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Effects of Nano Silica and Anti-Stripping Agents on Asphalt Performance: A Review Article

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ABSTRACT

The durability is considered the most critical issue for researchers and civil engineers of asphalt pavement over time, which is dependent upon its resistance to exposure conditions, repeated loading and environmental effects. Among the major distress modes that durability- associated of flexible pavement are moisture damage and permanent deformation. However, Moisture damage affects pavement durability through separation between aggregate and asphalt binder, resulting in a sequential failure. On the other hand, load- associated failure occurs as a result of permanent deformation of the asphalt pavement under repeated loading conditions and at high temperatures. Consequently, Recent advances in asphalt modification have been focused on improving the durability of asphalt mixtures using nanomaterials and chemicals. Preliminarily, Nano-silica has shown significant potential for enhancing binder stiffness and thermal stability and preventing permanent deformation. Conversely, Anti-stripping additives have shown promise in improving binder-aggregate bonds and preventing moisture damage. Although extensive research has been conducted on these additives as individual components, little emphasis has been given to their interaction. Within this review, a synthesis of current knowledge regarding nano silica and anti-stripping agents is provided, and their potential combined contribution to mitigating moisture damage and rutting is discussed. The results of these researches emphasize that a balanced modification strategy is required to simultaneously reinforce mechanical properties and interfacial bonding to develop long-lasting and sustainable asphalt pavements.

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1. INTRODUCTION

With the introduction of bitumen into the pot of life by Utnapishtim in the Epic of Gilgamesh, asphalt has shaped the course of human evolution; not only has it served as a sealant for ships but also as the basic glue that holds the bonds of civilization together and the foundation where the dreams of nations moved from the old overland paths to the historic roads of progress.

Roads have been serving as the main channel that connects human aspirations to achievements throughout the ages. In today’s world, the current aim for pavement engineers is not only limited to the construction of pavements but also to paving endless roads using advanced technology. It is a contest against time, and there is an urgent need to come up with advanced asphalt mixes that can survive environmental conditions and heavy loads.

The performance and longevity of asphalt pavements are significantly affected by environmental variables and increasing loads from vehicles [1]. From the various environmental parameters that impact the performance of pavements, the two that are considered the most important include moisture intrusion and repeated stress due to traffic loads [2]. Moisture intrusion weakens the bond between the asphalt binder and aggregates by causing debonding, which results in the loss of cohesive strength [3], [4]. Clearly, the level of damage caused by moisture intrusion depends on factors such as the nature of the binder used, aggregate composition, air voids, and environmental exposure.

With the combined effect of moisture damage and rutting represents a major challenge in flexible pavement systems [1]. Comprehensively, the ruts appear as longitudinal depressions along the wheel paths and result from the accumulation of permanent deformation under repeated loading, particularly at elevated temperatures [2], [5].
Thereafter, the moisture damage stage could start in rutting-dependent phenomena due to basin trap initiation inducing degradation of adhesive bonding which can accelerate permanent deformation by weakening the internal structure of the asphalt mixture, thereby reducing its resistance to shear stresses and traffic-induced densification [4], [6]. However, to mitigate these coupled distresses, various material modification techniques have been developed [7], [8]. The most common materials are “Polymers”, basically has been used to enhance the rheological behavior of asphalt binders in an effort to develop the general performance [6]. Rapidly, and in corresponding term, nano-silica has emerged as an effective reinforcing nanomaterial that improves binder stiffness, enhances thermal stability, and increases resistance to rutting through microstructural densification [6], [9]. In contrast, anti-stripping agents, particularly amine-based additives, are primarily used to improve the physicochemical interaction between binder and aggregate, thereby enhancing adhesion and reducing moisture susceptibility [10], [11]. As mutually agreed, limited research has systematically investigated the synergistic interaction of hybrid modification of nano-silica and anti-stripping agents under combined moisture and high-temperature conditions [4], [12]. By this context, the nano-scale stiffening can complement adhesion enhancement and whether this leads to a balanced improvement in both rutting resistance and moisture durability remains insufficiently understood. Furthermore, there is a lack of clear understanding regarding the optimal dosage combination and the interaction mechanisms at the microstructural level, particularly in relation to binder–aggregate interface behavior and mixture volumetrics [13], [14]. Therefore, an exhaustive study on the impact of nano-silica and anti-stripping additives needs to be conducted to achieve a modified strategy that considers both aspects of reinforcing and improving the bond between aggregates. The objective is to present a more practical method to enhance the behavior of asphalt mixtures with respect to moisture and load interactions.

2. RESEARCH METHODOLOGY

A systematic review methodology is used in this paper to examine the current literature regarding the modification of asphalt mixture with nanosilica and amine-based materials. This method was used in order to achieve scholarly objectivity in the research process.

