Resistance to Aging of Asphalt Modified with Multidimensional Nanomaterials: A literary Review

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Abstract

Multidimensional nanomaterials, is a resource that has been formed over time becoming a revolutionary technology with a transcendent character providing the use in asphalt construction procedures, benefiting in the aspects of resistance in the environments to the field of civil engineering, in the same way it is a way in the advance for a better conservation of horizontal works with a favorable impact on the materials used, helping to preserve the care of the environment. In such a way that, in this article, a systematic review is reflected, around the exhaustive research in the databases such as Scopus and Science Direct, compiling a sum of 85 articles, which are indexed in journals from 2017 to 2021, carried out correspondingly on the different investigations of the management of multidimensional nanomaterials in asphalts. The objective of this literary review is to transmit various research by authors such as: the impact on the life cycle of asphalt, the performance it produces, the profitability and the advantage of the teaching that multidimensional nanomaterials have left, to later show results that show a growth in yields in asphalts through the application of multidimensional nanomaterials, So that it presents greater efficiency in the resistance to aging of the asphalt it is concluded that the nanomaterials reduce the environmental impact caused by the field of the constructions, improving the anti-aging capacity of the asphalt.

Keywords

asphalt, multidimensional nanomaterials, environmental impact, resistance to aging

1 Introduction

Asphalt pavements are represented in high proportions in the field of road engineering in the world. Therefore, they must present excellent structural performances in the diverse pavements that are usually related to the different material properties, being something innovative the selection of the material for adequate structural performances in the asphalt pavements. Therefore, the joints of the pavement materials are in relation to the performance of the asphalt pavements [1]. Thus, they are incessantly subjected to the combinations of repetitive loads of vehicles, in the same way the environmental loads that occur over the years of services, causing cracking, furrow formation and damage that is caused by water on the surface of the asphalts. These forms of wear cause degradation in yields and reducing the life cycle of asphalt pavement, causing appreciable economic damage [2].

As time goes by, the various layers that can be found in asphalts are exposed to high magnitudes of stresses, the continuous effects of various climatic changes, the deformation caused in the asphalt layer, the stiffness of the upper asphalt layer and the relative displacement of the mineral particle in the mixtures of the upper layer. Therefore, it is interesting to use materials such as multidimensional nanomaterials to modify or ultimately improve the behavior of asphalt mixtures [3].

Because there is the phenomenon of aging that plays the key role in the deterioration of the performance of asphalt mixtures [4]. For this reason, in recent times, the various multidimensional nanomaterials that have been applied for the improvement of different material property. As are those of nanometer size, making them promising additives for the reinforcement of materials with good performance in asphalt [5]. Modifications are essential to improve the efficiency of asphalt mixtures and, to some extent, solve problems of premature failure [6]. Therefore, the application of multidimensional nanomaterials in pavement engineering potentially improves asphalt mixtures, including adhesion between asphalt binder cohesions, cracking strengths, wetting strengths, rutting layer performances, and layer interface bonds [7].

Multidimensional nanomaterials are novel materials that are renowned from considerable research, for which, it is developed all over the world, they are defined as microscale fillers being efficient as reinforcements of the fillers, in such a way they show improvements in the properties of mechanical behavior of the asphalt mixtures [8]. Therefore, the uses of multidimensional nanomaterials in asphalt mix additive application have been made to improve its performance against deformation, fatigue cracking, thermal cracking, moisture damage and oxidative aging [9].

Multidimensional nanomaterials are used as anti-aging composite modifiers to improve the performance of asphalts [10]. Since the various roads that were paved with different asphalt materials were experiencing deficiencies in cracking, rutting, rutting, thrusting, etc., reducing the service life and safety of the roads, increasing the cost of rehabilitation and maintenance. Reducing the useful life and safety of the roads, increasing the cost of rehabilitation and maintenance [11].

The Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) specifies that multidimensional nanomaterials are materials with an external dimension, as well as internal structuring having one or more types of dimensions in the range up to 100 nm, presenting several characteristics that are innovative in comparisons of the same materials without characters at certain nanoscales [12]. Being efficient having a significant effect on improving the properties of permanent deformations in bitumen and mixtures [13].

For this reason, multidimensional nanomaterials are used for the improvement of the rheological property and borehole fluid losses in relation to the water bases of the asphalt material, however, multidimensional nanomaterials not only cause an improvement in the property of asphalts, but also greatly help the anti-UV aging performance of asphalts, showing a high resistance to cracking at low temperature [14].

2 Methodology

In the presentation, literary review, different databases such as Scopus and ScienceDirect were deepened, fully detecting a sum of 85 articles that are indexed: 14 are from 2021, 22 from 2020, 36 from 2019, 9 from 2018 and 4 from 2017. The keywords that were used for the localization of articles are the following: asphalt modified nanomaterials and multidimensional nanomaterials. For a better extension of the search method in Table 1, the selected articles are shown, correlation to their years of publication and database.

For an adequate location in relation to the articles to be used, the distribution of various keywords in relation to the topic to be investigated is indispensable, therefore, the different filters are found since 2017 of the area to be investigated.

Table 2 shows the various search characters, in relation to the databases, resulting in the number of articles selected by keywords.

After the articles, a log was elaborated in which the databases, titles, year of dissemination, names of authors, DOI, journal are mentioned, for which, the research becomes organized.

3 Results and discussions

This article was adopted by disclosures of various studies with respect to the approaches presented by each author, in

Table 1 Manifest of selected articles, correlated to their years of publication and database (Source: Own elaboration)

Year of publication	Database		Sub Total
	Scopus	ScienceDirect	
2017	1	3	4
2018	2	7	9
2019	12	24	36
2020	20	2	22
2021	12	2	14
Total	47	38	85

Table 2 Various search characters (Source: Own elaboration)

Database	Keyword	Unfiltered search results	Years of filtered search	Thematic Area Filters	Filter Results	Selected articles
Scopus	asphalt and modified and nanomaterials	110	2017–2021	Engineering, materials Science	78	47
ScienceDirect	asphalt modified nanomaterials	656	2017–2021	Engineering, materials Science	323	23
	multidimensional nanomaterials	2443	2017–2021	Engineering, materials Science	775	15

order to exchange positions on the use of multidimensional nanomaterials in asphalt with the intention of improving its resistance.

3.1 What are multidimensional nanomaterials?

In 1994, the Society for Materials Research (SIM) proposed terminology for multidimensional nanomaterials in engineering. They were used in various asphalts with unusual material characteristics, such as susceptibilities to wetting, high and low temperature properties and pavement durability [15]. Therefore, in recent years, several studies have been carried out on the modifications of the asphalt mixture applied in various multidimensional nanomaterials. This has led to improvements in the performance properties of asphalt mixtures, such as their resistance to deformation and fatigue [16]. There are different types of multidimensional nanomaterials, among them we have the inorganic ones which are common, they are layered silicates, we also have the inorganic nanoparticles, which have attracted great attention due to their effect of superior modifications of asphaltic binders and their excellent stabilities to high temperatures and ultraviolet rays [17].

Therefore, multidimensional nanomaterials exhibit diverse properties that are innovative and acceptable due to their large surface areas and small sizes. Making it possible for nanomaterials to be used in various pavements [18]. Resulting with high ductilities, large surface areas, high deformation resistances and low electrical resistivities. Due to these unique characteristics, the application of multidimensional nanomaterials is very wide demonstrating that the addition remarkably improves the performance properties of the asphalt material [19]. Therefore, modification of asphalt binders by various modifiers is an effective method favoring roads in the future, this leads to multidimensional nanomaterials increase their tensile strength by 10 °C, indicating that it improves the performances at low temperatures [20].

Multidimensional nanomaterials refer to a material with a size between 1–100 nanometers (1 nm = 10^{-9} m) in at least one dimension, the properties of multidimensional nanomaterials are very different from those of normal sized materials [21]. They are classified into three types with one nanometer dimension: as zero to two-dimensional, being zinc oxides (ZnO), titanium (TiO2), inorganic nanoparticles, silica oxides (SiO2), iron oxides (Fe2O3), etc., being typical zero-dimensional materials, which help to reflect ultraviolet (UV) radiation [22]. Two-dimensional nanomaterials such as expanded organic

vermiculite (OEVMT) are used to improve the aging resistance of asphalts due to photoxidation and thermal oxidation [10]. Therefore, multidimensional nanomaterials have recently attracted considerable attention due to their small sizes and large surface areas, which can have long-term effects on the performance of various pavements. Multidimensional nanomaterials can be used to develop new pavement materials that can withstand traffic loads and environmental conditions [23]. Similarly, the addition of multidimensional nanomaterials to polymeric bitumen increases viscosity, stiffness, and improved shear parameters [24]. For this reason, the use of multidimensional nanomaterials is being applied in taking advantage of the improvement of various pavement properties of asphalt binder in relation to the large area of their surfaces that are specific, high surface energy and acceptable capacity in dispersions. However, they have shown that the modification effects are limited when they are used [25].

