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Effects of nanocharcoal coconut-shell ash on the physical and rheological properties of bitumen

Siti Nur Amiera Jeffry [a], Ramadhansyah Putra Jaya [a,*], Norhidayah Abdul Hassan [a], Haryati Yaacob [a], Jahangir Mirza [b,c], Siti Hasyyati Drahman [b]

[a] Faculty of Civil Engineering, Department of Geotechnics and Transportation, Universiti Teknologi Malaysia, 81310 UTM, Johor Bahru, Malaysia
[b] Faculty of Civil Engineering, Construction Research Centre, Institute for Smart Infrastructure and Innovative Construction (ISIIC), Universiti Teknologi Malaysia, 81310 UTM, Johor Bahru, Malaysia
[c] Department of Materials Science, Research Institute of Hydro-Québec, 1800 Mte. Ste. Julie, Varennes, Québec J3X 1S1 Canada

HIGHLIGHTS

- Nanocharcoal ash as bitumen modification has higher rutting resistance.
- Nanocharcoal ash has large surface area which increased the interfacial forces within the bitumen.
- Nanocharcoal ash enhanced the cohesion of the bitumen with improved the physical and rheological properties.

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ABSTRACT

Bitumen properties which correspond to high resistance to traffic and temperature are the prime requirements in prolonging the pavement life. To achieve these requirements, nanoscale materials are considered as potential candidates to increase pavement life. Therefore, to fulfill the need for sustainable structures, this research focused on nanosized (1–100 nm) charcoal from coconut-shell waste as an additive in bitumen. Particle-size analysis and transmission electron microscopy indicated that 15 h of ball-mill grinding produced nanocharcoal ash (NCA) with an average size of 57.7 nm. Then, 0% (control), 1.5%, 3%, 4.5%, 6%, or 7.5% NCA by weight of bitumen PEN 60/70 was added. Penetration, softening point, viscosity, ductility, and dynamic shear rheometer (DSR) tests were performed to investigate the physical and rheological properties of the modified bitumen. Rolling thin film oven and pressure aging vessel tests were used to simulate the aging properties of the bitumen. Results showed that NCA decreased the penetration and increased the softening point of the bitumen, whereas viscosity increased with increased NCA percentage. High rutting and cracking resistance at failure temperatures of 76 and 22 °C, respectively, in the modified bitumen were revealed by the DSR test. Notably, 6% NCA was the optimum content that can improve rutting and cracking resistance.

1. Introduction

Good-quality pavement should exhibit high structural integrity, which provides a strong, smooth, and safe riding surface for road users. However, due to numerous factors, mainly traffic and temperature, asphalt pavements tend to become damaged, which decreases the serviceability, efficiency, and safety of asphalt pavement [1–3]. In Malaysia, rutting and fatigue cracking are the common types of distress in asphalt pavements. One of the factors that lead to pavement distress is the poor bitumen properties. Bitumen is a viscoelastic material that is easily affected by temperature. Inadequate physical properties, such as stiffness, sensitivity to temperature, and rheological properties (resistance to rutting and fatigue cracking) are the factors that contribute to this problem. Considerable research regarding asphalt modification is required for compliance with the current traffic loadings and high temperature to prolong the life of the pavement [1,4].

Nanoscale materials have recently been considered as potential candidates for increasing the life of pavement. The nanosized particles range from 1 nm to 100 nm in size [5–11]. Accordingly, nanomaterials exhibit higher reactivity compared with other common-sized particles because of their small size. The small size of particles leads to large surface area, which can increase exposure

* Corresponding author.
E-mail address: ramadhansyah@utm.my (R.P. Jaya).

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to collisions and the frequency of collisions. Hence, the rate of reaction will increase, leading to strong interfacial forces, which improve the bonding between materials. A workshop by the National Science Foundation in 2006 indicated that nanoscience and nanotechnology can lead to improvements in the asphalt pavement technology [11]. FHWA (2008) [7] expected that one of the long-term effects of using nanomaterials in the pavement research is to obtain novel pavement materials with high resistance to traffic and environment. Numerous studies have incorporated nanomaterials as bitumen modifier owing to their unique properties, which improve both the rheological and engineering properties of bitumen and mixtures [12]. Various types of nanomaterials, such as nanoclay, nanosilica, carbon nanofiber (CNF), and others, have been used to modify the asphalt binder. Jamshidi et al. [12] reported that nanoparticles can improve both the rheological and engineering properties of bitumen and mixtures. Khattak et al. [13] showed that CNF improves the viscoelastic response and rutting resistance of bitumen. Shafabakhsh and Ani [14] utilized nano-TiO_2 and nano-SiO_2 in bitumen, producing higher resistance against rutting through the dynamic shear rheometer (DSR) test. Zhang et al. [15] reported that nano-SiO_2, nano-TiO_2, and nano-ZnO decreased penetration and increased softening.