2.1. Search Strategy and Data Sources

A complete literature search was conducted using high-quality databases such as ScienceDirect, Scopus, and Web of Science. This research study concentrated on scientific discoveries made in the last ten years, specifically in 2020 to 2025, to identify the most recent trends related to nanotechnology and chemical additions. The major keywords searched include: Modification of nano silica asphalt and amine-free anti-stripping additives for moisture sensitivity and rut resistance in bitumen.

2.2. Inclusion and Exclusion Criteria

In order to maintain integrity in science and the technical soundness of synthesized data, the following were taken into consideration for the selection of studies:
• Material aspect: Researches conducted on the effects of nano-silica on binder rheology [6] and the efficiency of anti-stripping additives, especially those without amine [10], [11].
• Performance criteria: Experimental studies utilizing standard measurements such as the Tensile Strength Ratio (TSR) measurement [12], [15], Indirect Tensile Strength (ITS) test [4], [9], Marshall Stability [4], [13], [16].
• Conditioning Variables: Papers that involved environmental stresses, such as moisture conditioning [4], [12] and fatigue cycles [2], [5].
Articles without any empirical data and those discussing other additives apart from the topic of interest were left out to keep the theme of the paper intact.

2.3. Data Synthesis and Analytical Framework

The reliability of the examined sources was determined by analyzing the results obtained experimentally under various conditions of aging processes, both short-term and long-term [2], [17]. Seriously, this allows for a critical evaluation of whether the proposed modifications offer sustained durability or merely short-term performance gains [5], [16].

Generally, in this research, the analysis was categorized into three distinct levels of interaction:

Microstructural Level: Evaluating how nano-scale particles modify the internal binder matrix and promote denser network formation [6].

Interfacial Level: Analyzing the chemical affinity and surface energy changes at the binder–aggregate interface facilitated by anti-stripping agents [10], [11].

Synergistic Level: Identifying the research gap concerning the integrated performance of both modifiers under simultaneous mechanical and environmental loading [4], [12].

3. MOISTURE DAMAGE and RUTTING MECHANISMS in ASPHALT MIXTURES

Reciprocal phenomenon of moisture damage- rutting induced deterioration is seen as a key issue in terms of pavement durability since it directly impacts the binder-aggregate interface [4]. Water infiltration into the asphalt mixture affects the adhesive properties at the binder-aggregate interface and its own internal cohesive strength due to the dipole effect of water [11], [12]. Additionally, the rate of progression of stripping is related to moisture susceptibility in pavement materials significant dependent upon binder-aggregate interaction, aggregate mineralogy and air void contents in the mixture [3], [4], [12], [15].

This causes gradual degradation in terms of stripping of the asphalt film from aggregate particles [5], [15]. However, from empirical aspects and experiments, it is obvious that moisture attack causes a reduction in the mechanical performance [18].

The compatibility of the binder and aggregate is one of the key factors in the determination of moisture resistance [12], [19]. Aggregates with certain mineral compositions may appear to have a poor affinity for the asphalt binder, which certainly leads to adhesive failure [10], [11]. Moreover, the presence of more air voids would allow more moisture to penetrate, thereby accelerating the degradation process [4], [15]. Moreover, the exposure to environmental factors, such as wet and dry cycles, would further lead to the degradation of the bond, particularly in places with changing weather [12]. Moisture damage would lead to raveling and degradation, which would, in turn, reduce the useful life of the pavement [2], [5].

On the other side, rutting is one of the major distress types in flexible pavements, mainly caused by the buildup of permanent deformation under repeated load effects [1], [5]. The appearance of rutting is characterized by longitudinal depressions along wheel tracks and is an indication of insufficient asphalt layer capacity to withstand repeated stresses [2]. The progression of rutting is closely related to the rheological characteristics of the binder and the mixture [6], [17]. At high temperatures, binder viscosity decreases, which reduces shear stresses and increases susceptibility to deformation [8], [20]. At this stage, repeated load cycles cause progressive densification and plastic flow in the asphalt layer [1].

Additionally, aging has been shown to influence rutting performance through the rheological properties of the asphalt binder [2]. The increase in the stiffness of the asphalt binder resulting from aging physical hardening has been shown to improve rutting resistance while reducing flexibility generating brittleness-induced cracks [2], [17]. The combined effects of temperature, traffic, and aging are controlling for the overall asphalt mixture rutting potential [12], [16], [21], [22]. Thus, it is imperative to understand both moisture damage and rutting for the formulation of strategies for improving asphalt pavement durability and stability, particularly through nanomaterial-based solutions [4], [7], [12], [23].

3.1. Nano Silica in Hot Asphalt Mixtures (HMA)

Recently, nano-silica has been identified as a promising nanomaterial for asphalt modification due to its extremely small particle size and high specific surface area and multifunctional performance among various nanomaterials used in asphalt pavements [6], [18], [23], [24], [25], [26]. These characteristics enable nano-silica to effectively interact with the asphalt binder matrix, even at relatively low dosages [6]. The major difference between conventional mineral fillers and nano-silica is that nano-silica not only serves to fill the voids in the binder but also influences the structure of the binder itself through physicochemical reactions [6], [17], [27], [28].

