Multiple Stress Creep and Recovery of Nanosilica Modified Asphalt Binder

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Abstract. The main objective of this study is to evaluate the effect of nanosilica (NS) concentration on the rutting parameter of based asphalt binder using the multiple stress creep and recovery (MSCR) test. NS with concentrations between 1% to 5% (1% increment) was used to modify asphalt binder. The nanosilica modified asphalt binder (NSMB) were aged using rolling thin film oven (RTFO) before tested. MSCR test was conducted at 64^{0}C with two stress level (100 Pa and 3200 Pa). The results found that the addition of NS reduced the accumulative strain of NSMB. Besides that, non-recoverable creep compliance decreased and recovery strain increased, which indicates an improvement of rutting resistance and elasticity of the binder, respectively. The grade of asphalt binder also improved from heavy (H) grade to extreme (E) grade. Overall, NSMB 2% show the best improvement in terms of Jnr and %R, thus NSMB 2% considered as a optimum percentage.

1 Introduction

Permanent deformation or rutting is one of the main problems in asphalt pavement; it is caused by repeated loading from heavy traffic loading which results in progressive accumulation of permanent deformation under repetitive tire pressures [1]. Rutting significantly affect the pavement performance and reduce its service life. The resistance of asphalt pavement to rutting depends on many factors. One of the main importance factor is the stiffness of the asphalt binder. Therefore, it is necessary to modify asphalt binder in order to improve it stiffness. The use of nanotechnology in asphalt binder modification promises better result in improving asphalt binder stiffness. Various nanomaterials have been used to modify asphalt binder such as nanosilica (NS).

NS has been widely used in polymer, concrete and asphalt binder as inorganic filler to improve the properties of polymeric, mechanical and bituminous materials. NS is an inorganic material which has a maximum dimension about 30nm. NS possesses good properties such as large surface area, good dispersal ability, strong adsorption, high

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chemical clarity and excellent stability [2]. Yao et al (2013) have used NS to modify asphalt binder. The addition of NS (4% and 6%) in the base asphalt binder decrease the viscosity value of base asphalt binder as well as anti-aging property. Besides that, the dynamic modulus of NS modified asphalt mixture is higher than the control asphalt mixture by an average 30%. NS also gives high contribution in increasing the value of flow number where it increases the flow number by an average of 300%. This value indicates that it has more possibilities to resist the permanent deformation at high temperature compared to control binder [3,4]

Previously, the rutting parameter (G*/sinδ) from dynamic shear rheometer (DSR) test was used to evaluate the rutting performance of asphalt binder. As the DSR test used low stress level (about 10%), thus it may underestimate the performance of modified binder. This is because at low strain level, the modifier may not be fully activated. Recently, the performance grade (PG) asphalt binder specification introduced the multiple stress creep and recovery test (MSCR) to indicate the rutting performance of the asphalt binder. The MSCR test was developed by D'Angelo et al (2007) to replace the dynamic oscillatory shear test at high temperature [5]. The non-recoverable creep compliance (J_{nr}) in MSCR test has higher correlation with rutting performance of asphalt binder compared to the rutting parameter (G*/sinδ) as reported by Federal Highway Administration (2011) and Asphalt Institute (2012)[6]. According to the AASHTO TP70 standard, the test consists of 10 cycles of creep and recovery. Each cycles consist of 1s loading and 9s recovery upon two different stress level started with low stress level (100 Pa) and followed by high stress level (3200 Pa)[7]. The use of two different stress levels in the MSCR test correlated with varrying traffic loading levels on the pavement surface. Fig. 1 show the typical creep and recovery in MSCR test.

The main objective of this study was to evaluate the high temperature rutting performance of NSMB using MSCR. The effect of NS on J_{nr} and %R of base asphalt binder will be explored as an indicator of rutting performance. Maximum NS percentage for asphalt binder also will also be determined.

