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Characterisation of Colloidal Nanosilica Modified Asphalt binder

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Abstract. Nanosilica (NS) has been used in this study as an asphalt binder modifier to improve the binder properties. Penetration grade 60/70 (PEN 60/70) asphalt binder was modified with NS in colloidal form with an average size of 10 to 15 nanometer (nm). The nanosilica modified asphalt binders (NSMB) were tested for different tests such as physical properties, atomic force microscopy (AFM), dynamic shear rheometer (DSR), multiples stress creep and recovery (MSCR) and asphalt pavement analyser (APA). The result obtained from physical properties shows that the additions of NS significantly improve the properties of base asphalt binder in terms of penetration, softening point and viscosity. It was also found that NSMB is stable during the high temperature storage period. SEM images showed that NS particles dispersed well in base asphalt binder and AFM images showed that the addition of nanosilica in asphalt binder improved its surface stiffness. In addition, NSMB significantly increases the G*/sinδ value, failure temperature, and percentage creep recovery while, decreased the non-recoverable creep compliance, which indicated higher elasticity and beneficial in increasing the rutting resistance as compared to the base asphalt. On the other hand, from APA test, it was found that NSMB reduced the rutting depth of asphalt mixture. It can be concluded from the analysis that a maximum of 2% NS be added into the base asphalt for optimum binder modification.

1. Introduction

Bitumen or asphalt binder is a complex hydrocarbon and it can be naturally occurring or residue from the distillation process of crude petroleum. Asphalt binder can be described as adhesive or glue in asphalt pavement. Since the properties of asphalt acts sticky, then it acts as a binder to bind aggregate and filler together in asphalt pavement. Although the asphalt binder used in small amounts (only about 5% to 5.5% by weight of aggregate), it plays a significant role towards the performance of flexible pavement. The increasing number of vehicles, particularly heavy vehicles, can lead to the permanent deformation of flexible pavement. Besides that, the hot, wet equational climate is also another factor that contributes to poor performance of asphalt binder properties on different wheater condition [1].

Polymers have been used for last 40 years in asphalt binder modification to improve asphalt binder properties such as styrene-butadiene-styrene (SBS) and styrene butadiene rubber (SBR). Although these polymers all improve bitumen properties to some extent, there are still some drawbacks limiting the future development of asphalt binder modification using polymers, such as high cost, low aging resistance and poor high temperature storage stability [2]. Therefore, the use of nanomaterials for asphalt modification should be explored to overcome these drawbacks and further improve asphalt pavement performance.

Nanomaterial is a material that has at least one dimension is on the nanometer scale that is one billionth of a meter (10^{-9} m). Because of their chemical and physical characteristic, nanomaterial have been used by a number of researchers and engineers to modify the asphalt binder in order to improve the properties of asphalt binder and performance of asphalt mixture [3]. Besides that, based on previous studies, properties such as stability, bonding, resistance, and durability can be improved by using nanomaterial because its high specific area. High specific area of modifier can optimize active interaction between the nanoparticles and their environment. The most common nanomaterials used includes nanoclay (NC), carbon nanotube (CNT), carbon nanofiber (CNF) and nanosilica (NS).

Nanosilica becomes very attractive for use in bitumen modification because its interaction surface area which is much larger compared to that of conventional filler [4]. The addition of NS powder in the base asphalt binder decrease the viscosity value, improved anti-aging property, rutting and fatigue cracking performance of NS modified asphalt binder [5-7]. The resilient modulus, stiffness modulus, and tensile strength of NS modified asphalt mixture also improved. However, asphalt modification with nanomaterials especially in powder form required the use of high shear mixing technique rather than ordinary mechanical mixing technique due to possibility of segregation and agglomeration. If nanosilica particles agglomerated, they would be in the order of micrometers instead of nanometers [3] as impact the properties of nano asphalt modification not fully maximized. The main objective of this study is to characterize the properties of asphalt binder modified with nanosilica in colloidal form as well as to determine the optimum nanosilica percentage for asphalt modification

2. Experimental plan

2.1. Materials

Asphalt binder used in this study was penetration grade 60/70 (PEN 60/70) which was supplied by Shell Bitumen. The physical properties of the base asphalt binder and nanosilica used in this study are shown in **Table 1** and **Table 2** respectively.

