

The Possibility to Reuse Nanocomposite Industrial Wastes for Asphalt Binder Modification Technology

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Abstract

A nanocomposite solid waste polymer has been used for increasing the durability of pavements that the softness of asphalt binder drops seriously at high temperature. The research is concerned with the possibility of utilizing locally available materials as an ingredient in asphalt concrete to enhance pavement performance, increase the mixture engineering property and at the same time decreasing the amount of bitumen required. The experimental work includes characterization of bitumen by using super pave tests (Dynamic Shear Rheometer) for both neat and modified bitumen. In this specific investigation the wet process is used for introducing the Portland cement, ceramic dust and Hydrate lime into bitumen during a modification process. Overall, 3 specimens with, 3 modifiers together with content 0 (neat bitumen), 1.5, 3.0 and 4.5 % by weight of asphalt binder were prepared. By considering the results generated from Dynamic Shear Rheometer (DSR); the isochronal plots indicates that a neat asphalt binder modified with composite of Portland cement, hydrate lime and ceramic dust resulting in the decreasing phase angle value and at the same time increasing the stiffness modulus of bitumen. This indicates that, on the 1 side, better stiffness and elastic behavior that the asphalt binder can directly suit for higher stability to resist rutting, hence, bitumen performance was upgraded with content of modifiers increased. On the other side, the heat insulation effect of the Portland cement, hydrate lime and ceramic dust will improves the temperature susceptibility of the asphalt binder which corresponds to permanent deformation resistance.

Keywords: Asphalt, Cracks, Durability, Mortar, Polymers, Rutting, Stiffness

Introduction

Bitumen is temperature susceptible road construction material; viscous fluid at high temperature and elastic solid at low temperatures. This affects the properties and performance of a mixture[1-3]. The durability of road paved is related to a performance of bitumen and gradually deteriorates because of the combined effect of variation in daytime climatic condition and excessive overloading of slow moving heavy vehicles [4]. From this view, the bitumen needs to be modified by improving its viscoelastic properties to control temperature susceptibility of asphalt binder thus, to minimize over stiffness at low temperature and over flexible at high temperature [5]. Recently, it was evidenced that addition industrial waste composite materials have more attractive attentions in the area of asphalt modified, thus, to produce more efficient asphalt mastic coated aggregate [6] and prevent pavement temperature based distresses such as rutting, fatigue cracking and thermal cracking [7]. As some theoretical trends highlighted based on Saturates, Aromatics, Resins and Asphaltenes (SARA) bitumen fractions; the additive polymers absorbs maltenes oils and high asphaltenes content results in changing the characteristics of bitumen, which enhances the stiffness and elastic behavior of the bitumen at high temperature achieves good compatibility between them for resistance to rutting [5,8,9].

Despite of its usage, environmental pollution is one of the causes of industrial waste materials [10]. The overall cost of hot Mix Asphalt is ever-increasing because of bitumen is a by-product of a depleting petroleum resource [11], not locally available which is imported material especially in developing countries. Considering these difficulties several researchers utilized environmental friendly industrial

waste materials as an innovation options in the technology of asphalt modification. The recycled use of industrial wastes is not solely addressing the engineering properties of asphalt binder, but also environmental solution for pollution. However, despite these numerous studies on the industrial waste materials [12-17] none of this study has addressed to develop new high quality bitumen by improve viscoelastic properties of bitumen performance on high temperature. So far, the effect of Portland cement, hydrate lime and ceramic dust composite on rheological properties of asphalt binder and temperature susceptibility of bitumen has been investigated.

Materials and methods

Materials and sample preparations

The materials prepared for different experimental works are 4 in type. These are unmodified (PEN) 80/100 penetration grade bitumen which is the control material, Portland cement, hydrate lime and ceramic dust were selected based on its purpose. The control material; unmodified bitumen selected in this study for modification because of less stiff or softer material which is commonly used at low temperature locations. In the view of the purpose of the study; such kind of binder needed to evaluate its stiffness and permanent deformation resistance to use at hot temperature locations. For the base material described above, conventional tests such as penetration test at 25 °C ductility test at 25 °C and softening point tests were conducted to check the physical properties of unmodified bitumen before modifications [18-20]. The physical properties of unmodified binder which satisfy with specifications were listed in **Table 1**. Three modifiers were selected from solid waste disposal manually, cleaned, dried and crushed into small pieces into necessary sizes. Then 3 modifiers were sieved with important sizes of less than 75 μm were used in this study for bitumen modifications.

