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Characterization of the rate of change of rheological properties of nano-modified asphalt

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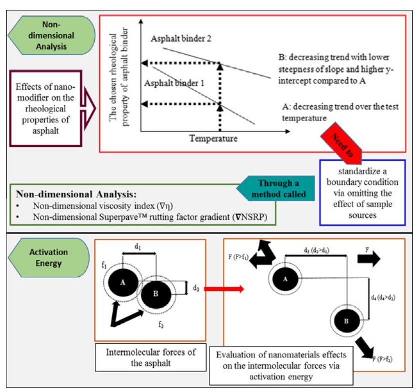
HIGHLIGHTS

- To evaluate the changes in asphalt behavior at the viscous and visco-elastic conditions.
- Non-dimensional analyses were used to characterize the Nano-modified asphalt performance.
- Samples evaluation were conducted at various Nano-material type and content, and test temperature.
- Effects of Nano-modifier on the intermolecular forces of bitumen were evaluated using activation energy.

GRAPHICAL ABSTRACT



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ABSTRACT

This study aims to characterize the rate of change that takes place in the rheological properties of asphalt binders modified with numerous types and contents of nano-materials. The effects of nano-materials on the activation energy of modified asphalt binders under the viscous and visco-elastic behavior were also investigated. Through the research findings, the application of non-dimensional analyses using relative viscosity and relative $G^*/\sin\delta$ (NSRP) are very meaningful to evaluate the rate of change in the rheological properties of asphalt binder per one unit percent of nano-material. It is also found that the non-dimensional viscosity index ($\nabla\eta$) and non-dimensional Superpave™ rutting factor gradient (∇NSRP) are influenced by the type and content of nano-material, and test temperature. The activation energy analysis has confirmed that the changes in amount of energy consumed are not only influenced by the type and content of nano-material, but also the physical phase of the modified asphalt binders.

1. Introduction

Nanotechnology encompasses techniques, devices and systems that are associated with the nanometer scale. Nanotechnology is widely used to develop a new generation of materials with superior performance to enhance the macroscopic properties of materials [1–4]. Mulenga and Robery [5] stated this technology provides access to the world of the tiniest particle in civil engineering, where the dimension of the materials fall under the range of 1–100 nm for at least one side of the particle dimension. Due to its miniature size and high surface area, the reactivity of nano-material is typically higher compared to normal size materials,

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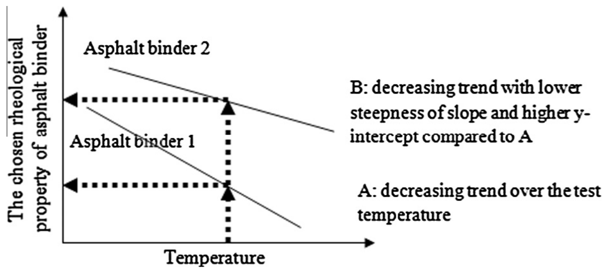

Fig. 1. Effects of asphalt binder types or sources on the rheological properties.

which is beneficial to improve the rheological properties of asphalt binders and engineering properties of asphalt mixtures.

According to You et al. [6], although engineers and road builders are more interested in material behavior at meso and micro scales, the micro and Nano scales provide fundamental insight for the enhancement of science and technology. In the asphalt pavement industry, various types of Nano-materials have been developed and used, including Nano-silica powder [7], carbon Nano-fibers [8,9], carbon Nano-tubes [10–13], non-modified and polymer modified Nano-clay [6,14–16], as well as polysiloxane-modified montmorillonite [16,17]. The application of Nano-materials as asphalt modifier is growing rapidly due to its unique characteristics that significantly improve the performance of asphalt binder. Based on a study by Cheng et al. [18] on the effects of micro and Nano-size hydrated lime on warm mixture asphalt (WMA) performance, it was found that the Sasobit® WMA mixtures that incorporated Nano-size hydrated lime had a significant increase in indirect tensile strength (ITS), toughness and flow number in both, dry and wet conditions compared to specimen containing micro-size hydrated lime.