Table 1: Physical properties of asphalt binder

Test	Data
Penetration, 25°C, 100 g, 5 s (dmm)	60-70
Softening Point (°C)	48-56
Solubility (%)	99.5
Ductility, 25°C (cm)	100.0
Flash point (°C)	276
Loss of heating (%)	0.2
Relative density 25°C	1.00 – 1.06

Table 2: Properties of NS

Properties	Value
Appearance	Slightly milky transparent to translucent liquid
SiO2 (wt%)	30±1%
Na2O (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. Sample preparation

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 a mechanical mixer. Asphalt binder was heated up to 160°C until it achieves the processing viscosity. A cylindrical container was filled with about 400g of the base asphalt binder and was placed on a hot plate. The temperature of hot plate was set to 160°C to maintain the viscosity of asphalt binder during mixing. The speed of stirrer was set to 2000 rpm. The mixing process continued for one hour in order to achieve uniform dispersion of NS. To facilitate in referring each sample containing different NS content, they were named by the following abbreviations: NSMB 0%, NSMB 1%, NSMB 2%, NSMB 3%, NSMB 4% and NSMB 5%. In order to understand the microstructure changes of the NSMB and the physical dispersion of the nanosilica particles in asphalt binder, Scanning Electron Microscopy (SEM) was used. **Figure 1** shows the microstructure of NSMB that was changed significantly compared to the base asphalt binder. The white spots as shown in the SEM image represent nanosilica particles. The SEM image of NSMB shows the well-dispersed nanosilica particles in the asphalt binder matrix. Well dispersion of nanosilica in asphalt binder may be helpful for the modulus improvement of nanosilica modified asphalt binder and mixture.

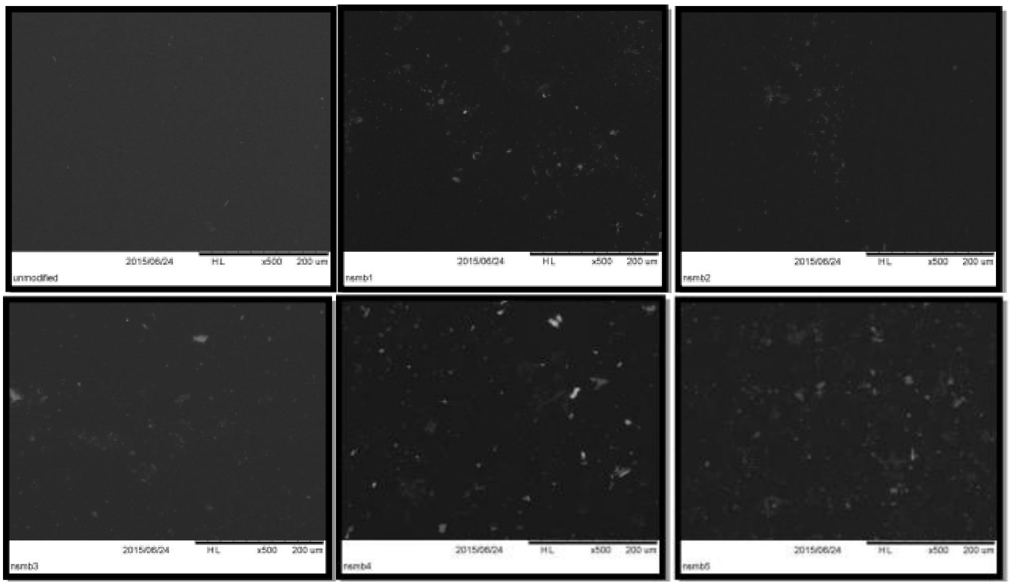

Figure 1: SEM image (From top left NSMB 0%, NSMB 1%, NSMB 2%, NSMB 3%, NSMB 4% and NSMB 5%)

2.3. Physical properties
The physical properties of NSMB were characterized using conventional methods such as softening point test, penetration test, ductility test, storage stability and viscosity test. The softening point test as to ASTM was D36 used to determine the consistency of binder. Penetration test as to ASTM D5 was used to evaluate the consistency of an asphalt binder. Ductility test measured the ability of asphalt binder to elongate before breaking. Storage stability was used to evaluate the high temperature storage stability of modified asphalt. Rotational Viscometer test ASTM D 4402 was used to measure viscosity of the asphalt binder at application temperature to determine the handling and pumping properties at the terminal, plant facility and refinery.

2.4. Atomic force microscopy
In the AFM sample preparation, the NSMB was heated at 160°C for one hour and dropped on the glass slide surface. Then, the glass slide was placed in the oven at 160°C for 10 minutes in order to

obtain a smooth and glossy surface of the asphalt binder. The dimension of the asphalt droplet should be about 1 cm in diameter. Next, the glass slide was removed from the oven and cooled at room temperature for 24 hours before being tested. In this study, a non-contact AFM (model EX-100) was used. Topographic image was scanned using silicon probe. The cantilever was 125 μm long with a curvature radius of 5-10 μm. The drive frequency was about 300 kHz and the scan rate were 0.5 Hz. All AFM images were measured in a dimension of 20 μm x 20 μm.

