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Effects of polymer modified nanoclay on the performance of asphalt mixture

E. Siddig, P. Cheng*, Y. Li
Northeast Forestry University (*NEFU*)*, Harbin, China*
** E–mail: chengpeifeng@nefu.edu.cn*

Keywords: asphalt binder, asphalt mixtures, rheological properties, rutting parameters, nanoclay

Abstract. Recently, polymer-modified nanomaterial has received extensive attention as a key solution for improving the performance of asphalt binders. This study investigates the effect of polymer modified nanoclay (PMN) that made of ethylene vinyl acetate copolymer and nanoclay mixtures on the high-temperature performance of the asphalt binder and mixture. Moreover, the modified binder samples are prepared with PMN by using melt processing technique at concentrations of 1 %, 3 %, 5 % and 7 % with the weight of asphalt. Furthermore, the effect of the modifier on the binder properties is assessed using conventional tests like penetration and softening point, viscosity measurements, multiple stress creep recovery, and dynamic shear rheometry. Additionally, wheel tracking and moisture sensitivity tests are applied to investigate the high-temperature performance of the hot mix asphalt (HMA) mixture. The experimental results show that the rheological and physical properties are improved when PMN is used. The addition of PMN to HMA mixtures significantly improves the resistant to the rutting and moisture induced damages. Therefore, this study provides substantial technical support for improving the high-temperature performance of asphalt pavement in hot regions to reduce rutting concerns.

1. Introduction

The rapid economic growth increased number of vehicles per citizen and heavier traffic loads and speed. Thus, the asphalt pavement roads are required to increase its ability to carry the traffic loads under different conditions without causing distresses [1]. Rutting and moisture damage are among the most common problems of hot mix asphalt (HMA) asphalt pavement, and these defects increase further distress in the pavement. Therefore, the best performance is desired to encourage good adhesion and cohesion of the asphalt mixture to obey with the requirements of strong pavements that may enhance moisture susceptibility and rutting resistance of HMA mixture at high-temperature [2]. From this perspective, a significant amount of work has been done using various types of modifiers and additives. These includes carbon black, crumb rubber, sulfur, fly ash, bio oil, amine, and polymers, which improve the physical and rheological properties of asphalt binders [3–5]. Among them, the polymers which produce polymer modified asphalt (PMA) obtained the highest achievement.

Several polymers have been tested as modifiers, involving thermoplastic elastomers, plastomers, and reactive polymers. However, only thermoplastic block copolymers and ethylene-vinyl acetate (EVA) received an extensive application in practice [6, 7]. Some of these copolymers are acceptable in terms of performance and cost [8, 9]. Additionally, the EVA copolymer is known as one of the top modifiers that significantly enhances the rheological behavior, physical and mechanical properties of base asphalt [10]. That said, EVA are different from conventional asphalt in molecular weight, density, and chemical nature making the interphase of EVA modified asphalt inadequate, and it is easy to separate [11]. Furthermore, the interphase of EVA modified asphalt is reduced due to short-term aging of EVA binders through production, storage, and transportation, besides long-term aging during the service life of pavement [12]. Therefore, an EVA binder

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becomes hard and brittle resulting in pavement deterioration [13]. The EVA modified asphalt needs to be modified by another material to improve its performance.

Recently, nanomaterials have received considerable attention in the field of modified asphalt to produce more efficient materials. These materials can enhance the performance and strength of asphalt. Many types of nanomaterials have been applied to modify asphalt: e.g. nanotitanium, nanosilicon dioxide, nanoclay, and carbon nanofibers [14]. Recent studies demonstrated that the nanoclay can improve the characteristics of asphalt binders used in asphalt concrete mixtures. Polymeric nanocomposites are one of the common potential materials identified. The physical properties of the asphalt binder are effectively improved when a polymer is adjusted with small amounts of nanoclay, especially when the clay is dispersed at a nanoscopic level [8]. On the other hand, nanoclay (NC) have been utilized as a minor modifier to extra improve the performance of PMA [15–17]. However, limited work has been done to assess the asphalt modification using NC combined with EVA and the effect of NC on the interphase of EVA PMA. Comprehensive research is needed in this direction to understand the complex structure–property association in various nanocomposites. It is important to perform extensive rheological measurements and study the physical and mechanical properties of asphalt mixtures made from the various content of polymer-modified nanoclay (PMN) binder.

Therefore, this study aims to evaluate the effect of PMN on the high-temperature performance of asphalt binders and mixtures. The following binder properties were carried out i.e. penetration, softening point, viscosity measurement, multiple stress creep recovery and dynamic shear rheometry for unaged and rolling thin film oven test (RTFOT) aged binders. In addition, the HMA performance factors i.e. Marshall stability and flow, rutting resistance, and moisture sensitivity were examined.

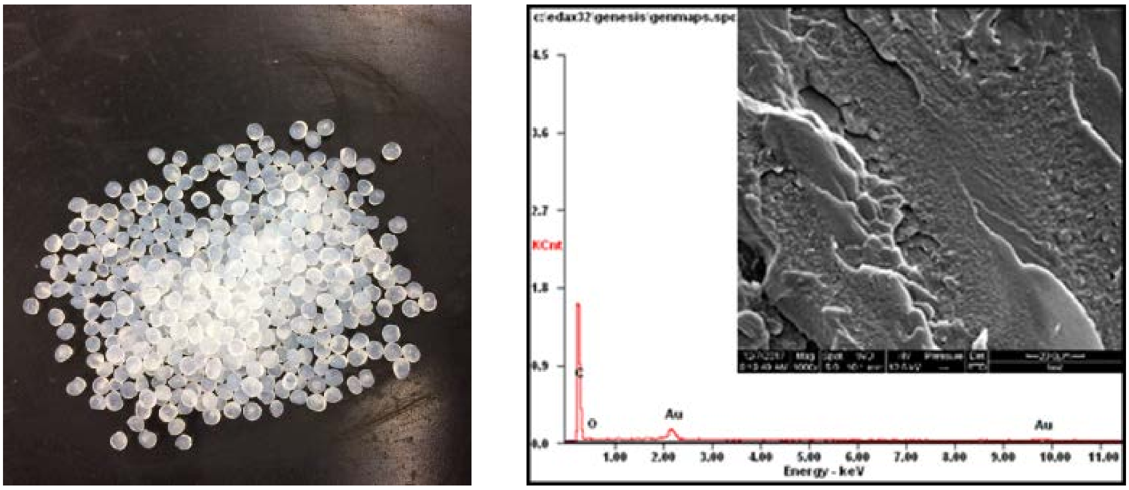
2. Materials and Methods

2.1. Materials

The paving asphalt AH-70#, according to the Chinese classification, was used to prepare a modified asphalt binder in this research. The physical properties of base asphalt are provided in Table 1. The EVA copolymer with a content of 28 % of vinyl acetate by weight was used as the polymer modifier (Figure 1). Properties of the EVA are presented in Table 2. The used NC modifier is delivered from montmorillonite clay mineral (see Figure 2) as provided by Fenhong Clay chemical factory, China. The properties of NC are given in Table 3. The aggregates (coarse and fine) used in this study are crushed basalt minerals with a maximal normal size of 16 mm delivered from Harbin, China. Figure 3 shows the aggregate gradation and further properties are presented in Table 4.

Table 1. Some properties of asphalt binder.

