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Effect of Fibers and Nanomaterials individually or in combination on the enhancement of asphalt mixes' performance: A review

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Abstract

Typical damage to asphalt mixtures includes fatigue cracking, moisture damage, high-temperature rutting, and low-temperature cracking. Modifying asphalt mix using a single modifier can contribute to road life extension, but it may also have drawbacks. To address these issues, research is being done on the impact of single and compound additives on asphalt and asphalt mix. Adding fibers to asphalt mix has been discovered in past investigations to promote increased longevity and enhanced functionality of roads. The performance of flexible pavements is improved by nanomaterials' extraordinary qualities, which include high functional density, remarkable sensitivity, distinct surface effects, large surface area, considerable strain resistance, and catalytic activity. In this sense, fibers and nanoparticles can both enhance hot mix asphalt (HMA). This article aims to offer a thorough understanding of the use of fibers, nanomaterials, and their combinations with other additives in asphalt binders and mixtures, drawing from an extensive review of the literature. When compared to the use of individual additives, it was determined that the application of composite technology in pavement construction can greatly extend the service life and overall performance of asphalt mixes.

Keywords: Asphalt mix, Fibers, Nanomaterials, single, combined modification

1. Introduction

The country's development, industrialization, and construction activities are increasing daily, and road pavement construction is one of the approaches to development [1]. The most common type of pavement used worldwide is hot mix asphalt (HMA) [2], which consists of base asphalt, mineral powder, aggregates, and voids [3]. Microcracks are progressively created inside asphalt pavement as a result of temperature shrinkage, moisture, traffic loads, and asphalt ageing throughout its service life [4,5]. Micro-cracks gradually develop into macro-cracks, resulting in the structural failure of asphalt pavement [6]. In asphalt pavements, rutting, fatigue cracks, and moisture damage are the most frequent deteriorations. These pavement degradations shorten the road's service life, driving comfort, and surface performance [7, 8]. To provide pavements with a longer service life, scientists and engineers are working to enhance the bitumen or asphalt mixture's qualities by adding new additives [9, 10]. This article aims to provide a comprehensive understanding of the application in the pavement engineering field (asphalt binders and mixtures) based on an exhaustive review of the literature.

2. Modified asphalt mix

Numerous studies and research efforts seek improved materials or modifications to enhance the properties of hot mix asphalt and mitigate asphalt pavement distress. The key to rutting resistance, pavement quality, and asphalt mixture durability is choosing the right kind and proportion of additives [11]. Research has shown that the performance of asphalt mixes can be enhanced using various additives, including polymers, nanomaterials, rice husk ash, natural fibers, and crumb rubber [12, 13, 14, 15, 16]. Generally, Asphalt modification materials fall into three categories: polymers, fibers, and nanomaterials. Although polymer modifiers are somewhat expensive, they have notable modifying effects. Additionally, certain hydrocarbons and their derivatives, such as oil and aromatics, can be used as modifiers [17, 18].

Reinforcing fibers to improve asphalt mixtures' performance has recently gained considerable attention. A few studies looked into how adding fiber reinforcement to asphalt concrete could improve its mechanical properties [19]. In the transportation industry, nanotechnology has attracted a lot of interest. One important area of research is the use of nanomaterials to modify asphalt [20, 21]. The use of fibers and nanomaterials in asphalt mix modification can have a significant impact on pavement thickness, primarily due to their role in improving the mechanical performance of the asphalt mixture [107, 108].

The integration of fibers and nanomaterials in asphalt mixes aligns with the global shift toward sustainable and green pavement technologies. By enhancing the mechanical properties and durability of asphalt mixtures, these additives contribute to longer service life and reduced maintenance needs. This, in turn, lowers the consumption of natural resources, energy, and emissions associated with frequent rehabilitation and reconstruction. Moreover, some fiber types can be sourced from recycled or waste materials, adding another dimension of environmental benefit. Therefore, evaluating the individual and combined effects of fibers and nanomaterials on asphalt performance not only addresses technical improvements but also supports the broader goals of sustainability in pavement engineering. *Aurangzeb, Q., et al. 2014* [105] supports how improved material performance reduces raw material use over the pavement lifecycle. *Vidal, R., et al. 2013* [106] highlights how improved asphalt technologies reduce energy demand and emissions. The ability of fibers to resist rutting is enhanced. Besides, while using fiber or nanomaterials in pavement construction may result in higher initial costs, it lowers maintenance costs over time [60, 109]. In this review, the effect of fibers and nanomaterials on asphalt mix performance separately or with other additives is discussed based on previous research.

3. Fibers modified asphalt mix as a single modifier

Fibers typically serve two important functions in asphalt mixtures: they stabilize the asphalt and reduce the drain-down effect, and they reinforce the asphalt mixtures to improve their mechanical performance [22]. Fibers greatly increase asphalt mortars and their mixtures' water stability, low-temperature crack resistance, and high-temperature stability [22, 23, 24, 25]. Fibers can create a three-dimensional network in the mortar, strengthening the skeletal structure and stabilizing and holding together fluid asphalts to prevent the asphalt from flowing at high temperatures [19].

Fibers can be classified as either natural or synthetic based on where they come from. The high stiffness and strength characteristics of synthetic fibers, including glass, steel, carbon, polymer, basalt, polypropylene, lignin, polyester, and aramid fibers, make them modifiers. New natural fibers with promising use in bituminous mixtures include hemp, coir, jute, sisal, bamboo, and flax. Fiber incorporation can enhance HMA's mechanical qualities, particularly its low-temperature performance [26, 27, 28, 29, 30, 31]. Fibers distribute stresses uniformly within the modified asphalt mix, preventing stress concentration. They form a superior interfacial adhesion with the asphalt mixture. As a result, fibers improve compressive strength and reduce the resilient deformation of asphalt [32, 33].