2.5. Aging Method
The rolling thin film oven (RTFO) equipment was used to simulate short term aging in accordance to ASTM D2872. In this test, the binder was heated and poured into a cylindrical glass bottles with a 35 g each. The glass bottles which contain the 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 a temperature of 163°C. Throughout the test, the opening glass bottles containing the binders were exposed to air pressure discharge of 4000 ml/min.

2.6. Dynamic Shear Rheometer
The testing sample was prepared by heating the NSMB at 160°C for 30 minutes to obtain the required viscosity before being poured onto the surface of a special wax paper. Then, the sample was sandwiched between fixed steel plates of a selected thickness. After the samples had cooled and solidified, they were cut to a testing diameter using a special cutter and placed on the lower of the selected testing spindle. The spindle was then attached to the DSR equipment for conditioning at the desired testing temperature before the testing was conducted. For this study Dynamic Shear Rheometer (DSR) test were conducted to determine permanent deformation or rutting of NSMB in terms of complex shear modulus (G*) and phase angle (δ) [5]. To predict the rutting resistance of asphalt binder, G*/sin δ was used. According to Superpave specification, the value of G*/sin δ for unaged sample and RTFO sample must be at least 1.0 kPa and 2.2 kPa respectively. A higher G*/sin δ value indicates a higher rutting resistance and elasticity of asphalt binder, while a lower G*/sin δ value below these values may be too soft to resist permanent deformation or rutting

2.7. Multiple stress creep and discovery
Multiple stress creep and recovery (MSCR) test was carried out at different temperature (58°C, 64°C and 70°C) using DSR equipment. 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 using 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 Jnr was defined as the ratio of the non-recovered strain to the stress applied during MSCR testing. 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.

2.8. Asphalt Pavement Analyzer
The APA testing was conducted in accordance to AASHTO TP 63-06. For this study, specimens were compacted to 7.0 ± 0.5 air voids using Superpave Gyratory Compactor with a diameter of 150 mm and a final height of 75 mm. Prior testing, specimens were conditioned at 60^0C for a minimum period of six hours. The APA testing was conducted under dry conditions and on pairs each time where each pair consists of two cylindrical specimens in a unique high density polyethylene (HDPE) designed moulds. Then, the cyclic load with a hose pressure of 690 kPa and wheel load of 445 N was applied on specimens for a maximum of 8000 times at a rate of 60 cycles/minute. Once the cycles reached the maximum number, the rut depth of the specimens are measured. Otherwise, the testing is terminated and the rut depth of that specimen is recorded as 12 mm if the specimen exhibited rut depth greater than 12 mm before the total numbers of cycles reached the 8000 cycles.

3. Result and Discussion

3.1. Physical properties

Table 3 shows the consistency property value of NSMB with various conventional test methods. It can be observed that there is a decrease in penetration and an increase in the softening point when NS was added into asphalt binder. This indicates that NSMB is more consistent and harder compared to the virgin asphalt binder as well as improving its high temperature susceptibility. However, the additions of NS significantly decreased the ductility value of NSMB. A possible explanation for this reduction in ductility is that the presence of high specific surface area in NS which leads to increase of asphalt absorption. The storage stability test was used to evaluate the stability and compatibility of the modifier in asphalt binder at high temperature. Since the difference of softening point value between the top and bottom section is less than 2.2°C [8-9], this means that NSMB is stable when stored at high temperature. Therefore, it can be concluded that NS is a stable material that can be used in asphalt modification. For viscosity test, the values of NSMB-1% to NSMB-5% increased significantly. These value complied with the Superpave standard specification, where the viscosity value for NSMB for all percentages is lower than the maximum limit of 3 Pa. The increase in the viscosity value at high temperature is beneficial for rutting resistance.

Table 3: Physical properties of NSMB

Test	NSMB 0%	NSMB 1%	NSMB 2%	NSMB 3%	NSMB 4%	NSMB 5%
Penetration, 25°C, (dmm)	65.0	43.5	41.1	33.3	29.1	30.7
Softening Point (°C)	52.3	58.9	60.3	62.4	63.4	60.0
Ductility, 25°C (cm)	140.0	129.0	85.5	70.2	51.7	46.3
Storage stability (°C)	0	0.2	0.2	0.2	0.3	0.5
Viscosity at 135°C (Pa.s)	0.7	0.8	0.9	1.0	1.2	1.2