3.2 Effect of the yield of the mechanical properties of multidimensional nanomaterials in the asphalt mixture

In recent years, more and more multidimensional nanomaterials are being used to modify the properties of the asphalt binder, including nanoclay, nano silicon dioxide, carbon nanofibers (NNFc), nanofibers (NNF), carbon nanotubes (NTC), etc. NTCs exhibit excellent mechanical properties in which Young's moduli reach approximately 1000GPa and tensile strengths reach 150 GPa, this is to be subjected to multidimensional nanomaterial diameters. The NTCs also have remarkable electrical and thermal conductivities; being attractive to the modification of asphalts and appear to be promising material additive for performance enhancements in building and structural materials [26].

Table 3 shows different nanoparticles with their effects on performance [27].

In Fig. 1, a flow of the materials approach involving nanomaterials in research can be shown [28].

3.3 Consequences of asphalts without multidimensional nanomaterials

One of the several most concurrent damages in the asphalt mixture is caused by destructive occasions by wetting on the asphalt binder cohesions and asphalt-aggregate binder adhesions, which are called wetting damages [29]. Also, thermal sensitivities of asphalt mixture are important problems, since asphalts contain bitumen that are sensitive and susceptible to heat, for these reasons, multidimensional nanomaterials are part of families of additives for

Table 3 shows different nanoparticles with their effects on performance [27]

| Nanomodifications		Binder sample	Effect on yields	
Nanoparticle	Percentages		Positive	Negative
Nanoclays	1%; 3%; 5%	PG 58-28; PG 64-28	Permanent deformations	-
	2%; 4%	PG 58-34	Permanent deformations; rigidity	Sensitivities to water
	4%	35/50	Marshall Stability	-
Nanosilicans	4%	PG 76	Sensitivities to water; permanent deformations; rigidity	-
	4%; 6%	PG 58-34 y ABS	Permanent deformations; Rigidities	-
	2%	60/70 y 5% SBS	Marshall Stability; stiffness; water sensitivities	-
Montmorillonite modified with polysiloxane	2%	PG 58-28	Sensitivities to water	Indirect tensile strengths
	2%; 4%	PG 58-34	Stiffness; permanent deformations	Sensitivities to water
	2%; 4%; 7%	60/70	Stiffness; water sensitivities	-
	6%	40/60	Permanent deformations; water sensitivities; rigidity	Fatigue life
Organophilic montmorillonite	3%	PG 58-22	Sensitivities to water; Fatigue life; stiffness, permanent deformations	-
	1.50%	PG 58-10 y 6% SBS	Sensitivities to water; Rigidities	-
	2%; 3.5%; 5% Tipo A	50/70	Marshall Stability; permanent deformations; tensile strength at 25 °C	Tensile strength at 15 °C
	2%; 3.5%; 5% Tipo B	50/70	Marshall Stability; Permanent deformations; Tensile strength at 25 °C	Tensile strengths at 15 °C
	2%; 3.5%; 5% Tipo C	50/70	Permanent deformations	Indirect tensile strength at 15 °C and 25 °C.
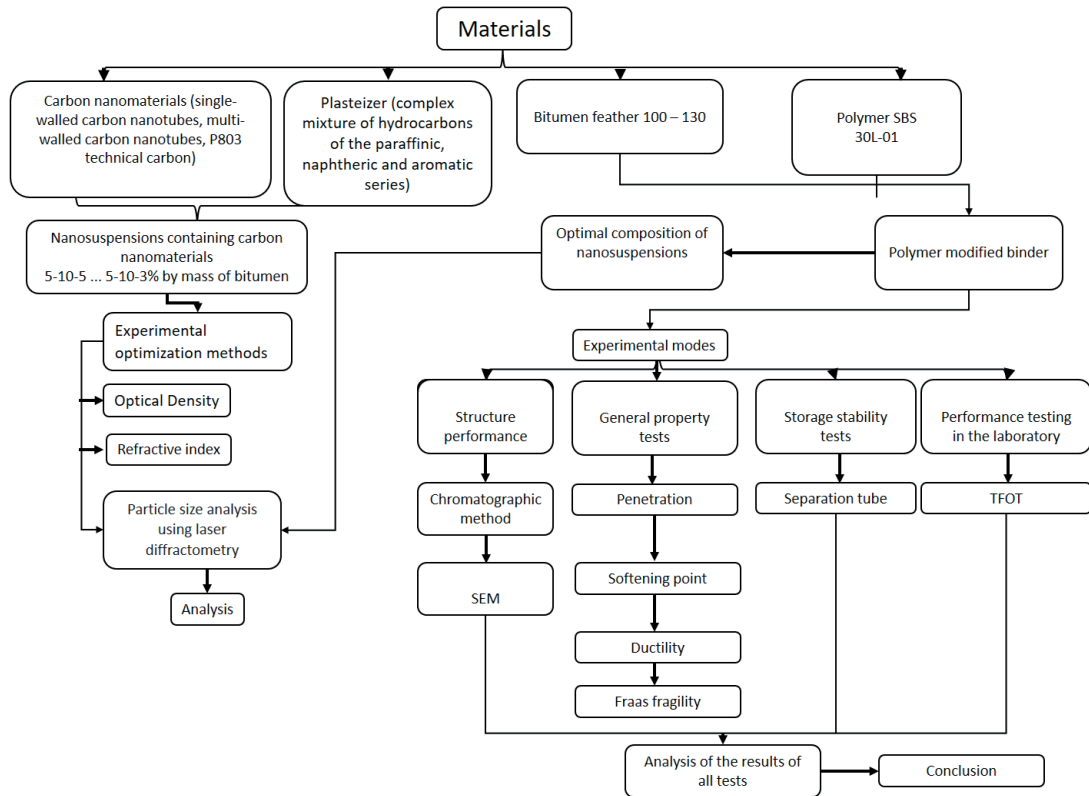
Fig. 1 The flowchart of the research approach [28]

improving the property of hot asphalts in terms of thermal sensitivities. According to studies, multidimensional nanomaterials composed of nano-silica are materials that improve the properties of bitumens and asphalt mixtures in the hot state [30].

Similarly, aging is the main factor responsible for problems in asphalt pavement, whereby, pavements do not perform well due to the deterioration of the internal structure of the material and environmental effects. Since 2000, different multidimensional nanomaterials have been used for better resistance to aging which results in a hard and brittle binder, thus decreasing its durability [31]. Therefore, asphalt, aged when exposed to heating, oxygen and solar radiations encountered during pavement constructions or service phases. Aged asphalt binders become more rigid and brittle, losing their adhesions in the aggregate, giving rise to major problems in pavements, such as fatigue, cracking and wetting, which seriously compromise pavement performance and shorten pavement lifetimes [22].

Similarly, due to the increase of populations, the improvement of mobility and the development of economies worldwide over the years, road traffic and vehicle loads that are supporting the different roads in the world are increasing considerably, climatic changes and ecological deterioration have caused fluctuations in temperatures over the years. Therefore, these circumstances have given rise to the needs for the exploitation of bituminous materials for the reinforcements of the mechanical responses of road surfaces, thus avoiding pavement degradations and guaranteeing longer service lives in service conditions [32]. Thus, it has been defined that asphalt aging occurs mainly in two different stages. The first stage is the mixing, spreading and rolling processes, accompanied by transport, storage, heating and mixing of hot aggregates, which causes the effect of short-term aging. The second stage mainly refers to the service stages of pavements, which are vulnerable to the impact of natural environments and climatic changes and, therefore, produce the effect of long-term aging [33].

Likewise, thermal or low temperature cracking is a recurrent problem in asphalt pavement, which originates in regions with cold climates exerting detrimental effects on the qualities and life of pavements, for which reason, it is sought to use agents for their rehabilitation with the options of having longer life cycles [34]. Similarly, thermal cracking causes accelerations in fatigue propagation of the asphalt mixture under traffic loading. The most

important pavement cracks are caused by the cold weather that extends day by day due to the passage of vehicles; crack creations and expansions that require premature and early repair [35].

