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Mechanical performance of asphalt mixture containing nano-charcoal coconut shell ash

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HIGHLIGHTS

- 6% Nano-charcoal ash significantly improved the asphalt mixture properties and performance.
- Nano-charcoal ash has increased the performance of asphalt mixture owing to aging reduction.
- Nano-charcoal ash enhanced the lowest surface roughness, leading to high adhesion between bitumen and aggregate particles.

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ABSTRACT

Rutting and fatigue cracking are issues in pavement engineering that led to numerous studies for improving pavement performance. Bitumen modification by nanomaterials is a method that can enhance the performance of asphalt mixtures due to the large surface area and small size (1–100 nm) of nanomaterials. Therefore, this research was focused on the influence of nano-charcoal coconut shell ash (NCA)-modified bitumen towards the engineering properties of asphalt mixtures. Engineering property tests were carried out on 0% (control), 1.5%, 6% and 7.5% NCA asphalt mixtures. These tests include Marshall analysis, indirect tensile strength (ITS), resilient modulus and dynamic creep test. The microstructure properties of the asphalt mixtures were evaluated using Atomic force microscopy (AFM) and field emission scanning electron microscopy (FESEM). Results showed that the Marshall stability, ITS, resilient modulus and dynamic creep of the asphalt mixture were significantly improved with the addition of 6% NCA. AFM results showed that 6% NCA has the lowest surface roughness which improved the adhesion of asphalt mixture. Flat and dense asphalt mixture was observed from FESEM which contributed to the enhancement of asphalt mixture engineering performance.

1. Introduction

The asphalt pavement is a type of road infrastructure that enables vehicles to travel from one place to another. This strong and durable infrastructure presents a smooth surface to provide safe riding quality for road users. Bitumen and aggregates are the main pavement materials designated to withstand loads under various environmental conditions. However, the service provided by asphalt pavement decreases with time due to the increased of traffic loading and sensitivity of bitumen towards temperature. Thus, bitumen modification has become a focus research area at present to improve the performance of asphalt pavements. Various modifiers and additives have been used to alter the physical and rheological properties of bitumen which could affect the performance of asphalt mixture [1,2].

Recently, nanomaterials have garnered considerable attention owing to their small size (1–100 nm) and large surface area, which can provide long-term effects on pavement performance [3,4]. The nano-size range contributed to the novel and unique properties of nano-materials [5]. Nano-materials can be used to develop novel pavement materials that can withstand traffic loadings and environmental conditions [6]. Numerous nano-materials have been incorporated in bitumen and resulted in enhanced performances of the asphalt mixture especially in rutting and cracking [4,7–12]. Yusoff et al. [13] reported that 4% nano-silica is the optimum content to improve the performances of the asphalt mixture.

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Based on resilient modulus test and dynamic creep test, 4% of nano-silica showed the highest and lowest values, indicating that the material can improve the rutting and fatigue resistance of asphalt mixtures. By contrast, Yao et al. [14] revealed that the rut depth of modified binder mixtures decreases in comparison with the control mixture, whereas the resilient modulus increases. These results indicate improved rutting performance. Nano-carbon and nano-rubber powders were utilised in asphalt binder by Yao et al. [15]. The performances of nano-carbon powder asphalt mixtures in terms of compression strength and resilient modulus were higher than those of the nano-rubber powder-modified asphalt mixtures. The same results were obtained by Shafabakhsh and Ani [8], who applied bitumen modified with nano-TiO_2 and nano-SiO_2 in mixtures with natural aggregates containing 50% steel slag. Marshall test for the mixture presented increased stability and lower rutting after the repeated load axial test. Given the environmental, health and safety issues, the use of natural sources, such as nanomaterials from waste materials, can help to reduce the risks of hazardous nanomaterials and are environmental friendly [3,16–18]. In addition, the requirements for sustainable structures can be fulfilled by reducing the waste materials [1,18,19]. Waste materials, such as palm oil fuel ash, rice husk ash and rattan coconut shell, have been used as additives in composite materials, and several waste materials have been utilised as nanomaterials [20–23], yielding satisfactory outcomes with the enhanced performances of composite materials.

Coconut shell has been incorporated as nanomaterials in bitumen modification owing to its strength, good quality and biodegradable properties in numerous composite structures [24–27]. In the previous paper, the used of nano-charcoal ash (NCA) from coconut shell as additive to modify bitumen, resulted in significant improvement in the physical and rheological properties [16]. Therefore, this study aims to assess the effect of NCA-modified bitumen in the performances of asphalt mixtures (AC14). This objective was achieved by analysing the engineering properties of the asphalt mixture through Marshall test, indirect tensile strength, resilient modulus and dynamic creep tests. Subsequently, AFM and FESEM analyses were discussed briefly to examine the microstructure properties of the modified bitumen and the asphalt mixture.