Test	Standard	Result
Penetration depth (100 g, 5 s, 25°C), 0. 1 mm	ASTM D5	75.05
Ductility (25 °C, 5 cm/min), cm	ASTM D113	150+
Softening point (°C)	ASTM D36	48.7
Specific gravity at 25 °C (g/cm^3)	ASTM D70	1.03
Flash Point (°C)	ASTM D92	320
Retained penetration after RTFO (%)	ASTM D5	63.5
Softening point (°C) after RTFO	ASTM D36	51.4



(**a**) (**b**)

Figure 1. The EVA copolymer (a) sample; (b) EDAX graph and corresponding SEM image.

Table 1. Physical and mechanical properties of EVA used in this study.

Property	Specification	Value
Molecular structure	–	Linear
Density (g/cm^3)	ASTM D792	0.9335
Physical form	–	pellet
Melt flow rate	ASTM D1238	7
Tensile strength (MPa)	ASTM D412	29
Flexural modulus (MPa)	ASTM D412	3100
Shore hardness (A)	ASTM D2240	70
Elongation at break (%)	ASTM D 412	800

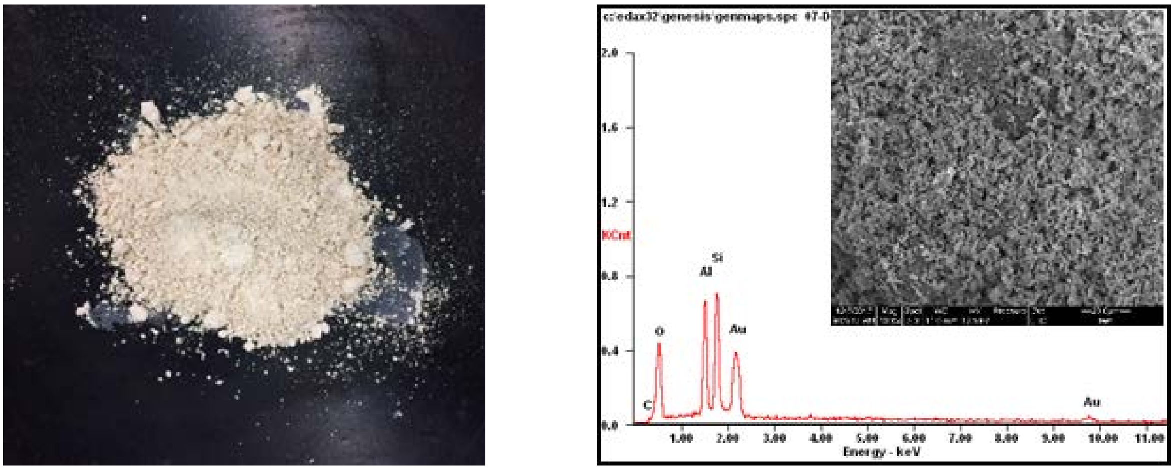


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Figure 2. The Nanoclay (a) sample; (b) EDAX graph and corresponding SEM image.

Table 2. Properties of the NC sample used in this study.

Property	Value
Base	Montmorillonite
Concentration of modifier %	48
PH	7.1
Free space between particles (A°)	60
Specific surface (m^2/g)	80
Density (g/cm^3)	6

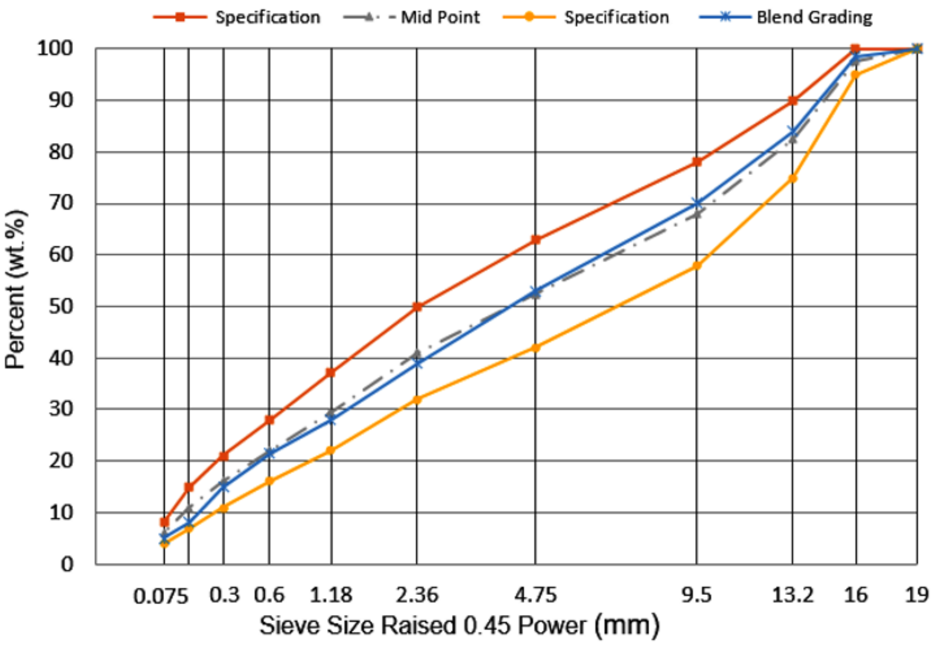

Figure 3. Aggregate gradation chart.

Table 3. Aggregates properties.

Aggregate Property	Value
Crushing value (coarse aggregate) (%)	13.1
Los Angeles abrasion value (%)	15.1
Apparent specific gravity	2.78
Water absorption (%)	0.39
Apparent specific gravity (fine aggregate)	2.69
Sand equivalent (%)	93.7

2.2. PMN Formulation

The PMN was produced by using a melt processing method because it is efficiently and simplicity. Firstly, a 60:40 mass ratio of EVA: NC are mixed under high shear at a rate of 60 rpm and for 15 minutes at 185 °C using a conventional twin-screw extruder mixer to produce sheets of about 2.0 mm thickness. Subsequently, the product was cooled for nearly three hours, followed by grinding to the required size by a sheet pelletizer. Finally, the PMN sample (see Figure 5) was characterized and utilized to prepare the modified asphalt binder samples with a different concentration.

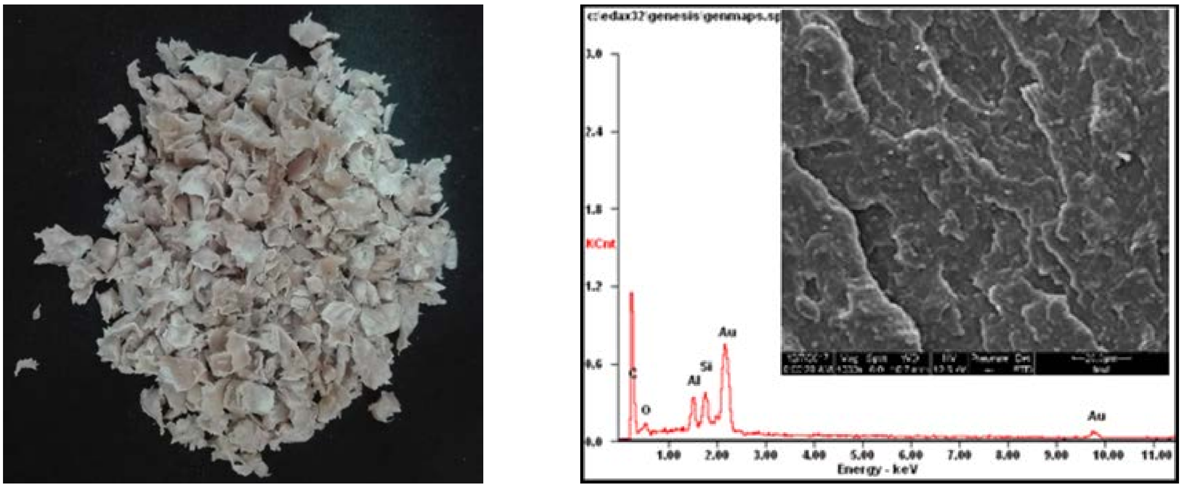

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Figure 4. The PMN (a) sample; (b) EDAX graph and corresponding SEM image.