The main contribution of greenhouse gas emissions, are longer transport distances, long construction seasons, with which the minimization of oxidative hardening of asphalt and the improvement of the workability of asphalt mixtures that can be given by nanomaterial technologies is sought [36]. To solve this problem the use as are multidimensional nanomaterials researchers have used being compatible with asphalt having great benefits [37].

3.4 Incidences of multidimensional nanomaterials on asphalt

Asphalt performance characteristics can be improved using multidimensional nanomaterials, such as additives in asphalt binder performance characteristics; decreasing fatigue and long-term aging, it can lead to an optimal 8% improvement in asphalt binder performance [38].

Asphalt pavement material designs are evolving in the directions of durability, performance and low energy consumption. The developments of high-performance asphalt materials with the concepts of long-life pavement designs. They enable the requirement of modified asphalt binder applications in pavement of high grades, have attracted wide attentions. The most widely used asphalt binder modifiers, such as heats mixes, bio-oil, geopolymers, metal particle rejuvenators, soybean derivatives, recycled bitumens, PET (polyethylene terephthalate) residue, steel slag, etc. modifiers or fillers to obtain excellent asphalt mixtures [39].

Table 4 shows the advantage and disadvantage of multidimensional nanomaterials [40].

The rejuvenator with multidimensional nanomaterials can be kept in a microcapsule during the first years of the pavement's service life. When microcracks appear, the load on the microcapsule causes it to rupture. As a result, the rejuvenator is released in the vicinity of the microcracks, improving the properties of the binder in that area, and increasing its self-healing properties [41]. Therefore, it is defined that these multidimensional nanomaterials can modify the internal structure of asphalt and improve its properties at high temperatures, increasing the resistance to plastic deformations and elasticities, as well as favoring other properties such as electrical conductivity [42].

Table 5 shows the nanomaterials in relation to the recommended content for use in modified asphalt.

Table 4 Advantages and disadvantages of multidimensional nanomaterials [40]

Techniques	Advantage	Disadvantage
Nanomaterials multidimensionals	Improved properties at high	High cost
	Improved fatigue properties	Reduced performance at low temperature for some nanomaterials
	Improvements in low temperature yields in certain nanomaterials	They are simply added
	Improvements in low temperature yields in certain nanomaterials	Specific segregations
	Reductions in moisture damage to asphalts	-
	Reductions in microcracks	-
	Improvements in resistance to aging	-
	Improvements of adhesive joints	-

Table 5 Multidimensional nanomaterials in relation to the recommendation volume for use in modified asphalt [19]

Asphalt	Nanomaterial	Volume
PG 58-34	Nano-SiO2	6.00%
PG 76	Nano-SiO2	4.00%
60/70 binder	Nano-SiO2	2.00%
PG 58-28	Nano-Clay	1.50%
60/70 bitumen	carbon nanotubes	1.20%
PG 70-22	nanofibrous carbon	4.0–12.0%
60/70 grade	carbon nanotubes	1.00%
PG 58-28	Nano-Clay	8.00%
70/100 binder	carbon nanotubes	> 0.5%
AH 90 asphalt	Nano-ZnO	0.25%
PG 64-22	carbon nanotubes	1.00%
PG 64-22; PG 52-28; PG 64-16	Nano-Carbon	1.50%

3.5 Disadvantages of multidimensional nanomaterials in asphalts

Multidimensional nanomaterials are extensively used in the preparation of modified asphalts because they improve the high-temperature performance of asphalts and have achieved fruitful results in civil engineering. However, they have focused primarily on materials analyses and formulations developments of nanomodified asphalts. In China, two structural models have been established for various nanomodified asphalt pavements with respect to the specifications that exist today. Various impacts of pavement thickness, material types and pavement design variables were analyzed in response to the mechanical performance of nanomodified asphalt pavements, thus adopting the principles of optimal mechanical performance and proposing the optimal combinations of nanomodified asphalt pavement structures [43].

3.6 Types of multidimensional nanomaterials in asphalts

Multidimensional nanomaterials composed of nano-TiO2 and nano-ZnO exhibit fatigue resistance due to improved cohesion and adhesion in asphalt binder and aggregate systems [44]. To combat the problems in asphalt concrete pavements, modifications of their asphalt binders are necessary and result in improved oxidative aging properties, increased resistance to rutting effects, and improved rheological properties of asphalt mixtures [45]. However, nano-TiO2 has the potentialities to promote photocatalytic and self-cleaning properties, being proportions of multifunctional effect and benefit when pavements are subjected to high solar irradiations [46]. Also, nano-ZnO yields improved aging resistance. Nano-ZnO particles in rod forms can increase the softening points of asphalts and reduce the penetrations (25°C), which have positive effects on the ductility (5°C), but when the contents are 3%, the ductility of asphalts will be affected. Therefore, nano-ZnO in rods significantly improve the UV resistances of asphalts [47].

In Table 6, properties of the multidimensional ZnO nanomaterial.

The multidimensional nanomaterial such as nano-bentonite, nano-hydrated lime (NCH), nano-silica and nano-CaCO3. With 20% hydrated lime fillers and 4% nano-hydrated lime to the binders, the resistance value of the

Table 6 Properties of the multidimensional nanomaterial ZnO [18]

Property	Value
verage particle size	30 nm
Surface	~50 m² = g
Morphology	Almost spherical
Color	Milky white
Specific gravity (true)	~5.506 g = cm³

mixtures increases up to 60% [48]. Similarly, multidimensional nanomaterials, composed of nano-Bentonite and ZycoTherm, result in potentially improved high temperature susceptibility strengths, storage stabilities, rheological properties of asphalt binder samples and slightly improved with nanomodification [49].

Table 7 shows the properties of the nanomaterial NCH Table 8 shows the chemical composition of the nano lime.

Multidimensional carbon-based nanomaterials. One of the most common types of these composites has been carbon nanotubes (CTNs). It has also been shown that the incorporation of CTNs reduces the permanent fatigue and degradation of asphalt mixtures, improving resistance to thermal cracking and reducing aging [50]. Similarly, nanomaterials composed of nano-montmorillonite (NMMT) and nano silicon dioxide (NDS) show superior performance in pavement rutting [51].

Multidimensional nanomaterials consisting of layered silicates and non-organic nanoparticles are promising agents to combat aging of styrene-butadiene-styrene modified asphalt binder. Such multidimensional nanomaterials allow increasing the strength by increasing their elastic resilience and decreasing the flow viscosity [52].

Multidimensional nanomaterials composed of surface-modified zinc nano-oxide (nano-ZnO) and expanded organic vermiculite (EOV) improve shear deformation resistance, as well as thermal aging resistance [53].

Multidimensional nanomaterials of carbons act as effective modifiers of bitumens due to their stiffness and strength. Thus, nanofibrous carbons (CNF) were prepared from chrome-tanned polishing powders (these are solid wastes generated by the leather industry) with due care to avoid oxidations, additions of nanomaterials with bitumens cause particle-particle collisions due to the strong diffusion characteristic leading to high degrees of agglomerations in bitumen blends. Therefore, another objective

of the studies is also to achieve suitable mixtures of NFC and bitumens compared to the mixtures using the heating method by conventional methods and/or microwaves [54].

The use of different multidimensional nanomaterials, with the inclusion of nanoclay (bentonites and halloysites) as well as cellulose nanocrystals, is an alternative of great potential for the improvement of various characteristics of asphalt and the extension of the useful life of the asphalt pavement. They are remarkable in taking advantage of the high temperature property of modified asphalt mixtures, as well as taking into account the costs of multidimensional nanomaterials and are cost-effective alternatives for asphalt modifications [55].

Modification by means of multidimensional nanomaterials has led to significant increases in several properties of asphalts. However, over the course of the service life, oxidations come to affect the contributions of the already modified asphalt and subsequently originate divergences from the desired ones. The most important property that has been affected due to oxidation is the adhesive characteristic of the asphalt that is improved. Describing as multidimensional nanomaterial having at least one dimension between 1 and 100 nm. With characteristic that presents nanoparticle with different conventional material due to higher proportions between surfaces, volumes and sheet of nanometer dimension [56].

