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A Comprehensive Review of the Impact of Nanomaterials and Fibers on Asphalt Mixtures and Their Performance

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Abstract.

The increase in traffic volumes and the rising cost of bitumen make it necessary to enhance the performance of asphalt binders through bitumen modification. Various types of nanomaterials have been used as additives to bitumen to improve the properties of asphalt mixtures, particularly in terms of resistance to aging, cracks caused by stress and temperature changes, moisture-induced damage, and permanent deformation. Several relevant studies have been reviewed, focusing on nanomaterials such as Nano Calcium carbonate, nano-silica, and carbon nanotubes. Additionally, the effect of fiber additives in asphalt mixtures has been examined, highlighting the different types of fibers used, their properties, testing methods, and mix design tests for fiber-reinforced asphalt mixtures. A wide variety of fiber types have been used in asphalt mixtures, including natural fibres and synthetic fibres. Recycled fiber materials, such as newsprint fibers, carpet fibers, and recycled tire fibers, have also been utilized. This review summarizes the performance of nanoparticles and fibers as asphalt modifiers. Several relevant studies have been reviewed, addressing nanomaterials and fibers.

Keywords: Asphalt mixes, Experimental tests, Nanoparticles Modifiers, Fibers Modifiers.

1. Introduction

The increase in traffic volumes, the rising weight of trucks, and higher tire pressures pose significant challenges to the pavement system, leading to deformations such as rutting, stripping, and fatigue cracking [1]. Therefore, the concept of modern technology, known as nanotechnology and fibers, has been introduced as an alternative to enhance the physical and rheological properties of asphalt binders and mixtures, thereby improving the performance of asphalt mixtures [2]. Although improvements in asphalt binder and mixture performance have been achieved using other types of modifiers at macro and micro scales, exploring the impact of nanotechnology and fibers on road pavement performance remains an intriguing area of study [3]. Consequently, the application of nanotechnology and fibers in asphalt mixtures has been widely investigated and reported worldwide.

Nanotechnology and fibers are considered among the latest advancements in pavement engineering aimed at developing a safe and sustainable infrastructure [4], [5]. Despite extensive exploration by researchers, material producers, and engineers over the years, the use of these technologies remains limited. Therefore, new efforts have been made to explore and develop both nanomaterials and fibers for pavement applications, with the goal of enhancing the mechanical and physical properties while improving the durability of asphalt mixtures.

Previous studies have also proven that various types of modifiers, such as recycled rubber, fibers, and polymers, are used to improve the performance of asphalt binder [6], [7].

These improvements include resistance to moisture, permanent deformation, fatigue life, aging resistance, and low temperature [4], [8]. Among all these modifiers, polymer has been the most widely used in asphalt binder modification. However, one of the major drawbacks are pure polymer modifiers is that most polymers are thermodynamically incompatible with asphalt binder due to significant differences in density, polarity, molecular weight, and solubility between the polymer and the asphalt binder. This can lead to phase separation during thermal storage, which may not be immediately apparent but can adversely affect the material when used in construction.

As a result, many researchers have turned to using nanomaterials to modify asphalt binder due to the rapid development of nanotechnology and its ability to overcome this issue. A nanomaterial is defined as a material with at least one dimension ranging between 1 and 100 nanometers. According to previous research, the properties of nanomaterials, including physical, chemical, and biological characteristics, significantly differ from their original forms. Additionally, the unique effects of nanomaterials, such as the macroscopic quantum tunneling effect and surface effect, are attributed to their large surface area and small particle size. Notably, nanomaterials exhibit high-temperature sensitivity, high ductility, large surface area, high strain resistance, and low electrical resistivity.

On the other hand, if the primary purpose of adding fibers is to reduce binder loss, high fiber strength is not necessary. Instead, fibers that can absorb or retain the binder are used for such applications. This section describes the properties that affect fiber performance, how these properties are measured, and the types of fibers used.

This research summarizes the findings of the literature review on the use of nanomaterials and fibers in asphalt mixtures. The results are categorized according to nanomaterials and fiber types, including a summary of the types used and their typical properties, testing methods for both nanomaterials and fibers, and the significance of these tests. Additionally, it covers mix design, production, and construction of asphalt mixtures enhanced with these materials, as well as their laboratory and field performance in dense-graded, open-graded, and gap-graded mixtures. Finally, the research presents an economic feasibility analysis of fibers.

2. Materials

2.1 Nano materials

2.1.1 Nano Calcium carbonate

Physical properties are presented in Table 1. Calcium carbonate is a material considered highly suitable for applications requiring precise rheological control and enhancement of mechanical properties [9]. Among recent studies on the modification of asphalt materials using nanomaterials, calcium carbonate nanoparticles have demonstrated significant potential in improving asphalt performance.

Research has shown that utilizing this material as a nano modifier leads to noticeable improvements in the rheological properties and mechanical performance of asphalt binders. Rheological tests of nanomodified asphalt binders indicate an increase in the dynamic shear modulus (|G*|) and a reduction in the phase angle (δ), particularly at calcium carbonate nanoparticle addition levels close to 5%. Furthermore, an increase in the |G*|/sin δ parameter has been observed, which is initially employed in the Superior Performing Asphalt Pavements (SUPERPAVE) methodology as an indicator of an asphalt binder's resistance to permanent deformation [10].