2.3. Preparation and Characterization of PMNs Binder

Energy Dispersive Analysis X-Ray (EDAX) is an analytical technique to complete the elemental and chemical analysis. The EDAX was used to analyse the elemental compositions of NC, EVA, and PMN during imaging in SEM. Figure 5 demonstrates the Field Emission Scanning Electron Microscope (FE-SEM) machine and Pelletizer machine used in this work. The EDAX results and its corresponding SEM images are displayed in Figures 1, 2 and 4. An electronic beam SEM and EDAX systems were used to inspect the chemical composition of PMN, NC, and EVA samples. The characterization was done at several locations of NC, EVA, and PMN samples. The SEM micrographs of EVA, NC, and produced PMN are shown in Figures 1, 2 and 4, respectively. Figure 4 shows the PMN of the melted EVA matrix mixed with NC and indicates the homogeneity of the mixture, good distribution, and dispersion of nanoclay layers in the polymer matrix. The segregations, inclusions and agglomeration of nanoclay particles did not occur. This confirmed that the processing and mixing techniques adopted to prepare PMN can create a homogeneous distribution.

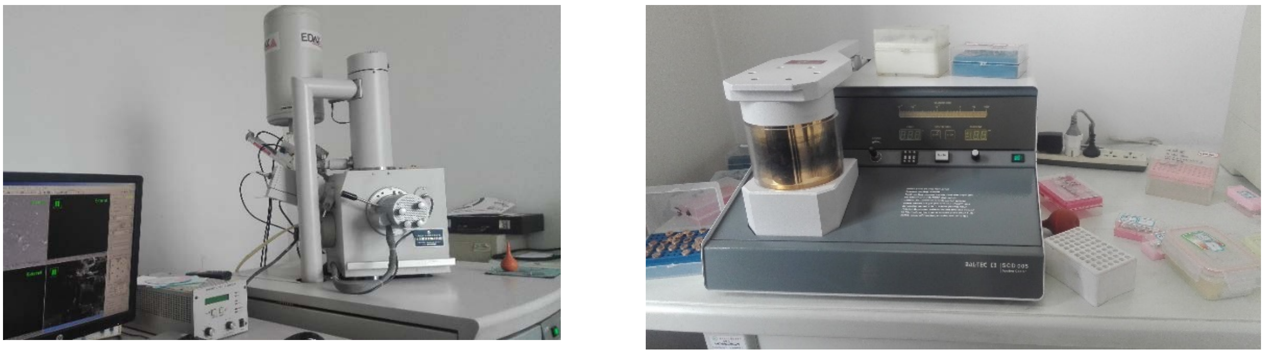

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Figure 5. (a) Field Emission Scanning Electron Microscope; (b) Pelletizer machine.

The PMN binders were prepared by utilizing a mechanical mixer and a high-shear mixer. More specifically, 500 g of base asphalt was heated to reach 0.175 Pa.s of viscosity level. Later, different mass concentrations of PMN (1, 3, 5, and 7 %) by weight of base asphalt were gradually added to the base asphalt. The material was mixed at 500 rpm for 10 minutes in a mechanical mixer. Consequently, the samples were shifted to the high-speed mixer and mixed at a speed of 4500 rpm while maintaining a temperature of 150±5 for 45 minutes. Finally, the mixtures were degassed for 5 minutes to remove air molecules trapped during mixing.

2.4. HMA Mixtures Preparations

Marshall's mix design method (ASTM D-1559) is used in China to optimize HMA mixtures. In this study, five asphalt percentages (3.5 %, 4.0 %, 4.5 %, 5.0 % and 5.5 %) were used for the HMA mixture's design. It has been detected that at 4.0 % air voids, the required asphalt content is 4.8 %, as the optimum asphalt content (OAC) used for preparing all HMA mixtures.

2.5. Testing Procedure

2.5.1. Binder Properties Testing

The rheological properties of PMN asphalt binders were assessed using conventional tests (softening point and penetration), as well as rotational viscosity, Multiple Stress Creep Recovery (MSCR) and Dynamic Shear oscillatory (DSR), according to the corresponding specifications ASTM D36, ASTM D5, ASTM D4402, ASTM D7405, and ASTM D4402.

The DSR test is applied to measure viscoelastic behaviour (rheological behaviour) of asphalt at intermediate to high temperatures. The complex shear modulus (G^*) and phase angle (δ) are measured to determine the rutting parameter ($G^*/\sin(\delta)$) of a binder. In this study the DSR tests were conducted for both unaged and RTFO-aged binders using a 25-mm-diameter plate and a 1 mm gap with a fixed oscillation frequency of 10 rad/sec (1.59 Hz to simulate the track run with a speed of nearly 55 mph) and a shear stress of 12.5 % applied to unaged and 10 % RTFO to aged binders, based on ASTM D4402.

The MSCR test was established to evaluate the high-temperature permanent deformation resistance of modified asphalt binder. It was adopted as a high-temperature rutting parameter for the Performance Grading (PG) of asphalt binders under the Superpave system in (FHA 2011) to replace the existing high-temperature binder test ($G^*/\sin\delta$). In this paper, The MSCR test was performed on by the DSR device to obtain non-recoverable creep compliance (Jnr) and percent recovery (R) of RTFO-aged asphalt binder at 52, 58, 64, 70 and 76 °C with 0.1 and 3.2 kPa creep stress according to ASTM D7405. A total of 10 cycles of creep and recovery 1 s of constant shear load and 9 s of recovery using a constant shear load of 0.1 kPa, followed by 10 cycles with a constant shear load of 3.2 kPa [18]. The compliance value at 0.1 and 3.2 kPa was denoted as Jnr0.1 and Jnr3.2.

2.5.2. Mixture Performance Testing

To evaluate the performance of PMN-modified asphalt mixture on the mechanical properties of HMA, the Marshall stability and flow, indirect tensile strength (ITS), and wheel tracking test (rutting test) were performed according to ASTM-D1559, ASTM D4867, and AASHTO T 324.

The Marshall stability and flow test were performed in line with ASTM D1559. Marshall specimens were stored in a water bath at a temperature of 60 °C for 35 minutes before starting the test. After 35 minutes, the specimens were placed in the Marshall apparatus and tested directly. The Marshall stability was applied at maximum load with a constant strain of 51mm per minute up to failure. During the test, a dial gauge was used to measure the vertical deformation of the specimen. The Marshall flow value was expressed as the vertical deformation that happens at the failure point of a specimen.