The impact of different fiber kinds, such as steel, polyester, polypropylene, and natural fibers, on the functionality of asphalt mixtures has been the subject of numerous studies. These experiments have repeatedly demonstrated that the addition of fibers can enhance asphalt mixtures' stiffness, tensile strength, and resistance to rutting and cracking. Fibers have also been shown to improve asphalt mixtures' resilience to moisture and their ability to withstand freeze-thaw cycles [34, 35, 36, 37, 38].

Despite the promising results, the mechanisms by which fibers improve the performance of asphalt mixtures are not yet fully understood. Furthermore, the optimal type, dosage, and distribution of fibers in asphalt mixtures remain unclear. This article aims to provide a comprehensive review of the literature on the effects of fibers on asphalt mixtures, focusing on the mechanical properties, durability, and potential applications of fiber-reinforced asphalt mixtures.

Asphalt mixtures frequently contain a variety of fibers, each of which has unique properties [39,40, 41, 42, 43]. Polyester and glass fibers have superior mechanical qualities when compared to lignin fiber, however, they also have drawbacks. The synthetic chemical fiber known as polyester is not very durable. In the meantime, because of its soft texture, polyester fiber clumps together in an asphalt mixture and is difficult to distribute uniformly [44, 45]. The smooth surface of glass fibers results in weak bonding with asphalt and generates environmental pollutants during production [46]. The addition of cellulose fibers reduced the phase angle and dynamic modulus of the asphalt mixture. On the other hand, fiber-modified asphalt mixtures were able to decrease their stiffness while increasing their flexibility [47]. This review focuses on the impact of using several types of fibers in asphalt mix modification in the following section.

3.1. Carbon fibers modified asphalt mix

Geckil, T., et al. 2020 [48] said that carbon fibers with physical properties mentioned in Table 1 enhanced asphalt mixtures to moisture damage by making them more cohesive and durable. It can be seen as shown in Fig.1 (a) by the naked eye, and (b) Scanning Electron Microscopy (SEM). Carbon fibers have been recognized for their beneficial contribution to enhancing the performance of asphalt mixtures [49].

Table (1) Physical properties of carbon fiber [47]

Properties	Number of filaments	Yield texture, g/1000m	Tensile strength, ksi	Tensile modulus, msi	Elongation, %	Density, g/cm^3	Filament diameter, µ
Carbon fiber (TC-35/12K)	12 000	720	580	35	1.6	1.8	6.5

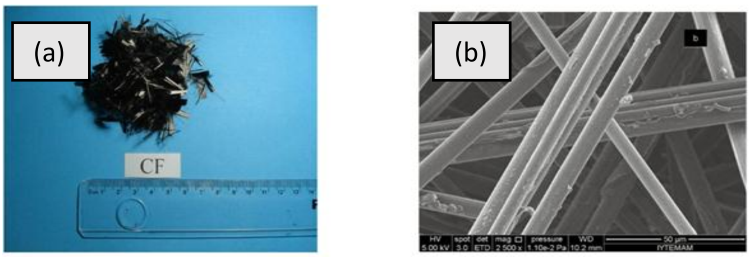

Fig.1. (a) Carbon fibers, (b) SEM of carbon fiber used in work [50]

Rasheed, S., et al. 2024 [50] demonstrated that adding 0.4% carbon fibers to the HMA produced the best results. Furthermore, lessening rutting in the asphalt mixture improved HMA's performance at a high temperature of 60°C. Improving the mixture's performance characteristics increases pavement durability, leading to a smoother and more comfortable

3.2. Ceramic fibers modified asphalt mix

Ceramic fibers (CFs) are produced by melting clay clinker at high temperatures and then using high-speed airflow to form continuous fibers, making them an excellent alternative to asbestos fibers. It can be seen as shown in Fig.2 (a) by the naked eye, and (b) Scanning Electron Microscopy (SEM) [52]. Ceramic fiber (CF) is a kind of industrial waste that is widely used for waste utilization and environmental protection. *Wang, X., et al., 2021* [52] reached that the Ceramic fibers with physical properties mentioned in Table 2 can enhance the mechanical properties, high-temperature stability, moisture resistance, and low-temperature cracking resistance of asphalt mixtures, with an optimal CF content of 0.4%. *Liu, F., et al. 2023* [53] demonstrated that the ceramic fibers positively impact the mechanical characteristics and pavement performance of the asphalt mixture.

Al-Saad, A. A., et al., 2022 [54] The ceramic fibers reinforced mixture's surface characteristics, particle

ride. *Xie, T. et al. 2023* [51] sought to determine the best carbon fiber asphalt mastic design by examining its rheological characteristics. After considering the test findings and modeling the performance characteristics using the response surface method, the ideal proportioning proposal was found to be 9% fiber content and 1 mm fiber length.

diameter size, and fiber distribution were all revealed by illustrated microscopic analyses. These included the network structure and strength mechanism, which enhanced the asphalt mixture's performance by creating a three-dimensional network.

3.3. Lignin fibers modified asphalt mix.

Lignin fiber with physical properties as mentioned in Table 3 [56], as a bio-based waste, has been used in the asphalt works because of its many benefits. It can be seen as shown in Fig.3 (a) by the naked eye, and (b) Scanning Electron Microscopy (SEM) [55].

The asphalt mixture's resistance to rutting and thermal cracking was enhanced by using lignin fibers, but its abrasion resistance, fatigue performance, and moisture stability were negatively impacted [55]. The lignin fiber improves the resistance to low-temperature cracking in asphalt mixes with a limited improvement in high-temperature performance. The best dosage was 0.3% of asphalt mix weight [56].