3.2. Atomic force microscopy

Figure 2 shows the 20 by 20 µm AFM topography image of NSMB. As shown in the figure, three distinctive phases clearly could be identified in both base asphalt binder and NSMB as reported in previous literature and the distribution of three phases seemingly random [10-12]. The phase was identified as catana phase, peri phase and para phase, whereas catana and peri phase appear to be dispersed phase and para phase appear to be dispersing phase. The overall size and shape of catana phase is rather variable for all samples which are approximately 7 µm to 12 µm in length and 1.0 µm to 1.5 µm in width. Table 3 shows the phase distribution of AFM image. From Table 3, approximately 11% of the phase distribution is associated with catana phase, 48% associated with peri phase and 41% associated with para phase. The distribution of the catana phase by area was 10% for NSMB-0%, NSMB-4% and NSMB-5%, and 13%, 15%, 8% by area for NSMB-1, NSMB-2, and NSMB-3 respectively. It was found the amount of catana phase increased significantly for NSMB-1% and NSMB-2% about 30% and 50% respectively compared to NSMB-3%, NSMB-4% and NSMB-5% samples, which only display nearly the same as NSMB-0%. The phase distribution between peri and para phase seem inverted at high percentage of nanosilica (NSMB-3% - NSMB-5%) where the para phase increased. Para phase are classified as low stiffness while peri and catana phase classified as high stiffness by Jager et al. (2014) [10]. As compared with Jager et al. (2004), it can be said that NSMB-3% - NSMB-5% did not have a significant influence to increase the stiffness of NSMB.

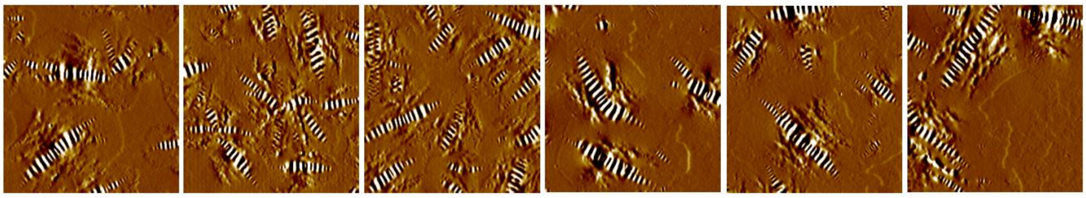

Figure 2: AFM image (from left: NSMB 0%, NSMB 1%, NSMB 2%, NSMB 3%, NSMB 4% and NSMB 5%)

Table 4: Phase distribution of AFM image

Phase distribution (%)	NSMB 0%	NSMB 1%	NSMB 2%	NSMB 3%	NSMB 4%	NSMB 5%
Catana phase	10	13	15	8	10	10
Peri phase	65	58	65	29	33	40
Para phase	25	29	20	63	57	50

3.3. Dynamic shear rheometer

3.3.1. Isochronal plot

Basically, an isochronal plot is a plot of some viscoelastic variable such as the complex viscosity, complex modulus and phase angle versus a range of temperature at constant frequency or loading time. The simplest benefit of isochronal plot is the relationship of viscoelastic variables at a range of temperature can be determined. **Figure 3** and **Figure 4** shows the isochronal plot of the complex modulus and phase angle versus temperature at the frequencies of 10 Hz or 1.59 rad for unaged and RTFO aged sample. The figure shows that the value of complex modulus is decreasing as the temperature increased. The difference of complex modulus between base asphalt binder and NSMB is higher at intermediate temperature but become lower at higher temperature after 64°C. Besides that, the complex modulus of NSMB is higher than the base asphalt binder. The higher value of complex modulus indicates that the binder has high potential to resist rutting. Therefore, NSMB has better performance compared to the base asphalt binder. Lower and higher value of phase angle represents elastic and viscous property of asphalt binder respectively. The typical asphalt binder has a phase angle between 0 and 90°C at a high-performance temperature. As shown in **Figure 3** and **Figure 4**, the phase angle lies between 60°C to 90°C. The phase angle of asphalt binder increased as the test temperature increase. Moreover, it is noted that the NSMB has a lower phase angle than base asphalt binder and exhibit more elastic and greater rutting resistance. Comparing unaged and RTFO aged samples, the complex modulus increased significantly while, the phase angle decreases slightly and this indicates that the stiffness of the binder increased after aging by RTFO. From both results of complex modulus and phase angle of unaged and RTFO aged, the NSMB 2% sample shows the most pronounced increase in complex modulus and decrease in phase angle, thus leading to the most strongly improved temperature susceptibility among all NSMB samples.