The wheel tracking test was used to evaluate the permanent deformation (rutting) performance of the HMA mixtures by recording the high-temperature stability of the asphalt mixture. In this test, the rut depth produced by the repeated wheel loading and pressure of 700 N and 0.7 MPa respectively was measured. The rutting test was executed according to the standard test method JTG E20-2011, T 0719 with the sample being kept at 60 ±1 °C for six hours. The dimensions of test samples were 300 mm × 300 mm × 50 mm. Dynamic stability (DS) can be calculated as follow:

$$\mathrm{DS} = \frac{\left(t_2 - t_1\right) N C_1 C_2}{\left(d_2 - d_1\right)}, \tag{1}$$

where DS is the dynamic stability (cycle/mm);

d_1, d_2 are rut depth (mm) at time t_1 (45 minutes) and time t_2 (60 min), respectively (mm);

C_1, C_2 are machine and specimen factors (here both are 1.0);

N is the number of times the wheel passes per minute (here it is 42 cycles/minute).

The moisture susceptibility test was executed by comparing the ITS of 6 Marshall samples compacted to 7 % air void. The samples were divided into two groups, each containing 3 samples of HMA mixture. The first group was immersed in water at 60 ±1 °C for 24 hours (conditional group) and the second group was set at 25±1 °C (unconditional group). Next, the samples were placed in a loading machine with the load at a speed of 50 mm/min to reach the failure point. The ITS and tensile strength ratio (TSR) can be calculated by Equations (2) and (3) respectively.

$$\mathrm{ITS} = \frac{2P_{\max}}{\pi t d}, \tag{2}$$

where ITS is the indirect tensile strength (Pa),

$P_{\max}$ is the maximum applied load (N);

t is the thickness of the specimen (mm);

d is the diameter of the specimen (mm).

$$\mathrm{TSR}(\%) = \frac{\bar{R}_{T2}}{\bar{R}_{T1}} \times 100, \tag{3}$$

where $\bar{R}_{T1}$ is the average ITS of an unconditional set (MPa),

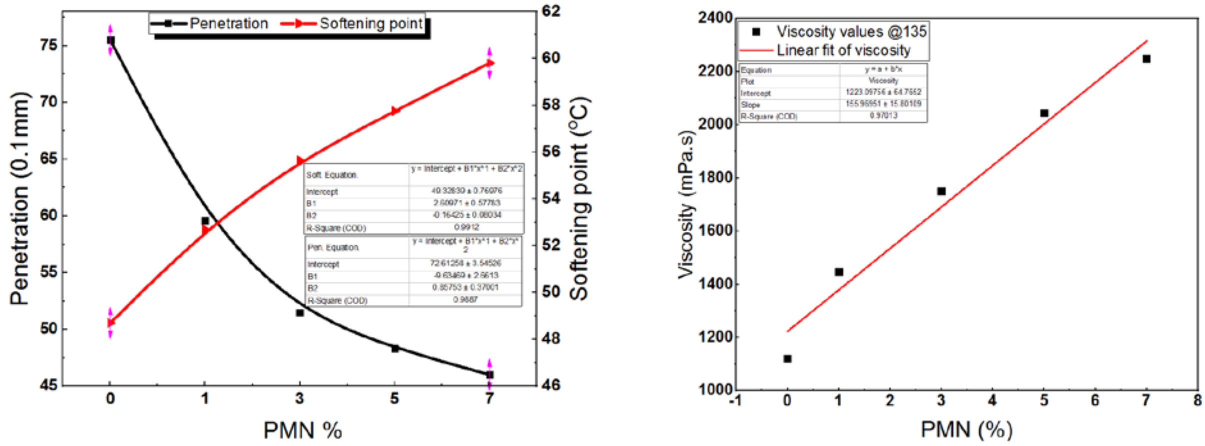
$\bar{R}_{T2}$ is the average ITS of conditional specimens (MPa) and TSR is the average tensile strength ratio (%).

3. Results and Discussion

3.1. Binder Properties Tests

The results obtained from the conventional test of PMN binder are displayed in Figure 6. From Figure 6(a) displays that the penetration depth of the asphalt binder is decreased while the softening point is increased with increasing PMN concentration. Obviously, the penetration values of asphalt were decreased by 21 %, 32 %, 36 % and 39 % for given concentrations i.e. 1 %, 3 %, 5 % and 7 % of PMN, respectively. The softening point increased from 48.5 to 60 with an increasing percentage of about 23 % of base asphalt. It is was greater than the maximum pavement temperature during the summer season. Importantly, this indicated that the PMN had a considerable enhancement on the consistency of the asphalt. Specifically, this enhancement made the PMNs modified asphalt binder more appropriate for pavement construction with a high bond strength and less susceptibility to permanent deformation at high-temperature.

Figure 6(b) illustrates the relationship between the rotational viscosity at a temperature of 135 °C and PMN content. It was observed that the viscosity values of asphalt binder have been increased linearly with PMN contents. The viscosity values of asphalt binder were increased by 29 %, 56 %, 83 %, and 101 % when the addition values of PMN content were 1 %, 3 %, 5 % and 7 % PMN. Clearly, the highest viscosity value is achieved at 7 % PMN modified binder. The increase in the value of viscosity was consistent with the specification limits (the SHRP specifications stated that the viscosity values at 135 °C should be ≤3.0 Pa s to avoid difficult workability induced by high viscosity). The viscosity within the prescribed range will increase the adhesion between aggregates and binder and improve the mixture's workability. Eventually, it will reduce the stripping rate and improve the stability of the asphalt concrete mixture.



(a) (b)

Figure 6. Effect of PMN content on the (a) penetration and softening point; (b) viscosity measurement.

3.1.1. Temperature Sensitivity

The effects of PMN as an additive on the temperature sensitivity were evaluated by penetration index (PI) and penetration viscosity number (PVN). The results of conventional tests (penetration, softening point and viscosity) were used to determine the PI and PVN. There are several models which define the consistency changes on asphalt with temperature. One of the famous models established by Pfeiffer and Van Doormaal [19] is stated as follows:

$$\mathrm{PI} = \frac{1952 - 500\ \log(pen) - 20SP}{50\ \log(pen) - SP - 120}, \tag{4}$$

where Pen is the penetration depth in 0.1 mm @25 °C;

SP is the softening point temperature.

Equation (4) was applied to determine the PI from the measured penetrations depth and softening point temperatures.

The asphalt binder used in the highway pavement has a PI range from –3 to +7 for high-temperature sensitivity binder and highly blown low-temperature sensitivity binder, respectively [19, 20]. Moreover, the PI of base asphalt is –0.522 whereas the value of PMNs binder increases with the increase of the modifier content up to +0.781 for PMN7 as illustrated in Table 5. This indicates that the temperature sensitivity of the asphalt has been decreased with the increasing of PMN content.

The PVN can be determined according to the value of penetration at 25 °C and viscosity at 135 °C using Equation (5) [21]

$$\mathrm{PVN} = 1.5\frac{4.258 - 0.7967 log\left(Pen_{25}\right) - log\left(Vis_{135}\right)}{0.795 - 0.1858 log\left(Pen_{25}\right)}, \tag{5}$$

where Pen_{25} is the penetration depth in 0.1 mm @25°;

Vis_{135} is viscosity value @135 °C.

Table 5 presents the PVN values and reflects that all PMN-binder samples are less susceptible to temperature variations than the base asphalt. Most significantly, the asphalt binder used for pavement construction has a PVN range from –2.0 to +0.5 pertaining to high-temperature sensitivity and low-temperature sensitivity, respectively [7, 22]. In this study, the PVN values varied between 0.097 and 0.145 for 0 and 7 % of PMN binder. These PVN values lie within the referenced range. Thus, base asphalt is considered as the maximum temperature sensitivity binder, and PMN is the minimum temperature sensitivity binder. Therefore, the temperature susceptibility was considerably reduced in the PI and PVN for PMN modified asphalt binders. This indicates that they are more disposed to permanent deformation at high temperatures and become rigid and brittle at low temperatures. The PI and PVN values propose that PMN binder is appropriate to use in road pavement.