In addition, the use of multidimensional nanomaterials in improving different characteristics of asphalts has been found to be advantageous. Carbon nanotube (CNT)-modified asphalt with the addition of 0.5%, 1.0% and 1.5% increases the resistance to moisture damage, 1.0% and 1.5% CNT, respectively, outperformed the combination of the corresponding polymer-modified asphalts. However, the possibilities of multidimensional nanomaterials in the fields of pavement engineering still require in-depth

Table 7 Properties of the nanomaterial NCH [34]

Properties	NCH
Structure	Hexagonal
Particle shapes	Cubic
Refractive index	1.1–1.5
Specific gravity (gr/cm^3)	2.24
Specific surface (m^2/gr)	16
Average particle size (nm)	42 $\approx$
Water content (%)	0.75 $\leq$
Bulk specific gravity	0.5–0.6
pH	12.4

Table 8 Chemical compounds of the multidimensional nanomaterial nano lime [44]

Composition	Nano lime (%)
MgO	6.32
CaO	86.44
Al2O3	1.15
SiO2	2.26
Na2O	0.23
Fe2O3	0.35
TiO2	0.04
MnO	0.11
K2O	0.17

evaluations of several unexplored characteristics. One of them is the resistance to wetting attacks, which are very complicated issues [57].

Nanomodifiers improve the characteristics of substrates characteristic of the substrate compared to their macro- and micro-sized counterparts. Multidimensional nanomaterials possess incredible characteristics, which make them suitable as additives in asphalt [58]. The optimum ratio of the modified asphalt is characterized by optimum performances, the asphalt modified by Nano-CaCO3/ nano-ZnO/SBR compound with 6% in the mixture reducing asphalt aging and viscosity. Similarly, the complex shear modulus increases by 24.1% at 82°C, the stiffness modulus decreases on average by 21.1% [59].

Multidimensional nanomaterials have great potentials for the improvement of the performance of base asphaltic binders. The applications of nano-TiO2/CaCO3 in bitumen with different dosages. Optimal viscosity is obtained, similarly, a reasonable dosage of nano-TiO2/CaCO3 of 5% by weight of the base bitumen was recommended for the mechanical properties to be improved by reducing the temperature sensitivity of bitumen [60].

Damage caused by wetting and aging results in joint damage to asphalt binders during service life and is therefore quite difficult to overcome. The applications of crumb rubbers, for the best behaviors of the asphalt material, therefore, the use of these multidimensional nanomaterials such as CNTs are mixed in different percentages, 0.5%, 1% and 1.5%. With weights, any type of doses is recommended, ranging from 0.5 to 1.5% by weight, revealing an effective technique for the development of temperature performance of asphalt binders, significantly improving the asphalts to overcome the damage caused by moisture and aging due to exposure to outdoor environments as paving materials [61].

Nano-silica increases the shear modulus and viscosities of asphalt, due to which it increases the anti-aging performance, unfavorable fatigue cracking behavior, rutting resistance and anti-abrasion characteristics of asphalts. The additions of 1 to 2% of nano-silica to the asphalt mix allow to reduce the penetration capacities and the flexibilities. Moreover, nano-silica (NS) has gained great attention from researchers in the pavement for the elaboration of asphalt mixtures with the fruitful properties due to the stability it offers [62].

Multidimensional nanomaterials that are not organic, such as nano-SiO2 nano-ZnO, nano-TiO2 and nano-CaCO3 are added to asphalts as modifications Nano-TiO2 can improve the fatigue strengths and increase the viscosities of asphalts. Nano-TiO2 can strengthen the bonds between asphalts and aggregates. Nano-CaCO3 can reduce the contact angles of asphalts and improve the wettability of asphalts and aggressiveness. In addition, nano-SiO2 can effectively improve the performance of asphalts at elevated temperatures. Nano-TiO2 and nano-SiO2 can improve hardness and viscosity properties by an average of 30% and 109%, respectively. Although inorganic nanomaterials can develop some of the properties of asphalts, in order for the changes to be diverse, they can also improve the properties of asphalts [63].

Nanoclays are layered mineral silicate nanoparticles, nanoclays are grouped as bentonites, montmorillonites, kaolinites, etc. Nanoclays are most popular multidimensional nanomaterials for making polymer nanocomposites because of their low costs of productions, their abundances in natures, such as their small amount needed 0.5%, 1% and 2%; for modifications of asphalt binders and inherent characteristic, they can give improvements in the rheological property of asphalt binders, such as increasing complex moduli and decreases in phase angles of asphalt binders [64].

Nanosilica is generally used to prepare the mixture of polymeric nanocomposite to the large reactions in silica materials and binders of asphalts, in which the optimum contents of nanosilica are 6% in asphalt binders results in higher dispersions of nanosilica and polymers in bitumen mixtures relative to other multidimensional nanomaterial [65]. Nanosilicas in asphalt improves the overall performances of asphalt binders for satisfying the multifunctional requirements of asphalt pavements [66].

Nanosilica such as nanoclay, nanosilica, hydrated nanocalcite, nanoscale plastic powder, nanofibers and nanotubes are some of these materials which with different percentages of (0, 0.2, 0.4, 0.4, 0.7 and 0.9%) Can improve the rheological characteristics of the binder, causing improvements in mix resistances against wetting, rutting and fatigue damage [67].

Multidimensional nanomaterials are used in asphalt binder in order to increase the behaviors and temperature susceptibilities of asphalt pavements. Suitable concentrations of multidimensional nanomaterials can help continuous phases during binder modifications [68]. To this end, hydrated lime as a nanomaterial could effectively improve moisture susceptibility in asphalts. The effect of Zycosoil nanomaterial on the properties of dry process asphalt mixture with three dosages (0.25%, 0.50% and 0.75%), they found that Zycosoil could improve moisture susceptibility [69].

For asphalt durability improvement, there are three types of multidimensional nanomaterials in the fields of retardants. The first is zero-dimensional nanomaterials, which have three dimensions on the nanometer scales, such as oligosilicon and spherical silica nanoparticle. The second are one-dimensional nanomaterials, in which two dimensions of the dispersed phases are of nanometer sizes, such as carbon nanotube. The third are layered nanomaterial, which has only one dimension of nanometer sizes and the typical layered material are montmorillonites, graphite oxide nanomaterials, layered metal hydroxides [70].

Multidimensional nanomaterials such as nanoclays, nanosilicas, nanocalcites, carbon nanotube and graphite nanoplatelet are used in asphalt binder and asphalt mixtures. The nanomodified material show significant improvement in mechanical and thermal property. It is observed that 2% of nanoclays (in masses of binders) improve the moduli of shear complexes by 184%. The uses of hydrated nano-lime can reduce by 75% in order to increase the resistance capabilities of the asphalt mix to moisture attack. The incorporations of 2–4% of multidimensional nanomaterial (in asphalt binder masses) significantly increase the rutting resistance capabilities in asphalt mixture [71].

The uses of multidimensional nanomaterials produce larger surface areas and higher catalytic effects that can be directly or indirectly attributed to a smaller dimension. The physical and chemical characteristic of the nanometer dimension particle are different from that of traditional material, mainly because of the higher proportions between the surface areas, volumes and quantum effects produced by special confinements. Types of multidimensional nanomaterials, such as nanoclays, zinc nanooxides, nanochalcone, and carbon nanotube (CNT), in certain percentages as CNT contents vary at 0%, 0.4%, 0.75%, 1.5% and 2.25% by weight of the control binders, have attracted the attention of research societies in recent years for their capabilities to enhance the different rheological characteristic of asphalt binders. Among the various multidimensional nanomaterials, NTC have received considerable attentions due to their excellent aspect ratios in mechanical and thermal property [72].

The multidimensional nanomaterial Zycosoil with three dosages (0.25%, 0.50% and 0.75%) on the performance in asphalt mixture improves the ability to resist moisture and reduction of gases produced by vehicles. Several researchers have found that some liquid antistripping agents can significantly improve the moisture resistance of virgin asphalts or warm mixes [73]. The pollution of the environment is becoming more and more serious, and the ways to control pollution from vehicle exhaust gas emissions are causing significant problems worldwide. Multiple research have been carried out to explore materials capable of degrading NO2, and it was found that, as photocatalytic materials, certain nanoparticles such as nano-TiO2 with different contents (0%, 1%, 2%, 5%, 10%), can undergo redox reactions under irradiation. Several cities worldwide have carried out research and engineering applications with instructive results [74].

