt performance by improving moisture resistance, stability, tensile strength, fatigue, and fracture resistance. Its lower dosage makes it more cost-effective than other nanomaterials. Additionally, nano-iron improves aging resistance, offering long-term durability and potential savings on maintenance, making it a cost-effective choice over the pavement's lifespan.

Future research should focus on improving distribution techniques, assessing environmental impacts, reducing costs, enhancing standardization efforts, and exploring multifunctional nanomaterials. Innovations in smart pavements and sustainable practices hold promise for enhancing asphalt durability and lifespan. In conclusion, while nanomaterials offer significant potential to improve asphalt performance and sustainability, continuous research and innovation are essential to overcome current challenges and fully realize the benefits of this technology in engineering.

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CONFLICT OF INTEREST

The authors have no financial interest to declare in the content of this article.

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