2.1.1.1 Application of Calcium carbonate in Modified Binder

From a rheological perspective, and according to the results discussed in Research Paper (Manfro et al., 2022), Nanocomposites showed enhanced high-temperature performance relative to the conventional asphalt binder. Specifically, the addition of 5.5% nano-calcium carbonate (nano-$CaCO_3$) improved the continuous high-temperature grade, decreased the non-recoverable creep compliance (Jnr3.2 – 70℃) by 36%, increased the percent recovery (%R3.2 – 70℃) by 38%, and elevated the traffic classification from "Heavy" (H) to "Very Heavy" (V) according to the AASHTO M332 standard. These rheological parameters emphasize the role of nano-$CaCO_3$ in improving the resistance to permanent deformation in asphalt mixtures modified with nanomaterials.

Concerning the moisture damage resistance of asphalt mixtures, based on testing conducted with the French traffic simulator (Orniéreur), Figure 1 shows the permanent deformation results of asphalt slabs subjected to void saturation levels ranging from 55% to 80%, followed by freezing at -18℃ for 16 hours, and then immersion. These results are further analyzed according to the three performance categories defined by the Laboratoire Central des Ponts et Chaussées (LCPC) [11]. As shown in Figure1, Following the conditioning process, the original asphalt mixture showed a permanent deformation of 7.7% after 30,000 cycles. This indicates a significant reduction in mixture performance after water exposure, as Class 1 is designated for regions with light traffic loads and mild temperatures (approximately 15℃) [12]. Conversely, the nanomodified asphalt mixture exhibited a permanent deformation of only 4.2% after conditioning, representing a 47% reduction in rutting compared to the conditioned reference mixture. Consequently, even after water exposure, the nanomodified mixture maintained its classification within Class 3.

Besides, when comparing the results between the control and conditioned groups, the reference mixture exhibited an 81% increase in permanent deformation after conditioning, whereas the nanomodified mixture showed a lower increase of 54%.

2.1.2. Nano-silica

Silica is an abundant compound worldwide and is widely used in industries to produce silica gels, colloidal silica, fumed silica, and others [13]. Nano-silica, on the other hand, is an inorganic material primarily produced from silica-containing precursors. There are several methods for producing nano-silica, such as the vapor-phase method, the sol-gel method, and others. However, the sol-gel method is considered the most commonly used due to its mild conditions and high product purity of the resulting product [14].

Nano-silica has gained increasing attention due to its applications in emerging fields such as medicine and drug delivery. Additionally, amorphous nano-silica is used as a nano-biopesticide. The significance of these nanomaterials lies in their low production cost and high-performance characteristics. According to [15],), nano-silica possesses a large surface area, strong adsorption capacity, good dispersibility, high chemical purity, and excellent stability. As a result, incorporating nano-silica is anticipated to improve the performance characteristics of asphalt and its constituents. The primary physical and chemical properties of nano-silica are outlined in Table 2 Moreover; Figure 2 shows the nano-silica morphology.

2.1.2.1 Utilization of Nano-silica in Asphalt mixture Modifications.

An investigation into the application of nano-silica for modifying asphalt mixtures was carried out to enhance the rheological, physical, and mechanical properties of the material. Laboratory assessments performed by [16], The incorporation of nano-silica has been shown to improve the resistance to rutting at high temperatures and to enhance fatigue resistance at intermediate temperatures, in comparison to the control mixture. The research was conducted with a polymer-modified asphalt (PMA) mixture, incorporating different amounts of nano-silica (0%, 2%, and 4% relative to the weight of the asphalt binder).

Figure 3 shows the outcomes of the resilient modulus test conducted at 25°C. The results reveal that the PMA mixture containing 4% nano-silica demonstrates the greatest resistance to fatigue deformation, exhibiting the highest value for resilient

