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Predicting rutting performance of carbon nano tube (CNT) asphalt binders using regression models and neural networks

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HIGHLIGHTS

- The effect of CNT, loading frequency and temperature on complex modulus and rutting resistance were investigated.
- The addition of CNT to the neat binder lead to improve rutting resistance and mechanical behavior.
- ANN techniques to be more effective in predicting the rutting properties of the CNT modified binder.
- R^2 values in ANN, multiple and linear regression the data set are 0.997, 0.819, and 0.420, respectively.
- The proposed ANN model of the rutting performance of nano modified binders is quite accurate, fast and practical.

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ABSTRACT

The complex behavior of asphalt binders makes it difficult to accurately predict their complex modulus (G^*) and rutting performance ($G^*/\mathrm{Sin}\ (\delta)$). The aim of this study was to investigate the effects of loading frequency and temperature on rutting susceptibility of CNT asphalt binders. To predict the rutting performance of a CNT-modified binder, two techniques, i.e. regression models and artificial neural networks (ANN), were used. The proposed artificial neural network received CNT content, test temperature and loading frequency as the input and provided the complex modulus as the output. Totally, 480 combinations were evaluated. To test the effects of CNT content and mechanical properties on the rutting performance of the modified binders, the Response Surface Method was used. The results showed that the ANN technique performed better in predicting the rutting performance than regression models. R^2 values were 0.997, 0.819, and 0.420 in ANN, multiple regression, and linear regression, respectively. ANOVA tests showed that temperature, loading frequency and CNT percentage had a significant effect on complex modulus and rutting performance of the binder. In fact, CNTs enhanced the rutting performance and rheological behavior of the asphalt binder.

1. Introduction

An asphalt binder is a complex viscoelastic material that plays a significant role in determining asphalt pavement properties [1]. Because of increased axial loads, heavy traffic, and unfavorable atmospheric effects during the past decade, researchers tried to improve pavement properties by reinforcing them with crumb rubber and polymers [2–5]. However, recent improvements in nanotechnology and its effects on enhancing the properties of asphalt pavements have turned attentions to nanomaterials as alternative additives [6,7].

Among various nanoparticles that have so far been studied as possible asphalt binder modifiers, carbon nanotubes (CNTs) have received an increasing interest [8]. These long hollow cylinders of graphene with a diameter of at least 1 nm, are highly capable of improving the properties of road construction materials [9,10]. They were discovered by Ijima in 1991 [11] and are generally divided into single walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). Distinguished mechanical properties, together with high aspect ratios, have made CNTs valuable additives that can make stronger binder composites than traditional reinforcing materials [12].

In recent years, several studies have been carried out on the performance of CNT-modified asphalt mixtures [13–18]. Amirkhanian et al. [19,20] showed that a sufficiently high percentage of CNTs (>1%) can significantly affect the rutting and fatigue resis-

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tance of asphalt binders and mixtures. In their studies on CNT performance in road paving applications, Santagata et al. [21–24], found that CNTs improve asphalt mixtures' physical and mechanical properties in several aspects, including rutting and cracking resistance, aging, fatigue life and healing properties. Arabani et al. [12] investigated rutting and fatigue properties of CNT modified mixtures using resilient modulus, repeated load axial (RLA) and indirect tensile fatigue (ITF) tests. They found that adding CNTs could improve mechanical properties of asphalt mixtures against fatigue cracking and permanent deformation. Ameri et al. [25] investigated the effect of CNTs on fatigue fracture properties of asphalt mixtures through dissipated energy ratio and plateau value of asphalt mixtures. The results showed that adding CNTs could improve fracture resistance and fatigue life of asphalt mixtures. Goli et al. [26] concluded that CNTs helped to decrease temperature susceptibility and enhance physical and rheological properties of asphalt binders. Moreover, they found that the addition of CNTs proved effective in enhancing the storage stability of SBS modified asphalt binders.

Rutting is one of the major distresses in asphalt pavements. Despite many studies on the performance of modified binders, the mechanics of rutting are not yet fully understood [27]. Rutting caused by permanent deformation is mostly found in high-temperature areas. It is an undesirable phenomenon as it reduces pavement quality and increases maintenance costs [28,29]. Several models have been developed for predicting the rutting performance of asphalt binders [30,31] and mixtures [32,33] in recent years, with an increasing interest for ANNs – the computational models that simulate human brain [33]. They are powerful tools for analyzing complicated data and solving complex nonlinear problems [34]. The ANN approach is considered a black-box approach, since its internal structure does not give any insights on the causal relationships between inputs and outputs [35].

