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Applications of nanomaterials in highway pavements

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HIGHLIGHTS

> This study explores the applications of nanomaterials in highway pavements.

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ABSTRACT

Nanotechnology is attracting increasing interest in a broad range of applications. When assessing applications in the field of civil engineering, it is critical to have actual problems that applications can solve for the technology to have a positive impact on the general public's well-being. This article is about pavement engineering advancements that utilize nanomaterials to enhance society by meeting standard requirements and difficulties in the construction sector. These materials research projects are embarked upon to produce more efficient materials. The article has a comprehensive review of the application of nanomaterials, their usefulness, and their applications within the pavement engineering subject. Nanomaterial applications in cold regions, enhancement of physical properties of pavement materials, cost, and application of these materials in soil are all thoroughly covered. Concerns about Nanomaterials Even though nanotechnology and pavement engineering can be used in a lot of different ways and for a lot of different things, it is important to be realistic and accept the limitations and problems that come with the application of these materials, such as health, cost, and other implications. Because of the smaller size of its particles, the use of nanomaterials may present some new difficulties, such as poor packing density, large surface area, and a high cost. A smart design for nanomaterials would take into account these problems and also solve the problems that micrometer-scale materials cause.

1. Introduction

Nanotechnology is the study of matter at the nanoscale. The subject of this article, nanotechnology, deals with matter manipulation on atomic and molecular scales. The unique physical, chemical, mechanical, and optical characteristics of materials on this scale are what nanotechnology seeks to use. Stronger or having distinct magnetic characteristics, nanostructured materials are used in certain cases over other forms or dimensions of the same material. Some others, as far as the conductivity of heat and electricity are concerned, show superior performance. They may also change their chemical composition or even take on a different color when their size or shape changes. When it comes to nanotechnology in pavement materials, there is considerable potential for improvement, powerful enough to significantly alter widely used materials. The need to blend these materials in pavement engineering makes this a worthwhile course. This study investigates the potential application of nanoparticles on highway pavements. Nanosilica, nanoclay, nanocarbon tubes (CTNs), Zycosil, and nanofibers are among them. The use of carbon nano-fibers (CNFS), organic nanoparticles, use of nanomaterials in cold locations, usage of nanomaterials in enhancing the physical features of pavements, the cost of nanomaterials, and application of nanomaterials in soils are among the topics covered in this study.

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2. Nanotechnology

The capacity to understand and manipulate matter on the nanoscale (approximately 1 to 100 nanometers in size) allows for the harnessing of hitherto untapped phenomena and the creation of new opportunities. To create a new universe, it is necessary to use nanoscale science, technology, and engineering, which entails measuring, analyzing, and modifying matter at this length scale [1]. The majority of the current breakthroughs are focused on nanotechnology and the need to incorporate them into civil engineering practice, even if most nano-technical developments originate in disciplines like physics, chemistry, and electrical engineering. When comparing the properties of bulk materials and individual atoms or molecules to those at the nanoscale, there is a clear distinction. Specifically, materials with a nanostructured molecular structure have enhanced strength [2].

Smaller dimensions are just part of the picture when it comes to nanotechnology [3]. It is also possible to use the unique physical, chemical, mechanical, and optical characteristics of naturally occurring materials that exist at the nanoscale. Civilization is working hard to use nanotechnology in paving materials. Material characterization, prediction, and control of material characteristics are possible at the micron level due to nanotechnology. As a result of this technology, most materials, structures, exterior features, and internal components now have a better knowledge of their origins [3,4]. This study aims to improve the performance of materials used in transportation engineering by looking at the latest developments in nanoscience, ideas, and methods and how they are used in pavement engineering.

2.1. Nanotechnology and pavement

Due to the continuing increase in traffic loads and volume with the growing cost of crude oil as a byproduct, the need for better pavement durability, safety, and efficiency has become more important [4–6]. Considering the increasing applications of nanotechnology, asphalt modification is becoming more and more interwoven within the civil engineering industry. Today, asphalt's performance is aided by the addition of nanoparticles. Several experiments and projects have been organized to implement the modification procedure and subsequent improvement results obtained in asphalt, including the road transfer mechanism [7,8].

