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Nanomaterials in asphalt binder: A conspectus

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ABSTRACT

Nanomaterials have been applied in various sectors, such as chemical industry, automotive industry, medicine, and civil engineering. Several recent studies have used nanomaterials in pavement engineering because of their unique properties compared with other materials. This study focused on the nanomaterials in asphalt binder and on methods to produce nanomaterials. According to some reviews, nanomaterials can improve material properties and enhance the rutting resistance and fatigue cracking of the asphalt binder. Two ways to produce nanomaterials are top–down and bottom–up methods. Both methods focused on controlling the size, shape, and composition of the nanomaterials.

1. Introduction

Increasing traffic volumes by several vehicles, such as car, motorcycle, van, and lorry, leads to the high traffic loads onto the asphalt pavement. Moreover, high temperatures (hot country) and low temperatures (cold country) contribute to the worsening of the asphalt pavement. Hence, asphalt pavements deteriorate, as evidenced by rutting, fatigue cracking, raveling, and stripping, which reduce the serviceability of the pavement in terms of riding quality and user safety. Thus, improving the properties of the asphalt binder and increasing the performance of the asphalt pavement are important. One of the factors that lead to binder modification is the increased production of waste materials and industrial by-products [1]. Numerous materials, such as rubber, plastic, and polymers, have been utilized in an asphalt binder [1]. These materials are utilized in a micro-scale asphalt binder [2]. Several recent publications on nanomaterials in civil engineering, especially in materials science

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and technology, have been reported. According to the Federal Highway Administration [3], the application of nanomaterials in asphalt pavement can lead to the long serviceability of the pavement [4].

2. Characteristics of nanomaterials

Nanoscale is one billion of a meter, wherein the size is small. Nanomaterials are formed from nanoparticles with three dimensions in the range of 1–100 nm. The nanomaterials possessed nanosized unique properties. The two factors that rendered the nano-sized unique compared with the other scales are increase in surface area and quantum confinement [5,6]. The smaller the size of the material, the larger the surface area compared with the same volume of the material in a larger form. A large surface area can expose more collisions and increase the frequency of collisions. Hence, the rate of reaction will increase and will be more chemically reactive. Furthermore, nanoparticles adjust their energy level because of the changes in atomic structures.

This condition is attributed to the finite dimension, which makes the energy levels discrete and increases the band gap energy. Nanomaterials are used in various applications, such as in the chemical, automotive, *pharmaceutical*, electronic, and civil engineering industries. Nanostructured materials are classified as three-dimensional, two-dimensional, one-dimensional, and zero-dimensional, as shown in Fig. 1. Their compositions are one nano-dimension (nanothin-film), two nano-dimensions (nano-tubes, nano-fibers, and so on), and three nano-dimensions of nanomaterials (nanopowders, nanoparticles, and so on) [6]. Controlling the composition, size, and structure is important [7] to ensure that the desired properties of nanomaterials can be achieved.

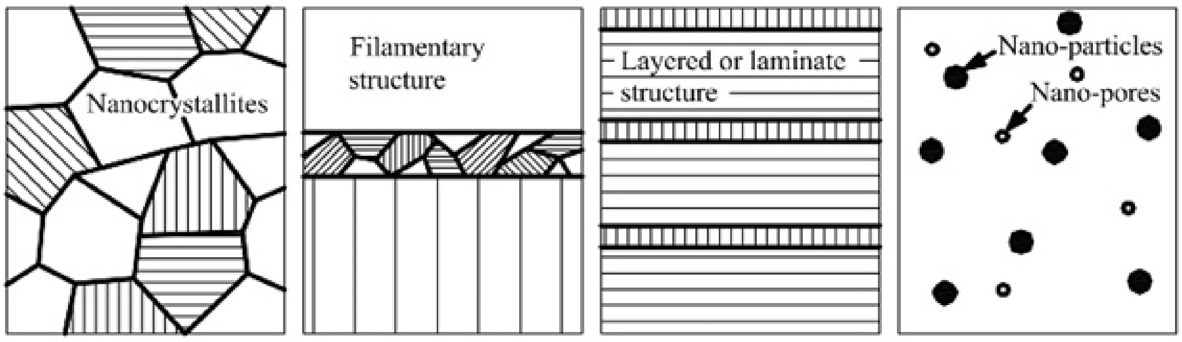

Fig. 1. classification of nanostructured materials

3. Nanomaterials in asphalt binder

The utilization of nanomaterials in asphalt binder was carried out to determine the effects of nanomaterials on the properties of the asphalt binder as well as the performance when applied in the mixture. Studies based on previous publications mostly used nano-sized inorganic materials to modify the asphalt binders. Various percentages of the nanomaterials were added and different methods of mixing were applied to the asphalt binder. Bitumen properties tests, asphalt mixture tests, and microstructural analysis were conducted in these studies. Alhamali et al. [8] reported that using nanosilica in asphalt binder PG 76 decreases the penetration value and increases the softening point value. The viscosity was increased when 2%, 4%, and 6% of nanosilica were added. These results showed that the stiffness of the bitumen was enhanced. However, when a dynamic shear rheometer (DSR) was used, the complex modulus (G*) was decreased except for the addition of 6% nanosilica. Scanning electron micrographs showed that the nanosilica particles were well-dispersed in the bitumen. Overall results indicated that 6% nanosilica was the optimum content that can improve bitumen in terms of rutting and fatigue cracking.