Previous studies on nanomaterials mostly utilized inorganic nanomaterials in the bitumen. One of the approaches to mitigate the risks of using hazardous nanomaterials on the environment, health, and safety is to replace these materials with an alternative [7]. Naturally sourced material is one such solution for this problem. Few studies that the incorporation of natural resource nanomaterials, such as palm oil fuel ash, rice husk ash, and rattan, in composite materials demonstrated that nanomaterials can enhance the properties and performances of materials [16–18].

Moreover, the production of nanomaterials from natural wastes can help to minimize the waste materials and fulfill the need of sustainable structures [1,19,20]. Among all waste materials, coconut shell is seen as the material with the most potential to be produced as nanomaterials because of its strength and good quality in various composite structures. Coconut shell is one of the agricultural wastes that are abundantly available and discharged by various industries [20–22] Coconut is the fourth crop in Malaysia after palm oil, rubber, and paddy, sequentially [23]. Coconut is an extremely strong, rigid, and lightweight material. In addition, the material is environmentally friendly because of its biodegradability and emission of a relatively low amount of carbon dioxide when burned [24]. Therefore, this paper focuses on the utilization of nanocharcoal ash (NCA) from coconut shell as the bitumen modifier and its effects on bitumen performance. Penetration, softening point, viscosity, and dynamic shear rheometer (DSR) tests were performed to investigate the effects of nanosized charcoal on the physical and rheological properties of bitumen.

2. Materials and method

2.1. Asphalt binder

The bitumen PEN 60/70 from Chevron, Malaysia was used. Table 1 shows its physical properties.

Table 1
Physical properties of PEN bitumen 60/70.

Specific gravity	1.03
Penetration at 25 °C (dmm)	60.9
Softening point (°C)	49.0
Viscosity at 135 °C (Pa·s)	0.5

2.2. Preparation of nanomaterial

Each 200 g of coconut shell was burnt in a furnace ($42 \times 53 \times 55\ cm^3$) at 450 °C for 5 min. This temperature was selected based on the thermal properties of charcoal [25–27]. Charcoal was then produced and crushed using the Los Angeles abrasion machine to produce finer sizes. The fine charcoal was subsequently sieved to obtain the particle sizes of less than 75 μm. The material was ground using a ball mill to obtain nanosized charcoal. A total of 56 steel balls of different diameters were used as grinding media. Table 2 shows the specification of the grinding media. The different grinding times were 5, 10, 15, and 20 h. A total of 100 g of material was fed into the ball mill for each grinding time. Particle-size analysis (PSA) and transmission electron microscopy (TEM) were carried out on the ground samples to check the size.

Table 2
Grinding balls.

Diameter (mm)	Weight (g)	Amount
25	407.2	7
20	513.8	17
16	252.5	17
12	97.1	15

2.2.1. Particle-size analysis (PSA)

The average particle size of ground samples, which were processed for 5, 10, 15, and 20 h, was analyzed by a PSA Malvern Zeta-sizer Nano-ZSP ZEN5600. PSA was used to obtain the average size from the peak of particle-size distribution of the sample. Dynamic light scattering technique was used in this test, in which the samples were prepared by using a wet process. This technique can be used to measure the particle and molecular sizes ranging from 0.3 nm to 10 μm.

2.2.2. Transmission electron microscopy (TEM)

TEM Hitachi HT7700 was used to visualize and analyze the nanocharcoal. This instrument can be used to measure the sample in the microscale (1 μm) to nanoscale (1 nm). TEM can analyze the sample with high-image resolution and magnification.

2.3. Bitumen modification

2.3.1. Modification using different particle sizes of charcoal

5, 10, 15, and 20 h ground samples (6% by weight of bitumen) were added in the bitumen PEN 60/70. The percentage was selected to examine the effects of the same amount of material with different particle sizes in asphalt binder. Moreover, 6% was selected for the study of the high effects of particles with and without nanosized charcoal in the bitumen.

2.3.2. Nanocharcoal ash (NCA) modified bitumen

NCA with amounts of 1.5%, 3%, 4.5%, 6% and 7.5% were added by weight of bitumen PEN 60/70. These percentages were selected based on the analysis of previous studies [12,14,28,29]. The 1.5% gap was selected to examine the sensitivity of the NCA content in the bitumen.

2.3.3. Blending process

The blending process was conducted by using a high shear mixer at 1500 rpm at 160 °C for 60 min. A speed of 1500 rpm was used to ensure that the additives were dispersed well in the bitumen. Blending was conducted at 160 °C because considerably high temperature level can cause the aging of bitumen. Approximately 60 min of mixing was used to ensure adequate mixing