The use of nanomaterials in pavements is for better, more durable, and longer-lasting asphalt pavements to be used for major infrastructure projects, such as airports, seaports, and roads. This is something that can be achieved by adding different nanoparticles. This topic is always being researched and developed to produce nanoparticles that are simpler to mix and more competitive in cost [9,10]. When conducting research, the use of nanoparticles follows a fast-track route, so the introduction of nanomaterials into asphalt pavements moves at the same pace as its development. High-temperature sensitivity, high ductility, large surface area, and high strain resistance, as well as low electrical resistivity, lead to more widespread use of nanomaterials [10,11]. The morphological characteristics of the nanoscale materials, and in particular, their nanoparticle characteristics, differ greatly from the scale-up [12] "Owing to its unique mechanical, thermal, optical, electrical, and magnetic characteristics, research on polymer grade nanocomposites is gaining increased attention among academics and industry" [13,14]. Included in this combination are a variety of hydrocarbon additives that have a range of hydrocarbon extracts ranging from those of a higher molecular weight to non-metallic additives. Asphalt is often used for its organic bonding properties when it is utilized as a waterproofing substance, a moisture resistance agent, or for corrosion prevention [15]. A summary of the advantageous applications of nano-particles as found in the literature review is presented in Table 1 below.

Table 1. A summary of certain nanomaterials and their applications as presented by the authors.

S/No	Nanoparticles	Application
1	Micro silica (silica fume)	Concrete's compressive and flexural strengths are enhanced.
2	Nano TiO_2	Surface cleaning of concrete pavements
3	Polymer fiber matrix using nano silica	The use of a self-structural health monitoring system in the repair and rehabilitation industries.
4	Carbon nano fibers (CNFs)	The compressive and flexural strengths of concrete may be increased, and self-sensing concrete can be used to monitor the structural state of the pavement. Offers outstanding mechanical characteristics, and high thermal conductivity,
5	Nano-silica (SiO_2)	Improves the viscosity of asphalt, replaces portion of cement to increase concrete strength and early and enhances pavement surface properties.
6	Nano phosphorus	Enhances the visibility on the road
7	Nanotechnology enabled sensors	Temperature, moisture, smoke, noise, strains, vibrations, fractures, and corrosion are all monitored and controlled.
8	Nano Clay	Improves stiffness and tensile strength, tensile modulus, flexural strength, and modulus of thermal stability.
9	Zycosil	In subgrades, it improves CBR value, soil plasticity, and breathability.
10	Nano Fibers	Improves surface-to-volume ratio, high porosity, significant mechanical strength, and flexibility in functionality

2.2. Nanosilica

Silica is abundant throughout the Earth. Colloidal silica, fumed silica, silica gels, and so on are produced by the majority of industrial processes. Recently, there are new applications for nanosized silicas, for example, they are extensively used in the medical and pharmaceutical fields [16]. Nano silica is recommended for use as nanobiopesticides as a result, nanocomposites that include silica are gaining some scientific attention. One of the advantages of these nanomaterials is that they are cheap to produce and have exceptional performance characteristics [17]. To lower the viscosity values of the nano-modified asphalt binder, nano-silica is usually mixed at an appropriate proportion with the conventional asphalt binder. Taherkhani and Afroozi investigated to determine the effects that varying amounts of nano silica had on the engineering qualities of 60/70 asphalt cement [18]. The qualities of modified penetration grade asphalt cement that included varying amounts of nano-silica (i.e. 1, 3, and 5 weight percent) were analyzed. Following the scanning electron microscope evaluation of the modified binder, the penetration grade, softening point, and ductility of the modified binder were determined. The penetration index of the binders was calculated by taking their penetration grade and their softening point into consideration. The findings demonstrated that an increase in nano silica concentration leads to an increase in binder stiffness while simultaneously leading to a reduction in ductility and temperature sensitivity. Taherkhani and Afroozi presented some of the findings graphically [18].

