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The effects of moisture susceptibility and ageing conditions on nano-silica/polymer-modified asphalt mixtures

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HIGHLIGHTS

- We investigate the effect of ageing and moisture susceptibility on nano-silica/PMA.
- The presence of nano-silica reduces susceptibility to moisture damage of PMA.
- The strength of nano-silica/PMA is increased.
- Susceptibility to oxidative ageing also is significantly reduced.

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ABSTRACT

This study investigates the performance characteristics of polymer-modified asphalt mixture (PMA) with the addition of nano-silica particles. Polymer-modified asphalt, PG-76, was mixed with nano-silica at concentrations of 0%, 2% and 4% by weight of asphalt binder. Asphalt mixture tests such as moisture susceptibility, resilient modulus and dynamic creep were conducted to evaluate the performance of PMA mixed with nano-silica under various ageing and moisture susceptibility conditions. During the mixing process, the binders were kept at 160 °C and blended using a shear rate of 1500 rpm (rpm) for approximately 1 h. Microstructure examinations of the asphalt binders were then carried out using scanning electron microscopy (SEM). The SEM images show that the nano-silica particles disperse well in the asphalt binder matrix. Nano-silica reduces the susceptibility to moisture damage and increases the strength of asphalt mixes. It is also observed that fatigue and rutting resistance are enhanced for PMA mixed with nano-silica particles. Ageing index values show that the susceptibility to oxidative ageing is significantly reduced with the increase of nano-silica content, particularly in the case of long-term ageing. The addition of 4% nano-silica with PMA appears to have the greatest potential for beneficial modification of the binder.

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1. Introduction

For several decades it was accepted that the empirical method of blending different types of base (unmodified or neat) asphalts was the only way to improve the binding characteristics [1]. However, in recent years, increased traffic levels, larger and heavier trucks, new axle designs and increased tyre pressures have added to the already severe load and environmental demands on the highway system, resulting in the need to enhance the performance of the existing asphaltic material [2,3]. In addition, a better understanding of the behaviour and characteristics of binders, in conjunction with the greater development of technology, has encouraged and enabled researchers to examine the benefits of introducing additives and modifiers into the asphalt. The modifiers that are available fall into various categories, such as naturally occurring materials, industrial by-products and waste materials, as well as carefully engineered products. Some of the more common categories include reclaimed rubber products, fillers, fibres, catalysts, polymers (natural and synthetic) and extenders, to name a few [4].

Among them, a blend of asphalt with polymer is the most popular to improve the fundamental characteristics of asphalt, as its characteristics are related to the performance of asphalt mixes. Polymer-modified asphalt has been used for many years with mixes and their usage is forecast to continuously increase in the

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immediate future, particularly in Europe, the USA, Canada and Australia [5]. For example, in the United Kingdom, the first polymer used was natural polymer latex rubber in the middle of the 1800s [6,7]. Polymer-modified asphalt improves resistance to rutting, abrasion, cracking, fatigue, stripping, bleeding and ageing at high temperatures, and improves flexibility at low temperatures [8]. In addition, the structural thickness of asphalt pavement could also be reduced [9,10].

According to Lu et al. [11] different types of polymers are commercially available to be mixed with asphalt; however, there is no universally superior polymer type and therefore selection should be made carefully and according to the specific needs. The level of improvement depends on factors such as polymer characteristics, polymer content and the nature of the asphalts [11–15]. Polymer-modified asphalts with similar polymer content and prepared with identical penetration grade asphalts but from different crude sources have different chemical composition and performance characteristics. Many researchers have shown that polymer-modified asphalts improve the potential deficiencies and therefore the overall performance of asphalt mixture pavements [9]. The styrenic block copolymers (e.g. styrene–butadiene–styrene, SBS) appear to have the greatest potential for beneficial modification of asphalt [2,16–19].

Despite such achievements, many challenges still remain. A major concern related to asphalt modified with polymer is its lack of morphological stability during long storage. The incorporation of the polymer means the mixing tank operation for asphalts need to be altered to fulfil its special needs. In addition, incorporation of polymer can also increase the cost of the binder by between 30% and 100% and boost the overall cost of the asphalt mixture by between 10% and 40% [20]. Ponniah and Kennepohl [21] show that the life cycle cost is ineffective if its cost needs to be overcome, even though it is widely understood that it lasts longer and saves on repair costs. Studies show that the use of polymer-modified asphalt could result in net savings of up to 20% over a 20-year period. This savings could possibly increase by up to 45% if user costs and accidents are taken into account [21].