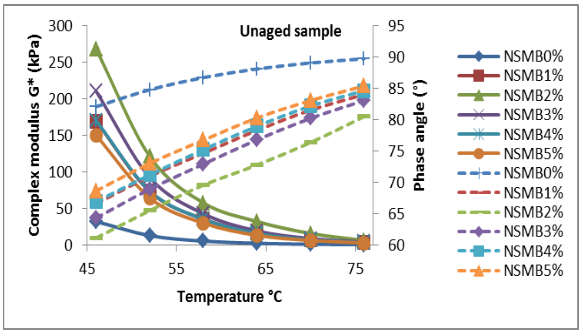

Figure 3: Isochronal plot of the complex modulus and phase angle at 10 Hz for unaged sample

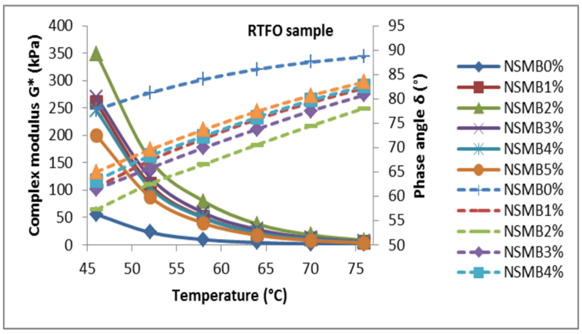

Figure 4: Isochronal plot of the complex modulus and phase angle at 10 Hz for RTFO sample

3.3.2. Rutting resistance

For further evaluation of rutting resistance of the asphalt binder at high temperature, the ratio G*/sinδ is commonly used. The G*/sinδ is defined as the stiffness indicator for evaluating the rutting resistance of asphalt binder [13]. The Superpave technique requires G*/sinδ = 1 kPa for unaged sample and G*/sinδ = 2.2 kPa for the RTFO sample as the minimum rutting parameter (Khadivar and Kavussi, 2013). As shown in Figure 5 and Figure 6, the G*/sinδ values of NSMB reduced as the temperature increased from 46°C to 76°C. From the figures, all the NSMB passed the minimum value of G*/sinδ (1.0 kPa) for all testing temperatures, while the value of G*/sinδ for based asphalt binder achieved 1 kPa after the test temperature reached 72.2°C. Similar trends for NSMB after RTFO aging can be observed in Figure 6. Again, all the NSMB passed the minimum value of G*/sinδ (2.2 kPa) for all testing temperature for RTFO sample. The value of G*/sinδ for base asphalt binder achieved 2.2 kPa after 69.6°C. Comparing the values of G*/sinδ between for both unaged and RTFO aged samples, NSMB 2% has the highest value compared to other sample for all testing temperature.

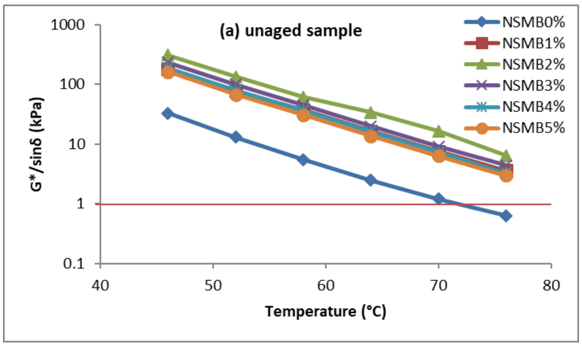

Figure 5: Rutting parameter (G*/sinδ) vs temperature of NSMB unaged sample

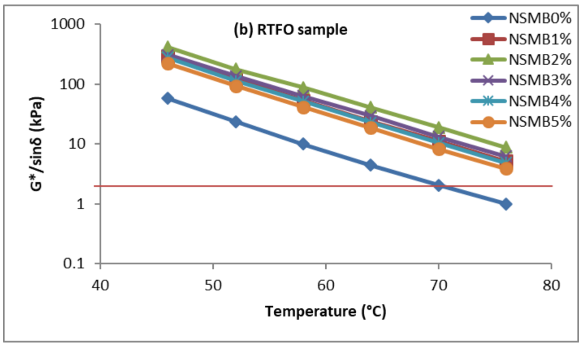

Figure 6: Rutting parameter (G*/sinδ) vs temperature of NSMB RTFO sample

3.4. Multiple stress creep and recovery

3.4.1. Strain

Figure 7 represents an example of one cycle of strain output from MSCR of NSMB. Figure 8 – Figure 10 showed the typical strain outputs from MSCR testing of NSMB at different testing temperature for the whole cycles. In this paper, two stress levels of 100 Pa and 3200 Pa was used. The first 100 s represents low stress level and next 100 s represent a high stress level as shown in Figure 8 - Figure 10. The MSCR test result included two phase which is creep phase and recovery phase to complete one cycle. At one-second creep phase, the strain was increasing under loading. At 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. This MSCR test result is a reflection of the visco-elastic-plastic property of asphalt binder; where this can be explained that, when the load is removed, the elastic strain recovered quickly, while the viscous strain recovered slowly [14].