Methods

Once the bitumen quality was evaluated and 3 modifiers were prepared. Then, during modification process, bitumen (PEN) 80/100 approximately 600 g was heated at mixing temperature of $135 \pm 5^\circ\text{C}$. Upon reaching the average temperature, waste modifiers powder was slowly added into bitumen at operated mixer of 600 rpm for 30 min with the content of 1.5, 3 and 4.5 % by weight of asphalt binder separately. Overall, 3 specimens were prepared. After entire bitumen modification was prepared, as per of AASHTO T240 (ASTM D2872) aged modified bitumen was prepared in a laboratory that may represent real field behavior of asphalt binder and afterwards, neat and modified asphalt were evaluated using Super pave test (Dynamic Shear Rheometer) like Stiffness complex modulus, Phase angle, Performance Grade (PG) for 1.59 Hz to evaluate the rheological properties of binder for resistance to rutting. See **Figure 1**.

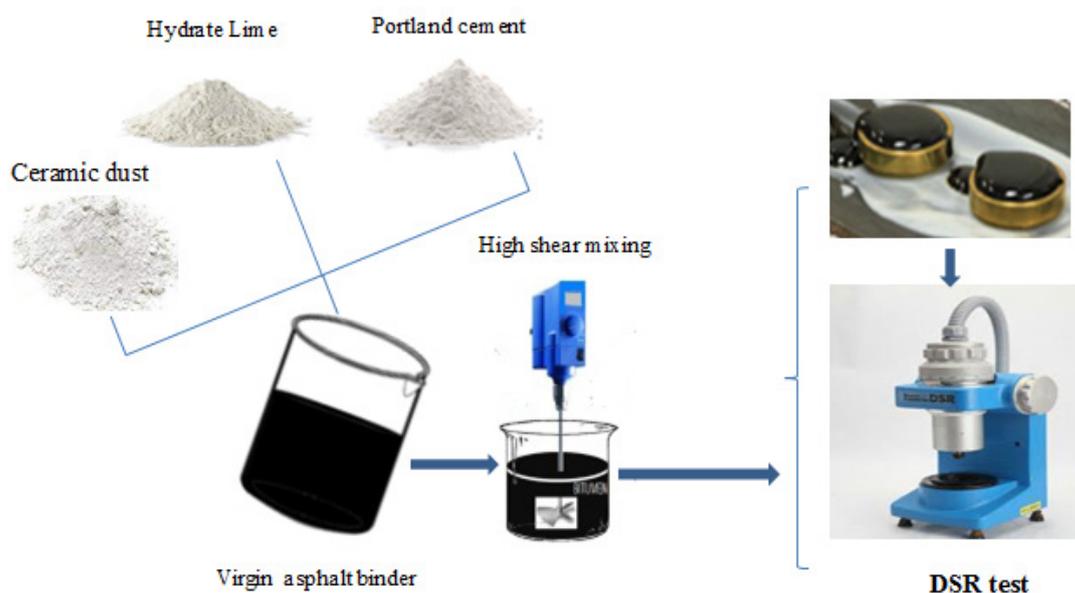


Figure 1 Mixing process of virgin bitumen with modifiers.

Table 1 The physical properties of PEN 80/100 bitumen.

Test Type	Method	Specification	Neat bitumen results
Penetration , 25 °C	ASTM-D5	80 - 100	93
Ductility at 25 °C	ASTM-D113	100 (min)	100+
Softening point °C	ASTM-D36	42 - 51	45

Results and discussion

Stiffness modulus (G*) isochronal plots

The influence of temperature and time of loading on stiffness of bitumen has been evaluated by Dynamic Shear Rheometer (DSR) and viscoelastic data can be presented over a wide range of temperatures (52, 58, 64, 70 and 76 °C) at a constant frequency of 1.59 Hz using an isochronal plot for the purpose of complex modulus (G*) or phase angle (δ) of un-aged and aged binder comparison at various temperatures as shown in **Figures 2** and **3** and **Figures 4** and **5**, respectively. As can be observed in **Figures 2** and **3** stiffness modulus values was more significantly pronounced compared a base material. Meaning, the higher values of G* indicates the strong candidate of stiff binder behavior. Obviously, complex modulus is related to stiffness of bitumen which reveals rutting resistance.