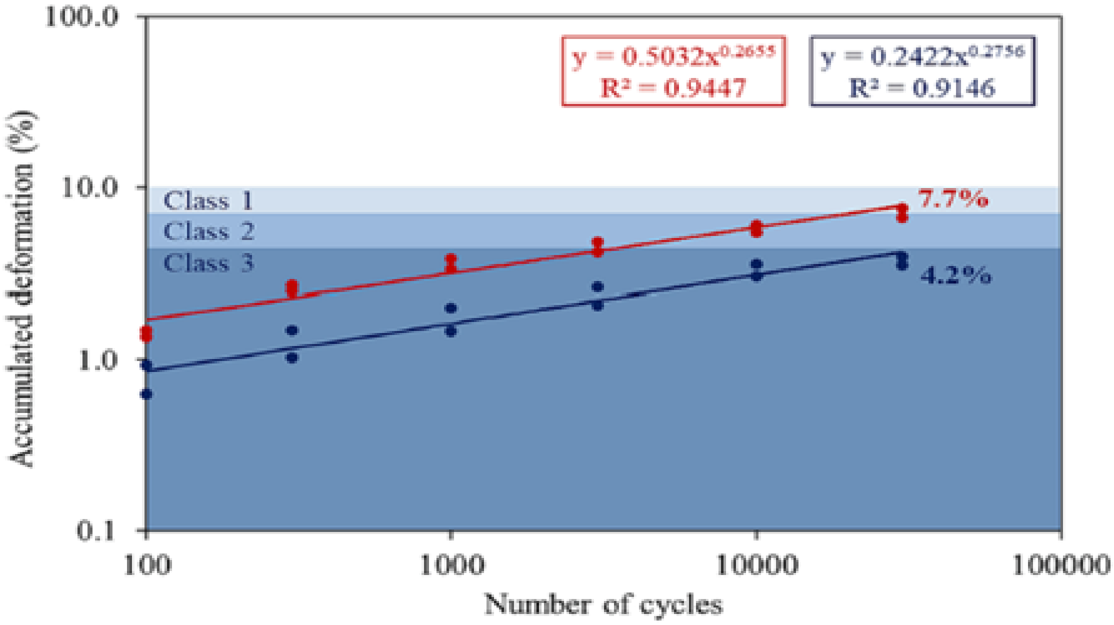


Fig. (1) Wheel track rutting as a function of the number of cycles for asphalt mixtures belonging to the conditioned group [12].

Table 1. Physical properties of NCC.[17]

Property	Result
Surface area (m^2/g)	247
Diameter (nm)	60–70
Specific Gravity	2.84
Passing sieve No. 200 (0.075 mm)	96

Table 2. Properties of nano-silica [18].

Color	white				
True density, g/cm3	2.4				
Surface area, m2/g	180-600				
Bulk density, g/cm3	<0.10				
Purity, %	+99				
	SiO2	Ti	Ca	Na	Fe
Chemical properties	>99%	<120ppm	<70ppm	<50ppm	<20ppm

modulus. Similar patterns were observed in the aged samples, confirming that the inclusion of nano-silica improves the resistance to fatigue deformation at intermediate temperatures for both the unaged and aged mixtures. Another notable observation was that, as the temperature increased, the gap in resilient modulus values became more significant, with a reduction in stiffness observed at 40°C, as depicted in Figure 4. Based on the changes in resilient modulus at higher temperatures, it appears that the PMA mixture with 4% nano-silica shows the highest resistance to rutting compared to the control mix. These results are consistent with those from previous studies conducted by [16]and. [19], The study revealed that asphalt mixtures modified with nanomaterials exhibit reduced rut depths compared to the control mixture, with higher nanomaterial content leading to even smaller rutting depths. Additionally, the dynamic creep test showed a further improvement in rutting resistance, as illustrated in Figure 5. The findings suggest that adding nano-silica can decrease rutting depth by nearly 50% compared to the control mix, with the PMA mixture containing 4% nano-silica demonstrating the lowest values for permanent deformation.

(a) Nano-$CaCo_3$ (b)Nano-Clay (c) Nano-Silica

Fig. (2). Nanoparticles used in study [20], [21]

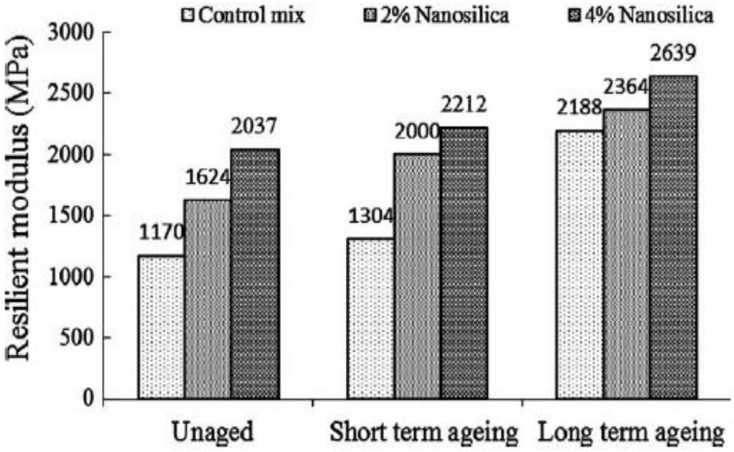


Fig. (3) Resilient modulus test at 25 ºC [22].

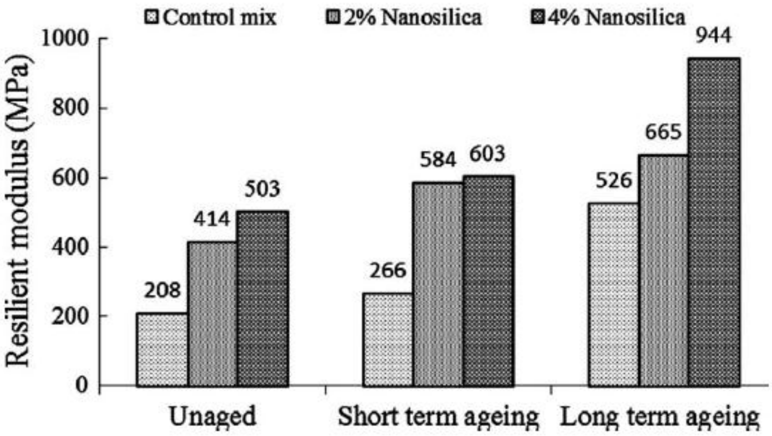


Fig. (4) Resilient modulus test at 40 ºC [22]