In Japan, they built highways using the pore structures of road surfaces to load TiO2 powders to obtain the effects of photocatalytic decays of automobile exhaust gases. In Italy, they evaluated the effects of photocatalytic degradations of nano-TiO2 and placed test sections of 7000 m^2 in the form of coatings. The Municipal Park of Antwerp in Belgium built sidewalks of about 10,000 m^2 with nano-TiO2 cementitious bricks. In Guerville, France, nano-TiO2 was sprayed on the walls of three buildings for studies of their NO2 degradation in atmospheres. The various studies found that the cured cement samples showed good NO2 degradation in atmospheres under UV irradiation [75].

Asphalt pavements easily suffer from rutting due to high temperatures and reductions in asphalt stiffness. Increased bitumen viscosities play important roles in asphalt pavement cracking at low temperatures. Additions of bitumen modifiers are common approaches to improving pavement properties. Numerous bitumen modifiers such as nanomaterials have many benefits in asphalts [76].

Multidimensional nanomaterial can repair the reduction in mechanical strength caused by rubber aggregates. It can be confirmed that the pre-coatings of rubbers aggregates with a few layers of cements pastes, asphalt mixture with 50% mineral aggregate can effectively improve the mechanical performances of Portland cement concrete containing recycled rubbers aggregates, applying pre-coated rubbers particles of cements to prepare concretes. Pre-coating was found to improve compressive strengths and reduce permeabilities [77].

The modification to bitumen is given due to its sensitivities to temperatures, high resistances, large surfaces, high ductility, low electrical resistivities, and deformations, multidimensional nanomaterials are added, in this case NTCs, for which, the additions of 1. 5% additions of such nanomaterial are optimal mixtures, resulting in delayed elasticities, however if the additions were 3% of NTCs would increase even more, likewise effectively improve the performance of bitumen at high temperature [78].

The physical and rheological properties of the asphalt mixture influence pavement performances at low and high ambient temperatures. Additions of modifiers, such as nanoadditives, improve the performances of bitumen and asphalt concrete mix [79]. Therefore, there is a wide range of additives, such as waste materials, multidimensional nanomaterials, which are added to bitumen in mixtures in order to increase the performance of asphalts, showing that, in conditions with temperatures of 160°C, desirable performances are obtained [80].

Table 9 strength results are shown for various types of multidimensional nanomaterials.

Table 9 Resistance results in relation to different types of multidimensional nanomaterials (Source: Own elaboration)

Nanomaterials in asphalt				
Types of nanomaterials	% additional	Numerical value	Result	Ref.
Nanoclays	1%, 3%, 5 % and 7 % in weigh.	Optimum value of 5 % by weight.	Improves the high temperature resistance of asphalt by 3.73% for a temperature of 76 °C.	[81]
Nano Fe2O3	0,1%, 0,4%, 0,8% and 1,2%	The optimum value is between 0.8%.	As the percentages of Nano Fe2O3 increase, the fracture toughness increases to reach its maximum value at the percentage of 0.8%, achieving the significant improvement of 32% in fracture toughness.	[82]
Montmorillonite nanoclays	1%, 2%, 3% and 4%	3% montmorillonite, 4% of nanoclays.	The mixes modified with 3% montmorillonite in the performance in permanent deformations. Asphalts modified with 4% nanoclays have improved rutting resistance.	[13]
El Nano-SiO2	4%	4% nano-SiO2 is considered the optimal dose.	Improved UV aging. It can also solve the problem of low temperature cracking.	[14]
El nano-TiO2	0.5%, 3.0%, 6.0% and 10,0%	Optimal 5% and 10%.	0.5% TiO2 improves the fatigue resistance of asphalt, and 10.0% improves the resistance to permanent deformation.	[46]
Nano SiO2 y Nano TiO2	1.2% and 0.9%.	Optimum percentage of 1.2%.	The addition of 1.2% Nano SiO2 at 40 °C increases the rutting strengths of the mixes by approximately 100% and also increases the fatigue life of the bitumen samples by 50%.	[83]
Carbon nanotubes (NTC)	0.5%– 2%	They were carried out with the estimated values and did not represent improvements in the asphalt.	NTCs are not resistant to compression. Therefore, their hollow structures with high and thin walls in relation to aspects, are sensitive to buckling when loaded in axial compression.	[84]
Graphene oxide (OG) and rice husk ash (CCA)	0.075% and 10%	Both values are worked taking into account that the particle size of OG is less than 3 μm.	Increase in compressive strength, at 3 days of 23.15%, 7 days of 18.19% and at 28 days of 17.67%.	[85]
OEVMT, nano-ZnO, nano-TiO2 y nano-SiO2	1% de OEVT and 3% (nano-ZnO, nano-TiO2 and nano-SiO2), respectively.	The appropriate correlation is 0.87	Compared to SiO2 and TiO2, ZnO modified asphalts with a correlation of 0.87 show higher adhesion and lower Young's modulus of different aging patterns.	[10]
Nano-Bentonite	2 %, 4% and 6%	Optimum Binder Content 4.26%, 4.4%, 4.38%, respectively.	According to the specifications in the penetration test (0.1 mm) results 61.0 60.0 57.7, respectively. And in the softening point test (°C) according to ASTM D 36-06 specifications, the results are 52.9, 53.2, 54.7, respectively.	[49]
Nanomaterial ZnO	1%, 3% and 5%.	1% is not an effective ratio and 5% is a much more effective ratio for modifications.	The softening point is 49.9, 50.4 and 52.9, respectively. Penetration index is -1.290, -0.899 and -0.384, respectively. Specific gravity (g = cm³) is 0.842, 1.06 and 0.926, respectively.	[18]
Nano ZnO	1%, 3%, 5% and 7%	It is within the deformation range: 50–200 μ.	The ductility increases by 141, >150, >150 and >150, respectively; with respect to the AC Base (85/100) which results in a ductility of 125; according to ASTM D113-79 specifications).	[9]
NTC/ Polyethylene	2.5%–4.0%	Optimum contents, binders with 1.0% NTC and 4.0% PE show potential improvements in rolling resistance.	CNT/PE additions lead to increased softening points, decreased penetrations and higher binder ductility.	[5]

Continuation of Table 9

Types of nanomaterials	% additional	Numerical value	Result	Ref.
Nanocal	2%, 5% and 8%	Value of the optimum percentage of nanomaterial is 8%.	The free energy of cohesion for an asphalt binder modified with nano lime is 31.78, 36.22 and 39.94 mJ/m2, respectively; having a higher free energy of cohesion, making them resistant to crack fatigue failure that can occur in asphalt binder membranes.	[44]
Polyvinylpyrrolidone-stabilized graphene nanoparticles (NPsG - PVP)	0.5%, 1.0%, 1.5% and 2.0%	The optimum recommended doses of NPsG-PVP for the modification of modified asphalts is 1.0% to 1.5%.	Exploits in rutting strengths and fatigue damage tolerances of modified asphalts and low temperature cracking performances.	[32]
Nanoclay	1%, 2%, 3% and 4%	Optimum percentage value is 3%.	The results indicate that the addition of nanoclays up to 3% increases the permanent deformation resistance, however, the addition of 4% is unfavorable, causing a decrease in resistance due to the large spaces in the binder particles.	[13]
Nano glass fiber	0.2–0.6%	Optimum percentage of 0.6%.	Resulting in an increase in tensile modulus of 60 GPa, with elongations of 3 to 4%, with elastic recoveries of 100%, thus improving fatigue strength and ductility.	[62]
Silica nanoparticles (NPS)	0.5%	Optimum percentage of 0.5%.	The resistance to cracking and fatigue cracking of the asphalt binder was 12, similarly, the fracture energies at low temperatures and the ductility of the asphalt binders increased by 205% after aging.	[75]
Nanoclay	1%, 3% and 4%	Optimum nanomaterial percentage value is 4%.	The addition of 4% nanoclay resulted in a 15% increase in the modulus of rigidity.	[27]
Nano-ZnO	1.0%–5.0%	Optimum nanomaterial percentage value is 5%.	When additions of 3.0% nano-ZnO in patterned asphalts result in improved low-temperature ductility.	[63]

4 Conclusions

Multidimensional nanomaterials have been successfully used in asphalts helping to predispose to an adequate risk analysis and ideal conservation of resources that are in overexploitation. Different types of mix design are made in function of an adequate management to protect asphalts that are damaged by the different climates caused by global warming, becoming a magnificent tool in civil engineering.