Regarding the above, ANNs have received much attention in predicting the properties of asphalt binders and mixtures [36–43] and structural performance of asphalt pavements [44–46]. Cooper et al. [47] investigated the use of an ANN model in predicting fatigue cracking and J-integral of Semicircular Bend (SCB) specimens containing reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS). The authors concluded that the ANN technique had an acceptable level of accuracy to predict the critical strain energy release rate of aged asphalt mixtures. Zavrtanik et al. [48] evaluated the application of ANN and regression for modeling air void content in aggregates. A total number of 17,296 asphalt mixtures were evaluated by different parameters such as binder content, sieve analysis, maximum density of aggregates and air void content in aggregate mixtures. The results showed that the ANN model was more effective in predicting the air void content in various aggregate mixtures studied compared with the regression models. Venudharan et al. [30] evaluated the use of an ANN model in predicting the rutting performance of asphalt rubber. The results showed that the ANN technique is an appropriate approach for predicting the rutting performance of rubberized binders. Golzar et al. [49] introduced a behavior prediction model for polymer binders at low temperatures based on their previous investigations on polymer modified binders. The findings indicated that ANNs were able to predict the behavior of modified binders at low temperatures.

Until now, many studies have investigated the modification of materials with CNTs [50,51], however, only a few have worked on predicting the rutting performance of asphalt mixtures modified with nano-materials. In addition, the literature shows that up until now, no relationship has been found between the principal parameters affecting binder rutting properties. The only method that can show such relationships is factorial Design of Experiments (DOE), which uses techniques such as Response Surface Methodology (RSM) [52]. RSM is a set of statistical and mathematical techniques for optimization and improvement processes and is mostly used when the goal is to optimize an output variable influenced by many independent variables [53]. It can be used to establish an adequate functional relationship between the responses of a group of related control variables.

The aim of this study was to use RSM to evaluate the combined influence of nanomaterial content (in this study CNTs), test temperature and loading frequency on the rutting resistance of binders. In addition, an ANN algorithm was used to predict the rutting performance of modified asphalt binders based on CNT dosages and mechanical test parameters.

2. Research objectives

The overall goals of this study are as follows:

- To determine the effect of CNTs, loading frequency and temperature on complex modulus and permanent defamation of modified asphalt binders;
- To examine the effect of CNTs and mechanical test parameters on rutting susceptibility of modified binders and interactions between input variables using RSM;
- To investigate the possibility of using a multilayer feed-forward ANN, multiple regression and linear regression to predict the rutting performance of the modified asphalt binder.

3. Materials and methods

3.1. Materials and sample preparation

The samples were prepared by dispersing 0.3, 0.6, 0.9, 1.2 and 1.5 wt% CNTs in the base binder (PG58-16). Tables 1 and 2 show the properties of the base binder and CNTs used. In order to prevent damage to nanoparticles as a result of inappropriate dispersion, and to obtain an end product with desirable properties [54,55], the ultrasonic mixing procedure was used due to the large surface area of nano materials [21,56]. Blending was performed using a 65 watt ultrasonic mixer at 120 °C for 15 min [56].

3.2. Test method

Since an asphalt binder is a viscoelastic material, its rheological behavior depends on both temperature and loading frequency. Accordingly, it may vary from purely viscous to purely elastic. Complex modulus (G^*) a property of viscoelastic materials is the ratio of the absolute value of the peak-to-peak shear stress (τ) to the absolute value of the peak-to-peak shear strain (γ) [57]. It is an important indicator in the Superpave Performance Grading (PG) System. In this study, oscillatory tests were carried out using a dynamic shear rheometer (DSR). Frequency sweep tests were performed in which two log decades of frequency, from 0.1 to 100 Hz, were covered at various temperatures between 30 and 60 °C.

Table 1
Properties of the base binder.

Aging states	Test properties	Test result
Unaged binder	Penetration @ 25 °C (0.1 mm)	68
	Softening point (°C)	51
	Viscosity @ 135 °C (Pa.s)	0.373
	Ductility (cm)	Over 100
	$G^*/\mathrm{Sin}\ (\delta)$ @ 1 (kPa)	62.70
RTFO aged residual	$G^*/\mathrm{Sin}\ (\delta)$ @ 2.2 (kPa)	63.07
RTFO + PAV aged residual	$G^*.\mathrm{Sin}\ (\delta)$ @ 5000 (kPa)	16.12
	S-value @ 300 (MPa)	11.47
	m-Value @ 0.3	9.95
Performance Grade	PG	58–16