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Short Communication

Investigation of Effect of Nano-alumina Additives on Dynamic Performance and Corrosion Resistance of Asphalt Coating on Carbon Steel

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This work aims to consider the impact of nano-alumina (NAs) on mechanical properties of asphalt concrete and electrochemical behavior of modified asphalt mixtures in deicer solution. Dynamic modulus and electrochemical impedance spectroscopy (EIS) tests were employed to study the effects of NAs on asphalt concrete. The lower phase angle and higher dynamic modulus was found in asphalt mixtures with 4.0 wt% NAs than that of without NAs which caused high resistance in deformation of asphalt concrete. The EIS results indicated that a slight amount of the NAs in asphalt concrete improved significantly corrosion resistance and enhanced durability of asphalt pavement. These findings indicate that the NAs were more efficient to enhance the mechanical characteristic, decrease the porosity of asphalt mixtures and improve uniformity and compaction of asphalt concrete.

Keywords: Nano-alumina; Asphalt Concrete Mixture; Dynamic modulus; Electrochemical impedance spectroscopy

1. INTRODUCTION

Scientists are working to improve the quality of asphalt pavements and have applied various methods to modify asphalt binder [1, 2]. Now, the addition of nanomaterials is a usual technique applied for modification of binder, but uses of various types of nanomaterials have also been assessed [3, 4]. Nano-reinforced materials have the potential for redefinition of the using traditional-materials, both in terms of potential applications and performance [5, 6].

Recently, nanomaterials in asphalt mixture such as carbon nanoparticles, carbon nanofibers, nano-SiO2, nanoclay, and sub-nanosized hydrated lime have been developed quickly as they have unique and extensive properties such as the high surface work, structural features, quantum effects, large fraction of surface atoms and spatial confinement [7-9]. For example, carbon nanofiber-modified asphalt mixes would enhance resistance to permanent deformation, fatigue and stiffness characteristics of the asphalt mixture [10-12]. Due to high tensile strength for carbon nanofibers, hot and cold temperature behavior of asphalt mixes was also expected to develop. Also, nanofiber-modified asphalt can indicate a higher quality asphalt mix for pavements. Some scholars have revealed that using nanocalcium carbonate to improve asphalt can improve low-temperature toughness properties and increase rutting resistance [13, 14]. Using nanoclays, modify some properties of asphalt binder, such as rutting. However, it cannot have the appropriate effect of the fatigue characteristic [15, 16]. Nanomaterials have an extraordinary potential for enhancing the performance of asphalt mixtures and binders. It is expected that these can modify or enhance the asphalt pavement properties [17].

Most of the above studies have been restricted to asphalt binders. However, its use in asphalt mixtures have not yet been completely investigated. In this study, nano-alumina is used to modify asphalt mixtures. This study focused on the effect of nano-alumina content to modify asphalt mixes and its mechanical and electrochemical evaluation.

2. MATERIALS AND METHOD

Aluminium oxide (Alumina) nano-powder with 50-200 nm particle size was purchased from sigma Aldrich. Performance-graded asphalt cement (PG 46-34) was used in this work. The concrete aggregates was involved of 43% granite crushed fines, 41% granites coarse aggregate, and 16% silica sand. The nano-alumina (NAs) was added in asphalt composition with various weight of 0, 1, 2 and 4 wt%. The aggregates were dried through a desiccator at 100 °C temperature. Then, the aggregates were blended with bitumen. During mixture process, the viscosity was stayed at 160 ± 10 centistoke. A compacting machine was applied to make compact asphalt concrete (compacted 60 times). Asphalt mortar was located in an oven in a high curing 120 °C temperature.

A carbon steel with 6 mm diameter was used as working electrode in electrochemical impedance spectroscopy (EIS) analysis. All working electrodes were polished by SiC sheets. Then, the carbon steels were washed through water under ultra-sonication. Asphalt binders were heated up to 170 °C for 30 minutes. Then, the NAs were successively added and stirred to attain good uniformity when heating. Some drops of asphalt binder including NAs were poured on the surface of carbon steel. Then, the electrode was moved to an oven at 120 °C for 20 minutes. The asphalt coating-steel was allowed to cool down in lab environment. Then, the asphalt coating-steels were frozen to prevent any softening of the asphalt. $MgCl_2$ anti-icing chemicals was utilized in this work as an electrolyte solution. The deicer was diluted by tap-water at ratio of 1:4.