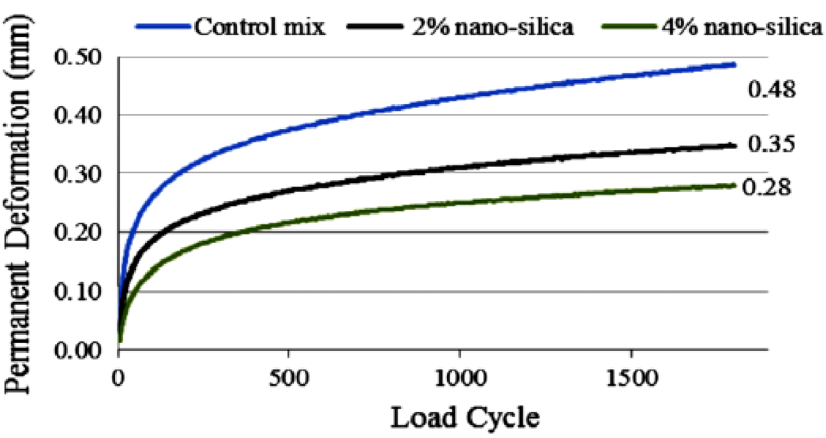


Fig. (5) Dynamic creep test result for un-aged mixtures [22].

2.1.3. Nano-clays

Nano-clays refer to water-containing aluminosilicate minerals, typically belonging to the phyllosilicate group such as montmorillonite and kaolinite. They are made up of nanoscale platelets characterized by a large surface area and high aspect ratio as shown in table 3, which help improve mechanical strength and barrier properties when integrated into a polymer matrix [23]. In general, nano-clays possess the potential to notably influence the rheological behavior of different materials. Numerous studies have explored their application in improving asphalt binders. While some types show a minimal impact on viscosity and stiffness, others have delivered encouraging outcomes. When finely dispersed, even small amounts of nano-clay can enhance various physical characteristics such as stiffness, tensile strength, tensile modulus, flexural strength, and thermal stability. Typically, bitumen modified with nano-clay exhibits an increased elastic modulus and reduced mechanical energy dissipation compared to unmodified bitumen [23]

2.1.3.1. Application of Nano clays in Modified Binder

In a study by (Paul and Robeson, 2008), asphalt binders were enhanced using bentonite clay (BT) and its chemically treated counterpart (OBT) through a process that combined ultrasonic energy and shear mixing. This modification led to improved rutting resistance and better low-temperature performance, including enhanced resistance to cracking [24]and [25]. The improvement in rigidity and durability of modified bitumen varies according to both the temperature and the concentration of nano clay incorporated. Additionally, nano clay is often used as a supplementary additive to boost the effectiveness of bitumen blended with styrene–butadiene–styrene (SBS) [19]. Recent studies have reported an increase in the rutting resistance factor according to the Superpave (Superior PER forming asphalt PAV Ements) standard, while rotational viscosity tests indicated a substantial rise in viscosity [26]. Moreover, incorporating nano clays into asphalt mixtures has demonstrated a positive impact on enhancing their resistance to aging [27]

2.1.4. Carbon Nano Tube

A carbon nanotube (CNT) is a cylindrical nanostructure composed of a single layer of graphite rolled into a seamless hollow tube, with diameters starting at one nanometer. The discovery of CNTs was first reported by Iijima [28], who synthesized them using the arc discharge method and described their helical microtubular structures, which are closely related to fullerenes. Since then, significant research efforts have been dedicated to CNT synthesis and applications due to their exceptional electronic and mechanical properties[29]. Carbon nanotubes (CNTs) are generally classified into two primary types: single-walled (SWCNTs) and multi-walled (MWCNTs), based on the number of graphene layers they contain. However, MWCNTs are preferred as modifiers due to their superior stiffness, ease of production, and cost-effectiveness in large-scale manufacturing (Steyn et al., 2013). Currently, various methods are available for CNT production. Among the commonly employed methods for synthesis, the most prevalent are laser ablation, arc discharge, and chemical vapor deposition (CVD) [30].

Table 3. Physical properties of NC.[17]

Property	Result	Oxide composition	Content,%
Type of mineralization	Montmorillonite	Na2O	0.98
Density	0.65	MgO	3.29
Particle size (nm)	1–2	Al2O3	19.6
Surface area (m2\g)	266	SiO2	50.95
Electrical conductivity value	—25	K2O	0.86

Ion exchange coefficient	48	Cao	1.97
The empty gap between the rats (Å)	60	TiO2	0.62
Color	Pale yellow	Fe2O3	5.62
Humidity (%)	1–2	L.O.I	15.45
Specific gravity	3.6	_	_