2. Materials

2.1. Nano-charcoal ash from coconut shell

Considering the grindability of the coconut shell and energy consumption, waste coconut shell was burned in a furnace at the optimum temperature of 450 °C [28–30]. Through this process, impurities in coconut shell can be reduced with the increment of carbon content. Then, charcoal was obtained from coconut shell after the process. Charcoal was subsequently crushed using the Los Angeles Abrasion machine and then sieved to obtain particle sizes of <75 μm sieve size. For obtaining nano-sized powder, the fine charcoal was ground using a ball mill, which is simplest and cheapest fabrication method to break particles into nanomaterials [31–33]. Grinding was carried out for different durations of 5, 10, 15 and 20 h to find the optimum time that can yield nano-sized charcoal. The number of balls in the ball mill was fixed to 56 balls. A 100 g portion of the material was fed into the ball mill for each grinding time. Nano-size analysis of the charcoal was discussed in a previous paper [16]. Table 1 shows the properties of the NCA. The average size and specific surface area of the particle were determined by particle size analyser and BET single-point test, respectively. Meanwhile, chemical components and elements were obtained from proximate and ultimate analyses, respectively. Fig. 1(a) shows the size and shape of NCA particles through a high-resolution image at 100 nm scale by using transmission electron microscopy (TEM). Meanwhile, Fig. 1(b) indicated the particles in the circle region have spherical and crushed shapes with sizes ranging from 17 nm to 50 nm.

2.2. Bitumen

Bitumen PEN 60/70 was used in this research. The physical properties of bitumen fulfilled the local and international standards as shown in Table 2. The evaluation of the control and NCA modified bitumen was carried out prior to use them as modified bitumen in asphalt mixture. 0%, 1.5%, 3%, 4.5%, 6% and 7.5% NCA bitumen was evaluated through the penetration, softening point, ductility, viscosity and dynamic shear rheometer (DSR) tests. On the basis of previous bitumen evaluation [16], 6% NCA was recorded as the optimum NCA content due to its high significant effects in modifying the bitumen compared to other contents. The large surface area of NCA created strong particles forces with the bitumen. High stiffness of the bitumen was produced and enhanced the performance of rutting and fatigue cracking compared to the control bitumen. Therefore, 6% NCA was utilized in the bitumen for the assessment of the asphalt mixture. In addition, the minimum (1.5%) and maximum (7.5%) contents of the NCA were evaluated in the asphalt mixture. The minimum NCA content was analysed to account for the small amount of nanomaterials to be incorporated in the asphalt mixture for cost reduction. The maximum NCA content was analysed in order to maximize the usage of waste materials. This procedure was conducted to indicate any significant improvement when these percentages were applied in the asphalt mixture.

Table 1
Properties of NCA.

Properties	Content
Average size (nm)	57.7
Specific surface area (m^2/g)	112.74
Proximate analysis (%)	Moisture = 1.264 Volatile = 13.67 Fixed carbon = 78.32 Ash = 6.513
Elemental analysis (%)	C = 77.4 H = 2.7 N = 0.24 S = 0.13 O = 19.5

2.3. Aggregate

Granite aggregate was used in this research. The physical properties of the aggregate satisfied the local and international standards as shown in Table 3. The high specific gravity of the aggregates contributed to strong aggregates. Water absorption was <2%, indicating that the aggregates did not absorb high bitumen content; thus, less bitumen was required. The aggregates also exhibited high durability because the aggregate impact value (AIV) and aggregate crushing value (ACV) were lower than the required value.

2.4. Preparation of modified bitumen and asphalt mixture

NCA with content of 1.5%, 6% and 7.5% was added by weight of bitumen. A uniform mixing state was achieved by mixing with high shear mixer at speeds of 1500 rpm for 60 min at temperature of 160 °C. Stable state of the modified bitumen was recorded when the storage stability test was performed after the bitumen modification. A speed of 1500 rpm was adequate to blend the NCA, which can be dispersed well in the bitumen owing to the nano-scale size. A temperature of 160 °C was employed during blending because excessively high temperature can lead to bitumen aging. A mixing duration of 60 min was selected to ensure adequate mixing between the additive and bitumen and to function as a homogenous binder [7]. The modified bitumen was then utilized in the production of asphalt mixture. The type of asphalt mixture used was AC14 dense graded. The particle size distribution of AC14 is presented in Fig. 2, with median gradation selected between the lower and upper limits. 0% (Control), 1.5%, 6% and 7.5% NCA asphalt mixtures were produced with the replicate of three for each mixture. Both the bitumen and aggregates were mixed until all aggregates were adequately coated. Mixing (0.17 ± 0.02 Pa s) and compacting (0.28 ± 0.03 Pa s) temperatures [1] were used for each type of mixture based on the viscosity standard. The loose asphalt mixture was compacted using the Marshall compactor for 75 blows/face compaction. The verified asphalt mixtures at optimum bitumen content (OBC) were carried out prior to performance testing.

3. Experimental works

3.1. Marshall stability and flow test

The Marshall test of a compacted mixture was carried out in accordance with ASTM D6927 [41]. The parameters that were obtained in this study include stability, flow, stiffness, density, void in total mix (VTM), and void filled with bitumen (VFB). Each parameter requires a specific range to be fulfilled to ensure adequate durability of the mixture during its service. Marshall analysis