

Dynamic modulus of nanosilica modified porous asphalt

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Abstract. Porous asphalt (PA) is a flexible pavement layer with high interconnected air void contents and constructed using open-graded aggregates. Due to high temperature environment and increased traffic volume in Malaysia, PA may have deficiencies particularly in rutting and stiffness of the mix. A possible way to improve these deficiencies is to improve the asphalt binder used. Binder is normally modified using polymer materials to improve its properties. However, nanotechnology presently is being gradually used for asphalt modification. Nanosilica (NS), a byproduct of rice husk and palm oil fuel ash is used as additive in this study. The aim of this study is to enhance the rutting resistance and stiffness performance of PA using NS. This study focused on the performance of PA in terms of dynamic modulus with the addition of NS modified binder to produce better and more durable PA. From the result of Dynamic SPT Test, it shows that the addition of NS was capable in enhancing the stiffness and rutting resistance of PA. The addition of NS also increase the dynamic modulus value of PA by 50%.

1. Introduction

Malaysia is a tropical country which have a rainy season along the year. Rainfall is well known as a main contributor to the occurrence of various problems for asphalt pavement. Such problem include water ponding above the pavement, which cause splashing and skidding for the road users, leading to accidents and traffic congestion. These problems are closely related to traffic safety which is a highly concerned issue to the people and governments all over the world. Thus, porous asphalt (PA) is introduced to overcome these problems. PA is well-known for its advantages in improving skid resistance of pavement during rain, reducing splashing effects, and producing lower riding noise [1]. These advantages are due to the high porosity possessed by the pavement layer which allows for high drainage capability of surface run-off. However, due to the high porosity, water tends to flow inside the pavement, which may cause moisture penetration, raveling, loss of stability and load bearing capacity of PA [1]. This will result in the loss of adhesive bonding between aggregate and binder which. Besides that, rutting easily develops due to the lack of strength of PA layer [1]. Thus, the binder used should be strong enough to provide adequate bonding to the aggregate especially for PA. In addition, although PA is considered as a non-structural layer in flexible pavement, porous asphalt is still the uppermost layer of pavement. Thus, it deteriorates and defects such as rutting and fatigue cracking occur due to the imposed traffic loadings and effects of the environment. Main parameter that usually used to measure rutting resistance of PA is dynamic modulus.



Dynamic modulus measures the stiffness and viscoelastic properties of the asphalt concrete mixes. The protocol of dynamic modulus defines as a linear viscoelastic test for asphaltic materials. Typically, mixtures with higher dynamic modulus values tend to have better rutting resistance [2,3]. Besides that, the stiffness value (dynamic modulus) is a key property of the material to evaluate strains and displacements in any pavement or road structures [2-3]. In addition, the mixtures with a softer asphalt binder revealed a lower dynamic modulus compared to those with a stiffer asphalt binder [4]. Brown *et al.* [5] stated that the evaluation of dynamic modulus of asphalt mixture has significant relationship with various aggregate structures. A study by Apeagyei [6] also reported that there was a good correlation between dynamic modulus and rutting.

One of the way to enhance dynamic modulus of PA is by binder modification. Previously, binder is modified using polymers such as SBS, SBR, EVA and EGA. However, these types of binder modifiers have several weaknesses such as low ageing resistance and poor storage stability [7]. Therefore, there is a need to improve binder modification to overcome those problems. Other than polymer modifier, nanomaterials is also can be used to improve the properties of asphalt binder. In this regard, this study focused on the usage of the nanoparticle technology as an additive for the binder to overcome the permanent deformation and at the same time preserve the drainage capability of PA.

2. Experimental Plan

2.1. Material selection

Porous Asphalt grading A and B as per PWD Malaysian Specification for Road Works [8] were used for this study. The weight of aggregate for each sample was approximately 1100 g. PEN 60-70 type of binder was used and the binder was mixed with different proportions of nanosilica (NS) ranging from 1 to 6 % by weight of binder. NS used was in colloidal form with the average size within 10 to 15 nanometer (nm). Figure 1 below shows the aggregate gradation for PA Grading A and B in accordance to PWD Malaysia Standard Specification while table 1 shows the properties of NS used in this study.

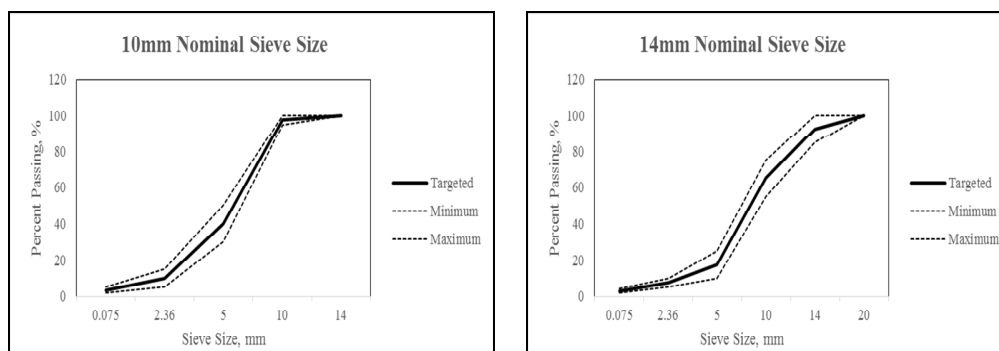


Figure 1. Aggregate gradation for PA.

Table 1. Specification of nanosilica.