Based on past research findings, nano-silica can be used within a dosage of around 2 to 6% of the weight of the asphalt binder, depending on the expected outcome [13], [16].The particle size of nano-silica generally ranges between 10–100 nm, which contributes to its high reactivity and dispersion competence within the binder matrix [6].

To achieve proper dispersion, the mixing process is commonly conducted at temperatures between 140–160°C, with mixing durations ranging from 30 to 60 minutes, often using high-shear or mechanical mixers at rotational speeds sufficient to prevent agglomeration, (in contrast of polymers, which required longer time for mixing) [6], [29]. These parameters play a critical role in ensuring uniform distribution and maximizing the effectiveness of nano-silica within the asphalt system.

Experimental studies have demonstrated that the incorporation of nano-silica into asphalt mixtures improves resistance to moisture damage (measured by TSR) from 74% to 91% when a 6% of nanosilica is utilized [3], [4], [15], [30]. Whereas [18] had reported in an experimental study that nano-silica-modified mixtures exhibited higher Indirect Tensile Strength (ITS) by 15 and 30% under both dry and moisture-conditioned conditions. Additionally, the Tensile Strength Ratio (TSR) showed notable improvement, indicating enhanced resistance to moisture susceptibility up to 90% [12], [18]. However, these improvements are influenced by mixture characteristics such as binder type and air content [13], [14].

Side-by-Side, the nano-silica has revealed a significant impact reach to 40% on rutting performance, and this improvement is reinforced by an increase in stiffness [1], [5], [20], [31], [32], [33]. [2] evaluated nano-silica-modified hot mix asphalt under short-term and long-term aging conditions using wheel tracking tests. Their findings indicated a substantial reduction by 50 % in rut depth with increasing nano-silica content, particularly under high-temperature conditions. This suggests that nano-silica enhances both short-term stiffness and long-term resistance to permanent deformation [2], [17], [19].

Similarly, [16], [34] reported that increasing nano-silica content leads to higher Marshall stability by 15 to 25 % and the softening point had been increased up to 10 degrees, along with minimized penetration values, indicating increased binder stiffness. However, excessive nano-silica content may negatively affect mixture workability, so it is essential to highlight the importance of determining an optimal dosage which were recommended between 2-4% by weight of asphalt cement [16], [29].

At the microstructural level, the reinforcing effect of nano-silica is attributed to enhanced binder cohesion and the formation of a denser internal structure [6], [35], [36]. [6] emphasized that silica nanoparticles contribute to the development of a physically interconnected network within the binder, improving resistance to mechanical stresses. This microstructural enhancement explains the observed improvements in tensile strength and rutting resistance [27], [29].

Overall, nano-silica modification improves asphalt mixture performance through a combination of mechanical reinforcement and internal structural stabilization [16], [18], [25], [37]. This is evident in its inherent ability to enhance binder cohesion, increase stiffness, and reduce susceptibility to permanent deformation makes it a promising material for improving pavement performance under operating conditions [2], [12].

3.2. Amines and Adhesion Enhancement

The issue of moisture-induced degradation still constitutes a primary problem in terms of ensuring the long-term properties of HMA, particularly in areas suffering from a repeated cycle of wetting. Generally, Recent studies have proven the effectiveness of using amine stripping agents in increasing moisture resistance indicators [10], [11], [38], [39]. In a study by Muhmood et al. (2025), researchers investigated asphalt mixes using chemical additives. In the same relation, the study found a significant reduction in the stripping percentages of the asphalt mixes by 85 to 95%, compared to those without any additives. The mixes also showed improved Retained Strength Index (RSI), which is a measure of resistance to strength loss after exposure to moisture [10]. This shows that the additive improves the stability of the binder film around aggregate particles, hence reducing stripping [4], [38], [41].

[11], [42] provided further evidence of improved interfacial properties by investigating Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR) in hot mix asphalt mixes after being treated with amine-free anti-stripping agents. The results obtained from their study show that mixes treated with anti-stripping agents possess a higher retained tensile strength by 15 to 22% after being subjected to conditioning, which is a clear indication of improved binder-aggregate interaction [11], [43]. This is true regardless of the conditioning time, which shows that the additive is effective in long-term resistance against moisture damage [11], [12].

Additionally, the evaluation of the moisture resistance of the moisture indicators and the influence of the non-amine anti-stripping agents on the mechanical properties during cyclic loading had also been studied. [19] studied sandstone asphalt mixtures with specific anti-stripping agents and reported improved adhesion grades and fatigue performance by 20% under dry and 45% immersed conditions. The overall improved fatigue life of the asphalt mixtures by 28% therefore, the researchers clarify the role of improved interfacial bonding in the prevention of stripping and the maintenance of structural integrity [5], [19], [22], [44], [45].