Meanwhile, the incorporation of nanosilica-modified bitumen PG 76 in asphalt mixture was carried out by Yusoff et al. [9]. The moisture sensitivity test, resilient modulus test, and dynamic creep test were conducted on unaged-, short-term aged-, and long-term aged-modified asphalt mixtures. In this study, bitumen was modified using 4% and 6% nanosilica. The moisture sensitivity test showed that 4% of modified asphalt binder exhibited the least susceptibility to moisture damage. Meanwhile, for the resilient modulus and dynamic creep tests, the 4% modified asphalt binder indicated the highest and lowest values for all aged bitumen, respectively. In addition, SEM analysis showed that the nanosilica dispersed significantly in the asphalt binder. However, Yao et al. [10] showed that adding the nanosilica in bitumen PG 58 decreases viscosity.

Moreover, the complex modulus (G*) was decreased as well except for the 13 °C long-term aged-modified binder. On the basis of the mixture's performances, the rut depth of the modified binder mixtures was lower than that of the control mixture. The dynamic modulus of the 6% modified asphalt mixture was higher than that of the 4% and control mixtures. These results revealed that the rutting performance and anti-stripping property were improved. In addition, microstructure analysis using SEM exhibited significant dispersion of nanosilica in the bitumen. Fourier transform infrared spectroscopy indicated that the oxidant reactions were decreased, suggesting the reduction of aging. Other than nanosilica, nanoclay has also been used as a binder modifier [11–13]. Their results showed that non-modified nanoclay (NMN) has a higher viscosity than polymer-modified nanoclay (PMN) and control binder. As for the DSR test, Yao et al. [12] found that the complex shear modulus (G*) of NMN and PMN is higher and lower than that of the control binder, respectively.

However, from the dissipated work per load cycle perspective, PMN can improve the high temperature for the unaged, short-term aged, and long-term aged bitumen because of their high recovery ability compared with NMN. Yao et al. [14] utilized nanocarbon powder and nanorubber powders in asphalt binder. Different percentages of the nanomaterials were used in bitumen 60/80. The penetration and softening point tests were decreased and increased, respectively. The viscosity showed improvement as well in values less than 3 Pa•s. The optimum contents of nanocarbon powder and nanorubber powder were 2% and 1%, respectively. The performance of nanocarbon powder asphalt mixtures in terms of compression strength and resilient modulus was higher than that of nanorubber powder-modified asphalt mixture. Atomic force micrographs showed that both nanomaterials were dispersed uniformly in bitumen. Zhang et al. [15] used non-modified and surface modified nano-SiO2, nano-TiO2, and nano-ZnO incorporated in bitumen PEN 70. Their results revealed that non-modified nanomaterials and modified bitumen decreased the penetration value and increased the softening point and viscosity values.

Nevertheless, the results were weakened after the surface modified nanomaterials, mainly ZnO. The same results were obtained by Shafabakhsh and Ani [16], who used nano-TiO2 and nano-SiO2 in bitumen PEN 60/70 and the mixtures as natural aggregates with 50% steel slag. The results of the binder property test revealed that the penetration and softening point values were decreased and increased, respectively. The viscosity also increased and the DSR showed that the modified bitumen had a higher resistance to rutting than the original bitumen. The Marshall test for the mixture exhibited higher stability and less rutting after the repeated axial load test. SEM analysis indicated that the adhesion between the bitumen and aggregate was improved. Khattak et al. [17] utilized carbon nanofibers in three types of bitumen and conducted binder property tests. The results indicated that the carbon nanofiber-modified bitumen can improve the response of viscoelasticity and resistance to rutting, as well as increase the fatigue life.