2.3. Nanoclay

The addition of nanoclay to some materials improves their compatibility with organic monomers and polymers. Nano-composites are composed of a mix of polymers with layered silicates with a layer thickness of around one nanometer. Clay minerals exist naturally, and their development is subject to natural fluctuation. A nano-clay (up to 700–800 m^2/g) is created when clay discs are separated from each other. In the process, the nanoclay and bitumen interact more intensively, with better output [18,19].

Even when a single kind of montmorillonite nano-clay is added, the stiffness and viscosity of particular bitumen are usually positively altered. In practice, some physical characteristics of bitumen (stiffness and tensile strength, tensile modulus, flexural strength, and modulus of thermal stability) may be improved when small quantities of clay are used. The elasticity of the nanoclay generally tends to be greater, as is the dissipation of mechanical energy [19]. To strengthen and alter the asphalt binder, bentonite clay and organically modified bentonite are employed. They were made using a mixture of modified asphalt binders, which are created through a melting process through the process of shearing stress. Rutting resistance is significantly improved in bitumen with the addition of Nano clay, an increase in asphalt rheological characteristics, and resistance to cracking significantly improves when bentonite clay is added to asphalt [20–22]. Polymer nanocomposites are one of the most intriguing materials discovered recently, and the physical properties are effectively improved by modifying a polymer with tiny amounts of nano clay, provided the clay is distributed at the nanoscale level [22,23]. Nanoclays are used as a secondary modification to further improve the performance characteristics of modified asphalt [24]. The potential of nanoclays included in sodium montmorillonite and organophilic montmorillonite seems promising to minimize continuing deformation or rutting of asphalt pavements. The combination of clay and polymer leads to a greater dispersion of polymer in asphalt, thus affecting the ultimate rheological characteristics of asphalt [25].

2.4. Nanocarbon Tubes (CTNS)

Taking into account the existing building materials, carbon nanotubes prove to be the most solid material because of the characteristics they have. As a result, carbon nanotubes are 120 times stronger than steel and much lighter than steel [26]. Asphalt combined with carbon nanotubes is very durable and weather-resistant, which makes it recommended for applications on bridges and boat surfaces [26,27]. CTN materials are currently being used for state-of-the-art bridges with enormous hanging cables composed of steel wire that are smaller and more resistant than traditional steel materials [28,29]. Nano carbon tubes (CTNs) in concrete may fill pores; their compressive strength is increased and the pore wall structure is made homogeneous [30]. The world's first test section of road pavement with graphene nanotubes showed a 67% increase in resistance to cracks and ruts [30]. Meanwhile, Graphene is a two-dimensional carbon material made up of sheets of carbon atoms organized in a honeycomb lattice, each sheet being one atom thick.

2.5. Zycosil

Zycosil is a novel nanomaterial that was created for waterproofing with ultraviolet resistance, thermal resistance, and wind erosion resistance. Its nano-size penetration and eco-friendly capabilities make it highly advantageous. It also has certain common characteristics, such as a permanent water-resistant coating over various kinds of soil, stones, and other building materials on roads. Unending critical underground drainage problems in road construction and repair can be achieved by using the Zycosil reactive bonding ability. Research shows that Zycosil in subgrades maintains California Bearing Ratio (CBR) value, soil plasticity, and breathability. However, Zycosil has some restrictions. The solvent used had a negative impact on pre-existing cracks [31]. Ashraf presented Zycosil application to a road [32].

2.6. Carbon Nano-Fibers (CNFs)

Carbon nanofibers (CNFs) are also excellent for interfacial bonding and high tensile modulus and have large surface areas like other nanomaterials. Carbon nanofibers are highly graphical, very compatible, and may be distributed in isotropic or anisotropic modes with most polymer processing methods. You may disperse them into many other matrices, including elastomers, thermoplastics, metals, ceramics, thermosets, and so on, and they will retain their exceptional mechanical properties and great heat conductivity. Carbon nanofibers have a distinctive surface state to make it easier to function and adapt the nanofibers to host polymers or applications with other surface modification methods [32].