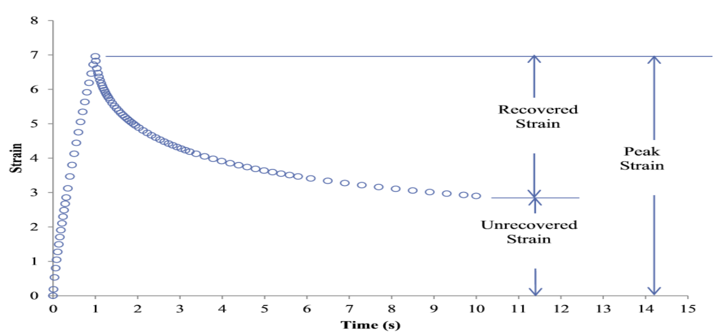

Fig. 1. Typical creep and recovery in MSCR test

2 Environmental program

2.1 Materials and sample preparation

The study used 60/70 Penetration Grade (60/70 PEN) of asphalt binder. Then, the binder was modified with NS with average size of 10-15 nm. Table 1 shows the properties of asphalt binder and NS. Asphalt binder was blended with 1% to 5% NS (1% increment) by weight of the virgin asphalt binder. The modification of asphalt binder was conducted by mechanical mixer. Asphalt binder was heated up to 160°C until it achieved the processing viscosity. Cylindrical container was filled with about 400g of hot asphalt and placed on a hot plate. The temperature of hot plate was set to 160°C to maintain the viscosity of asphalt binder during mixing. NS was gradually added into the hot asphalt binder while stirring with the mechanical steel stirrer. The speed of stirrer was set to 2000 rpm. The mixing process continued for one hour in order to achieve uniform dispersion of NS. The modified binder was placed in the oven to remove the bubbles, before preparing the test sample. To facilitate in referring each sample, nanosilica modified asphalt binder (NSMB) were named using following abbreviations: NSMB 0%, NSMB 1%, NSMB 2%, NSMB 3%, NSMB 4% and NSMB 5%.

Table 1. Properties of asphalt binder and NS

Materials	Properties	value
Asphalt binder	Softening point (°C)	48-56
	Penetration (0.1 mm)	60-70
	Ductility (cm)	>100
	Flash point (°C)	331
Nanosilica	Appearance	Slight milky transparent to translucent liquid
	SiO_2 (wt%)	30±1%
	Na_2O (wt%)	0.5%
	pH (20°C)	8.5-10.5
	Density (20°C, g/cm3)	1.19-1.22
	Particle size (nm)	10-15

2.2 Short term aging

The RTFO equipment was used to simulate short term aging according to ASTM D2872. In this test, the hot binder was poured into a cylindrical glass bottle with a 35 g each. The glass bottles which contained binder were placed horizontally in a rotating carriage slots in the oven. Then, the carriage was rotated at a rate of 15 rpm for 85 minutes in the oven at temperature of 163°C. Throughout the test, the opening glass bottles containing the binders were exposed to the air pressure at 4000 ml/min.

2.3 Multiple stress creep and recovery

Multiple stress creep and recovery (MSCR) test was carried out on RTFO aged sample at temperature 64°C using DSR equipment in accordance with AASHTO TP70. Two different stress levels were chosen, 100 Pa and 3200 Pa. Two continuous sets of ten loading cycle of repeated creep and recovery testing was applied. The test used 1s creep load followed by 9s recovery for each cycle. The main parameters achieved from MSCR are recoverable strain (R) and non-recoverable creep compliance (J_{nr}). R value provides an indication of the presence of elastic response and stress dependency of the binder, while J_{nr} was defined as the ratio of the non-recovered strain to the stress applied during MSCR testing. R and J_{nr} were calculated using the following equations:

$$R = \frac{\varepsilon_p - \varepsilon_u}{\varepsilon_p} \times 100\% \tag{1}$$

$$J_{nr} = \frac{\varepsilon u}{\sigma} \tag{2}$$

where, Ɛp represents the peak strain, Ɛu represents the unrecovered strain and σ represents the stress level. The average of R of 10 cycles at 100 Pa and 3200 Pa are calculated and expressed as R100 and R3200 respectively, while the average of J_{nr} at 100 Pa and 3200 Pa are expressed as $J_{nr}100$ and $J_{nr}3200$. The stress sensitivity parameter, Rdiff and J_{nr}-diff are calculated using the following equation;

$$Rdiff = \frac{R100 - R3200}{R100} \times 100 \tag{3}$$

$$J_{nr}\text{-}diff = \frac{jnr3200 - jnr100}{jnr100} \times 100 \tag{4}$$

3 Result and discussion

3.1 Strain

Fig. 2 shows the typical strain outputs from MSCR testing of NSMB at 64^{0}C with two stress levels. The first 100 second represents low stress level (100 Pa) and next 100 second represents a high stress level (3200 Pa). Fig. 3 represents one cycle of MSCR of NSMB at 100 Pa. The MSCR test result included two phase which is creep phase and recovery phase to complete one cycle. As can be seen from the Fig. 3, in the one-second creep phase, the strain is going up under loading. In the nine-second recovery phase, the strain recovered when the loading was removed. In the recovery phase, the strain recovered immediately at the beginning but the recovery rates decreased with time. Also, the strain and recovery rate was very high at the beginning of the cycle, but the rate decreased with time as shown in Fig. 2. This MSCR test result is a reflection of the visco-elastic-plastic property of asphalt binder; when the load is removed, the elastic strain recovered quickly, while the viscous strain recovered slowly [8]. Comparing the accumulated strain by the stress level, it can be observed that the accumulated strain at low stress level is lower than at high stress level. This indicates that, with the increasing stress level, the accumulated strain also increased. In terms of the effect of NS on the MSCR results, it seems that the accumulated strain is significantly reduced compared to base asphalt binder. This indicates that NS improve the stiffness of the asphalt binder at high service temperature. It can be concluded that NSMB2% has lower accumulated strain compared to other percentages of NSMB.