4. Nanomaterials in other composites

Nanomaterials from agricultural wastes, such as POFA, CS, RHA, and rattan, have not been utilized in asphalt binder modification. This type of nanomaterials was mostly incorporated in the mortar, concrete pavement, and composite structure. Nikmatin et al. [18] studied the effects of the thermal physical properties of nano-rattan as a filler in polypropylene (PP) composites. Thermal analysis (TGA/DTA) revealed that PP containing 5% nano-rattan exhibits improved thermal stability. Meanwhile, Rajak, Majid, and Ismail [19] reported that the nano-POFA utilized in the cement paste can enhance and harden cement paste by forming a dense and closely packed microstructure because of the filling effect and pozzolanic reactions in the pastes. Meanwhile, Hussin et al. [20] assessed nano-POFA as a partial cement replacement in mortar mixes. The results revealed that 80% nano-POFA resulted in a high compressive strength of approximately 32% at 28 days compared with the control mortar. Moreover, the porosity was reduced by 51% at 365 days, which was proven by FESEM analysis. Ibrahim et al. [21] reported that adding nanosilica from the RHA in porous concrete pavement can improve the strength and durability of the material and enhance the physical and chemical properties of the porous concrete pavement. These studies indicate that the nanomaterials produced from agricultural wastes can improve the physical and chemical properties of materials.

5. Production of nanomaterial

The size, shape, and composition of the nanomaterials must be controlled during manufacturing to obtain the desired properties of nanomaterials [7,22]. Top–down and bottom–up methods are generally employed to produce nanomaterials. Top–down methods involve bulk materials that can be reduced in size. The process is called particle breakage to obtain finer materials up to the nano-scale. This method is generally used to produce small materials from the large size materials by mechanical, physical, and chemical processes [22–25]. By contrast, bottom–up methods involve atoms and molecules combined by chemical or physical reactions to produce nanostructures. This process produces large materials from small materials through chemical vapor deposition, atomic layer deposition, crystal growth, and self-assembly [22–25].

Pacheco-Torgal et al. [26] reported high milling energy and chemical synthesis as two ways to produce nanomaterials. The methods used in the production of nanomaterials in asphalt binder have not been discussed to date. As for previous studies that utilized nanomaterials in composite structure, mortar, and concrete pavement [18–20,27,28], top–down methods were chosen. Mechanical process by grinding is a type of top–down methods used by most researchers. Nikmatin et al. [18] used a hammer mill to grind rattan. The rattan was crushed until the sieve size of 75 µm and ground for several times. The results provided the desired sizes at 30 min of grinding within the range of 15–48 nm. Meanwhile, some researchers used a ball mill to produce nanomaterials [19,20,27]. Nano-POFA was sieved through 150 µm prior to grinding. Grinding for 30 h can produce nanomaterials with a size of 20–90 nm [19]. Meanwhile, Abdul Shukor Lim et al. [27] and Hussin et al. [20] obtained nano-POFA with a size of 50–100 nm.

The processes to obtain nanomaterials include crushing the materials to finer sizes, sieving to obtain 150 µm or 75 µm, and grinding. These reviews showed that grinding by ball milling was the mostly used method to obtain nanomaterials. Hart [22] reported that ball milling is the simplest way of grinding materials to the nano-scale. In general, the ball mill works by the kinetic process of the cylinder bowl, which makes the particle break to smaller sizes because of the striking and impact applied by the steel balls to the materials [29–31]. In addition, the optimum time of grinding to produce the desired nanomaterials must be obtained to ensure that the shape, size, and compositions of the nanomaterials are controllable.

6. Further research

Through this overview, a research gap has been found. Hence, nanocharcoal ash from CS will be used in the modification of asphalt binder. To this extent, the nano-sized agricultural waste materials incorporated in asphalt binder have not been studied. Top–down methods will be used to produce the nano-sized CSC. The optimum time must be determined prior to the nano-sized grinding of the material. Laboratory-scale ball milling will be used to grind the material. Subsequently, the nano-sized CSC will be incorporated into the asphalt binder to be applied into the asphalt mixture. The penetration test, softening point test, asphalt mixture stability test, and morphological analysis of the mixture using field emission scanning electron microscopy will be carried out.

7. Conclusion

The asphalt binder property tests showed that all modified binders demonstrated low penetration values and high softening point values. Meanwhile, the viscosity was increased. These results showed that the stiffness of the modified binders was increased. When applied in asphalt mixture, the stability was improved and strength was enhanced. The nanomaterial-modified asphalt binder increased the rutting resistance and fatigue cracking. The service life of the asphalt pavement can also be increased. Morphology analysis revealed that the nanomaterials dispersed significantly in the asphalt binder. Top–down and bottom–up methods are generally used to produce nanomaterials. However, both methods focused on controlling the size, shape, and composition of the nanomaterials prior to utilization in other Materials.

Nanomaterials have the potential as a modifier in asphalt binder to improve the performance of pavement. However, there are still many challenges and limitations to implement the nanomaterials in this field. The effects of the nanomaterials toward the health and safety, costs and environment need to be considered [3,32]. It is therefore the partnership between the scientists and engineers are important in order to solve the problems. Hence, the opportunities of the nanomaterials to be developed in the pavement engineering field should be taken.

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