The use of multidimensional nanomaterials is estimated with high costs, however, the benefits they bring with them make them effective. For asphalt mixtures, these nanomaterials in their different dimensions are beneficial, they improve their properties generating a much longer useful life for asphalts, as well as providing methods considered valuable in the research of innovative materials.

Nanomaterials, with the course of time, will achieve improvements in their properties, which makes them a useful material that will boost research, all of this is supported by studies that favor them.

Multidimensional nanomaterials reduce the excess consumption of resources used in asphalts because it extends the life cycle, therefore, the environmental impact that this generates I turn it positive for its appropriate characteristics, directly benefits the population by reducing CO_2 awareness to care for green areas.

References

[1] Wang, R., Yue, M., Xiong, Y., Yue, J. "Experimental study on mechanism, aging, rheology and fatigue performance of carbon nanomaterial/SBS-modified asphalt binders", Construction and Building Materials, 268, 121189, 2021.
https://doi.org/10.1016/j.conbuildmat.2020.121189

[2] Wang, H., Guo, Y., Shen, A., Yang, X., Li, P. "Effect of Nanoclays on Moisture Susceptibility of SBS-Modified Asphalt Binder", Advances in Materials Science and Engineering, 2020, 2074232, 2020.
https://doi.org/10.1155/2020/2074232

[3] López-Montero, T., Crucho, J., Picado-Santos, L., Miró, R. "Effect of nanomaterials on ageing and moisture damage using the indirect tensile strength test", Construction and Building Materials, 168, pp. 31–40, 2018.
https://doi.org/10.1016/j.conbuildmat.2018.02.110

[4] Crucho, J. M. L., das Neves, J. M. C., Capitão, S. D. de Picado-Santos, L. G. "Evaluation of the durability of asphalt concrete modified with nanomaterials using the TEAGE aging method", Construction and Building Materials, 214, pp. 178–186, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.04.121

[5] Liang, M., Su, L., Li, P., Shi, J., Yao, Z., Zhang, J., Jiang, H., Luo, W. "Investigating the Rheological Properties of Carbon Nanotubes/ Polymer Composites Modified Asphalt", Materials, 13, 4077, 2020.
https://doi.org/10.3390/ma13184077

[6] Shah, P. M. Mir, M. S. "Application of nanotechnology in pavement engineering: a review", Canadian Journal of Civil Engineering, 47(9), pp. 1037–1045, 2020.
https://doi.org/10.1139/cjce-2019-0395

[7] Mousavinezhad, S. H., Shafabakhsh, G. H., Jafari Ani, O. "Nano-clay and styrene-butadiene-styrene modified bitumen for improvement of rutting performance in asphalt mixtures containing steel slag aggregates", Construction and Building Materials, 226, pp. 793–801, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.07.252

[8] Zangena, S. A. "Performance of asphalt mixture with nanoparticles", In: Nanotechnology in Eco-efficient Construction, Woodhead Publishing, 2019, pp. 165–186. ISBN: 978-0-08-102641-0
https://doi.org/10.1016/B978-0-08-102641-0.00008-6

[9] Azarhoosh, A. R., Nejad, F. M., Khodaii, A. "Nanomaterial and fatigue cracking of hot mix asphalt", Road Materials and Pavement Design, 19(2), pp. 353–366, 2018.
https://doi.org/10.1080/14680629.2016.1261724

[10] Hong, H., Zhang, H., Zhang, S. "Effect of multi-dimensional nano-materials on the aging behavior of asphalt by atomic force microscope", Construction and Building Materials, 260, 120389, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.120389

[11] Pirmohammad, S., Majd-Shokorlou, Y., Amani, B. "Experimental investigation of fracture properties of asphalt mixtures modified with Nano Fe2O3 and carbon nanotubes", Road Materials and Pavement Design, 21(8), pp. 2321–2343, 2020.
https://doi.org/10.1080/14680629.2019.1608289

[12] Taherkhani, H., Afroozi, S., Javanmard, S. "Comparative Study of the Effects of Nanosilica and Zyco-Soil Nanomaterials on the Properties of Asphalt Concrete", Journal of Materials in Civil Engineering, 29(8), 4017054, 2017.
https://doi.org/10.1061/(ASCE)MT.1943-5533.0001889

[13] Ameli, A., Babagoli, R., Khabooshani, M., AliAsgari, R., Jalali, F. "Permanent deformation performance of binders and stone mastic asphalt mixtures modified by SBS/montmorillonite nanocomposite", Construction and Building Materials, 239, 117700, 2020.
https://doi.org/10.1016/j.conbuildmat.2019.117700

[14] Qian, G., Yang, C., Huang, H., Gong, X., Yu, H. "Resistance to Ultraviolet Aging of Nano-SiO2 and Rubber Powder Compound Modified Asphalt", Materials, 13, 5067, 2020.
https://doi.org/10.3390/ma13225067

[15] Chen, Z., Zhang, D., Zhang, Y., Zhang, H., Zhang, S. "Influence of multi-dimensional nanomaterials composite form on thermal and ultraviolet oxidation aging resistances of SBS modified asphalt", Construction and Building Materials, 273, 122054, 2021.
https://doi.org/10.1016/j.conbuildmat.2020.122054

[16] Adnan, A. M., Luo, X., Lü, C., Wang, J., Huang, Z. "Improving mechanics behavior of hot mix asphalt using graphene-oxide", Construction and Building Materials, 254, 119261, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.119261

[17] Zhu, C., Zhang, H., Zhang, Y. "Influence of layered silicate types on physical, rheological and aging properties of SBS modified asphalt with multi-dimensional nanomaterials", Construction and Building Materials, 228, 116735, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.116735

[18] Saltan, M., Terzi, S., Karahancer, S. "Mechanical Behavior of Bitumen and Hot-Mix Asphalt Modified with Zinc Oxide Nano-particle", Journal of Materials in Civil Engineering, 31(3), 4018399, 2019.
https://doi.org/10.1061/(ASCE)MT.1943-5533.0002621

[19] Li, R., Xiao, F., Amirkhanian, S., You, Z., Huang, J. "Developments of nano materials and technologies on asphalt materials – A review", Construction and Building Materials, 143, pp. 633–648, 2017.
https://doi.org/10.1016/j.conbuildmat.2017.03.158

[20] Wang, J., Zhang, H., Zhu, C. "Effect of multi-scale nanocomposites on performance of asphalt binder and mixture", Construction and Building Materials, 243, 118307, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.118307

[21] Guo, W., Guo, X., Chang, M., Dai, W. "Evaluating the Effect of Hydrophobic Nanosilica on the Viscoelasticity Property of Asphalt and Asphalt Mixture", Materials, 11, 2018.
https://doi.org/10.3390/ma11112328

[22] Zhang, S., Hong, H., Zhang, H., Chen, Z. "Investigation of anti-aging mechanism of multi-dimensional nanomaterials modified asphalt by FTIR, NMR and GPC", Construction and Building Materials, 305, 124809, 2021.
https://doi.org/10.1016/j.conbuildmat.2021.124809

[23] Jeffry, S. N. A., Jaya, R. P., Abdul Hassan, N., Yaacob, H., Satar, M. K. I. M. "Mechanical performance of asphalt mixture containing nano-charcoal coconut shell ash", Construction and Building Materials, 173, pp. 40–48, 2018.
https://doi.org/10.1016/j.conbuildmat.2018.04.024

[24] Mirsepahi, M., Tanzadeh, J., Ghanoon, S. A. "Laboratory evaluation of dynamic performance and viscosity improvement in modified bitumen by combining nanomaterials and polymer", Construction and Building Materials, 233, 117183, 2020.
https://doi.org/10.1016/j.conbuildmat.2019.117183

[25] Ren, J., Zang, G., Xu, Y. "Formula and Pavement Properties of a Composite Modified Bioasphalt Binder Considering Performance and Economy", Journal of Materials in Civil Engineering, 31(10), 4019243, 2019.
https://doi.org/10.1061/(ASCE)MT.1943-5533.0002888

[26] Xin, X., Yao, Z., Shi, J., Liang, M., Jiang, H., Zhang, J., Zhang, X., Yao, K. "Rheological properties, microstructure and aging resistance of asphalt modified with CNTs/PE composites", Construction and Building Materials, 262, 120100, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.120100

[27] Lopes Crucho, J. M., Coelho das Neves, J. M., Dias Capitão, S., Picado-Santos, L. G. "Mechanical performance of asphalt concrete modified with nanoparticles: Nanosilica, zero-valent iron and nanoclay", Construction and Building Materials, 181, pp. 309–318, 2018.
https://doi.org/10.1016/j.conbuildmat.2018.06.052