A traditional three-electrode cell system was used for measuring EIS with an asphalt-coated steel working electrode, a platinum mesh as counter electrode and a saturated calomel electrode (SCE) as the reference electrode. EIS analysis were done at a frequency range of 0.01Hz to 0.1 MHz at the amplitude of 10 mV. The particle size distribution of the powder was measured by photon correlation spectroscopy using a Malvern Zetasizer Nano ZS laser particle size analyzer. The instrument was equipped with a He-Ne laser source (=633 nm) and at scattering angle of 1730. The dispersion concentration was around 0.1 g/L. ZSimpWin was used to understand the experimental data. Modified asphalt concretes were exposed to indirect tensile loading at different loading frequencies. The experiment was performed by a closed-loop servo-hydraulic machine, produced by material testing procedure. The dynamic modulus test protocol proposed by Kim et al. [17] was used with small modification. The scanning electron microscope (SEM) was used to consider the surface morphologies of the nano-alumina.

3. RESULTS AND DISCUSSION

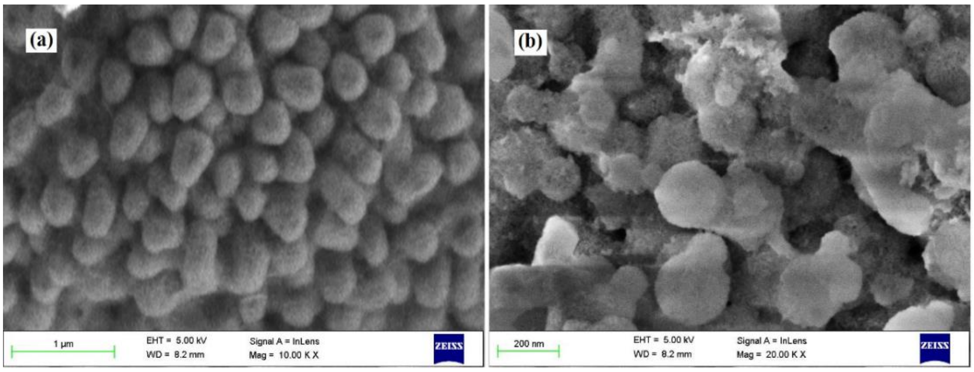

Figure 1. The FESEM images of the nano-alumina particles

Figure 1 shows the FESEM image of the nano-alumina which indicates the formation of particle-like with globular structure which have net uniform distributions and high agglomerations. The alumina nanoparticles are revealed to agglomerate together quite considerably. This value can be probably lower than the actual due to the agglomeration of particle. The size distribution of nano-alumina used in this work were measured by a zetasizer. As shown in Figure 1, the maximum nano-alumina size intensities range from 10 nm to 600 nm. This exhibited that the nano-alumina distribution was broader and involved small and large particles.

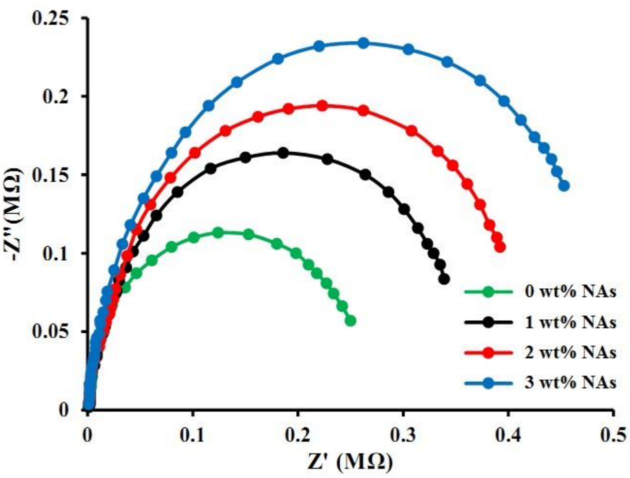

Figure 2. Nyquist diagrams achieved for the various nano-alumina asphalt mixture coated on carbon steel in deicer solution