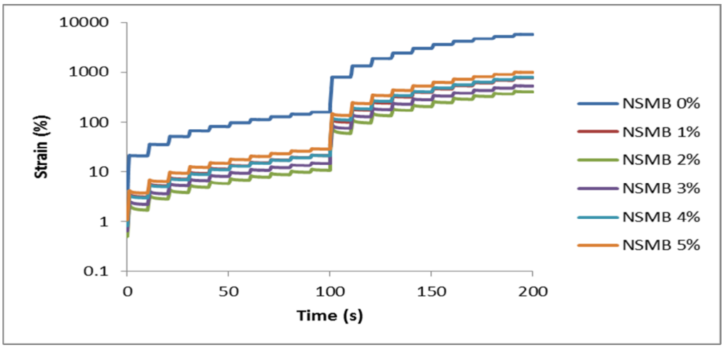

Fig. 2. Strain versus time of MSCR testing for ten cycle

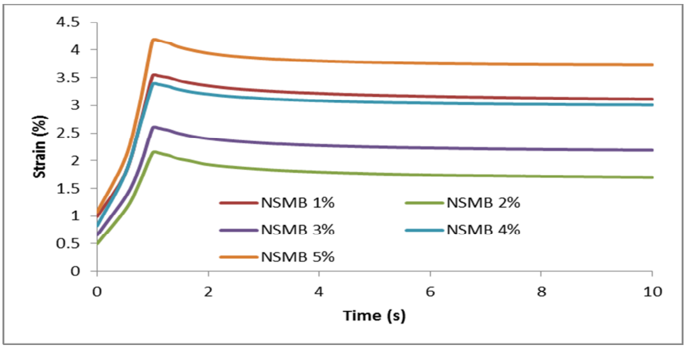

Fig. 3. Strain versus time of MSCR testing for one cycle at 100 Pa

3.2 Nonrecoverable creep compliance (J_{nr})

The J_{nr} parameter was proposed to measure the binder contribution to mixture rutting performance, where lower value of J_{nr} indicates better resistance to rutting performance and higher value of J_{nr} indicates poor resistance to rutting performance. Fig. 4 shows the J_{nr} results for NSMB at stress levels of 100 Pa and 3200 Pa. It was observed that the trends of the bar chart are similar for both stress levels. Also, J_{nr} increased slightly as the level of stress changed from 100 Pa to 3200 Pa. The changes of J_{nr} were more pronounced for NSMB0%. The addition of nanosilica into asphalt binder also reduced the value of J_{nr} compared with the base asphalt binder. For stress level of 100 Pa, the J_{nr} of NSMB 0%, NSMB 1%, NSMB 2%, NSMB 3%, NSMB 4% and NSMB 5% were 87.0%, 93.4%, 91.0%, 87.0%, and 82.5% lower than that of the base asphalt binder, respectively. For stress level of 3200 Pa, the J_{nr} of NSMB 0%, NSMB 1%, NSMB 2%, NSMB 3%, NSMB 4% and NSMB 5% were 86.8%, 93.1%, 90.9%, 86.6% and 83.6% lower than that of the base asphalt binder, respectively. The value of percentage difference between NSMB and base asphalt binder proved that addition of nanosilica reduced the value of J_{nr} and indicate that rutting resistance of asphalt binder improved.

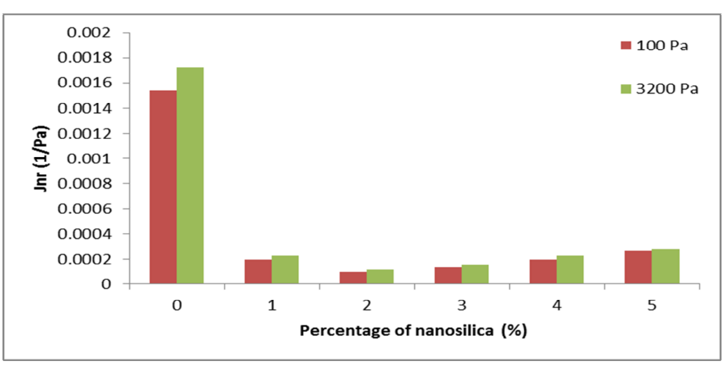

Fig. 4. Nonrecoverable creep compliance (J_{nr}) at difference stress level of NSMB