2.1.4.1. Utilization of CNTs in Asphalt mixture Modifications.

One of the most critical properties of nanomaterials in road construction is their ability to enhance the mechanical resistance of bituminous materials. Although extensive research has been conducted over the past decade on asphalt modification using various nanoparticles, limited studies have specifically addressed the effects of carbon nanotubes (CNTs) on asphalt binder and mixtures. Theoretically, incorporating CNTs into asphalt binder reduces penetration values and increases. The increase in softening point is attributed to the improved stiffness of the binder, a conclusion that was supported by [31]Their research revealed that incorporating higher amounts of CNTs into the binder notably raised the softening point, reflecting enhanced binder stiffness and improved resistance to temperature variations an important feature, especially in areas experiencing significant temperature changes throughout the day or high traffic stress. Additionally, lab-based assessments[31]demonstrated that the inclusion of CNTs leads to noticeable improvements in the rheological behavior of asphalt binders by raising the rutting resistance index, which contributes to better resistance of pavements against long-term deformation under traffic loads. The study also examined the rheological properties of aged binder, showing a similar trend to the unaged condition, with a notable increase in the rutting factor as the modifier content increased. However, it was found that incorporating 0.5% or less of CNTs did not result in significant performance improvements. These findings were supported by [32], They showed that incorporating higher concentrations of CNTs (above 0.5% of the binder weight) has a beneficial effect on the rheological characteristics of asphalt binders. These enhancements help minimize rutting issues under high-temperature conditions and reduce the likelihood of thermal cracking in colder environments. As a result, determining the appropriate dosage of the modifier is essential for optimizing binder performance.

Additionally, numerous other studies have investigated nanomaterials, as documented in Table 4**.**

Table 4. Properties of MWCNTs [31]

Property	Value
Colour	Black
Purity, (%)	>90
Outside diameter, (nm)	10 – 30
Inside diameter, (nm)	5 – 10
Length, (µm)	10 – 30
Density, (g/cm3)	2.1
Surface area, (m2/g)	>200

Table 5. Key research findings on using nanomaterials for asphalt enhancement

nano name and characteristics			**Effects of nano on asphalt mixtures**			
type	**optimum content (by weight of mixture)**	**OAC%**	**Air void (AV)**	**Marshall stability**	**Rutting performance**	**Reference**
Nano Calcium carbonate	4%	4.9%	4.5%	↑	↑	[17]
Nano-silica	5%	4.9%	3.2%	↑	↑	[17]
Nano-clays	7%	4.9%	3.4%	↑	↑	[17]

2.2 Fibres materials

This section outlines the primary classifications of fibres utilized in asphalt pavements, namely natural and synthetic fibres as shown in Table 6. It also discusses key factors relevant to pavement applications and elaborates on how fibres contribute to reinforcement within asphalt mixtures. Tables (7-11) present the physical properties of the studied fiber materials. Also, the figure 6 illustrated the shapes of the fiber materials that were used in this study.

Table 6. Different use of natural and synthetic fibres in asphalt mixtures and their effects.

Fibre name and characteristics			Effects of fibres on asphalt mixtures				
type	**optimum length of fibers**	**optimum content (by weight of mixture)**	**OAC%**	**Air void (AV)**	**Marshall stability**	**Rutting performance**	**Reference**
basalt	12 mm	0.35%	5.35%	-	↑	↑	[33]
Bamboo	6 ±2 mm	0.2–0.3%	5.21(0.2 % fibre),5.31 (0.3% fibre)	4.1 (0.2% fibre), 4.0 (0.3% fibre)	↑	↑	[34]
Jute	7.5 mm	31 µm	6.5	4.0	-	-	[35]
Polypropylene	19 mm	5	–	↑	↑	-	[36]
Polyester	6.35 mm	0.35% in dense-grade mixtures	Around 4.63	Around 4.35	↑	↑	[37]
Carbon	20 mm	0.4%	5.9↑	Around 6	↑	↑	[38]

2.2.1. Natural fibres

Natural fibers originate from naturally occurring raw materials and are categorized into three primary groups based on their source: animal-based, plant-based, and mineral-based fibers. This section primarily highlights the application of plant-derived fibers, including bamboo, coconut (coir), jute, and sisal, alongside mineral fibers in asphalt mixtures.

2.2.1.1. Basalt fiber

Basalt fibers are manufactured through specialized processing of natural basalt rocks to achieve the final form. In earlier research, various fiber lengths were explored—some studies used chopped fibers with a fixed length of 6 mm [6], while others experimented with a range of lengths including 3, 6, 9, 12, and 15 mm [39]. These fibers exhibit notable mechanical properties, including a tensile strength of around 2100 MPa, an elastic modulus of 105 GPa, and an elongation of about 2.6%. Their thermal resistance is also significant, with a melting point above 1400°C. For preservation, the fibers are packed in polyethylene bags coated with nylon to maintain airtight and moisture-resistant conditions until blending with the binder.