Table 4. Penetration index (PI) and penetration viscosity number (PVN).

PMN %	PI	PVN
0	–0.522	0.097
1	–0.124	0.105
3	0.188	0.112
5	0.482	0.125
7	0.781	0.145

3.1.2. Dynamic Shear Oscillatory Test

The complex shear modulus ($G*$) and phase angle (δ) are generally used to characterize viscoelastic properties of asphalt binders. Figure 7(a) and (b) show ($G*$) and (δ) versus temperature, obtained from DSR test of base and PMNs modified asphalt binder before and after RTFO aging respectively. As can be seen from Figure 7 the values of $G*$ are significantly decreased. On the other hand, the values of δ were gradually increased with increasing temperature for all binders (base and modified asphalt). The results given in Figure 7 show that $G*$ values increased, while the δ magnitudes decrease with increasing of PMN %. This increase in $G*$increases indicates that PMN binder is stiffer than unmodified asphalt which may increase the contribution of asphalt in permanent deformation resistance. Furthermore, a decrease in δ after adding PMNs indicates improves in the elastic response of asphalt binder, which can recover to its original shape after being deformed by a load. Comparing the values of G^* and δ before and after RTFOT aging, it can be noticed that the G^* and δ values for the RTFO-aged binders are higher than the unaged binders. Indicates that PMN had stiffening effects on the asphalt binders. In contrast, the reduction in δ value gives an indication of more elasticity. Therefore, the hardness of asphalt was increased after adding PMNs led to improves the high-temperature performance of asphalt. Additionally, PMNs had a positive effect in enhancing the aging resistance of the asphalt binder.

The rutting parameter $G^*/\sin(\delta)$ is used to evaluate the resistance of asphalt binders to permanent deformation at high temperatures. $G^*/\sin(\delta)$ values of base and PMN- modified asphalt binders are presented in Figure 8. It is shown that the $G^*/\sin(\delta)$ increased with increasing PMN %, while significantly decreased with increasing temperature for both modified and unmodified asphalt binder. However, $G^*/\sin(\delta)$ of PMNs modified binder's is always higher than that of base asphalt at the same temperature before and after RTFO aging. Therefore, the PMNs enhances the high-temperature performance of the base asphalt binder by increasing resistance of asphalt binder to rutting.

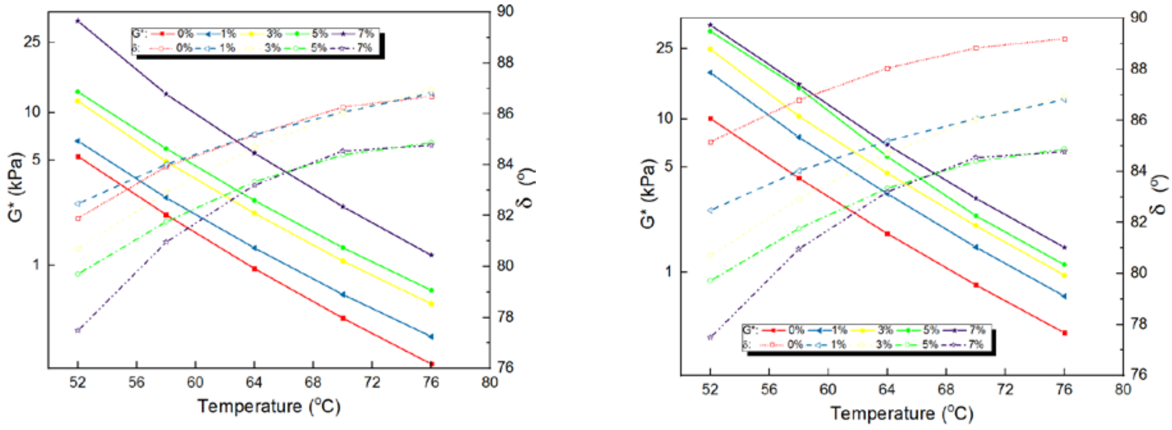


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Figure 7. Complex shear modulus G^* (left) and phase angle δ (right) at different temperature (a) before and (b) after aging.

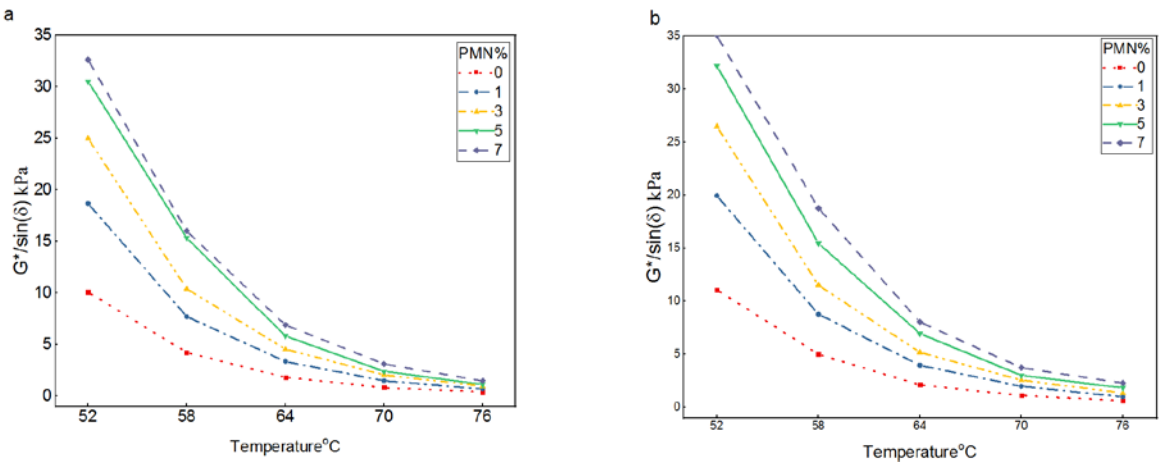

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Figure 8. Rutting parameters ($G^*/\sin(\delta)$) based on DSR measurements at different temperatures (a) before and (b) after aging.

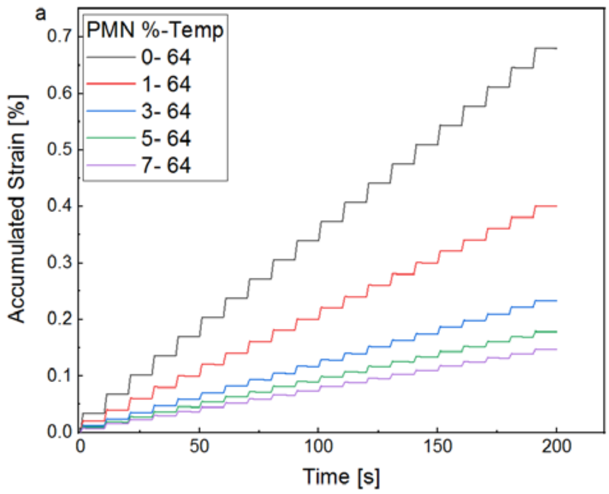
The critical temperature (Tc) conducted by performance grade (PG) is the temperature at which [$G^*/\sin(\delta)$ ≤ 1 kPa] at a frequency of 10 rad/s and strain value is 10 % for an un-aging binder, and that at which [$G^*/\sin(\delta)$ ≤ 2.2 kPa] at strain value is 12 % and a frequency of 10 rad/s for a RTFO aging binder. Consequentially, the Tc is determined from DSR software and presented in Table 6, Tc of PMN was higher than that of the base asphalt, proving that modified binders with higher PMN contents have higher critical temperatures leads to improve the PG-temperature grade. It also observes from Table 6, that the Tc of asphalt binders after RTFO aging is lower than that before aging. However, the true PG-temperature grade of base asphalt was shifted from PG58-xx to PG76-xx for PMN binders with concentrations of 7 % by weight. The PG76-xx binder can be successfully implemented into pavement construction in hot climates, owing to its good high-temperature performance.