Fig. 2 indicates the Nyquist diagrams for the various nano-alumina asphalt mixture coated on carbon steel in deicer solution. Figure 3 indicates an equivalent circuit model was used to fit EIS diagrams in Fig. 2. Rs presents the electrolyte resistance. R_f and C_f are the resistance and capacitance of asphalt mix coated on carbon steel, respectively. R_{ct} and C_{dl} are the charge-transfer resistance and double-layer capacitance of the steel-electrolyte interface [18, 19]. Rs had insignificant effect on the system impedance. R_{ct} and C_{dl} consider the corrosion resistance of the steel/electrolyte interface that were not correlated with the asphalt mixture coating. Consequently, in this work, the parameters of R_{ct}, C_{dl} and Rs were not considered for further analysis.

R_f can describe the electrochemical properties of improved asphalt concrete and the resistance of deicer solution with the air voids, interconnected pores and cracks. Furthermore, the thickness of the asphalt coating as a main factor to evaluate the R_f value should be studied [20]. To avoid this problem, the thickness of asphalt mixture on all carbon steel samples were controlled through the PosiTest DFT. The asphalt mixture thickness for all samples was approximately 80 mm.

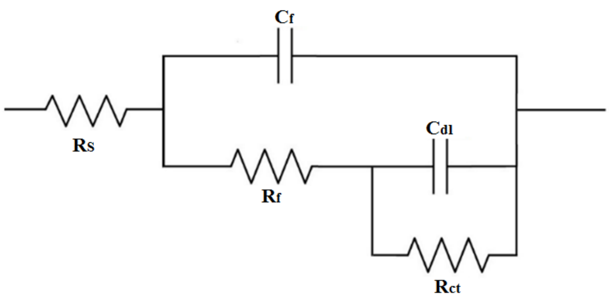

Figure 3. The equivalent circuit model

The shape of Nyquist plot for all specimens shows a popular response of asphalt mix immersed in deicer solution. The calculated R_f, R_{ct}, C_{dl} and C_f values are shown in table 1.

Table 1. R_f, R_{ct}, C_{dl} and C_f values of the samples

Nano-alumina content	R_s ($\Omega.cm^2$)	R_f ($M\Omega.cm^2$)	C_f ($nFcm^{-2}$)	R_{ct} ($M\Omega.cm^2$)	C_{dl} ($nFcm^{-2}$)
0.0 wt%	23.4	0.14	2.14	0.28	3.43
1.0 wt%	25.6	0.21	1.79	0.37	1.24
2.0 wt%	24.7	0.29	0.64	0.43	0.96
4.0 wt%	25.1	0.36	0.43	0.51	0.72

As shown, the R_f for asphalt mixes with increasing NAs was significantly increased, while the C_f was decreased. The reduction of capacitance values by increasing NAs content indicated that the deicer solution had little penetration in the asphalt mix by the air voids, interconnected pores and cracks. Moreover, the increase of resistance by addition of NAs can be related to the best dispersion property of the NAs in the improved asphalt concrete. The higher resistance suggested formation of a more uniform and compact asphalt layer on the steel surface, likely attributable to the outstanding dispersion property of the NAs in the modified asphalt and its high aspect ratio and large active surface area. This consequently resulted in the reduced number and size of pores and pathways from which the deicer solution can penetrate and deleteriously interact with the asphalt concrete [21]. Therefore, such an improved compactness and uniformity of the asphalt by the NAs was beneficial [22]. The EIS findings indicated that the asphalt mix incorporated by a small amount of NAs can clearly enhance its ability in deicer resistance. Furthermore, these results indicate the important role of NAs in modifying the microstructural properties of asphalt binder even under attack of a high deicer concentration.

Dynamic modulus of modified asphalt mixtures with various content of NAs were assessed under load indirect tensile. Figure 4a reveals a typical diagram for dynamic modulus of modified asphalt mixtures at varied loading frequencies in room temperature. As shown in Fig. 4a, the values of dynamic modulus increases as the loading frequency increases. It shows that the modified mixtures reveal higher average values of dynamic modulus than the mixtures without NAs. Furthermore, the phase angles of modified asphalt mixtures were lower than the blank sample (Figure 4b).