2.2.1.1.1. Application of basalt fiber in Modified Binder

Incorporating basalt fibers (BFs) into asphalt mixtures has shown to notably decrease rutting depth and improve dynamic stability. Based on wheel tracking test results, using 0.3% BFs by the weight of aggregates led to a reduction in rutting depth by nearly 30% after 20,000 loading cycles [40]. Comparable outcomes were reported by [41]in the Hamburg wheel tracking test conducted on open-graded friction course (OGFC) mixtures, where the inclusion of fibers led to a noticeable decrease in rutting depth. The study also recommended 0.15% as the most effective dosage of basalt fibers, In a similar investigation[42] incorporated 0.3% basalt fibers into the asphalt mix, resulting in a peak dynamic stability of 5568 cycles/mm approximately 1.25 times higher than that of the mix without basalt fiber reinforcement.. The improvement in asphalt performance is attributed to the ability of basalt fibers to absorb light components in the asphalt, increasing the viscosity of the asphalt mastic. Additionally, the fiber bridging effect enhances the bonding strength within the mixture. However, [6] found that dynamic stability initially increased with basalt fiber content but then decreased after exceeding the optimal dosage of 0.4%. When this percentage is exceeded, fiber agglomeration due to uneven distribution and excessive asphalt absorption leads to reduced high-temperature stability.

2.2.1.2. Bamboo fibres

Bamboo, a fast-growing woody member of the grass family (Poaceae), is recognized for its quick regeneration following harvest. It primarily flourishes in tropical, subtropical, and temperate zones, especially across Southeast Asia and South America [43]. The production of bamboo fibers primarily follows two methods: chemical and mechanical processing [44]. In the chemical method, crushed bamboo undergoes alkaline hydrolysis using sodium hydroxide (NaOH) before the cellulose fibers are treated with carbon disulfide (CS_2) in a multi-stage bleaching process. On the other hand, the mechanical method, though more labor-intensive and costly, is regarded as more environmentally friendly [45].It involves using natural enzymes to break down the bamboo fibers, which are then washed, mechanically processed, and spun into yarn. Application of Bamboo fiber in Modified Binder

[46] explored the effectiveness of using bamboo fibers to improve the performance characteristics of asphalt mixtures. They incorporated different amounts of bamboo fibers into both dense-graded asphalt (DG) and stone matrix asphalt (SMA) mixtures. Results from thermal stability evaluations revealed that bamboo fibers exhibit adequate resistance to heat, allowing them to withstand the elevated temperatures typically experienced during the mixing and compaction processes. Regarding mechanical performance, bamboo fiber-reinforced mixtures demonstrated excellent moisture resistance, as confirmed by Marshall stability and freeze-thaw cycle tests, achieving results comparable to or even superior to those of polyester and lignin fiber mixtures. Additionally, these mixtures exhibited improved rutting resistance and enhanced crack resistance at low temperatures. The research suggested that the ideal proportion of bamboo fibers is between 0.2% and 0.3% by weight for dense graded (DG) mixtures, while a higher content of 0.4% is more suitable for stone matrix asphalt (SMA) mixtures. Similarly, [47] found that bamboo fiber serves as an effective alternative to lignin fiber, particularly due to its ability to enhance low-temperature performance and moisture resistance, although lignin fiber demonstrated superior mechanical strength. The results also emphasized that the coarse surface texture and high oil absorption ability of bamboo fibers enhance the ductility and bonding characteristics of the asphalt mastic. In addition, the notable density and durability of bamboo fibers were found to play a significant role in improving the asphalt mixture's flexibility and its ability to resist cracking.

2.2.1.3. Jute fibres

Jute is a natural bast fiber derived from the Tiliaceae plant family, with major production concentrated in nations like India, Bangladesh, Pakistan, China, and Brazil [48]. Thanks to its smooth texture, low heat conductivity, and affordability, jute fiber has found widespread application in sectors such as textiles, construction, and automotive manufacturing [48]. Like other natural fibres, jute is mainly composed of cellulose, hemicellulose, and lignin [49].

2.2.1.3.1. Application of jute fiber in Modified Binder

The investigation focused on incorporating jute fibers to reinforce asphalt mixtures. Flow tests and Marshall stability indicated that the addition of and 1%0.5% from jute fibers enhanced stability by 10% and 29%, respectively. Furthermore, the optimal asphalt content increased from 4% to 5%. Mixtures modified with jute fibers showed improved resistance to deformation compared to the unmodified versions, with 0.5% being identified as the most effective dosage.

Similarly, [35]examined the effects of three different fiber types (jute, polyester, and carbon fibers) on stone matrix asphalt (SMA) mixtures, varying fiber content (0.25%, 0.5%, and 0.75%) and fiber length (5, 7.5, and 10 mm). The results showed that the addition of 0.5% fibers with a length of 7.5 mm from all three types significantly improved rutting resistance and stability in SMA mixtures. Carbon fibers provided the most notable improvements, enhancing rutting resistance and dynamic stability by 53% and 100%, respectively. Polyester fibers followed, then jute fibers, which improved these properties by 34% and 63%. However, jute fibers excelled in minimizing asphalt binder drain-down.

2.2.2. Synthetic fibres

Synthetic fibers are man-made materials produced through processes such as spinning, polymerization, and filament processing [16]. According to [50], synthetic fibers can be classified into three main categories: organic fibers, including polyamides, polyester, and polyolefins; inorganic fibers, such as glass, carbon, and boron; and a miscellaneous group of other fibers. This section highlights three key types of synthetic fibers polypropylene, polyester, and carbon fibers focusing on their applications and impact on the performance of asphalt mixtures.