Yao et al. [15] found that asphalt binders incorporating non-modified Nano-clay and polymer modified Nano-clay have higher stiffness and lower deflection than the specimen prepared using base asphalt binder, which indicated a better resistance to rutting. Nazzal et al. [19] also revealed that Nano-clay material increases the adhesive forces of the asphalt binder, however slightly decreases the cohesive force. Goh et al. [20] studied the synergistic effects of Nano-clay and micro-carbon fiber on the moisture sensitivity of asphalt mixture in terms of tensile strength ratio (TSR). The results indicated that the TSR values of all mixtures containing Nano-clay as well as micro-carbon fiber are greater than the recommended TSR value, with the minimum value of 0.9. Goh et al. [20] also investigated the effects of NaCl, $MgCl_2$ and $CaCl_2$, as deicers, on the tensile strength of Nano-clay and micro-carbon fiber modified mixtures. The results showed that the incorporation of 1.5% Nano-clay material in the mixtures have increased the tensile strength of the tested specimens, hence the mixtures are able to endure the effects of deicer materials on asphalt pavement.

Table 2
Types of modifier used in this study.

Types of modifier	Description	% Modifier used	Sample designated
PMN	Polymer modified Nano-clay	2 4	2%PMN 4%PMN
NPMN	Non-modified polymer Nano-clay	2 4	2%NPMN 4%NPMN
MCF	Carbon micro-fiber	2 4	2%MCF 4%MCF
NI.44P	Nanomer I.44P	2 4	2%N144P 4%N144P
NS	Nano-silica	4 6	4%NS 6%NS

Yao et al. [16] studied the effects of short-term aging on asphalt binders incorporating nanomer I.44P, micro-carbon fiber, non-modified Nano-clay and polymer-modified Nano-clay in terms of aging index. The results indicated that addition of Nano-clay powder reduced the aging impact on asphalt binder. This result is consistent with the Fourier Transform Infra-red Spectroscopy (FTIR) outputs indicating lower carbonyl index in the modified asphalt binder. Khattak et al. [9,21] studied the effects of carbon Nano-fiber (CNF) on rheological properties of asphalt binders and performance of asphalt mixtures. The results indicated that presence of CNF in asphalt binder will significantly enhance the rheological properties of asphalt binders in terms of viscosity, $G^*/\sin\delta$ and fatigue life. The results also showed that CNF modified mixtures have higher dynamic modulus, ITS, stiffness and fatigue life as compared to control samples.

Based on previous studies, there are several impacts on rheological properties and performance of Nano-material modified asphalt binders and mixtures that can be observed through various mechanisms. Such materials may have identical effects on a given rheological properties; however lack of suitable parameter(s) to present the data and enable precise assessment on the rate of change of the rheological characteristics of the Nano-modified binders should be taken into consideration. This paper attempts to fill this gap via proposal of new parameters based on the rheological properties of asphalt binders that enable researchers to characterize sensitivity of the Nano-modified binders based on the independent variables such as Nano-material type, content, test temperature and binder type.

2. New parameters and aspects

As previously mentioned, appropriate parameters are required to assess the rate of change of modified asphalt binders' rheological properties, which can be used as indicator(s) that govern the

Table 1
Example computations of reduction in the relative viscosity.

T^a (°C)	Viscosity (MPa s)				Relative viscosity (%)				Reduction in the relative viscosity (%)	
	Un-modified binder (control)		Modified binder		Un-modified binder[b]		Modified binder[c]		Modified binder[d]	
	1 Asphalt A	2 Asphalt B	3 Asphalt A	4 Asphalt B	5 Asphalt A	6 Asphalt B	7 Asphalt A	8 Asphalt B	9 Asphalt A	10 Asphalt B
120	980	1100	880	970	1	1	0.897	0.881	−10.20	−11.81
140	300	420	250	350	1	1	0.833	0.833	−16.67	−16.67
150	120	180	100	140	1	1	0.833	0.777	−16.67	−22.22

[a] Temperature.
[b] Omitting the effects of the binder source (e.g. 980/980 = 1, as shown in columns 5).
[c] Viscosity values in columns 3 and 4 are divided with the control binders (columns 1 and 2) respectively, e.g. 880/980 = 0.89 as presented in column 7.
[d] Changes in the reduction of relative viscosity: $(\frac{\text{column7}-\text{column5}}{\text{column5}} * 100)$, the result is recorded in column 9. The same calculation is used for values in column 10.