Table (2) Physical properties of ceramic fiber [52]

Properties	Length (mm)	Diameter (µm)	Density, g/cm3	Maximum working temperature (°C)	Tensile strength (MPa)
Ceramic fiber	2-4	2-3	1..8	1600	3000

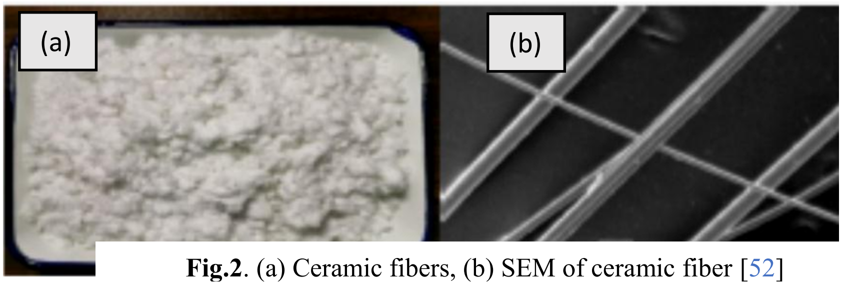

Fig.2. (a) Ceramic fibers, (b) SEM of ceramic fiber [52]

Table (3) Physical properties of lignin fiber [56]

Item	Length (mm)	Specific Area (10−3 m2/gm)	Diameter (mm)	Aspect Ratio (mean)	Density (g/cm3)	Melt Temperature (°C)
Value	1.10	118.1	0.045	24	1.28	>200

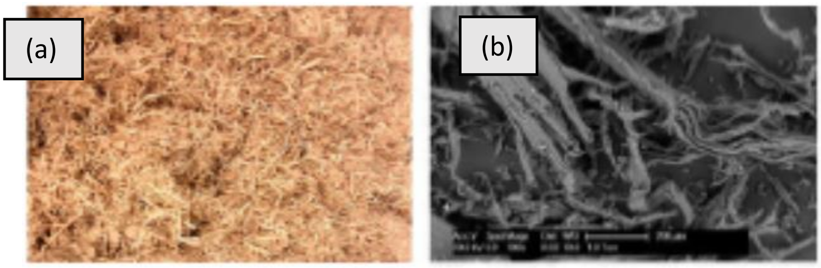

Fig.3. (a) Lignin fibers, (b) SEM of lignin fiber [55]

Asphalt is partially absorbed by lignin fiber, which is generally thought to reduce abrasion resistance [57]. Because of its low strength, lignin fiber has a strong adsorption to asphalt; however, the enhancing impact is hardly noticeable [58]. Furthermore, there are several types of lignin fiber, such as lignin fibers and lignin powder. Research on the effects of these various lignin compounds on asphalt mixture performance is also warranted.

3.4. Glass fibers modified asphalt mix.

Glass fiber with physical properties as tabulated in Table 4 is an inorganic fiber with a high tensile strength. Glass fiber has been effectively employed in earlier research to alter asphalt mixtures to increase their deformation capacity. It can be seen as shown in Fig.4 (a) by the naked eye, and (b) Scanning Electron Microscopy (SEM).

Klinsky, K. E., et al., 2018 [4] stated that glass fibers can improve hot mix asphalt's stiffness and tensile strength, but handling them properly during construction is necessary. Nonetheless, there have been reports of increased voids in the mix and decreased rigidity and stability. *Guo, Q., et al., 2015* [59] demonstrated that the asphalt mixture treated with glass fiber may be resistant to the onset of cracks. This will help to keep the pavement from cracking in cold weather. It has been demonstrated to improve asphalt mixtures' ductility, resistance to cracking, and fatigue performance [56].

For clarification, not limitation, Table 5 contains some experimental tests that assess the asphalt mix properties affected by adding fibers. Based on previous studies, the kind, length, and percentage of fibers and the temperature of the test can affect the asphalt mix.

Table (4) Physical properties of glass fiber [56]

Item	Length (mm)	Diameter (mm)	Melt Temperature (°C)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Value	12	0.045	860	3400	76

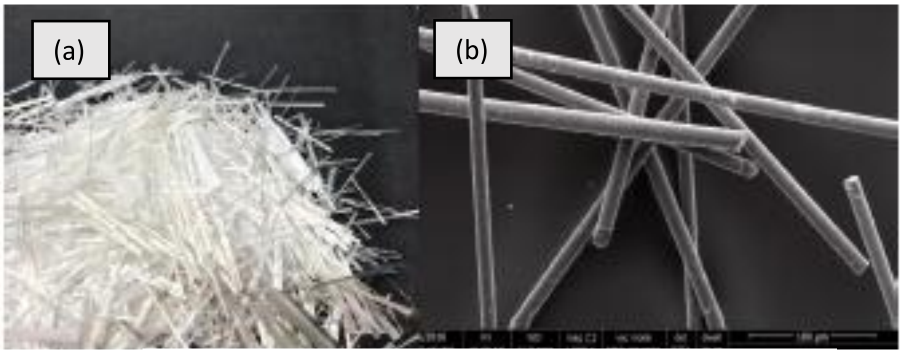

Fig.4. (a) Glass fibers, (b) SEM of glass fiber

Table (5) Effect of using different types of fibers as a single modifier on the asphalt mix.

Reference\ Dosage	Tests	Modification effect
Geckil, T., et al. 2020 [48] Carbon fibers of 0.3%, 0.5%, and 0.7% by weight of bitumen, with 12.5 mm length	-Marshall flow and stability. The modulus of indirect tensile stiffness. -Stiffness creep. -Indirect Strength of Tensile. -Moisture resistance.	-A 25% increase in shear stress resistance. -At 40°C, the fatigue life increased by 51%. -at 60 °C, enhanced the resistance to persistent deformation by 2.25 times.
Mawat, H. Q., et al.2020 [49] Carbon fibers with three distinct lengths of 1.0 cm, 2.0 cm, and 3.0 cm were added to the asphalt mixture at concentrations of 0.10%, 0.20%, and 0.30% by weight.	-Index of Retained Strength. -Indirect Tensile Test. - Marshall Test.	-The mixture showed an increase in void content, a decrease in flow value, and an increase in stability. - The index of maintained strength improved by 12.52% and the indirect tensile strength ratio by 11.23% with the addition of 2.0 cm long carbon fibers at 0.30%. The ideal fiber content for each of the three fiber lengths was likewise found to be 0.30 percent by weight of the mixture.
Rasheed, S., et al. 2024 [50] Carbon fibers at 0.2, 0.4, and 0.6% by weight of bitumen, with 12.5 mm length	-Marshall Stability and flow. - Rutting resistance test. -Indirect Tensile Strength. -Moisture resistance.	-Rut depth decreased by 50%, flow decreased by 23%, and Marshall Stability increased by 48%. - There was an 88.6% improvement in the indirect tensile strength. - Moreover, 88% moisture susceptibility was attained.
Xie, T. et al. 2023 [51]	-A sweep of frequencies.	-The dynamic modulus master curves showed that