In **Figure 2**, G* values shows almost uniformly increased in the temperature range of 52 to 70° C as modifiers content increased and gradually decreased in between temperature of 70 to 76 ° C with the same G* value except the slope of G* for 4.5 % for modified bitumen. This situation indicates the temperature susceptibility of bitumen at high temperature. At this point, it’s obvious that modifiers elements (Portland cement, hydrate lime and ceramic dust) added to the asphalt binder will thicken the binder; thus, the G* of the 4.5 % asphalt modified with powder was increased compared to a base material. In **Figure 3**, complex modulus values of neat and modified binders are smaller values in before aged than after aged; i.e. aging improves stiffness (complex modulus) because of oxidization. In temperature range from 52 to 70°C , base bitumen plotted a sharp increase in G* slope indicates gradually reduction of G* value as a temperature increases which represents improved stiffness of bitumen and at the same time lower temperature susceptibility of asphalt binder.

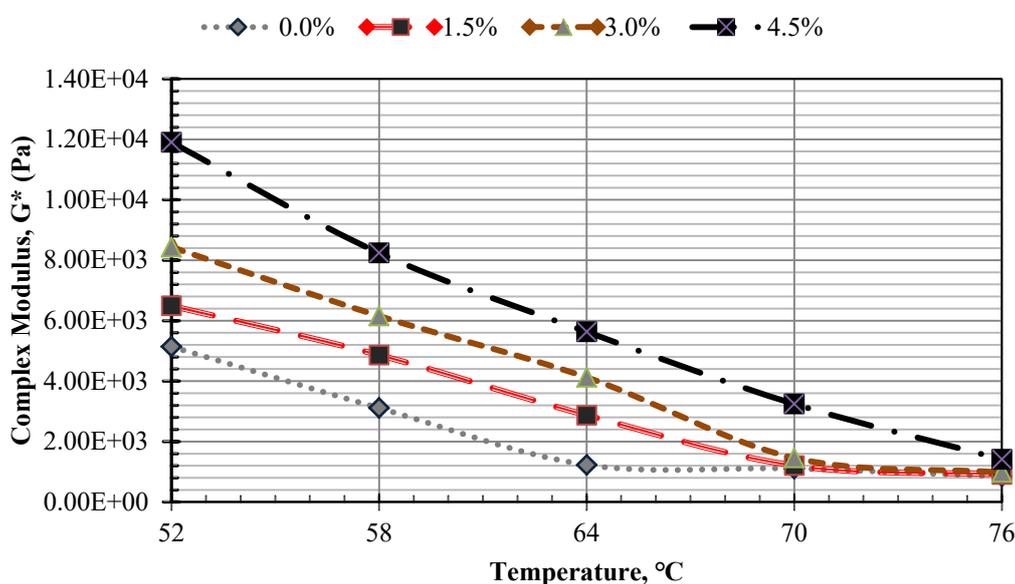


Figure 2 Isochronal plot of complex modulus at 1.6 Hz for un-aged binder conditions.

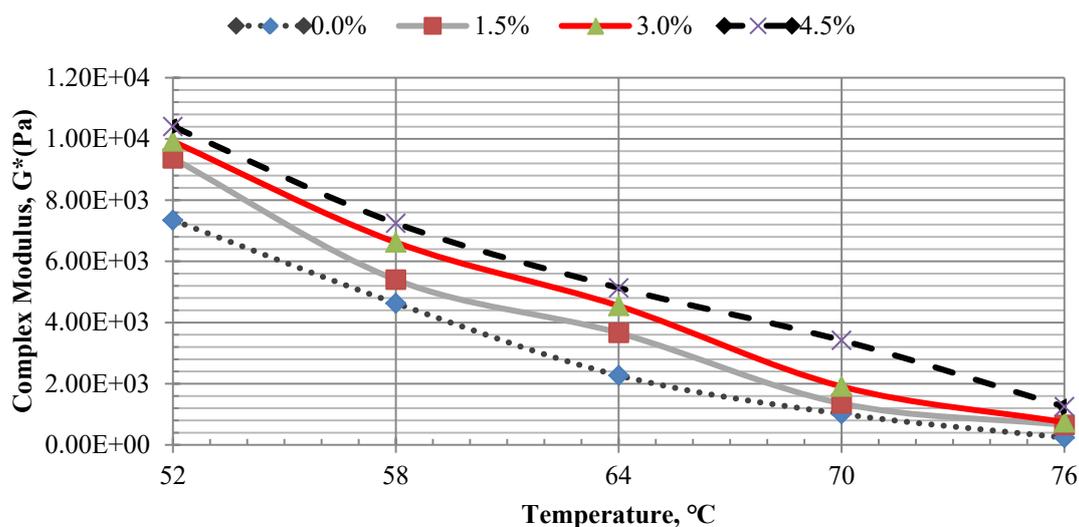


Figure 3 Isochronal plot of complex modulus at 1.6 Hz for aged binder conditions.