[28] Shekhovtsova, S., Korolev, E. "Formation of polymer modified binder structure in the presence of carbon nanomaterials", Construction and Building Materials, 303, 124591, 2021.
https://doi.org/10.1016/j.conbuildmat.2021.124591

[29] Hamedi, G. H. "Evaluating the effect of asphalt binder modification using nanomaterials on the moisture damage of hot mix asphalt", Road Materials and Pavement Design, 18(6), pp. 1375–1394, 2017.
https://doi.org/10.1080/14680629.2016.1220865

[30] Firouzinia, M., Shafabakhsh, G. "Investigation of the effect of nano-silica on thermal sensitivity of HMA using artificial neural network", Construction and Building Materials, 170, pp. 527–536, 2018.
https://doi.org/10.1016/j.conbuildmat.2018.03.067

[31] Alam, G., Hafeez, I., Yaseen, G., Nasir, M. A., Hussain, A., Ahmad, N. "Assessing the aging tendency of asphalt binder using a thermal cycler", International Journal of Pavement Engineering, 23(8), pp. 2503–2514, 2020.
https://doi.org/10.1080/10298436.2020.1861279

[32] Liu, J., Hao, P., Jiang, W., Sun, B. "Rheological properties of SBS modified asphalt incorporated polyvinylpyrrolidone stabilized graphene nanoplatelets", Construction and Building Materials, 298, 123850, 2021.
https://doi.org/10.1016/j.conbuildmat.2021.123850

[33] Wang, R., Yue, J., Li, R., Sun, Y. "Evaluation of Aging Resistance of Asphalt Binder Modified with Graphene Oxide and Carbon Nanotubes", Journal of Materials in Civil Engineering, 31(11), 4019274, 2019.
https://doi.org/10.1061/(ASCE)MT.1943-5533.0002934

[34] Hamedi, G. H., Ghahremani, H., Saedi, D. "Investigation the effect of short term aging on thermodynamic parameters and thermal cracking of asphalt mixtures modified with nanomaterials", Road Materials and Pavement Design, 22(12), pp. 2838–2865, 2020.
https://doi.org/10.1080/14680629.2020.1808520

[35] Shafabakhsh, G., Sadeghnejad, M., Ebrahimnia, R. "Fracture resistance of asphalt mixtures under mixed-mode I/II loading at low-temperature: Without and with nano SiO2", Construction and Building Materials, 266, 120954, 2021.
https://doi.org/10.1016/j.conbuildmat.2020.120954

[36] Mansourkhaki, A., Aghasi, A. "Performance of rubberized asphalt containing liquid nanomaterial anti-strip agent", Construction and Building Materials, 214, pp. 468–474, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.03.071

[37] Vamegh, M., Ameri, M., Naeni, S. F. C. "Performance evaluation of fatigue resistance of asphalt mixtures modified by SBR/PP polymer blends and SBS", Construction and Building Materials, 209, pp. 202–214, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.03.111

[38] Yılmaz, B., Ebru Gürbüz, H. "Rheological and morphological evaluation of nanoclay modified asphalt binder", Construction and Building Materials, 313, 125479, 2021.
https://doi.org/10.1016/j.conbuildmat.2021.125479

[39] Wang, R., Xiong, Y., Yue, M., Hao, M., Yue, J. "Investigating the effectiveness of carbon nanomaterials on asphalt binders from hot storage stability, thermodynamics, and mechanism perspectives", Journal of Cleaner Production, 276, 124180, 2020.
https://doi.org/10.1016/j.jclepro.2020.124180

[40] Behnood, A., Gharehveran, M. M. "Morphology, Rheology and Physical Properties of Polymer-Modified Asphalt Binders", European Polymer Journal, 112, pp. 766–791, 2018.
https://doi.org/10.1016/j.eurpolymj.2018.10.049

[41] Shirzad, S., Hassan, M. M., Aguirre, M. A., Mohammad, L. N., Cooper Jr., S., Negulescu, I. I. "Rheological properties of asphalt binder modified with recycled asphalt materials and light-activated self-healing polymers", Construction and Building Materials, 220, pp. 187–195, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.05.189

[42] Casado-Barrasa, R., Lastra-González, P., Indacoechea-Vega, I., Castro-Fresno, D. "Assessment of carbon black modified binder in a sustainable asphalt concrete mixture", Construction and Building Materials, 211, pp. 363–370, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.03.255

[43] Gu, W., Tian, Y., Zhang, X. "Mechanical Response and Structure Optimization of Nanomodified Asphalt Pavement", Advances in Civil Engineering, 2021, 6286704, 2021.
https://doi.org/10.1155/2021/6286704

[44] Azarhoosh, A., Abandansari, H. F., Hamedi, G. H. "Surface-Free Energy and Fatigue Performance of Hot-Mix Asphalt Modified with Nano Lime", Journal of Materials in Civil Engineering, 31(9), 4019192, 2019.
https://doi.org/10.1061/(ASCE)MT.1943-5533.0002836

[45] Sackey, S., Lee, D.-E., Kim, B.-S. "Life Cycle Assessment for the Production Phase of Nano-Silica-Modified Asphalt Mixtures", Applied sciences, 9, 1315, 2019.
https://doi.org/10.3390/app9071315

[46] Rocha Segundo, I., Landi, S., Margaritis, A., Pipintakos, G., Freitas, E., …, Carneiro, J. "Physicochemical and Rheological Properties of a Transparent Asphalt Binder Modified with Nano-TiO2", Nanomaterials, 10, 2152, 2020.
https://doi.org/10.3390/nano10112152

[47] He, Z., Xie, T., Li, Q., Wang, P. "Physical and Antiaging Properties of Rodlike Nano-ZnO-Modified Asphalt", Journal of Materials in Civil Engineering, 33(11), 4021316, 2021.
https://doi.org/10.1061/(ASCE)MT.1943-5533.0003947

[48] Razavi, S.-H., Kavussi, A. "The role of nanomaterials in reducing moisture damage of asphalt mixes", Construction and Building Materials, 239, 117827, 2020.
https://doi.org/10.1016/j.conbuildmat.2019.117827

[49] Raufi, H., Topal, A., Sengoz, B., Kaya, D. "Assessment of Asphalt Binders and Hot Mix Asphalt Modified with Nanomaterials", Periodica Polytechnica Civil Engineering, 64(1), pp. 1–13, 2020.
https://doi.org/10.3311/PPci.14487

[50] Yan, T., Ingrassia, L. P., Kumar, R., Turos, M., Canestrari, F., Lu, X., Marasteanu, M. "Evaluation of Graphite Nanoplatelets Influence on the Lubrication Properties of Asphalt Binders", Materials, 13, 772, 2020.
https://doi.org/10.3390/ma13030772

[51] Ezzat, H., El-Badawy, S., Gabr, A., Zaki, S., Breakah, T. "Predicted performance of hot mix asphalt modified with nano-montmorillonite and nanosilicon dioxide based on Egyptian conditions", International Journal of Pavement Engineering, 21(5), pp. 642–652, 2020.
https://doi.org/10.1080/10298436.2018.1502437

[52] Zhang, D., Chen, Z., Zhang, H., Wei, C. "Rheological and anti-aging performance of SBS modified asphalt binders with different multi-dimensional nanomaterials", Construction and Building Materials, 188, pp. 409–416, 2018.
https://doi.org/10.1016/j.conbuildmat.2018.08.136

[53] Zhu, C., Zhang, H., Xu, G., Shi, C. "Aging rheological characteristics of SBR modified asphalt with multidimensional nanomaterials", Construction and Building Materials, 151, pp. 388–393, 2017.
https://doi.org/10.1016/j.conbuildmat.2017.06.121

[54] Murugan, K. P., Balaji, M., Kar, S. S., Swarnalatha, S., Sekaran, G. "Nano fibrous carbon produced from chromium bearing tannery solid waste as the bitumen modifier", Journal of Environmental Management, 270, 110882, 2020.
https://doi.org/10.1016/j.jenvman.2020.110882

[55] Johnson, T. W., Hashemian, L. "Laboratory evaluation of modified asphalt mixes using nanomaterial", Journal of Testing and Evaluation, 49(2), 20190840, 2021.
https://doi.org/10.1520/JTE20190840