3.3 Percentage recoverable strain (%R)

The percentage recoverable strain is used to determine the elastic behavior of asphalt binder under loading. It is an important parameter to evaluate the ability of asphalt binder to recover after deformation. The higher percentage of recoverable strain of asphalt binder indicates the lower susceptibility to permanent deformation. Percentage recoverable strain showed an inverse relationship with nonrecoverable creep compliance. Fig. 5 shows the percent recoverable strain at stress levels of 100 Pa and 3200 Pa. As it can be seen that the NSMB have a higher value of percent recoverable strain compared to the control binder. This indicates that the addition of small percentages of nanosilica improves elastic recovery of asphalt binder and improves its rutting resistance. By comparing the results at two stress levels, the value slightly decreased at 3200 Pa compared to the value at 100 Pa. For stress level of 100 Pa, the %R of NSMB 0%, NSMB 1%, NSMB 2%, NSMB 3%, NSMB 4% and NSMB 5% were 80.6%, 89.0%, 85.0%, 78.8%, and 77.9% higher than that of the base asphalt binder, respectively. For stress level of 3200 Pa, the Jnr of NSMB 0%, NSMB 1%, NSMB 2%, NSMB 3%, NSMB 4% and NSMB 5% were 94.1%, 96.8%, 95.6%, 92.6% and 92.2% higher than that of the base asphalt binder, respectively. Saboo and Kumar (2015) reported that if binder has at least 20% recovery, irrespective of any stress level or temperature, it will indicate the presence of delayed elastic behavior. By comparing with this study, the addition of 2% of NS passed the minimum strain recovery [9].

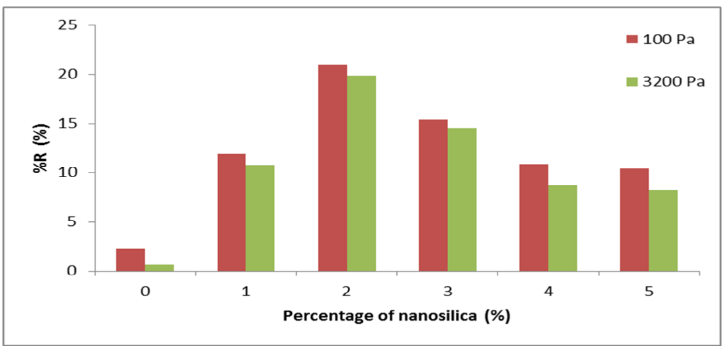

Fig. 5. Percent recoverable strain (%R) at difference stress level of NSMB

3.4 Stress sensitivity

Percent difference of non-recoverable creep compliance (J_{nr}-diff) and creep recovery (Rdiff) is a measure of the sensitivity of the asphalt binder to the increasing stress level. Lower values of J_{nr}diff and Rdiff indicate less stress sensitivity of the asphalt binder. Fig. 6 shows the stress sensitivity of J_{nr}diff and Rdiff for NSMB. According to Superpave MSCR procedure [2], the maximum value for J_{nr}diff are 75% at the high PG grade and the loading-unloading times of 1-9s. From Fig. 6, it can be seen that, at high percentages of nanosilica shows high sensitivity compared to low percentages of NS. All percentages of NSMB complied with the specification. J_{nr} of NSMB2% had the highest stress sensitivity at high service temperature. In contrast, %R exhibit less sensitivity at high service temperature against rutting.

3.5 Relationship between Jnr and %R

Fig. 7 shows the relationship between %R and J_{nr} at different stress levels of NSMB. This graph was divided into 4 grades in accordance to AASHTO TP70 which are standard (S) $J_{nr} < 4.5$ 1/kPa, heavy (H) $J_{nr} < 2.0$ 1/kPa, very heavy (V) $J_{nr} < 1.0$ 1/kPa, and extreme (E) $J_{nr} < 0.5$ 1/kPa based on the value of J_{nr}. As can be seen from the graph, the standard (S) grade was neglected because there was no value in that grade. From Fig. 7 and Table 2, it was observed that the base asphalt binder can be classified as standard (S) and heavy (H) grade while NSMB can be classified for all grades. This proved that NSMB improved the rutting performance and improved the grade of the asphalt pavement.