Phase angle (δ) isochronal plots

The DSR test is performed by placing a thin film of bitumen or binder in between upper and lower plates or under shear stress whilst measuring resultant shear strain. G^* is a determine stress-strain ratio and Delta (δ) is an indicate amounts of recoverable and non-recoverable deformation. The result δ are highly influenced by temperature and loading time (frequency) i.e. Asphalt tend to be elastic behavior ($\delta = 0^\circ$) at cold temperatures, all deformation are temporary under short loading time whilst asphalt exhibit viscous liquid ($\delta = 90^\circ$) at hot temperature, all deformation are permanent under long loading time particularly, for unmodified bitumen; phase angle increase as temperature increase. The binder viscoelastic materials can be characterized between (0° and 90°) at a normal service temperature presented in the form of phase angle, δ curves for un-aged and aged bitumen. The phase angle, δ , indicates the lag in the stress response compared with the applied strain. Thus, the phase angle is important in describing the viscoelastic properties of a material such as bitumen. In other word, phase angle, δ , the angle in radians or degrees, between a sinusoidal applied strain and the resultant sinusoidal stress in a controlled-strain testing mode, or between the applied stress and the resultant strain in a controlled-stress testing mode. Basically; considering the nature and speed of site traffic under climatic conditions, particularly, for unmodified bitumen; phase angle increase as temperature increase during winter months, all deformation are permanent (non-recoverable) under slow moving heavy goods vehicles with high axle loads that influence asphalts than fast moving vehicles. The accumulation of such unrecoverable deformation due to number of loads increases risk of rutting. However, introducing appropriate polymer is important to make bitumen stiff and more elastic with reduced phase angle to decrease the risk of permanent deformation caused by viscous flow under applied loading.

As shown in **Figures 4** and **5**, reduced phase angle value was observed with respect to the content of modifiers. However, amongst all modified bitumen; 4.5 % modified bitumen shows the improvement in elastic response and stiffness of bitumen to decrease the risk of permanent deformation caused by viscous flow under applied loads.

Significantly asphalt binder ages (oxidizes) gradually happen when asphalt molecules are exposed to the influence of temperature in the presence of air or oxygen from the environment and gradually losing its viscoelastic behavior, which leads bitumen hardening, and ultimately brittle those contribute to adhesion failure like aggregate loss and cracking [21]. As can be seen in **Figure 5**, there was different in phase angle values compared to a control material. The phase angle value of unmodified bitumen was approach to 81° showing the loosing of its elasticity properties when testing temperature was rising to 76°C . In comparison to un-aged modified bitumen exhibited the lower value of δ indicates that a delays in the elastic material response to the stress at high temperature.