From Figure 8 - Figure 10, it could be seen that the accumulated strain at low stress level is lower than accumulated strain at high stress level. This indicates that, with the increasing stress level, the accumulated strain also increased. With the addition of NS into base asphalt binder, the accumulated strain was significantly reduced. This indicates that NS improved the stiffness of the asphalt binder at high service temperature. Besides that, it can be observed that the accumulated strain increased when the temperature increased. The increase can be seen clearly, especially for NSMB-0%. Additionally, the rapid increase in strain of NSMB-0% could indicate that it has higher temperature susceptibility compared to other NSMB. By comparing the effect of NS percentage, it could be seen that NSMB-2% has the lowest accumulated strain than other percentages of NSMB.

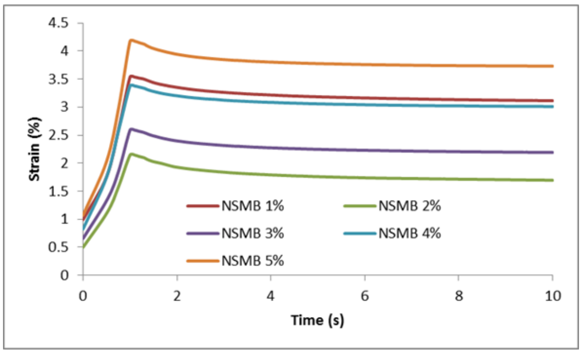

Figure 7: Strain versus time of MSCR testing for one cycle at 100 Pa

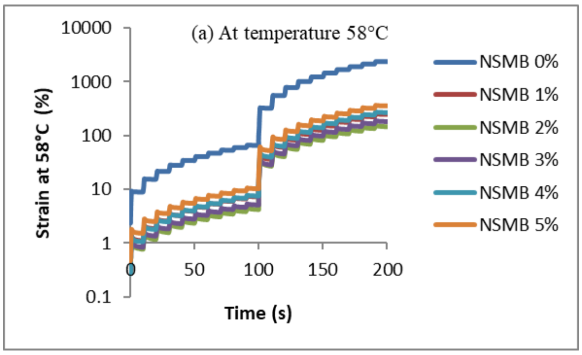

Figure 8: MSCR result at temperature 58°C

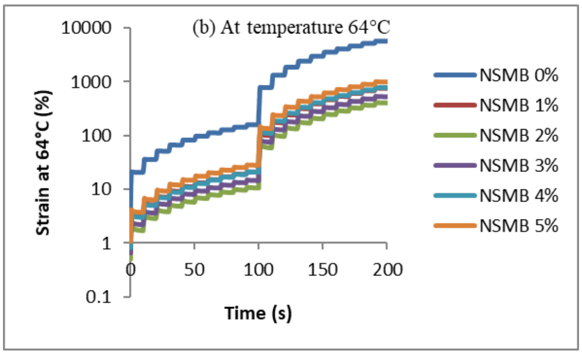

Figure 9: MSCR result at temperature 64°C

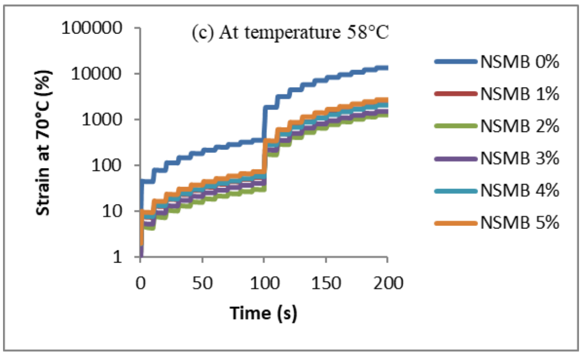

Figure 10: MSCR result at temperature

3.4.2. Nonrecoverable creep compliance

The non-recoverable creep compliance (J_{nr}) parameter was used to measure the resistance against rutting performance of asphalt binder at high temperature under repeated load. Lower value of J_{nr} indicates better resistance to rutting performance and higher value of J_{nr} indicates poor resistance to rutting performance. Figure 11 and Figure 12 shows J_{nr} results for NSMB at stress levels of 100 Pa and 3200 Pa for different test temperature. The results show that the trends of the bar chart are similar at both stress levels. J_{nr} increased slightly as the level of stress changed from 100 Pa to 3200 Pa. Besides that, the bar chart in Figure 11 and Figure 12 shows the J_{nr} increased as temperature increased. The increasing value of J_{nr} was more pronounced for the temperature of 70^0C. In addition, the NSMB reduced the value of J_{nr} compared with the base asphalt binder. The value of percentage difference between NSMB and base asphalt binder proved that the addition of NS reduced the value of J_{nr} and indicated that rutting resistance of asphalt binder improved.