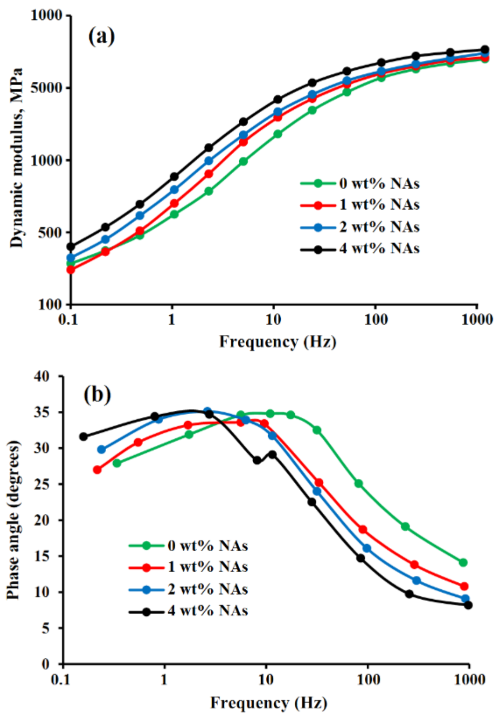

Figure 4. Typical diagram for (a) dynamic modulus and (b) phase angle of modified asphalt mixtures at varied loading frequencies in room temperature

An asphalt mixture with low phase angle and high modulus can lead to high deformation resistance. Moreover, short-term aging of mixtures can enhance the modulus and reduce the values of phase angle. While the mixing procedure was used based on the same rutting indexes (G*/sinδ) for all prepared mixtures, this procedure was a little sensitive to mixing period [23]. A few minutes increase in mixing time can lead to an increase of the G*/sinδ in the binder. Thus, the increase of rutting index in the modified mixture was because of the short-term aging in the binder during process. A pair t-test was performed to check whether the average values were meaningfully individual from each other. Obviously, there was a difference of 0.1 between the modules of bare and modified mixtures. Nevertheless, such an increase in dynamic modulus and reduction in phase angle can not be considered as an improvement in the mixture property. Hence, the prepared mixture was applied as the reference for phase angle and modulus comparisons to discuss any enhancement due to the modification of NAs. Furthermore, figure 4 indicates comparisons of the phase angle and modulus of modified mixtures with various NAs content. As shown in Figure 4a, for mixtures with high NAs concentration, the dynamic modulus of the modified asphalt mixture was increased by the increase in NAs content. Modified asphalt mixture with NAs shows variation in the values of dynamic modulus with respect to the prepared mixture without NAs at high-frequency levels. The paired t-test indicated that there was a variance between the two values of moduli at the significance level of 0.1. Moreover, the d values in NAs mixtures are much different than prepared mixtures without NAs. As a result, the value of dynamic modulus for asphalt concrete mixtures was considerably enhanced by incorporating NAs. These findings were considerably comparable with previous works in modified asphalt concrete with addition of the graphite nanoplatelets [24], nano-silica [25], carbon nanofibers [26] and gilsonite [27]. These findings indicate that the NAs were more efficient to enhance the mechanical characteristic, decrease the porosity of asphalt mixtures and improve uniformity and compaction of asphalt concrete.

4. CONCLUSIONS

In this work, the impact of NAs on mechanical properties of asphalt concrete and electrochemical behavior of modified asphalt mixtures in deicer solution were considered. Dynamic modulus and electrochemical impedance spectroscopy tests were employed to study the effects of NAs on asphalt concrete. For asphalt mixtures with high NAs concentration, the dynamic modulus of the modified asphalt mixture was increased. The lower phase angle and higher dynamic modulus was found in asphalt mixtures with 4.0 wt% NAs than that of without NAs which caused high resistance in deformation of asphalt concrete. The EIS results indicated that a slight amount of the NAs in asphalt concrete improved significantly corrosion resistance and enhanced durability of asphalt pavement. These findings indicate that the NAs were more efficient to enhance the mechanical characteristic, decrease the porosity of asphalt mixtures and improve uniformity and compaction of asphalt concrete.

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