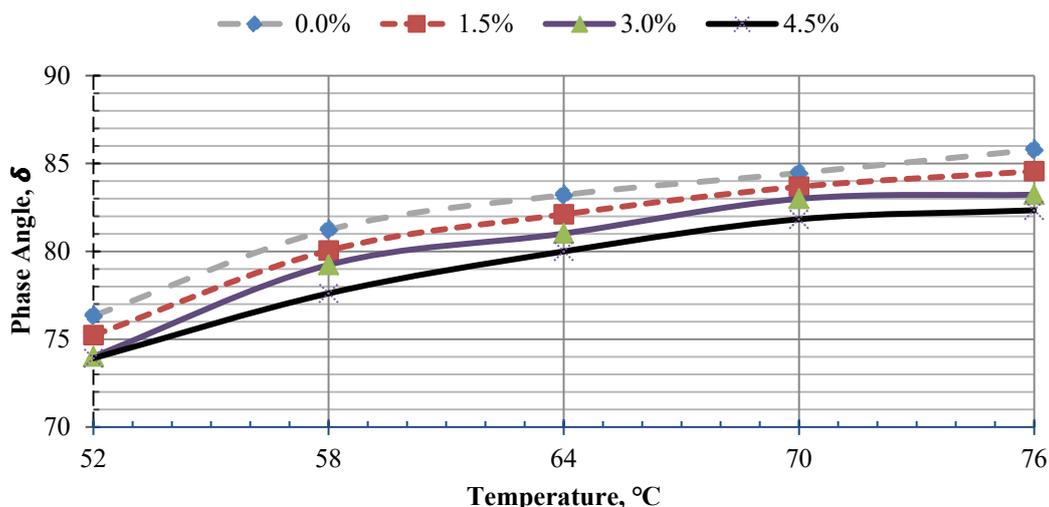


Figure 4 Isochronal plot of phase angle at 1.6 Hz for un-aged binder conditions.

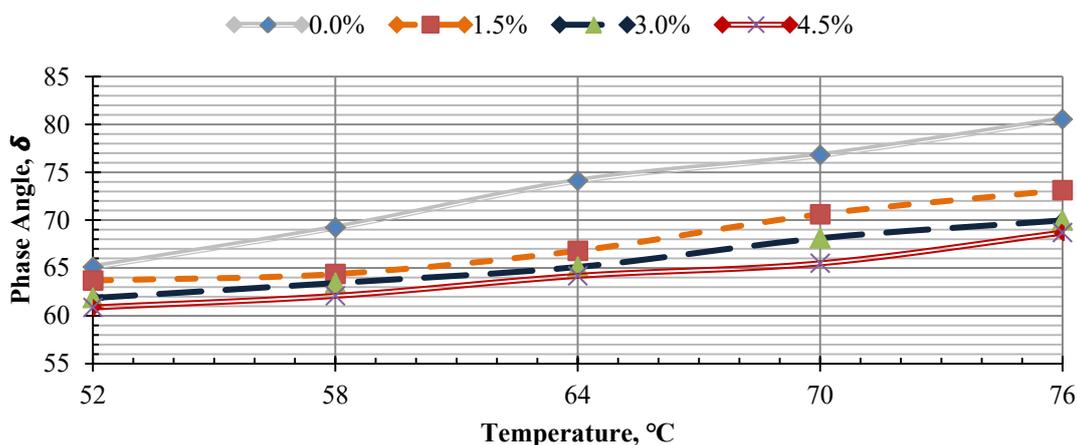


Figure 5 Isochronal plot of phase angle at 1.6 Hz for aged binder conditions.

Performance grade (Rutting resistance at high temperature)

The Strategic Highway Research Program (SHRP) originally developed during the Super Pave specification in the early 1990s. This standard specifies properties of the materials that should be satisfied under certain climatic conditions at which pavement, serves at expected temperature and aging conditions by evaluating binder to resist rutting at high temperature and low thermal cracking at low temperature. A temperature at which binder must attain properties changes determined by PG tests as per of AASHTO T315 specifications, i.e. at high temperature; neat binder stiffness ($G^*/\sin \delta$) is required to be ≥ 1.00 kpa and aged binder stiffness is greater than or equal to ≥ 2.2 kpa. Nevertheless, this requirement should be satisfied if the bitumen was expected to serve in a hot climate [17]. This shows the stiffness of the binder will have sufficient permanent deformation resistance.

The fail temperature was considered to determine a true grade (continuous performance grade) of the binders. These procedures tested the specimens at a starting temperature and increased temperature to the next PG grade if the $G^*/\sin \delta$ value was greater than the value required by AASHTO M320 (1.0 and 2.2 kpa for un-aged and aged binder). As can be shown in **Figure 6**, the maximum temperature for true grade classification of un-aged binder; 59.7 - xx, 68.5 - xx, 73.8 - xx and 78.2 - xx as well as for aged binder 67.3 - xx, 74.9 - xx, 75.8 - xx and 79.6 - xx at 0 - 4.5 % of modifiers by 1.5 % increments were determined. From this view, the aged binder showed the maximum failure temperatures compared with an

un-aged binder as the content of modifier increases. As per of AASHTO M 320, the determined high temperatures of the binder samples were presented in **Figure 7**.