Carbon fibers at three percentages, 3%, 6%, and 9% by mass of asphalt, with three lengths (0.5, 1, and 2 mm)	-A sweep with linear amplitude. -Multiple recovery from stress creep. -Adaptive recuperation. The rheometer for bent beams. -The performance of fatigue. - Resistance to rutting. -The capacity for elastic recovery. -The asphalt mastic's low-temperature performance.	the stiffness of the modified asphalt mastic and deformation resistance gradually increased with fiber length and content. The asphalt mastic that has been treated with more fibers and for a longer period has stronger elastic capabilities at both low and high temperatures, according to the phase angle master curves. - Stability at high temperatures. -The asphalt's fatigue resistance, fatigue life at medium temperatures, and cracking resistance at low temperatures were all decreased by the addition of carbon fibers. - Longer fiber asphalt mastic has a greater potential for elastic recovery. By raising the creep rate, the temperature increase enhanced the asphalt's low-temperature performance.
Wang, X., et al., 2021 [52] Ceramic fibers at 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% of asphalt mix weight with 2-4 mm length	-Marshall test. -wheel tracking. -Marshall Immersion Test. -The freezing-thawing test. -Bending test at low temperatures.	-The Marshall stability was increased by 17.5% at 0.4% CF. -The rut depth dropped by 23.1% and the dynamic stability increased by 27.3%. - The adjusted asphalt mixture's immersion residual stability increased by 6.4%. - The ITS increased by 20% and the TSR by 8.8%. -The failure strain was improved by 9.6%.
Al-Saad, A. A, et al., 2022 [54] Ceramic fibers at 0%, 0.75%, 1.5%, and 2.25% of asphalt mix weight	-Marshall stability test. -Wheel tracking test.	-The Marshall stability was improved by 22.05%. - Rutting depth was reduced by 27.71%.
Luo, D., et al., 2019 [56] 0.2–0.4% lignin fiber of asphalt mixtures.	-Marshall Stability Test. -Water Stability Tests (Marshall Immersion Test, Freez–Thaw Splitting Test). -Low-Temperature Three-Point Bending Test	-The optimum asphalt content increased by 0.45%. - The MSR improved by 4.7%. -The TSR value increased by 3.07%. -The asphalt mixtures' maximum tensile strain and bending tensile strength increased by 24.7% and 19.1%, respectively.
Zhang, Y., et al., 2020 [55] 10% of the bitumen weight of Lignin fibers with a length range of 3 to 6 mm	-Cantabro tests (moisture susceptibility, thermal and fatigue cracking resistance, rusting, raveling). -Test for wheel loading tracking. The test for semicircular bending. -Bend test for four-point beams. -Cyclic freezing-thaw test.	- Cantabro loss was increased by 15.56 (negative effect). -Rutting depth was improved by 28.5%. -Dynamic stability was increased by 20.09%. -The ratio of fracture energy was increased by 34.8%. -Negative effect on fatigue life and TSR.
Luo, D., et al., 2019 [56] 0.2–0.6% glass fiber of asphalt mixtures	-Marshall Stability Test. -Water Stability Tests (Marshall Immersion Test, Freez–Thaw Splitting Test). -Low-Temperature Three-Point Bending Test	-The optimum asphalt content increased by 0.15%. -The MSR improved by 9.8%. -The TSR value increased by 7.31%. -The maximum tensile strain and bending tensile strength of asphalt mixtures increased by 19.1% and 18.3%, respectively.

4. Nanomaterial-modified asphalt mix as a single modifier

Nanomaterials are substances characterized by having at least one dimension within the nanoscale range of 1 to 100 nanometers, or they are constructed from such nanoscale components [61]. Depending on their dimensional characteristics, nanomaterials can be divided into several types: zero-dimensional (0D) materials like nano-zinc oxide (NZ) and nano-silica (NS) particles [62, 63]; one-dimensional (1D) structures such as carbon nanotubes (CNTs) [64]; two-dimensional (2D) forms including graphene oxide

(GO) and nano-clay (NC) [65, 66]; and certain polymeric materials like styrene-butadiene-styrene (SBS) and styrene-butadiene rubber (SBR) [67].

Nanomaterials have been found to improve various performance characteristics of asphalt mixtures, such as resistance to rutting and fatigue, Marshall stability, indirect tensile strength, resilient modulus, and durability against moisture damage [68, 69]. Research by Zhang et al., 2021 [70] demonstrated that incorporating nano-silica, nano-titanium dioxide, and nano-zinc oxide enhances asphalt's resistance to UV-induced aging. In contrast, nano-calcium carbonate, carbon nanotubes, and layered silicates are effective in delaying the effects of thermo-oxidative aging. Moreover, the use of multi-dimensional nanomaterial modifiers-comprising a combination of nano metal oxides and layered silicates, greatly improves the resistance of both base asphalt and polymer-modified asphalt to UV and thermal-oxidative aging. An optimal amount of ZnO nanoparticles can enhance the high-temperature performance of asphalt by increasing the softening point, reducing the penetration value, and improving rutting resistance. These performance improvements result from the synergistic effects of both physical and chemical modifications [71].