In recent years, nanotechnology has become a promising and creative technique in the material industry, and nano-materials have been widely applied to various fields across the world [19]. The Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) defines nano-material as a material with one or more external dimensions, or an internal structure having one or more dimensions of the order of 100 nm or less, and which can exhibit novel characteristics compared to the same material without nano-scale features [49]. A number of researchers have used nano-material in Portland cement materials. However, nano-material use in asphalt pavement started relatively late. In this area, nano-technology is used as a form of new material, device and system at the molecular level. There are various nano-materials, which have been or have potential to be used to modify asphalt, such as nano-clay, nano-silica, nano-hydrated lime, nano-sized plastic powders, or polymerised powders, nano-fibres, and nano-tubes, to name a few [19,22,23].

One of the nano-materials commonly used for asphalt modification is nano-clay [24–35]. A low percentage of nano-clay has been observed to increase the softening point and decrease the penetration and ductility values. The use of nano-clay-asphalt nano-composites also increases resistance to ageing [36]. It has also been observed that the storage stability of modified asphalt decreases when the nano-clay content increases [28]. Nano-clay modification improves the rheological properties of the binders by increasing the stiffness of asphalt and decreasing the phase angle (improves elasticity) compared to conventional asphalt; hence this can also reduce the ageing effect [24]. For example, in some research work, it was found that 2% of nano-clay in the asphalt may increase the shear (complex) moduli by as much as 184% [22]. This indicates that the rutting resistance of such asphalt is likely to have been improved. This material has also been used as a secondary modifier to further enhance the performance properties of SBS-modified asphalt [33,34].

You et al. [22] and Yao et al. [19] found that the rutting depth using an asphalt pavement analyser (APA) illustrated that the addition of 2–4% nano-silica by weight of asphalt can reduce the rutting depth by almost half. Furthermore, it was found that the rut depths of nano-materials-modified asphalt mixtures decrease compared to the control mixture, and smaller rutting depth was observed when a greater percentage of nano-materials were used in mixtures. However, research conducted on asphalt mixtures modified with nano-materials is scarce compared to binder modification with nano-material particles. Therefore, this study aims to investigate the performance characteristics of polymer-modified asphalt mixture (PMA) mixed with nano-silica under ageing and moisture susceptibility conditions. The nano-silica was added to the base asphalt at concentration of 2% and 4% (by weight). Asphalt mixture tests such as resilient modulus, dynamic creep and moisture sensitivity were conducted to evaluate the performance of modified mixtures. It is expected that the use of a secondary modifier will further enhance the performance properties of PMA. Details of the tests and discussion of the results obtained from the testing can be found in the following sections.

2. Experimental design

2.1. Binder

The climatic condition in countries like Malaysia are fairly consistent throughout the country and the supply of performance graded (PG) asphalt binder in this region is based on the higher temperatures. This study does not consider low temperature environments because the temperature in this country rarely falls below 30 °C during daylight hours and usually lies within the range of 35–45 °C. Polymer-modified asphalt, PG-76 (Dorotech Hr-Super) is used as a control sample; its physical and rheological properties are shown in Table 1. It is observed that the physical and rheological properties of PG-76 follow the minimum requirements as compared to the standard specifications.

2.2. Nano-silica

Silica is an abundant compound worldwide that is largely employed in industries to produce silica gels, colloidal silica, and fumed silica, etc. [37]. Nano-sized silica is interesting because it is applied in emerging areas like medicine and drug delivery [38]. Amorphous nano-silica is qualified as a nano-bio pesticide. Nano-silica particles have been used in the industry to reinforce the elastomers as a rheological solute [39] and cement concrete mixtures [40]. Nano-silica composites have attracted some scientific interest as well. The advantage of these nano materials resides in the low cost of production and the high performance features [41]. According to Yao et al. [19], nano-silica is also a material with a huge surface area, strong adsorption, good dispersal ability, high chemical purity and excellent stability. Fig. 1 shows the nano-silica particles used in this study.

The PG-76 was prepared by a mechanical mixer. This control binder was modified in the laboratory. The nano-silica particles were added to the control asphalt binder at concentrations of 0%, 2% and 4% (by weight of the asphalt binder) and mixed in a high shear rate machine. It was observed that once the nano-silica had dispersed and melted in the control sample, the surface of the asphalt binder had a few floating bubbles [19]. During the mixing process, the binder samples were kept at 160 °C and blended using a shear rate of 1500 rpm (rpm) for 1 h. The PG-76 compounded with nano-silica was then mixed with coarse and fine aggregates using a wet process.

2.3. Scanning electron micrographs (SEM) images analysis

The mixed asphalt binder underwent a scanning electron micrograph (SEM) analysis to understand the microstructure change of the modified binder, as well as the physical dispersion of the nano-silica particles. Fig. 2 shows the SEM images of all samples that were obtained at different magnifications. It is observed that the agglomeration process between nano-silica particles still occurs even though the material was prepared at nano-scale (Fig. 2a). However, the presence of nano-particles is still small enough compared to polymer-modified asphalt; it is scattered uniformly in Fig. 2c and d.

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