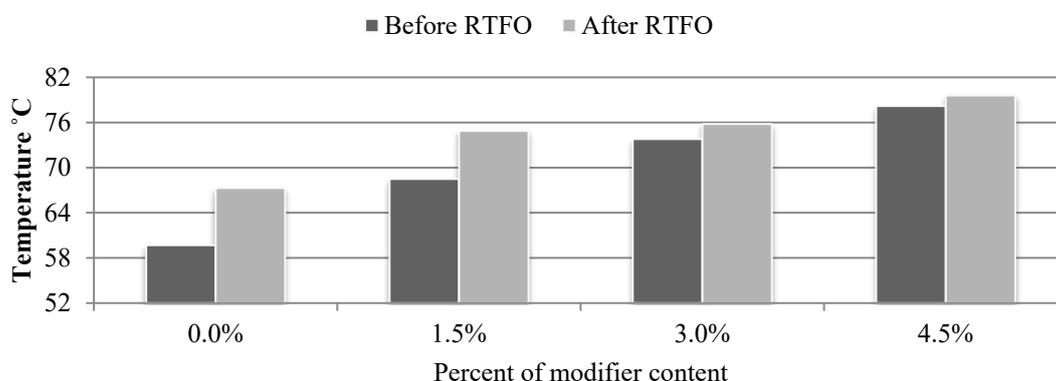


Figure 6 Failure temperature of modified bitumen for un-aged and aged conditions.

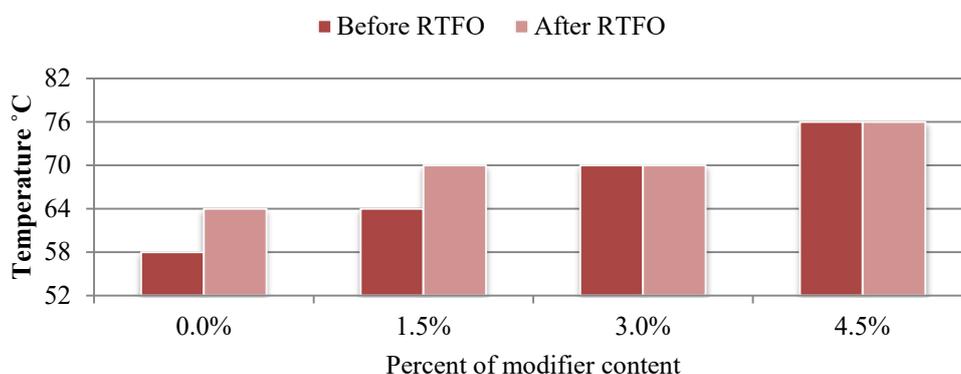


Figure 7 Determined performance grade high temperature of modified bitumen for un-aged and aged conditions.

Conclusions

In this research, the rheological properties of original and modified asphalt binder with Portland cement, ceramic dust and hydrate lime were conducted and analyzed. On account of the research results obtained from Dynamic Shear Rheometer (DSR) that were discussed above, the following items can be drawn; the isochronal plots indicates that the neat asphalt binder modified with composite of Portland cement, hydrate lime and ceramic dust resulting in the decreasing phase angle value and at the same time increasing the stiffness modulus of bitumen. This indicates that, on the one side, better stiffness and elastic behavior that the asphalt binder can directly suit for higher stability to resist rutting, hence, bitumen performance was upgraded with content of modifiers increased. On the other side, the heat insulation effect of the Portland cement, hydrate lime and ceramic dust will improves the temperature susceptibility of the asphalt binder which corresponds to permanent deformation resistance. It is envisioned that these improvements contribute to the rutting performances of asphalt concrete or mixture due to binder stability to sustain at hot climatic conditions. Due to the limited scope of the thesis work, the study recommends for Portland cement, hydrate lime and ceramic dust as a modifiers, blending with bitumen. Besides, Future scope is highlighted for further investigation of fatigue and low thermal cracking instrumented with Pressure Aging Vessel and Cyclic dry and wet loading simulator for long-term performance of Flexible Pavement Analysis or Behavior under different climatic conditions.