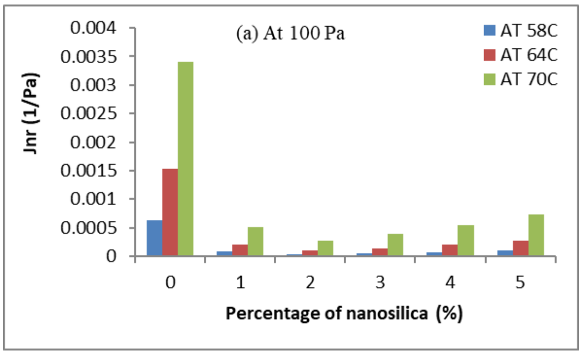

Figure 11: Jnr of NSMB at different temperature at 100 Pa,

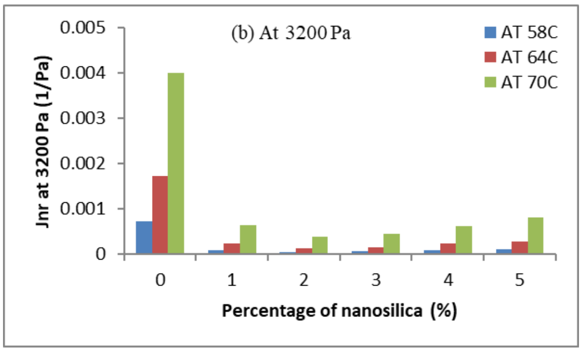

Figure 12: Jnr of NSMB at different temperature at 3200 Pa

3.4.3. Elastic response

The percentage recoverable strain (%R) was used to determine the elastic behaviour of asphalt binder under loading. It is an important parameter to evaluate the ability of asphalt binder to recover after deformation. The higher percentages of %R of asphalt binder indicate the lower possibility to permanent deformation and vice versa, the lower percentages of %R indicate the higher possibility to permanent deformation. The %R showed an inverse relationship with Jnr. Figure 13 and Figure 14 show the %R of NSMB for different temperature at stress level of 100 Pa and 3200 Pa. As it can be seen, the NSMB a higher value of %R compared to the base asphalt binder. Comparing the results at the two stress levels, the value of %R slightly decreased at 3200 Pa compared to the value at 100 Pa. Thus, this indicates that the additional of small percentage of NS improved elastic recovery of asphalt binder and improves it rutting resistance. Moreover, various temperatures also give an effect to %R value where the value of percent recovery decreased as temperature increased. Saboo and Kumar [15] reported that if a binder has at least 20% recovery irrespective of any stress level or temperature, this will indicate the presence of delayed elastic behavior. From the Figure 13 and Figure 14, the black line shows the min %R. It was found that, only NSMB-2% and NSMB-3% at 58°C for both stress level passed the minimum strain recovery.

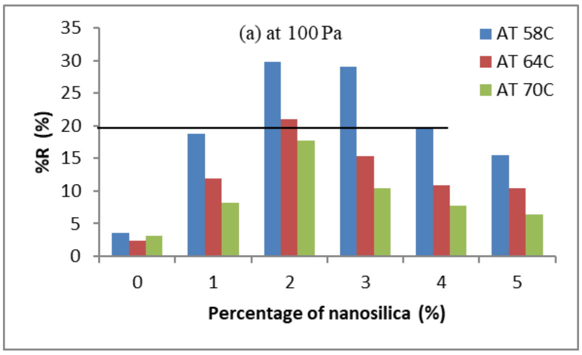

Figure 13: %R at different temperature at 100 Pa stress level

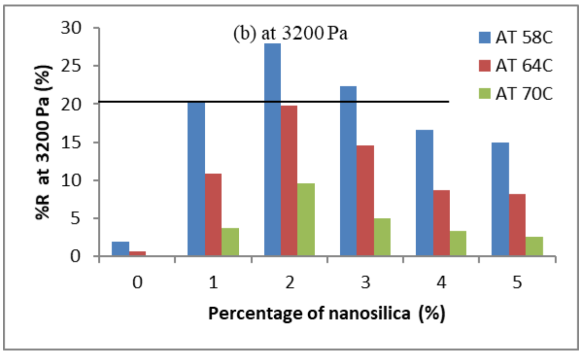

Figure 14: %R at different temperature at 3200 Pa stress level

3.5. Asphalt Pavement Analyzer

Figure 15 and Figure 16 shows the rutting depth vs number of cycle and rutting depth vs percentage of nanosilica respectively. From the figure, the results showed that the rutting depth of NSMB mixture was lower than rutting depth of the base asphalt mixture. This result indicates that the addition of NS into an asphalt binder reduced the rutting depth. The lowest rut depth was found in mixture with NSMB 2% mixture which is 1.493 mm, followed by NSMB 1%, NSMB 4%, NSMB 5%, NSMB 3% and NSMB 0% which are 1.767 mm, 2.2 mm, 2.321 mm, 2.637 mm and 2.851 mm. Thus, it can be concluded that mixtures containing NSMB 2% produce better rutting resistance.