Kordi et al., 2017 [72] observed that increasing the concentration of nano-sized Fe_2O_3 in asphalt mixtures led to a noticeable reduction in rutting depth. This improvement was attributed to the material's high surface area, which contributes to its filling and reinforcing effects, thereby enhancing the bonding strength among asphalt particles. Similarly, *Zahid et al., 2022* [73] reported that incorporating carbon nanotubes and nano-clay into hot mix asphalt (HMA) improved key performance parameters such as dynamic modulus, stiffness, rutting resistance, dynamic stability, and moisture susceptibility. Incorporating nanoparticles can markedly enhance asphalt's properties, including its viscosity, stiffness, elasticity, fatigue resistance, aging resistance, and ultraviolet radiation resistance, thereby improving pavement quality and prolonging service life. While challenges remain, including high costs, limited scalability, and environmental concerns, a life cycle analysis suggests that the long-term economic benefits of nanomaterials, such as reduced maintenance costs and extended pavement lifespan, make them a viable solution for road engineering [74, 107].

4.1. Nano silica modified asphalt mix

Silica, with the chemical formula SiO_2, shares a structural resemblance with diamond and occurs naturally in both crystalline and amorphous forms. It can be seen as shown in Fig.5 (a) by the naked eye, and (b) Scanning Electron Microscopy (SEM). The chemical and physical characteristics of nano-silica are detailed in Tables 6 and 7, respectively. Owing to its high surface area, excellent dispersibility, strong adsorption ability, and remarkable stability, nano-silica finds extensive application in both medical and engineering domains. These properties make it particularly suitable for use as a catalyst support and a filler in plastics [75, 76].

Taherkhani, H., et al., 2016, and Shafabakhsh, G., et al., 2015 [77, 78] have shown that nano-silica reduces the penetration of bitumen, primarily because of its strong reinforcing ability, which helps stabilize the asphaltene component relative to the maltene phase. Additionally, nano-silica improves the compressive strength and moisture resistance of asphalt mixtures. However, an increase in air void content can negatively affect the compressive strength of asphalt mixes modified with nano-silica [79].

The incorporation of nano silica has a greater positive impact than micro silica on various asphalt cement and mix properties, contributing to more durable pavements. Specifically, at a 6% nano silica content, it enhances performance and helps reduce the lifecycle costs of pavement [80].

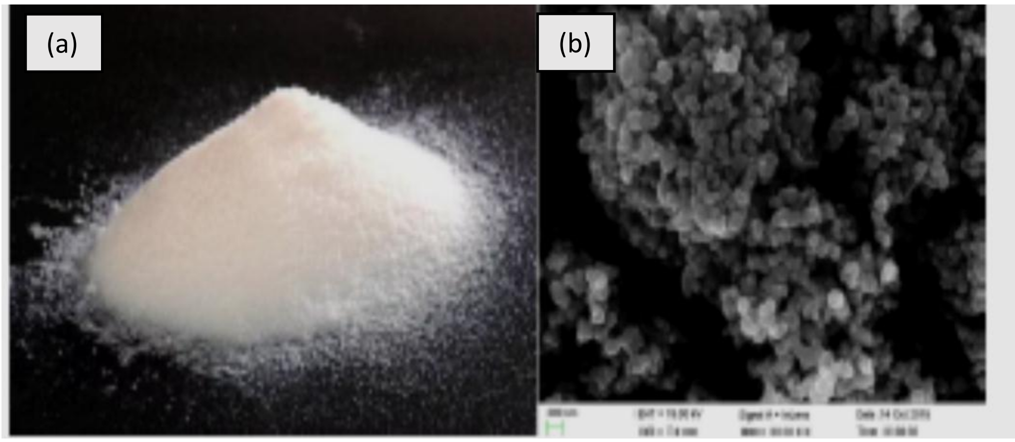

Fig.5. (a) Nano silica, (b) SEM of nano silica

Table (6) Chemical composition of Nano silica [81].

Item	SiO2 (%)	Ti (ppm)	Ca (ppm)	Na (ppm)	Fe (ppm)
Nano silica	≥99%	<120	<20	<50	<200

Table (7) The physical properties of Nano silica [81].

Diameter (nm)	Surface volume ratio (m^2/g)	Density (g/cm^3)	Melting point (^oC)
20-30	130-600	2.1	1,600

The impact of nano-silica (NS) on asphalt viscosity varies and is not consistent across all cases, as it is affected by several factors such as NS concentration, temperature, and the inherent characteristics of the base asphalt. This highlights the need for additional studies to fully explore and clarify how NS content influences asphalt viscosity under a range of conditions [74].

4.2. Nano-Titanium modified asphalt mix

The chemical formula of Nano Titanium is TiO2; it can be seen as shown in Fig.6 (a) by the naked eye, and (b) Scanning Electron Microscopy (SEM). The chemical composition and physical properties of nano-silica are shown in Tables 8 and 9, respectively. The surface free energy (SFE) method indicates that Nano-TiO_2 enhances the wettability of the asphalt binder on the aggregate, improving adhesion between the binder and the aggregate [82]. *Enieb, M., et al., 2023* [83] revealed that nano titanium dioxide (nano-TiO_2) improves the rheological and physical properties of both unaged and aged asphalt binders. Research also indicates that nano-TiO_2 enhances the rutting resistance of asphalt mixtures. In addition to absorbing, reflecting, and scattering ultraviolet radiation, nano-TiO_2 has been found to provide effective UV shielding [84, 85].

Mohammed, A. M., et al., 2024 [86] observed that increasing the nano-TiO_2 content from 3% to 7% enhances the asphalt's resistance to rutting at elevated temperatures and improves its Performance Grade (PG)—by approximately one grade at 3% and up to two grades within the 5–7% range. This indicates that nano-TiO_2 contributes to increased asphalt stiffness. At intermediate temperatures, the fatigue factor ($G^* \sin \delta$) of PAV-aged asphalt rises by 5% and 7% with TiO_2 content, reflecting a higher complex modulus and reduced fatigue resistance as the nano content increases. At lower temperatures, greater nano-TiO_2 concentrations result in elevated creep stiffness and m-values. However, the increased stiffness combined with lower m-values at (-6°C and 12°C) may raise the risk of cracking in cold conditions. Overall, incorporating 5% nano-TiO_2 enhances the physical performance of asphalt, particularly improving its resistance to rutting and fatigue.