Table 5. True Grade Temperature (PG Grade) for permanent deformation.

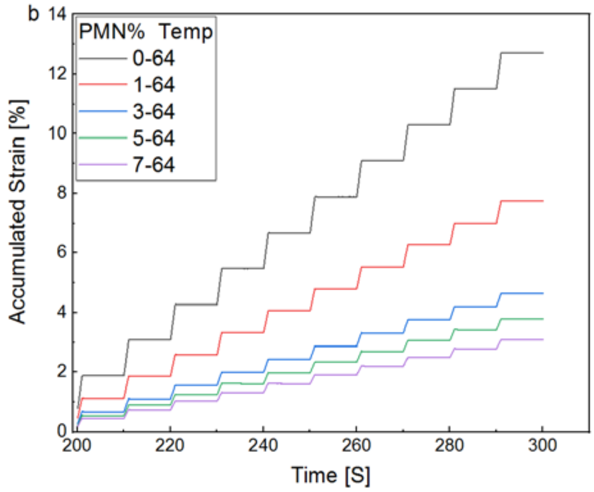
PMN %	True Temperature				PG Grade
	Before RTFOT		After RTFOT		
	Tc [°C]	$G^*/\sin(\delta)$	Tc [°C]	$G^*/\sin(\delta)$	
0	64	2.19	63	5.051	PG58-XX
1	67	1.31	68	3.961	PG64-XX
3	71	1.074	70	2.559	PG70-XX
5	73	1.317	71	2.999	PG70-XX
7	77	1.171	76	2.276	PG76-XX

3.1.3. Multiple Stress Creep Recovery

Figure 9 displays the accumulated strain of PMN modified asphalt samples at 0.1kPa and 3.2kPa stress level at a temperature of 64 °C as an example. Comparing Figure 9 (a) and (b), it can be realized that a higher creep stress level was associated with a higher accumulated creep strain levels; it means that the stress level has a serious effect on the accumulated strain and the growth rate of strain direct proportion with stress level. With the same stress level, the addition of PMN reduced the accumulated strain value, and the asphalt binder modified by PMN had the lowest value and indicates the better rutting resistance. In order to evaluate the strain response by asphalt binder to stress, the non-recoverable compliance (Jnr) is presented in Figure 10. The Jnr is generally used as indicating to resistance against deformation of the binder at high temperature and repeated loading [23–25]. From Figure 10 Jnr values at both stress level (0.1 kPa and 3.2 kPa) of unmodified asphalt are greater than that of PMN modified asphalt at all temperature range. The Jnr decreased from over 16 to less than 4 kPa-1 for as the dosage of PMN increased from 1 % to 7 %. For instance, in Figure 10 (a) the Jnr value of base asphalt being lower by 45 %, 49 %, 61 %, and 80 % at PMN content of 1 %, 3 %, 5 %, and 7 % respectively. Figure 10 (b) show that the Jnr value of base asphalt being lower by 51 %, 48 %, 57 %, and 69 % at and PMN content of 1 %, 3 %, 5 %, and 7 % respectively. It indicates, the addition of PMN decreased the non-recoverable deformation of binder and can contribute to the rutting resistance of associated asphalt mixtures. The effects of PMN dosage on elastic recovery (R) at two stress levels are displayed in Figure 11. It can be detected that the asphalt binder samples prepared using PMN had much better recoveries than base asphalt. For the same sample, the lower stress level compares with a higher elastic recovery. The sample prepared with 7 % PMN gained the highest recovery at both 0.1 kPa and 3.2 kPa stress. After increasing the PMN %, the R-value is increased from around 8 % to nearly 30 %. For example, in Figure 11 (a) the R-value of base asphalt is increased from 9 % to 21.1 %, 32.1 %, 41.6 % and 45.3 % when used 1 %, 3 %, 5 %, and 7 % PMN respectively. Figure 11 (b) show that the R-value of base asphalt increased from 5 % to 14.2 %, 24.6 %, 33.35 and 38.71 % when used 1 %, 3 %, 5 %, and 7 % PMN respectively. However, variations of PMN dosage have had further influence on recovery values, which suggests that PMN has the ability to improve the elastic recovery of asphalt binder. The MSCR test results demonstrate that the PMN dramatically increases the resistance of binder to permanent deformation.

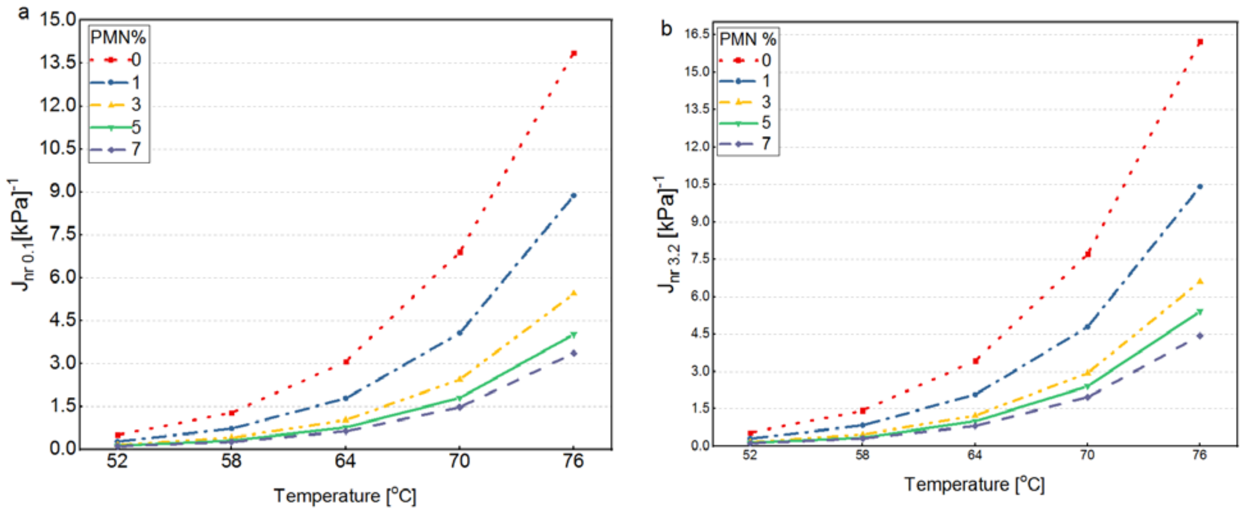


(**a**)