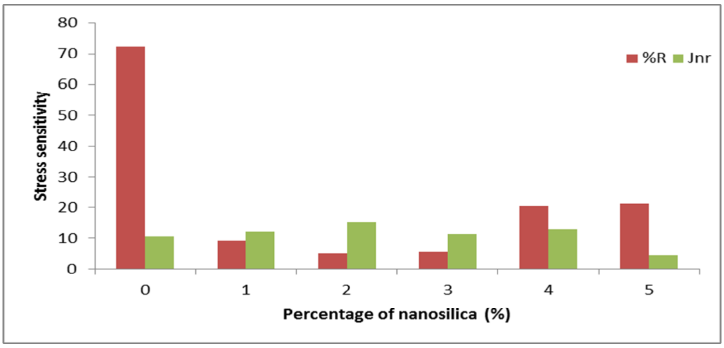

Fig. 6. Stress sensitivity of %R and J_{nr} of NSMB

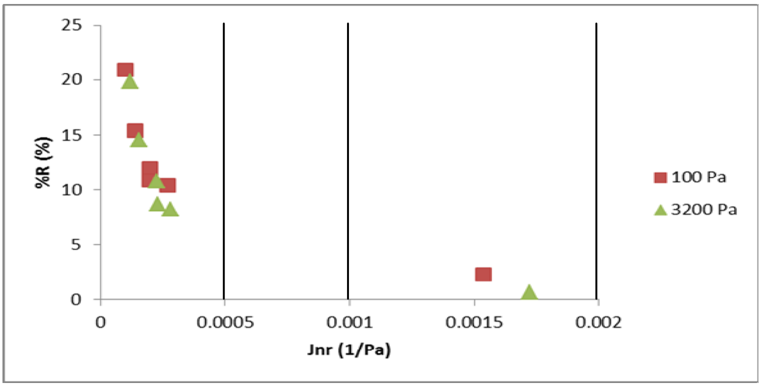

Fig. 7. Relationship between J_{nr} and %R of NSMB

Table 2. Suitability of NSMB for pavement grade at 64^{0}C

Type of grade	J_{nr} maximum (kPa)	100 Pa						3200 Pa					
		0%	1%	2%	3%	4%	5%	0%	1%	2%	3%	4%	5%
S	4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
H	2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
V	1	N	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
E	0.5	N	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y

(Y=Suitable, N=Not suitable)

4 Conclusion

This study investigated the effect of the NS on the rutting performance of asphalt binder using MSCR. By adding small percentages of NS in the base asphalt binder, the strain values decreased significantly. Besides that, the non-recoverable creep compliance (J_{nr}) also decreased, while percentage recovery increased. Thus, this indicates that high temperature stability and elasticity of NSMB improved. The grade of the asphalt binder also improved from Heavy (H) to Extreme (E). It was found that NSMB 2% has the greatest performance against rutting, compared to other NSMB.

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References

[1] S. Tayfur, H. Ozen, and A. Aksoy, Investigation of rutting performance of asphalt mixtures containing polymer modifiers, J. Constr. Build. Mater., **21**, 328-337 (2007)
[2] T.H. Hsieh, A.J. Kinloch, A.C. Taylor, and S. Sprenger, The effect of silica nanoparticles and carbon nanotubes on the toughness of a thermosetting epoxy polymer, Journal of Applied Polymer Science, **119**, 2135-2142 (2011)
[3] H. Yao, Z. You, L. Li, Lee, and S.W. Goh, Evaluation of the master curves for complex shear modulus for nano-modified asphalt binder, CICTP, 3399-3414 (2012)
[4] H. Yao, Z. You, L. Li, C.H. Lee, D. Wingard, Y.K. Yap, X. Shi, and S.W. Goh, Rheological properties and chemical bonding of asphalt modified with nanosilica, Journal of Materials in Civil Engineering **25**, 1619-1630 (2013)
[5] J. D'Angelo, R. Kluttz, R. Dongre, K. Stephens, and L. Zanzotto, Revision of the Superpave high temperature binder specification: The multiple stress creep recovery test, J. Assoc. Asphalt Paving Technol., **76**, 123-162 (2007)
[6] U.S Department of Transportation Federal Highway Administration, *The multiple stress creep and recovery (MSCR) procedure*, FHWA-HIF-11-038, (2011)
[7] AASHTO TP70-10 Multiple Stress Creep Recovery (MSCR), *Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR),* American Association of State and Highway Transportation Officials, (2013)
[8] X. Yang, and Z. You, High temperature evaluation of bio-oil modified asphalt binder using the DSR and MSCR tests, Construction and Building Materials, **76**, 380-387 (2015)
[9] N. Saboo, and P. Kumar, A study on creep and recovery behavior of asphalt binder, Construction and Building Material, **96**, 632-640 (2015)