4.3. Nano clay modified asphalt mix

Nano-clay plays a crucial role in enhancing the performance characteristics of both asphalt binders and mixtures. Its chemical composition is detailed in Table 10. Asphalt modified with nano-Al_2O_3 demonstrates improved rheological and physical behavior, offering greater resistance to fatigue cracking and rutting under high temperatures [87]. Nano clay can be seen as shown in Fig.7 (a) by the naked eye, and (b) Scanning Electron Microscopy (SEM).

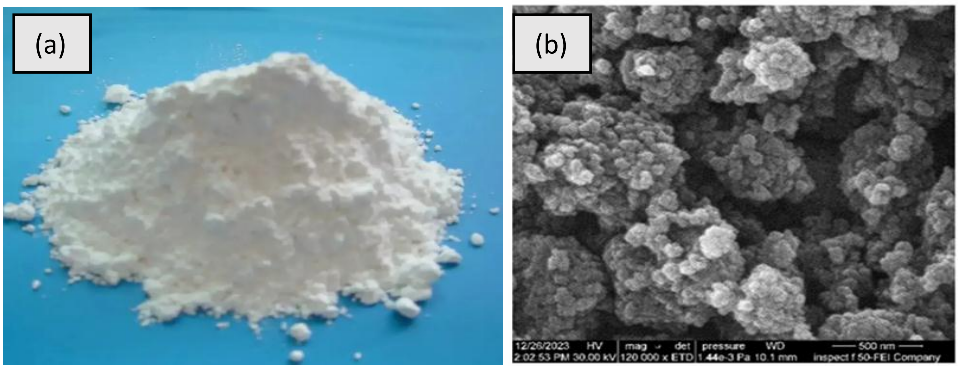

Fig.6. (a) Nano Titanium, (b) SEM of nano titanium

Table (8) Chemical composition of Nano Titanium [81].

Item	TiO2 (%)	Al (ppm)	Mg (ppm)	Si (ppm)	Ca (ppm)	S (ppm)	Nb (ppm)
Nano Titanium	≥99%	≤17	≤65	≤120	≤75	≤130	≤80

Table (9) The physical properties of Nano Titanium [81].

Diameter (nm)	Surface volume ratio (m^2/g)	Density (g/cm^3)	Loss of ignition (%)
20	10-45	3.9	8.24

Fig.7. (a) Nano clay, (b) SEM of nano clay

Even at low concentrations, nano-clay modifiers have been shown to effectively boost resistance to stripping, rutting, and cracking [88]. Additionally, nano-clay enhances key properties such as stability, resilient modulus, and indirect tensile strength, resulting in better performance than unmodified bitumen under dynamic creep conditions. However, it has a limited impact on improving fatigue resistance at low temperatures. The incorporation of nano-clay also leads to an increase in both the optimum binder content and total voids within the asphalt mix [89].

For clarification, not limitation, Table 11 contains some experimental tests that assess the asphalt mix properties affected by adding nanomaterials. Based on previous studies, the kind and percentage of nanomaterials and the temperature of the test can affect the asphalt mix.

Table (10) Chemical composition of the nano clay powder [90].

Oxide Composition	SiO2 (%)	Al2O3 (%)	Fe2O3 (%)	CaO (%)	MgO (%)	L.S.F. (%)	Insoluble residue, (%)	L.O.I. (%)	So3 (%)
Oxide (%)	58.7	0.81	0.31	0.34	0.16	0.002	55.24	40.62	0.06

Table (11) Effect of using different types of nanomaterials as a single modifier on asphalt mix.

Reference\ Dosage	Tests	Modification effect
Aljbouri, H. J., et al., 2023 [69] Nano silica at 1%, 3%, and 5% of asphalt binder weight	-Marshall Stability. -Uniaxial repeated loading test. -moisture susceptibility. -Indirect Tensile Strength test.	-Marshall stability was increased by 74%. -The improvement in unconditioned tensile strength was 18.9%. -The improvement rate of the Resilient modulus was 49.3%. -Permanent deformation was improved by 60.4%. - Improvement in design life by 56.6%. -The optimum content was 5%.
Mirabdolazimi, S., et al., 2021 [79] Nano silica at 0.2, 0.4%, 0.7%, and 0.9% by the asphalt weight, on two grades of bitumen (60-70 and 85-100 pen grade).	-Physical rheological properties of bitumen samples. -The modified Lottman test.	-A reduction in penetration grade was observed in both types of bitumen. -The softening point rose by 8% for 60–70 penetration grade and by 6% for 85–100 penetration grade bitumen. -Bitumen stiffness increased, while its elasticity and ductility decreased. -Nano-silica modification led to a viscosity increase of 41% in 60–70 penetration grade and 59% in 85–100 grade bitumen. -Adding 0.7% nano-silica raised the flash point by 4.5% for 60–70 and 4% for 85–100 penetration grade bitumen. -The optimal nano-silica content was determined to be 0.7% of the bitumen's weight. -Nano-silica also enhanced the indirect tensile