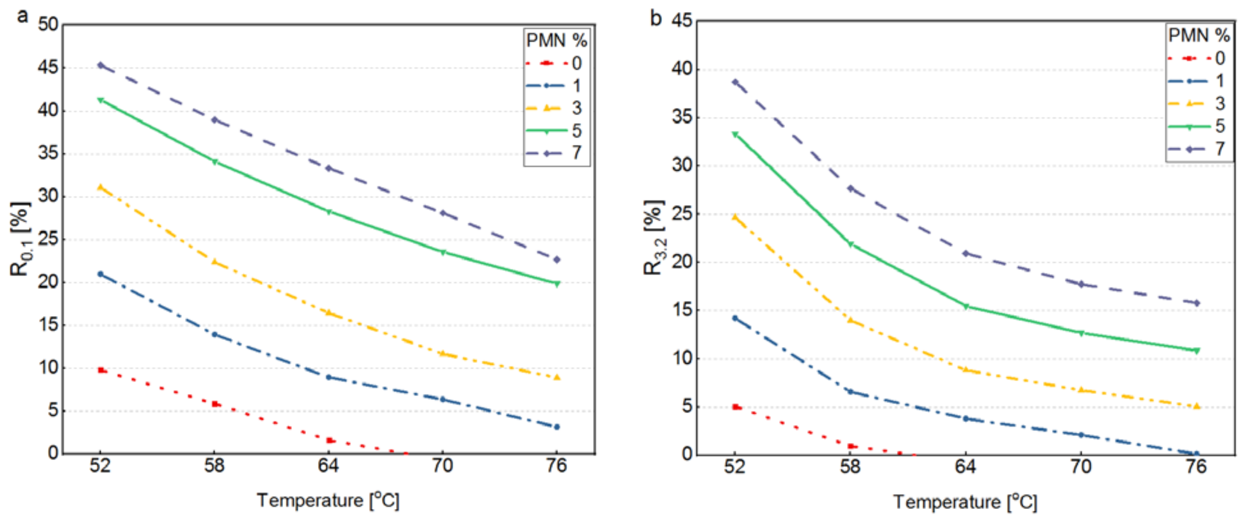
(**b**)

Figure 9. Accumulated strain on asphalt binder obtained from MSCR tests at 64 ° under different stress levels: (0–200 s) 0.1 kPa (a) and (200–300 s) 3.2 kPa (b).



(**a**) (**b**)

Figure 10. Non-recoverable creep compliance (Jnr) at different temperatures and stress levels; 0.1 kPa (a) and 3.2kPa (b).



(**a**) (**b**)

Figure 11. Elastic recovery (R) at different temperature and stress levels 0.1 kPa (a) and 3.2 kPa (b).

3.2. Mixture Performance Testing

3.2.1. Result of Marshall Tests

The relationships between average Marshall Stability (MS), Flow and Marshall Stiffness or Quotient (MQ) and PMN are presented in Figure 12. The MQ is the ratio of stability to flow and it indicates an estimate of the load to deformation ratio based on the specific conditions of the test, it can be used as a measure of the asphalt mixture's resistance to permanent deformation during service in life. In other words, MQ is described as the relationship between stability and flow. A higher MQ a stiffer mixture is which may indicate good permanent deformation resistance. Figure 12 shows that the addition of PMN increases the stability and decreases the flow value of the asphalt mixture. This implies that PMN has improved non-deformability of HMA mixture. Moreover, the mixture containing 7 % of PMN have greater stability and low flow compared with the control mixture. The acceptable Marshall Flow range is 2–4 mm corresponding to heavy traffic category. The Marshall Flow values present in Figure 12 were varied from 2.9 to 3.6 mm, which satisfy specifications criteria. Furthermore, the stability and MQ are both increased with increasing PMN content. The mixture with 7 % of PMN has stability approximately twice higher than that of the control mixture. Subsequently, maximum MQ was achieved by the mixture prepared using 7 % of PMN, while the base asphalt has a minimum value. These results indicate that PMN modified asphalt mixture may distribute the traffic loads to a larger area and superior resistance to permanent deformation, due to increase in mixture stiffness after adding PMN content.

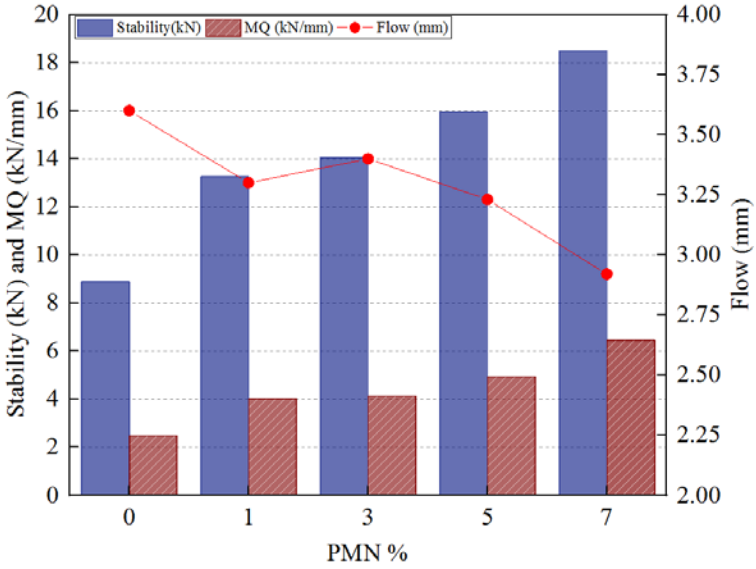


Figure 12. Effect of PMN % on Marshall stability (MS), quotient (MQ) and flow,

3.2.2. Results of Moisture Susceptibility Test

Moisture susceptibility of asphalt concrete mixtures usually concerned to like the potential of anti-stripping incident manifestation. Moreover, the stripping is considered one of the critical damage's occurrences in asphalt pavements [26]. Figure 13 presents the ITS test results for HMA mixtures, as the relationship between PMN % with the ITS (both dry and conditioned specimens) and TSR of control and PMN modified asphalt mixtures. Figure 13 shows that there are significant increases in both ITS and TSR due to the addition of PMN % as compared to the control mixture. From Figure 13, all mixtures prepared using PMN were exceeding the Superpave TSR criterion of 80 %, and the TSR values were increased from 77.5 % for the control mixture to 84.2 %, 88.1 %, 95.0 % 96.1 % corresponding to 1 %, 3 %, 5 % and 7 % of PMN modified asphalt mixture respectively. These results prove that ITS and TSR were significantly increased with increasing PMN %; this may increase the adhesion between aggregate and asphalt binder, which may reduce the stripping of HMA.

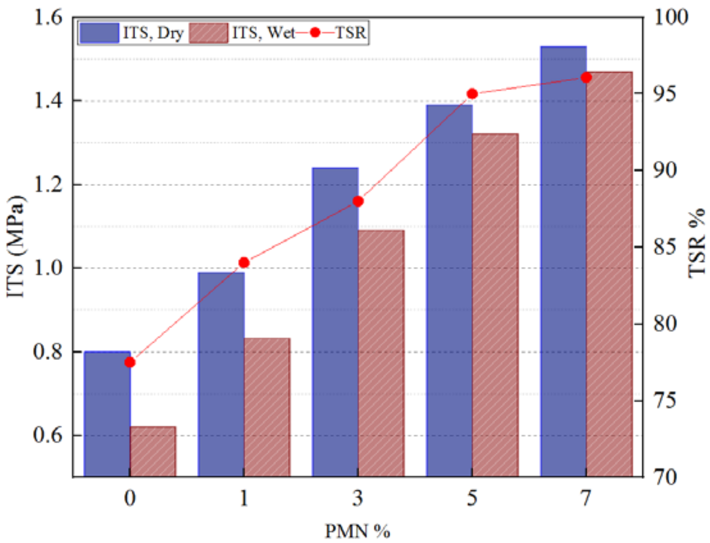


Figure 13. Effect of PMN % on indirect tensile strength (ITS) and tensile strength ratio (TSR).