2.7. Nanofibers

Nanofibers can be made from different kinds of polymers, both natural and man-made. They have different physical properties and uses, but they are all part of the Nano carbon family [33,34]. The size of the nanofibers varies depending on the polymer used and the manufacturing process [35]. All polymer nanofibers have the same huge surface-to-volume ratio, high porosity, significant mechanical strength, and flexibility in how they can be used.

2.8. Organic nanoparticles

If organic nanoparticles are added to asphalt, the chemical compatibility issue between nanoparticles and asphalt may be resolved. It also prevents the expense of surface functioning of inorganic nanoparticles. The carbon nanostructures, nanotubes, and nanofibers are another fascinating family of organic nanoparticles. Their primary usage has been discovered to be electronics-related applications, such as in electronic and optoelectronic devices or as electrodes and component buffer layers in polymer solar cell components [36]. This behavior of "filling" may be transmitted to construction material fields too.

Using nanostructured carbon materials generally provides better durability [36,37]; graphene, for example, when used as a modifier in asphalt impacts rigidity and improves elastic behavior. The major disadvantage, however, of using graphene as a bitumen modifier—and in general as an ingredient to enhance the mechanical performance of building materials—is the high cost of production. That is why graphene investigations are extremely limited and have been moved on to graphene-derivated nanomaterials such as graphene oxide (GO) and graphene Nanoplatelets or some inexpensive carbon nanotubes and carbon nanofibers [38].

Carbon nanotubes have been discovered to enhance rigidity and lower stress and also improve the mechanical efficiency of hot mix asphalt (HMA) [39]. Multi-wall carbon nanotubes also enhance the rheological characteristics. In this instance, the authors assume that greater defectiveness in multi-wall carbon nanotubes leads to improved rheological characteristics. Organic nanoparticles are undoubted of a chemical nature inherently compatible with that of bituminous materials, and their usage eliminates expenses of additional procedures involving the chemical alteration of the surface of nanoparticles, as in the case of inorganic nanoparticles. However, in certain instances, their costs are still considerable (graphenes, nanotubes). The growing market in the families of carbon and the development of technology specialized in the manufacture of materials of this type will cause a reduction in their prices and likely make carbon nanostructures more attractive to large-scale uses such as asphalt modification [40].

3. Application of nanomaterials in cold regions

According to research, adding nano clay changes to bitumen increases asphalt rigidity and rutting resistance [41]. The indirect tensile strength is also enhanced by the input of nanoclay modifications, which improves the resistance to aging. The elasticity of modified bitumen increases at high temperatures and the energy dissipation decreases due to the nanoscopic dispersion of the clay [41,42]. This improves the durability and life of asphalt pavements, which saves money for maintenance and repairs. However, the nano-material pavement may have certain drawbacks at low temperatures. Research indicates that nano clay-modified bitumen's fatigue resistance is less than untreated bitumen at low temperatures [43]. Despite the drawback of poor fatigue resistance, nano-modified bitumen has several benefits at low and high temperatures. Studies have also revealed that nano $CaCO_3$ modified bitumen has enhanced anti-deformation and anti-aging capabilities in low temperatures [44]. The increased tensile strength of modified asphalt in nano clay is another significant advantage [45]. This is very important because snow and ice can quickly destroy asphalt roads in colder climates. If roads could be designed to cause less damage from deicers, huge amounts of time and money could be saved by reducing the frequency of necessary repairs.

4. Use of nano materials in improving the physical characteristics of pavements

The usage of CNTs in bituminous binders and mixes affects their different characteristics. Its rheological properties, in particular, can be significantly extended [45,46]. It also reduces the underlay thickness and thus the use of stone materials [46]. It may also contribute to improved rutting resistance and reduced oxidative sensitivity. When changed with tiny quantities of nano clay, many physical characteristics (for example, rigidity and tensile strength, the modulus of tensile strength, resistance to bending, and modular thermal stability) of bitumen may be improved if the clay is distributed at the nanoscopic level. The bitumen modified by the nanoscale is typically significantly more elastic than untreated bitumen [47].