[56] Arifuzzaman, M., Gazder, U., Alam, M. S., Sirin, O., Mamun, A. A. "Modelling of Asphalt's Adhesive Behaviour Using Classification and Regression Tree (CART) Analysis", Computational Intelligence and Neuroscience, 2019, 3183050, 2019.
https://doi.org/10.1155/2019/3183050

[57] Mamun, A. A., Arifuzzaman, M. "Nano-scale moisture damage evaluation of carbon nanotube-modified asphalt", Construction and Building Materials, 193, pp. 268–275, 2018.
https://doi.org/10.1016/j.conbuildmat.2018.10.155

[58] ul Haq, M. F., Ahmad, N., Jamal, M., Anwar, W., Khitab, A., Hussan, S. "Carbon Nanotubes and Their Use for Asphalt Binder Modification: A Review", Emerging Materials Research, 9(2), pp. 234–247, 2020.
https://doi.org/10.1680/jemmr.18.00115

[59] Li, Z., Guo, T., Chen, Y., Liu, Q., Chen, Y. "The properties of nano-CaCO3/nano-ZnO/SBR composite-modified asphalt", Nanotechnology Reviews, 10(1), pp. 1253–1265, 2021.
https://doi.org/10.1515/ntrev-2021-0082

[60] Zhang, L., Gao, X., Wang, W., Wang, H., Zheng, K. "Laboratory Evaluation of Rheological Properties of Asphalt Binder Modified by Nano-TiO2/CaCO3", Advances in Materials Science and Engineering, 2021, 5522025, 2021.
https://doi.org/10.1155/2021/5522025

[61] Arifuzzaman, M., Tarefder, R. A., Islam, M. S: "The behavior of carbon nano-tubes (Cnts) as a modifier to resist aging and moisture damage in asphalt", Nanoscience and Nanotechnology - Asia, 11(2), pp. 224–229, 2021.
https://doi.org/10.2174/2210681210999200414113251

[62] Tanzadeh, R., Tanzadeh, J., Honarmand, M., Tahami, S. A. "Experimental study on the effect of basalt and glass fibers on behavior of open-graded friction course asphalt modified with nano-silica", Construction and Building Materials, 212, pp. 467–475, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.04.010

[63] Xu, X., Guo, H., Wang, X., Zhang, M., Wang, Z., Yang, B. "Physical properties and anti-aging characteristics of asphalt modified with nano-zinc oxide powder", Construction and Building Materials, 224, pp. 732–742, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.07.097

[64] Mansourian, A., Goahri, A. R., Khosrowshahi, F. K. "Performance evaluation of asphalt binder modified with EVA/HDPE/nano-clay based on linear and non-linear viscoelastic behaviors", Construction and Building Materials, 208, pp. 554–563, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.03.065

[65] Shafabakhsh, G., Rajabi, M., Sahaf, A. "The fatigue behavior of SBS/nanosilica composite modified asphalt binder and mixture", Construction and Building Materials, 229, 116796, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.116796

[66] Zhou, J., Chen, X., Xu, G., Fu, Q. "Evaluation of low temperature performance for SBS/CR compound modified asphalt binders based on fractional viscoelastic model", Construction and Building Materials, 214, pp. 326–336, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.04.064

[67] Sezavar, R., Shafabakhsh, G., Mirabdolazimi, S. M. "New model of moisture susceptibility of nano silica-modified asphalt New model of moisture susceptibility of nano silica-modified asphalt", Construction and Building Materials, 211, pp. 528–538, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.03.114

[68] Mirzaiyan, D., Ameri, M., Amini, A., Sabouri, M., Norouzi, A. "Evaluation of the performance and temperature susceptibility of gilsonite- and SBS-modified asphalt binders", Construction and Building Materials, 207, pp. 679–692, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.02.145

[69] Tang, J., Zhu, C., Zhang, H., Xu, G., Xiao, F., Amirkhanian, S. "Effect of liquid ASAs on the rheological properties of crumb rubber modified asphalt", Construction and Building Materials, 194, pp. 238–246, 2019.
https://doi.org/10.1016/j.conbuildmat.2018.11.028

[70] Zhou, B., Pei, J., Xue, B., Guo, F., Wen, Y., Zhang, J., Li, R. "Solar/road from 'forced coexistence' to 'harmonious symbiosis'", Applied Energy, 255, 113808, 2019.
https://doi.org/10.1016/j.apenergy.2019.113808

[71] Chen, S., You, Z., Sharif, N. P., Yao. H. Gong, F. "Material selections in asphalt pavement for wet-freeze climate zones: A review", Construction and Building Materials, 201, pp. 510–525, 2019.
https://doi.org/10.1016/j.conbuildmat.2018.11.276

[72] Ashish, P. K., Singh, D. "Effect of Carbon Nano Tube on performance of asphalt binder under creep-recovery and sustained loading conditions", Construction and Building Materials, 215, pp. 523–543, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.04.199

[73] Zhu, C., Tang, J., Zhang, H., Duan, H. "Effect of liquid anti-stripping agents on moisture sensitivity of crumb rubber modified asphalt binders and mixtures", Construction and Building Materials, 225, pp. 112–119, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.07.173

[74] Qian, G., Yu, H., Gong, X., Zhao, L. "Impact of Nano-TiO2 on the NO2 degradation and rheological performance of asphalt pavement", Construction and Building Materials, 218, pp. 53–63, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.05.075

[75] Karnati, S. R., Oldham, D., Fini, E. H., Zhang, L. "Surface functionalization of silica nanoparticles to enhance aging resistance of asphalt binder", Construction and Building Materials, 211, pp. 1065–1072, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.03.257

[76] Wei, K., Wang, Y., Ma, B. "Effects of microencapsulated phase change materials on the performance of asphalt binders", Renewable Energy, 132, pp. 931–940, 2019.
https://doi.org/10.1016/j.renene.2018.08.062

[77] Gong, F., Guo, S., Chen, S., You, Z., Liu, Y., Dai, Q. "Strength and durability of dry-processed stone matrix asphalt containing cement pre-coated scrap tire rubber particles", Construction and Building Materials, 214, pp. 475–483, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.04.151

[78] Yang, Q., Liu, Q., Zhong, J., Hong, B., Wang, D., Oeser, M. "Rheological and micro-structural characterization of bitumen modified with carbon nanomaterials", Construction and Building Materials, 201, pp. 580–589, 2019.
https://doi.org/10.1016/j.conbuildmat.2018.12.173

[79] Ghanoon, S. A., Tanzadeh, J. "Laboratory evaluation of nano-silica modification on rutting resistance of asphalt Binder", Construction and Building Materials, 223, pp. 1074–1082, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.07.295

[80] Yıldırım, Z. B., Karacasu, M. "Modelling of waste rubber and glass fibber with response surface method in hot mix asphalt", Construction and Building Materials, 227, 117070, 2019.
https://doi.org/10.1016/j.conbuildmat.2019.117070

[81] Siddig, E. A. A., Feng, C. P., Ming, L. Y. "Effects of ethylene vinyl acetate and nanoclay additions on high-temperature performance of asphalt binders", Construction and Building Materials, 169, pp. 276–282, 2018.
https://doi.org/10.1016/j.conbuildmat.2018.03.012

[82] Pirmohammad, S., Majd-Shokorlou, Y., Amani, B. "Experimental investigation of fracture properties of asphalt mixtures modified with Nano Fe2O3 and carbon nanotubes", Road Materials and Pavement Design, 21(8), pp. 2321–2343, 2019.
https://doi.org/10.1080/14680629.2019.1608289

[83] Shafabakhsh, G. A., Sadeghnejad, M., Ahoor, B., Taheri, E. "Laboratory experiment on the effect of nano SiO2 and TiO2 on short and long-term aging behavior of bitumen", Construction and Building Materials, 237, 117640, 2020.
https://doi.org/10.1016/j.conbuildmat.2019.117640

[84] Sadiq, M. M., Soroushian, P., Bakker, M. G., Balachandra, A. M. "Ultra high performance cementitious composites with enhanced mechanical and durability characteristics", SN Applied Sciences, 3, 676, 2021.
https://doi.org/10.1007/s42452-021-04628-y

[85] Shanmuga Priya, T., Mehra, A., Jain, S., Kakria, K. "Efect of graphene oxide on high strength concrete induced with rice husk ash: mechanical and durability performance", Innovative Infrastructure Solutions, 6, 5, 2020.
https://doi.org/10.1007/s41062-020-00378-9