Unlike nano-silica particles, which primarily influence internal cohesion and binder matrix rheology [6], anti-stripping agents primarily impact the binder-aggregate interface by enhanceing the TSR by 20 to 25% [10].

Mechanistically speaking, anti-stripping agents have a chemical impact by increasing the free energy of adhesion up to 50% in comparison with non-modified binders [4], [11]. This is particularly relevant with regard to modification methods since anti-stripping agents improve durability through bond stability without significantly impacting binder stiffness and resistance to deformation [12], [46], [47], [48], [49], [50].

3.3. Synergistic Potential of Combined Modification

The modification of asphalt mixtures using nanosilica and anti-stripping additives can be considered two separates yet possibly supplementary methods of improving the performance of asphalt mixtures by increasing TSR for HMA up to 90% under hybrid modification [12], [13], [35]. The incorporation of nanosilica primarily influences the internal structure of the asphalt binder, thereby improving cohesion and increasing mechanical stiffness [6], [27]. Various empirical studies have shown that incorporating nanosilica into the asphalt mixture can enhance tensile strength, rutting resistance, and thermal stability due to the high surface area of nanosilica and its ability to reinforce the matrix of the binder [6], [18], [51]. The incorporation of nanosilica into the matrix of the binder can enhance resistance to permanent deformation under high temperatures [2], [16].

3.4. Comparative Analysis of Previous Studies

A comparative summary of the key findings from previous studies on nano-silica and anti-stripping agents is presented in Table 1.

Table 1. Comparative summary of previous studies on nano-silica and anti-stripping agents in asphalt mixtures.

Study	Modifier Type	Dosage	Main Focus	Key Findings	Limitation
[1]	Nano-silica	2–6%	Mechanical properties	↑ ITS, ↑ TSR, ↑ stiffness	No adhesion analysis
[2]	Nano-silica	4%	Rutting resistance	↓ rut depth, ↑high-temp performance	No moisture interaction
[3]	Nano-silica	Variable	Binder properties	↑softening point, ↓ penetration	Workability issues not fully addressed
[4]	Anti-stripping (amine-free)	1–2%	Moisture resistance	↓ stripping, ↑ RSI	No mechanical evaluation
[5]	Anti-stripping	1–2%	Adhesion performance	↑ ITS, ↑ TSR	No rutting analysis
[6]	Anti-stripping	Not specified	Fatigue & adhesion	↑ fatigue life, ↑ bonding	No nano interaction

As shown in Table 1, most previous studies have focused on individual modification approaches, while limited research has addressed the combined or synergistic effects of nano-silica and anti-stripping agents.

4. CONCLUSION

Nano silica and anti-stripping agents represent two distinct yet complementary strategies for enhancing the performance of asphalt mixtures. The key function of nanosilica is that it increases the stiffness of the asphalt binder and contributes to its improved resistance against rutting and permanent deformations under high-temperature conditions. On the contrary, anti-stripping agents improve the interfacial adhesion properties between the asphalt binder and aggregates and increase their resistance to damage caused by water action. Therefore, the simultaneous use of both modifiers constitutes an innovative and effective solution to develop a more comprehensive asphalt system, although further research would be required for optimal dosage and material interaction studies.

Developing from the findings obtained from reviewing literature, this paper develops a synergistic approach that can be called the cohesion-adhesion balanced approach. This approach takes into account the two main failure modes of asphalt pavement that are cohesion failures and adhesion debondings. Under this approach, nanosilica is employed as a micro-reinforcement incorporated in the bulk asphalt binder. The use of nanosilica causes a denser microstructure of the binder, leading to better cohesion and, therefore, higher rigidity and rutting resistance. However, while all these benefits can be provided by nano silica in relation to the internal characteristics of the binder, such an additive does not always provide good interfacial adhesion with aggregate particles.

To overcome this drawback, anti-stripping chemicals, particularly modern formulations, are applied to operate within the interfacial transition region between the binding agent and the aggregate. Such chemicals manipulate surface energy behavior, allowing for strong chemical bonding, which maintains the consistency of the asphalt mix. Through the strengthening of this bond, they help minimize the possibility of water penetration and subsequent stripping.

The synergy of the double modification technique can be attributed to the fact that it is possible to simultaneously improve the mechanical strength through nanosilica and the environmental resistance through the anti-stripping additives. In this manner, the composition of asphalt changes from being a simple viscoelastic material into a superior form of reinforcement and bonding. The synergy helps to ensure that increased stiffness due to the application of nanosilica does not lead to fragility but is based on durable interfacial bonding, which allows effective load transfer even under challenging moisture environments.

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