The use of nanoclay in asphalt usually improves the viscosity and fatigue of asphalt binders. Research shows that even a tiny portion of nano clay may substantially enhance thermoplastic materials' compressive and shear strength. Adding titanium dioxide (TiO_2) to bitumen leads to a softening point greater than the bitumen base [48]. The performance of bitumen is enhanced while its visco-elastic performance significantly improves at higher temperatures. In comparison with conventional bitumen, this results in a reduction in penetration value as well as an increase in viscosity owing to the better relationship between bitumen particles produced with the integration of nano-particles. Finally, the improved efficiency of bitumen in softening point tests makes it more sensitive to variations in temperature.

Under different conditions and stresses from the outside, a nanomaterial is said to have different mechanical properties. Nanomaterials' mechanical characteristics have been the focus of considerable research for some time now. Although nanoparticles are not nanomaterials, this research aims to improve their mechanical characteristics by incorporating them into a matrix made up of materials that are. Few studies have examined the mechanical characteristics of pure nanomaterials. In Table 2, you can find out more about the mechanical properties of the metal nanostructures that were made.

This information includes the Vickers hardness, fracture toughness, ultimate tensile strength, fracture strength, and impact strength. Nanomaterials, including metal nanoparticles, have a much better fracture strength and toughness than solid Al_2O_3. Nanoparticle incorporation is the likely cause of this phenomenon. The nanocomposite's grain size is less than that of monolithic Al_2O_3 due to the pinning action of metal particles, which also leads to grain refinement and an improvement in the nanocomposite's mechanical characteristics [12]. Interestingly, nanocomposites containing nano-Cu are softer than monolithic Al_2O_3, while nanocomposites containing nano-Ni-Co are harder. This is likely because Cu has a lower hardness than Al_2O_3, and the addition of nano-Cu weakens the hardness of nanocomposites. Comparatively, nano-Ni-Co is harder than Al_2O_3. Adding nano-Ni-Co to nanocomposites makes them harder, up to a point [49]. The final three groups of numbers in Table 3 above demonstrate that the hybrid composites outperform the single-reinforced composites in impact strength, ultimate tensile strength, and Vickers hardness. The mechanical qualities of non-metallic nanoparticles are listed in Table 3.

Table 2. The nanomechanical characteristics of nano metals [12,49]

Material Sample	Fracture toughness (MPa√M)	Impact Strength (J/cm^2)	Ultimate Tensile Strength (MPa)	Fracture strength (MPa)	Vickers hardness (GPa) Fracture
Al_2O_3/Cu(oxide)	4.9±0.7	---	---	819±53	17.0
Al_2O_3/Ni-Co	4.3±0.5	---	---	1070±72	19.0
AA6061/nano B4C	---	12.36	201.54	---	69.39
AA6061/nano SiC	---	15.5	190.21	---	96.38
Monolithic Al_2O_3	3.6±0.3	---	——	536±35	17.8
AA6061/1.5SiC+1.5B4C	---	19.75	280.18	---	173.97
Al_2O_3/Cu(nitrate)	4.8±0.2	---	---	953±59	17.2

Table 3. Nonmetallic Nanomaterials structures and their mechanical properties [50]

Material Sample	Compressive strength (MPa)	Flexural strength (MPa)	Vickers hardness (GPa)	Tensile strength (MPa)	Young's/ Bending modulus(GPa)	Elongation at break (%)
p-type skutterudites+ 1.5 wt%	255±10	45±5	569±70	---	33±10	---
p-type skutterudites+ 0.5 wt	355±15	65±7	513±52	---	40±6	---
p-type skutterudites	630±20	105±10	576±52	---	44±8	---
p-type skutterudites+ 1.0 wt%	320±15	54±7	563±85	---	39±8	---
Kenaf fiber	---	---	---	500-600	40-53	1.5-3.5
oil palm empty fruit bunch fiber	---	---	---	50-400	1-9	8-18
90% nano- PLLA+ 10% nano-HA	---	142.5	---	53.2	3.5	---
100% nano-PLLA	---	135.6	---	55.6	3.3	---
70% nano- PLLA+ 30% nano-HA	---	130.3	---	42.3	3.9	---
80% nano- PLLA+ 20% nano-HA	---	156.8	---	48.6	3.8	---
60% nano- PLLA+ 40% nano-HA	---	125.9	---	38.6	4.1	---