2.2.2.1 Polypropylene fibres

Polypropylene (PP) fibres have become an essential component in modern construction materials, thanks to their low production cost, excellent dimensional stability, and superior mechanical properties. Numerous studies have explored their widespread use as a reinforcing agent in concrete, demonstrating their ability to enhance toughness and durability through a three-dimensional reinforcement mechanism [16].

[51] found that asphalt mixtures reinforced with polypropylene (PP) fibres at the optimal binder content exhibited enhanced performance, including higher Marshall stability, reduced flow values, extended fatigue life, and improved resistance to rutting and reflective cracking. Some research examined the effects of varying lengths and amounts of polypropylene (PP) fibres in asphalt mixtures. The Marshall stability and flow test results revealed that the ideal fiber length and content were 19 mm and 0.5%, respectively. Additionally, for recycled foamed asphalt (RFA) mixtures, polypropylene (PP) fibers with a shorter length of 10 mm and a lower content of 0.15% by weight of the asphalt mixture were also used, alongside hot mix asphalt (HMA) [52].

2.2.2.2. Polyester fibres

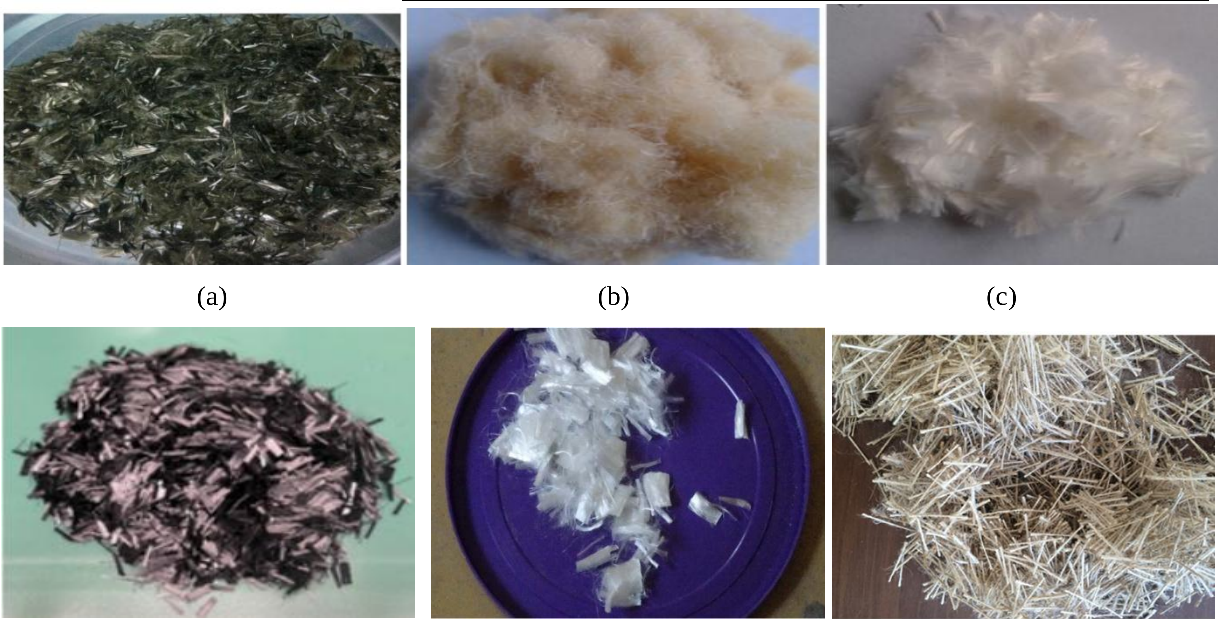
Polyester, another synthetic fiber of organic origin, is commonly utilized in asphalt mixtures as a reinforcing material to improve resistance to plastic deformation and fatigue [46]. [53] has explored the influence of polyester fibers on both the rheological properties of asphalt binders and the fatigue resistance of asphalt mixtures, with the dry method being used to prepare the modified mixtures. Tests conducted on asphalt mixtures showed that adding 0.3% polyester fibers (based on the asphalt mixture's weight) led to a reduction in both the dynamic modulus and phase angle, which in turn lowered the fatigue parameter. This suggests that the presence of fibers contributes to enhancing the asphalt mixture's resistance to fatigue damage.

2.2.2.3. Carbon fibres

Since both carbon fibres and asphalt (which primarily consists of hydrocarbons) are carbon-based materials, they exhibit excellent inherent compatibility, making them more advantageous than other fibres in bituminous mixtures. Additionally, carbon fibres offer a high melting point and exceptional tensile strength, further enhancing their suitability for asphalt applications. Depending on the size of the carbon fibres, they can be incorporated into asphalt mixtures using either the wet or dry mixing method. [38]. The study showed that incorporating carbon fibers of 12.5 mm and 20 mm length in asphalt mixtures resulted in higher stability and increased air void content, with a reduction in flow value. The most significant improvements in stiffness, resistance to permanent deformation, and fatigue performance were achieved when the fiber content was optimized at 0.4% of the total mix weight.