		strength (ITS) of the asphalt specimens under both dry and wet conditions.
Qasim, Z., et al., 2022 [80] Nano silica at 2%, 4%, 6%, and 8% by asphalt weight.	-Consistency tests of modified asphalt. -Superpave bitumen binder tests. -Mass losing test. -Bending Beam Rheometer. -Marshall stability and flow.	-The penetration is decreased by 4.5%, 10.6%, 15.1%, and 30.3%. -The softening point increased by 8%. -The viscosity increases by 52%, 171%, 233% and 395%. -The stiffness parameter increased by 12% and 17.7% for 4% NS at 70 and 76 °C. -Mass loss decreased with the increase in nano-silica. - m-value and creep stiffness increased to 6% of nano silica. -Optimum content of nano silica is 4.9% of asphalt weight. -Marshal stability was improved by 21%. - Flow value increased with the NS content up to 3.0% by wt.
Azarhoosh, A., et al., 2018 [82] Nano titanium at 6% of asphalt weight.	-Physical-rheological properties of bitumen samples.	-The penetration increased by 7%. -The softening point of the 85-100 pen grade bitumen increased by 10 %. -The ductility of bitumen was increased by 5%. -It increased the viscosity by 33%. -It increased the flash point by 8%.
Masri, K., et al., 2022 [91] Nano titanium with 1 to 5% of asphalt weight in Stone Mastic Asphalt.	-Morphological and chemical properties. -The mechanical performance of stone mastic asphalt.	-A 3% nano TiO_2 modified binder provides the greatest enhancement in both chemical and morphological properties. -A 5% nano TiO_2 modified binder shows notable improvements in penetration and softening point.
Mohammed, A., et al., 2024 [86] 1, 3, 5, and 7% of nano-TiO2 by weight of asphalt	-The physical and rheological tests. -Dynamic Shear Rheometer test. -Bending Beam Rheometer.	-A decrease in penetration was observed, with the most significant reduction of up to 22% at a 5% TiO_2 content. -The softening point values showed an increase of 6%, 13%, 16%, and 14%, indicating improved high-temperature performance. -asphalt with 5% TiO2 has the highest hardness. -The viscosity increased by approximately 29%, 42%, 56%, and 53% at 135°C, indicating enhanced resistance to flow at high temperatures. -The ductility value increased with the addition of nano-TiO_2, ranging between 112 and 123 cm. - The addition of nano-TiO_2 increases the stiffness of asphalt and improves its rutting resistance. - An increase in nano-TiO_2 content from 3% to 7% enhanced the elastic nature of asphalt by approximately 8%, 16%, and 18% at 25°C, and by 4%, 11%, and 14% at 28°C.
Aljbouri, H. J., et al., 2023 [69] nano clay at 3, 5, and 7% of asphalt binder weight	-Marshall Stability. -Uniaxial repeated loading test. -moisture susceptibility. -Indirect Tensile Strength test.	-Marshall stability was increased by 58%. -The improvement in unconditioned tensile strength was 20.3%. -The improvement rate of the Resilient modulus was 32.3%. -Permanent deformation was improved by 61.5%. - Improvement in design life by 35.7%. -The optimum content was 7%.
Hussein, H. Z., et al., 2021 [90] Nano clay at 3%, 5%, and 7% of	-Physical tests.	- NC improved the stiffness of asphalt. -The superior reduction in the penetration grades was noted at 7%.

the asphalt weight		-The penetration index values increased.
Aljbouri, H. J., et al., 2023 [69] nano carbonate calcium at 2, 4, and 6% of asphalt binder weight	-Marshall Stability. -Uniaxial repeated loading test. -moisture susceptibility. -Indirect Tensile Strength test.	-Marshall stability was increased by 15%. -The improvement in unconditioned tensile strength was 12.8%. -The improvement rate of the Resilient modulus was 7.9%. -Permanent deformation was improved by 7.7%. - Improvement in design life by 8.3%. -The optimum content was 4%.

5- Fibers and nanomaterials in a combined modified asphalt mix

Although modifiers have a significant effect on improving asphalt performance [92, 93], enhancing asphalt performance using single modifiers is challenging. To address these issues, research is being done on the impact of double additives on hot mix asphalt [94, 95, 96, 97]. *Guo, Q., et al., 2015* [59] noted that the issue of diatomite negatively affecting the low-temperature deformation properties of the asphalt mixture is addressed by incorporating glass fiber. Research indicates that incorporating glass fiber, polypropylene fiber, lime, and nano-silica powder into asphalt pavements enhances rutting resistance while also increasing both direct and indirect tensile strength [98]. Incorporating polypropylene (PP) and glass fiber (GF) into asphalt mixtures improves the mechanical properties and longevity of asphalt concrete pavements, while also reducing the draining effect of the asphalt material [99]. *Shafabakhsh, G., et al., 2021* [81] mentioned that the TiO2\SiO2 modified asphalt has more resilience against plastic deformation than conventional asphalt. *Fu, Z., et al., 2022* [100] illustrated that the Rheological properties of Basalt fiber and nano-TiO2/ZnO composite improve the performance of asphalt binder. It can delay the asphalt binder aging process. This review focuses on the impact of using several types of fibers in asphalt mix modification in the following part and Table 12; for clarification, not limitation, depending on previous research.

The use of polymers for modifying asphalt concrete (AC) mixtures presents several drawbacks that limit their widespread application in roadway construction. Recently, studies have concentrated on integrating supplementary materials, like nanomaterials, to counteract the adverse effects of polymers and improve the performance of asphalt concrete mixtures.

Table (12) Effect of using different fibers and nanomaterials in the combined modified asphalt mix.

Reference\ Dosage	Tests	Modification effect
Khater, A., et al., 2021 [101] 0.3% lignin fiber and 0.3% glass fiber of asphalt mixtures.	-Marshall Stability Test. -Water Stability Tests (Marshall Immersion Test, Freez–Thaw Splitting Test). -Low-Temperature Three-Point Bending Test	-The optimum asphalt content increased by 0.35%. -The MSR improved by 13.5%. -The TSR value increased by 8.71%. -Asphalt mixtures' bending tensile strength and maximum tensile strain improved by 26.5% and 48.8%.
Guo, Q., et al., 2015 [59] 12mm length glass fiber at (0.1- 0.2- 0.3) % and Diatomite at (0.1- 0.2- 0.3) % of asphalt mix weight	-Wheel tracking test. -Low temperature indirect tensile test. -Indirect tensile fatigue test. -Indirect tensile stiffness modulus test.	-The dynamic stability was improved by increasing the modifiers. -Due to the small amount of additives, the indirect tensile strength wasn't affected by the additives. -The fatigue life of the modified asphalt mix is greater than the control asphalt mix. -The stiffness modulus is greater than that of the control asphalt mix.
Cheng, Y., et al., 2018 [102] Diatomite is at 0.25% of filler weight, and basalt fibers are at 6.5% of asphalt mix weight.	-Wheel Tracking Test. -The Low-Temperature Indirect Tensile Test. -Moisture Susceptibility Test. -Fatigue test. -Freeze–Thaw Cycles Test.	-The dynamic stability was improved by 72.7%. -The strength and failure strain of the modified asphalt were higher than those of the control mix. -Adding basalt fibers to diatomite-modified asphalt decreases the resistance to moisture susceptibility.
Shafabakhsh, G., et al., 2021 [81] Different ratios of nano TiO_2% % \ SiO_2% (1.25\0.5), (2.5\1), (5\2), (6.25\2.5) % of bitumen	-Mechanical Tests. -Environmental Test.	The following results were observed for both conventional and modified asphalt: -Penetration at 25°C (d-mm): 66, 64.2, 61.7,