5. The cost of nanomaterials

The cost of most equipment and materials in nanotechnology is presently quite expensive, partly because it is an emerging technology but also because of the intricacy of the technology. In the case of nanomaterials, however, over time, prices have proven to drop. The assumption is that the cost of materials will drop as production methods improve. Since 1990, for example, CNT production costs have fallen significantly and may reach lower values in the future [48]. Bitumen accounts for approximately 0.5% of the mass in ordinary asphalt pavements and 5–17% of the cost of asphalt concrete. With the worldwide depletion of crude oil supplies, the price of bitumen may rise dramatically in the future. Nanotechnology may thus play a part in easing this issue. Also, both construction and maintenance costs need to be looked at in terms of how nanomaterials could be used in pavement engineering, with a focus on the short-term, long-term, and total cost of ownership. As far as maintenance costs are concerned, actions that can ensure minimum pavement maintenance have a direct impact on the life cycle cost during the maintenance period, which is preventable by the development of automatic crack filters and corrosion treatment. In addition, the life of the pavement may generally be enhanced by improving the pavement's resilience to environmental effects. The materials needed for the development of stronger pavement materials are decreasing (e.g., thinner pavement layers) and therefore influence the cost of construction. Life cycle impacts should be considered in any cost assessment in terms of improved paving durability and decreased maintenance needs [48].

6. Application of nanomaterials in soils

Although not formally described as such, many geotechnical substances may be termed nanomaterials, and their behavior has been researched on a nanoscale for many years. Soil is essentially a particulate substance with a large range of particles from less than 1 mm to 75 mm. A vast variety of particle sizes has made soil one of the most complex materials to study, simulate, and use. Unbound materials may also be called natural soils and gravel and consist of soil materials chosen for their particular features. Usually, water is added to these materials to guarantee optimum content, then the material is compacted. Changes in moisture content usually affect the behavior of these materials. A major difference in the usage of a mineral at the nanoscale is that the volume ratio of the surface area usually rises dramatically. Of course, one of the materials frequently seen in paving engineering is clay. Their reaction to changes in the moisture content of the material causes extremely unique difficulties in the pavement engineering area since most clays have low friction angles and some of them are expansive [12,49–53].

7. Future prospects

In light of the findings of this literature study, there are numerous properties of nanotechnology that may be used in the construction of pavements to improve their overall performance. Depending on the client's needs, flexible, breathable, ductile, permeable, or impermeable concrete qualities may be designed for specific purposes. The application of nanotechnology in engineered materials will facilitate the optimization of regional resource use and the minimization of wasteful transportation. With nanotechnology's continued development, there could be a reduction in the cost of pavement maintenance and an extension of the lifetime of pavement. It may also aid in the development of cement concrete and asphalt blends that can withstand environmental stresses such as freezing and thawing, sulfate, corrosion, acid rain, and others. This new idea could help make materials that can withstand blasts and conduct electricity, as well as materials that can sense changes in humidity, temperature, and even stress.

8. Conclusion

By enhancing building materials' performance and lowering energy consumption, nanomaterials may help reduce the use of natural resources. The use of nanomaterials in construction gives the construction of pavements a cheaper, quicker, safer, and more durable advantage. The inclusion of nanoparticles has been clearly shown to enhance the performance of asphalt binders. Properties like the softening point and viscosity of asphalt may be enhanced (raised) along with bitumen penetration. Furthermore, compared to conventional asphalt, the tensile strength of the modified bitumen is enhanced. The same goes for the rutting resistance, which is far better than conventional asphalt. Nanoparticles (considered additives) have not been very appealing to researchers since they are considerably more expensive than typical additives like polymers. Today, the constant commitment of more and more researchers in the area of nano-technology has resulted in the creation of many new creative and low-cost manufacturing techniques for nanomaterials and made them suitable for use in pavement materials such as asphalt binders. Many advanced research and development applications for asphalt mixtures that are made with nanomaterials are still being made to meet different needs in pavement engineering today.

Conflict of Interest

No conflict of interest was declared.

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