Table 7. Properties of basalt fiber (provided by manufacturers)[6]

Properties	Values	Specification
Density (g/cm3)	2.545	ASTM D3800
Heat resistance	180 °C, unchanged	N/A
Melting point (°C)	1500	ASTM D276
Corrosion resistance	High	N/A
Electrical conductivity	Low	N/A
Tensile strength (MPa)	≥3200	ASTM D2256
Modulus of elasticity (GPa)	≥96	ASTM C469
Fracture elongation (%)	3.2	ASTM D2256
Diameter (μm)	17	ASTM D2130



(a) (b) (c)

(d) (e) (f)

Fig. (6). The types of fiber that used in this study: (a) Basalt fiber[54]; **(b)and** (c) bamboo fiber and polyester fiber [34]; (d) Carbon fiber.[54];(e) Polypropylene Fiber[55]; (f) Jute fibers.[56]

Table 8. Properties of polyester fiber (provided by manufacturers).[6]

Properties	Values	Specification
Density (g/cm3)	1.364	ASTM D3800
Tensile strength (MPa)	≥1470	ASTM D2256
Fracture elongation (%)	6.0–8.0	ASTM D2256
Young modulus (GPa)	≥38	ASTM D638

Hot water resistance (°C)	≥104	N/A
Length (mm)	M ± 0.5	ASTM D204
Dispersivity (grade)	1–3	N/A
Diameter (µm)	24	ASTM D2130

Table 9. Physical Properties of polypropylene fibers. [57]

Property	Values
Appearance	Crimped white fiber
Relative density	0.91 g/cm3
Length	48 mm
l/d ratio	80
Thickness	0.6 mm
Width	1.1 mm
Tensile strength	450 MPa
Failure strain	15%

Table 10. Physical properties of Bamboo fiber [34]

Properties	Bamboo fiber
Fiber length (mm)	6 ± 2
Fiber diameter (µm)	20–60
Density (g/cm3)	1.36
Oil-absorptive properties	5.7

Table 11. Properties of utilized fibers. [35]

Property	Unit	Jute	Carbon
Density	g/cm3	1.42	1.82
Diameter	µm	31	8
Melting Point	oC	…..	970
Tensile Strength	MPa	356	≥ 4000
Price	$/kg	2	37

3. Conclusion

This document provides an overview of the commonly used nano-additives in bitumen modification, focusing on their mixing conditions and the effects they have on the mechanical properties of the binder .The study evaluates the performance of bitumen modified with nano-calcium carbonate, nano silica, nano clay, and carbon nanotubes, considering their effects on various distress factors such as fatigue resistance, rutting susceptibility, and self-healing capabilities. This article also examines the diverse applications of various fiber types in asphalt pavements, highlighting their impact on asphalt binders and mixtures.

- The incorporation of 4% nano-calcium carbonate (Nano-$CaCO_3$) into the binder resulted in an improvement in the continuous grading at high temperatures, along with a 36% reduction in non-recoverable creep compliance.
- Previous research has confirmed that asphalt mixtures modified with nanomaterials exhibit a reduction in rutting depth, with higher nanomaterial content enhancing rutting resistance. These findings were further supported by dynamic creep tests, which demonstrated that the addition of nano-silica significantly reduces rutting depth, achieving the lowest permanent deformation values in the PMA mixture containing 4% nano-silica.
- Additionally, earlier research has demonstrated that asphalt mixtures enhanced with nano clay show increased resistance to rutting, marked improvements in performance at low temperatures, and a significant boost in mixture stiffness.
- Moreover, previous studies have shown that modifying asphalt with more than 0.5%

carbon nanotubes (CNTs) positively influences its rheological properties.

- The incorporation of fibres into construction materials dates back thousands of years, with one of the earliest known uses being a 4000-year-old arch made of clay. Today, fibres play a crucial role in various building materials, including concrete, soil-based structures, bricks, and asphalt compositions. Extensive research has been conducted on their role in asphalt pavements, and their potential applications continue to be an area of interest for future studies.
- A review of both natural and synthetic fibres used in asphalt mixtures emphasizes their function as stabilizing agents, which help reduce asphalt bleeding and optimize binder content in the mix design. Furthermore, fibres act as reinforcement additives, enhancing rutting resistance, moisture susceptibility, crack resistance at low temperatures, and durability against freeze–thaw cycles. They also extend fatigue life, contributing to the overall longevity of asphalt pavements. These benefits are largely attributed to the physical properties of the fibres and the structural network they establish within the mixture
- While natural fibres offer significant environmental advantages and cost efficiency in production, their susceptibility to thermal degradation and decomposition must be carefully assessed. Implementing chemical treatments or protective coatings may serve as an effective solution; however, the associated costs and environmental implications should also be thoroughly evaluated.
- This research demonstrates that nano-enhanced fiber-reinforced asphalt mixtures achieve sustainable pavement solutions by combining extended durability with reduced environmental impact.

In conclusion, research on the use of nanomaterials and basalt fibers in enhancing asphalt mixtures is still ongoing, with recent studies opening new horizons for exploring the properties and performance of these materials under various conditions. With continuous advancements in material technologies and modeling, this field remains promising for further development and innovation, offering opportunities to improve road infrastructure and enhance its sustainability and efficiency in the long term.

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