weight.		59.1, and 60.5. -Softening Point (°C): 51, 55.3, 59.2, 61.1, and 56.5. -Ductility at 25°C (5 cm/min) (cm): 111, 92, 82, 78, and 81. -Penetration index: -0.356, 0.39, 0.99, 1.71, and 0.64. -Nanoparticles increased viscosity by approximately 250% on average at temperatures between 120°C and 160°C. -Modified binders exhibited increased stiffness. -Modified asphalt samples displayed more favorable elastic and viscous characteristics compared to untreated asphalt. -Modified samples showed improved tensile strain. -Additives reduced both the growth rate of micro-cracks and cracks due to creep. -The efficiency of nitrogen oxide (NOx) reduction in pollutant particles ranged from 41% to 63%.
Moussa, G. S., et al., 2021 [103] Nano clay at a concentration of 1–4% by weight of the asphalt binder was added to high-density polyethylene (HDPE)-modified AC mixture.	-Marshall Stability Test. -Moisture Damage Resistance test. -Stripping Susceptibility test.	-The addition of 1%, 2%, and 3% NC did not improve the stability or flow properties of HDPE. -With 4% NC, the stability value increased by 27.3%, while the flow value decreased by 22.8%. -NC significantly enhanced the stiffness of the mixture. -The dry compressive strength (CS Dry) of the HDPE and NC modified mixtures improved by 61.5%, 66.7%, 81.2%, 102.7%, and 88.4%. -For the immersed compressive strength (CS Immersed), the increases were even higher, at 81.2%, 100.1%, 125.5%, 152.3%, and 133.6%. -The punching strength was greater than that of the base mixture by 60.2%, 80.1%, 85.7%, 114.2%, and 112.8%.

Research on incorporating nanomaterials alongside polymers to enhance pavement performance has become a growing area of interest. Adding nanomaterials to polymer-modified asphalt not only bridges the gap between polymers and asphalt but also amplifies the polymer's effectiveness in improving asphalt performance, especially at high temperatures. Additionally, the inclusion of nano-clay (NC) particles in high-density polyethylene (HDPE)-modified mixtures has shown a positive impact on enhancing aggregate-binder adhesion [103].

Babagoli, R., et al., 2022 [104] The incorporation of Nano TiO_2/Styrene-Butadiene Rubber (SBR) into asphalt binder improves its rutting and fatigue resistance. However, as the content of Nano TiO_2/SBR increases, the storage stability of the binder decreases. Modified binders with Nano TiO_2/SBR show a significant potential for reducing pollution.

6- Conclusion and recommendation

This research aims to provide a comprehensive understanding of the application of fibers and nanomaterials individually or with other additives in pavement engineering. According to previous reviews, the main conclusions and recommendations can be outlined as follows:

1-Fibers used in asphalt mixtures serve as stabilizers to reduce the drain-down effect and as reinforcing agents to enhance the mechanical properties of the asphalt. They help improve the asphalt's high-temperature stability, low-temperature cracking resistance, and water resistance. Additionally, fibers can boost tensile strength, stiffness, moisture resistance, freeze-thaw durability, and resistance to cracking and rutting. The impact of fibers on asphalt mixture modification depends on factors such as fiber type, length, proportion, and mixing technique. However, challenges remain, including issues with compatibility, dispersion, adhesion, and the interactions between asphalt, fiber, and aggregate.

2-Nanomaterials improve the properties of asphalt mixtures by enhancing characteristics such as rutting resistance, fatigue resistance, Marshall stability, indirect tensile strength, resilient modulus, dynamic modulus, stiffness, and moisture resistance. They also improve high-temperature performance by raising the softening point and decreasing penetration values. The effect of nanomaterial modification is influenced by the type and concentration of the materials used. However, the broader adoption of these materials is hindered by issues such as poor compatibility, inadequate dispersion, high production costs, and environmental and health concerns.

3-Many single modifiers face limitations in improving either high-temperature or low-temperature performance of asphalt mixtures. As a result, using composite technology in pavement construction can positively influence the service life and overall performance of asphalt mixes. While most fibers improve low-temperature performance, nanomaterials are particularly effective at enhancing high-temperature performance. Asphalt mixtures reinforced with composite additives showed notable improvements in moisture resistance and low-temperature stability when compared to other mixtures.

For future research, it is recommended:

1. The interfacial interactions between asphalt, fiber, and aggregate require further investigation. A detailed study of the adhesive properties is crucial for understanding the cracking behavior of fiber-modified asphalt mixtures.
2. Thorough economic and environmental assessments are necessary before the large-scale application of nanomaterials.
3. There is a broad scope for evaluating the impact of various materials on the overall performance of asphalt mixtures to mitigate the limitations associated with single modifiers.

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Conflict of interest

The authors report no conflicts of interest with the funding organization or any entities referenced in this article in the past three years that could have impacted the research or its conclusions. Furthermore, all authors have received certification from their respective institutions for conducting research involving human subjects.

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