Acknowledgements

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References

- [1] AK Das and M Panda. Investigation on rheological performance of sulphur modified bitumen (SMB) binders. *Construct. Build. Mater.* 2017; **149**, 724-32.
- [2] Q Liu, Qiu, Y Qiu, A Rahman and H Ding. Application of steel slag powder to enhance the low temperature fracture properties of asphalt mastic and its corresponding mechanism. *J. Cleaner Prod.* 2018; **184**, 21-31.
- [3] JS Lee, JH Kim, OS Kwon and BD Lee. Asphalt binder performance grading of North Korea for Superpave asphalt mix-design. *Int. J. Pavment Res. Tech.* 2018; **11**, 647-54.
- [4] ZA Alkaissi. Effect of high temperature and traffic loading on rutting performance of flexible pavement. *J. King Saud Univ. Eng. Sci.* 2020; **32**, 1-4.
- [5] S Khatijah, A Bakar, ME Abdullah, R Buhari, MM Kamal, RA Rahman and MK Shamshuddin. Effect of waste nitrile latex on temperature susceptibility of bitumen. *Int. J. Integrated Eng.* 2019; **11**, 37-44.
- [6] F Cardone, F Frigio, G Ferrotti and F Canestrari. Influence of mineral fillers on the rheological response of polymer-modified bitumens and mastics. *Int. J. Traffic Transport. Eng.* 2015; **2**, 373-81.
- [7] GH Shafabakhsh and OJ Ani. Experimental investigation of effect of Nano TiO₂/SiO₂ modified bitumen on the rutting and fatigue performance of asphalt mixtures containing steel slag aggregates. *Construct. Build. Mater.* 2015; **98**, 692-702.
- [8] NS Mashaan, AH Ali, MR Karim and M Abdelaziz. A review on using crumb rubber in reinforcement of asphalt pavement. *Sci. World J.* 2014; **2014**, 214612.
- [9] H Wang, X Liu, H Zhang, P Apostolidis, T Scarpas and S Erkensa. Asphalt-rubber interaction and performance evaluation of rubberised asphalt binders containing non-foaming warm-mix additives asphalt binders containing non-foaming warm-mix additives. *Road Mater. Pavement Des.* 2020; **21**, 1612-33.
- [10] V Venudharan and KP Biligiri. Conceptualization of permanent deformation characteristics of rubber modified asphalt binders: Energy-based algorithm and rheological modeling. *Construct. Build. Mater.* 2016; **26**, 388-97.
- [11] M Habibi, O Moini, S Mohammad, R Paran and K Formela. Modification of thermal and rheological characteristics of bitumen by waste PET/GTR blends. *Construct. Build. Mater.* 2017; **134**, 157-66.
- [12] X Shi, L Cai, W Xu, J Fan and X Wang. Effects of nano-silica and rock asphalt on rheological properties of modified bitumen. *Construct. Build. Mater.* 2018; **161**, 705-14.
- [13] S Nur, A Jeffry, R Putra, N Abdul, H Yacob, J Mirza and S Hasyiyati. Effects of nanocharcoal coconut-shell ash on the physical and rheological properties of bitumen. *Construct. Build. Mater.* 2018; **158**, 1-10.
- [14] F Merusi, F Giuliani and G Polacco. Linear viscoelastic behaviour of asphalt binders modified with polymer/clay nanocomposites. *Procedia Soc. Behav. Sci.* 2012; **53**, 335-45.
- [15] B Golestani, F Moghadas and S Sadeghpour. Performance evaluation of linear and nonlinear nanocomposite modified asphalts. *Construct. Build. Mater.* 2012; **35**, 197-203.
- [16] S Ricardo, H Assis, D Oliveira, B Queiroz, D Cavalcante, C Kaynan, K Nunes, F Almeida, R Melo, D Christiane and L Lucena. Evaluation of limestone crushed dust aggregates in hot mix asphalt. *Construct. Build. Mater.* 2017; **148**, 659-65.
- [17] M Sutanto, N Bala, F Al Chodri and S Sunarjono. Effect of hydrated lime and portland cement on asphalt binders using DSR. *MATEC Web Conf.* 2018; **203**, 05006.
- [18] A Drews. *Standard test method for penetration of bituminous materials. Manual on: Hydrocarbon analysis.* 6th ed. 2008, p. 47-63.
- [19] A Drews. *Standard test method for softening point of bitumen (Ring-and-ball apparatus). Manual on: Hydrocarbon analysis.* 6th ed. 2008, p. 50-64.
- [20] R Standards. *Ductility of bituminous materials.* 2007, p. 42-5.
- [21] I Marek and C Malgorzata. Impact of the ageing on viscoelastic properties of bitumen with the liquid surface active agent at operating temperatures. *IOP. Conf. Ser. Mater. Sci. Eng.* 2017; **245**, 032049.