In order to further investigate the influence of PMNs on moisture-induced damage of asphalt mixtures, the Marshall conditioning (24 at 60 °C) was carried out and the results were compared to unconditioned Marshall specimens (35 min at 60 °C). The Marshal stability ratio (MSR) was determined as stability a ratio of conditioned to unconditioned specimens. The percent of MSR and Marshall stability values of conditioned and unconditioned specimens are presented in Figure 14. The PMNs mixtures have the highest MSR than that of control mixture. The stability ratio value of more than 75 % is suggested as a criterion for a mixture to be resistant to moisture induced damages. These results give great evidence, that the PMN-modified asphalt has the potential to improve the anti-stripping property and decrease the moisture susceptibility of asphalt mixtures. Therefore, the PMN modifier is considered a useful alternative to decrease the risk of moisture-induced damage in asphalt pavement.

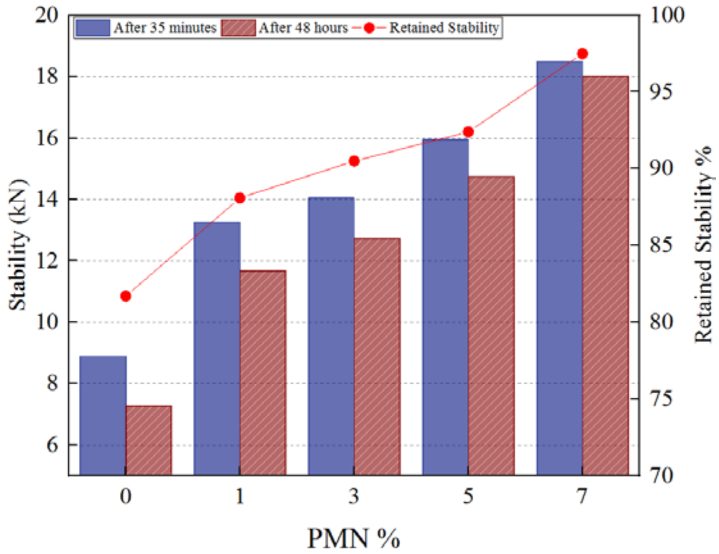


Figure 14. Effect of PMN % on marshal stability (MS) and marshal stability ratio (MSR).

3.2.3. Results of Wheel Tracking Test

The wheel tracking test (WTT) is applied to simulate the permanent deformation (Rutting) of HMA pavement induced by cyclic traffic loads under high-temperatures. In order to verify the binder test results and assess the high-temperature stability of PMN modified asphalt mixture, the WTT was conducted on 300×300×50 mm slab utilizing HYCZ-1 automatic rutting tester at 60 °C. The rutting test results are presented in Figure 15, in term of dynamic stability (DS) and rut depth and it is identified as effective and reasonable techniques to evaluate the high-temperature performance of asphalt mixture. From Figure 14, it can be seen that the usage of PMN significantly increased the DS and reduced the rut depth of HMA mixtures. Hence, The DS of base asphalt is increased by 69.7 %, 88.1 %, 92.6 %, and 94.4 %, while the rut depth is reduced by 36.9 %, 77.6 %, 81.9 % and 85.4 % corresponding to adding 1 %, 3 %, 5 % and 7 % of PMN respectively. Meanwhile, PMN modified asphalt mixture has excellent rutting resistance. This may be due to the fact that the gel structure damage of PMN is reduced under the mixing and rolling condition due to improves the viscosity of asphalt binder. Additionally, the flow deformation resistance of mixture was enhanced while the shear strength of the asphalt mixture is reduced under the same load. Therefore, PMN had effectively improved the resistance permanent deformation of asphalt mixtures, as well as the stiffening of the asphalt mixture. Finally, the capability of the asphalt mixture to oppose accumulated deformations due to repeated traffic loads has been increased as well.

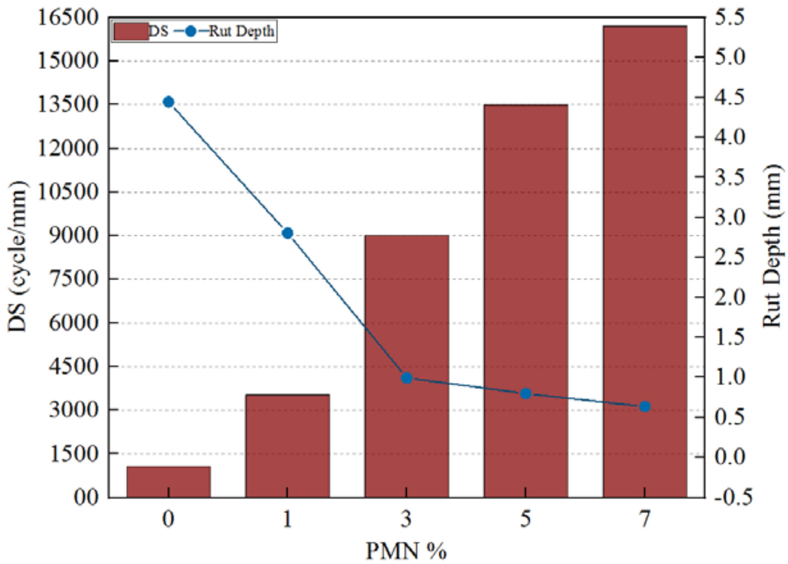


Figure 15. Effect of PMN % on dynamic stability (DS) and rut depth.

4. Conclusions

Based on the obtained results, the following specific conclusions can be drawn:

- The rheological properties of the asphalt binders at high temperatures were significantly improved via addition of PMN. Additionally, penetration index values and penetration viscosity number suggest that the addition of PMN declines the temperature susceptibility of asphalt binders.

- The rutting parameter $G^*/\sin(\delta)$ values obtained from DSR measurement were increased with increasing PMN %, while they are significantly decreased with increasing temperature. Therefore, resistance to permanent deformation and elastic response of the binder were improved. In addition, the MSCR test results demonstrate that the PMN dramatically increases the resistance of binder to permanent deformation by reducing the Jnr and increasing the recovery percent of asphalt binder. Furthermore, the PG grade base asphalt binder was improved after modification, this improvement indicated that the PMNs modified binder may be suitable for using in hot climates to develop stiff flexible mixture.

- The Marshall tests showed that the addition of PMNs increased the Marshall stability and reduced flow of the HMA mixture. Besides, the HMA mixtures which were prepared using PMN have achieved much better resistance to deformation owing to their high MQ values and Marshall stability. Thus, the PMNs modified asphalt might be suitable to use in paving places, where asphalt mixtures with minimal asphalt concentration with high stiffness were required.

- The results of the ITS test indicated that the TSR value of control mixture increased, because of the improvement of adhesion between aggregate and binder, which may reduce the stripping of HMA. Therefore, the moisture resistance of the asphalt mixture was significantly improved after PMN addition. A similar conclusion was carried out from Marshall immersion test.

- The rut depth of asphalt mixture was decreased with the increasing of PMN contents and dynamic stability. Interestingly, these indicate an improvement in permanent deformation resistance by asphalt mixtures, due to increasing stiffening of the asphalt mixture, and the capability of asphalt mixture to resist deformations at high-temperature and repeated traffic loads.

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Contacts:

Elfadil Siddig, +249918171460; elfadiladmali@ymail.com
Peifeng Cheng, +8613946139402; chengpeifeng@nefu.edu.cn
Yiming Li, +8618249504717; meng.huxiyou@163.com