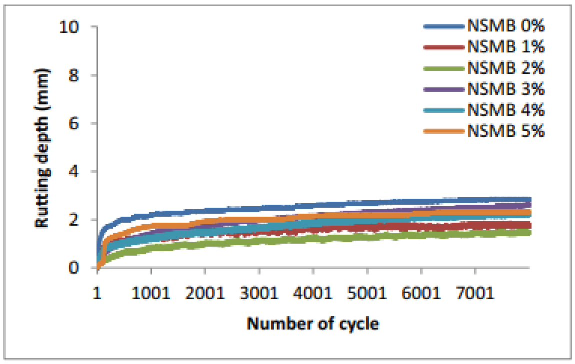

Figure 15: Rutting depth vs number of cycles

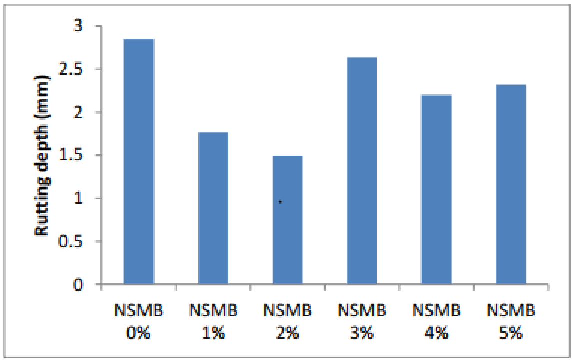

Figure 16: Rutting depth vs percentage of nanosilica

3.6. Ranking of the overall test result

From the overall test result and analysis, scoring and ranking method was developed in order to determine the best NS concentration for asphalt binder modification. Table 5 shows the result of scoring and ranking. The scoring was given a value from 1 to 6, whereby 6 is the best score and 1 is the worst score. From Table 5, NSMB2% is ranked first, followed by NSMB4%, next NSMB3% is ranked third, NSMB1% is fourth rank, NSMB5% is fifth rank and NSMB0% is ranked last. The scoring results suggest that NSMB2% and NSMB4% is the most suitable concentration to be used as bitumen modifier. From this result, the study found that by using nanomaterial (NS) only a small amount was required to modify the asphalt binder which is about 2% by weight of the binder.

Table 5: Ranking of NSMB

Type of test	NSMB 0%	NSMB 1%	NSMB 2%	NSMB 3%	NSMB 4%	NSMB 5%
Softening point	1	2	4	5	6	3
Penetration	1	2	3	4	6	5
Viscosity	1	2	3	4	6	5
Atomic Force microscopy	1	5	6	2	3	4
G*/sinδ (DSR)	1	4	6	5	3	2
J_{nr} (MSCR)	1	4	6	5	3	2
Rutting depth (APA)	1	5	6	2	4	3
Total score	7	24	34	27	31	24
Final ranking	**6**	**4**	**1**	**3**	**2**	**5**

Note 6 = best score, 1 = worst score

4. Conclusion

The following conclusions can be drawn from this research;

a) The result obtained from physical properties shows that the addition of NS significantly reduces the penetration and ductility of base asphalt binder. In other words, NS improved the softening point and viscosity of base asphalt binder. It was also found that all NSMB are stable during the high temperature storage period where the temperature difference between top and bottom was below than 2.2°C.
b) From the SEM images, NS particles dispersed well in base asphalt binder. AFM images showed that the typical bee structure (catana phase) existed and definitely improved its surface stiffness.
c) The addition of NS significantly increased the G*/sinδ value and failure temperature of asphalt binder which exhibits higher elasticity and beneficial in increasing the rutting resistance compared to the base asphalt. The effect of the NS on the rutting performance of asphalt binder was also tested using MSCR. The addition of NS in the base asphalt binder decreased the strain values significantly. Besides that, the non-recoverable creep compliance (Jnr) also decreased, while percentage recovery increased. Thus, this indicates that high temperature stability and elasticity of NSMB improved.
d) The study has evaluated the performance of rutting for asphalt mixture with NSMB. The additions of NS decrease the rutting depth. This indicated that the rutting resistance was increased by using NS as a binder modifier
e) The overall testing involved in this study were ranked to determine the optimum percentage of NS, then this study concluded the NSMB 2% was the optimum percentage.

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