Properties	Value
Appearance	Slight Milky Transparent
SiO ₂ (%)	30%
Na ₂ O (%)	0.5%
pH	8.5-10.5
Density	1.19-1.22 g/cm ³
Particle Size	10-15 nm

2.2. Binder modification

During modification process, NS was mixed in a reactor with continuous stirring. In this study, a control binder (Penetration Grade Pen 60-70) was used to prepare the modified binder. The binder then was heated at 160°C. The NS blends were then be transferred to the hot-melted asphalt and mixed with continuous stirring at 1800 rpm. This process was continued for one hour to obtain nano-modified asphalt binder. The asphalt binder was blended with 0% to 6% NS in increments of 2% by weight of the binders.

2.3. Design binder content

There are three main processes to obtain Design Binder Content (DBC) for porous asphalt, which are air void determination, lower limit determination and upper limit determination [8]. Air void determination was calculated based on the volumetric properties of PA. Among the volumetric properties are Theoretical Maximum Density (G_{mm}) and Bulk Specific Gravity (G_{mb}), Void in total Mix (VTM), Void in Mineral Aggregate (VMA) and Void filled with Asphalt (VFA). Then, Lower Limit and Upper Limit value of DBC are based on Cantabro Loss Test and Binder Draindown Test.

45 samples of PA (1100g per sample) for each grading were prepared for DBC determination. Fifteen samples were used for Cantabro Test, fifteen samples were used for Binder Draindown and another 15 samples were used for the determination of G_{mm} & G_{mb} . Samples for Cantabro Test and G_{mb} were compacted with 50 blows of Marshall hammer at every side based on Marshall mix design in accordance with [8] while loose samples were prepared for Binder Draindown test and G_{mm} .

The lower limit for design binder content is the average loss of mass in Cantabro test, where it should not more than 15%. In addition, the average air voids shall be less than 25% but shall not less than 18%. For the upper limit of design binder content, the average binder draindown shall not exceed 0.3% of total weight of the specimen [8].

The mean value from these limits were taken as initial design binder content. Each of design binder contents was tested and the binder content that meets all criteria was selected as Design Binder Content (DBC). Then, the same process were repeated to obtain DBC for 2%, 4% and 6% NS-PA.

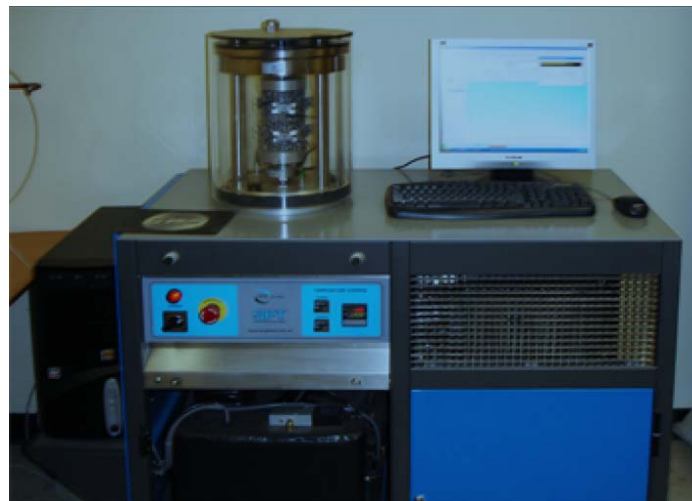
2.4. Dynamic SPT test

Dynamic Modulus Test is crucial to indicate the engineering properties of porous asphalt, especially to evaluate the resistance of porous asphalt towards permanent deformation. Simple Performance Tester (SPT) equipment was used to evaluate dynamic modulus of PA incorporated with various amount of NS (0%, 2%, 4% and 6% NS-PA). A total of 24 Superpave samples with two porous asphalt gradation (GA and GB) were prepared for this test. Each sample was approximately 5000 g in weight with 150 mm in diameter and 165 mm in height. After compaction and cooled to room temperature for 24 hours, the specimens were cored and trimmed from the centre of gyratory compacted specimen. The axial deformations were measured with displacement transducers referenced to gauge points connected to the specimens.

Prior to testing, the specimens must be placed in the testing chamber until the effective temperature, contact stress and confining pressure were achieved. To begin the test, the LVDTs were zeroed, and minimal contact load was applied to specimen. A sinusoidal compressive load was applied on the specimen in a cyclic manner. Three Linear Variable Displacement Transducers (LVDT) were placed at 120 degrees on the specimen surface to capture full range accumulation of the compressive permanent deformation. A continuous uniaxial sinusoidal (haversine) compressive stress at a specified test frequency is applied to the unconfined cylindrical test specimen in a cyclic manner. The dynamic load was properly adjusted during the tests to keep the strain level between 75 to 125 microstrain. The strain level should be checked after completion of the test, otherwise the dynamic pulse load is increased or decreased to adjust the strain to be within the limits. Each specimen was tested at five different temperatures and six frequencies for each test temperature as shown in table 2 while figure 2 shows the SPT machine.

Table 2. Dynamic SPT test condition.

Parameters	Values
Temperature (°C)	25, 30, 35, 40 and 45
Frequency (Hz)	25, 10, 5, 1, 0.5 and 0.1
Contact Load (kPa)	15
Axial Strains	75 to 150 microstrains
Dynamic Stress (kPa)	100

**Figure 2.** Dynamic SPT Machine.

3. Result and discussion

3.1. DBC determination

There are three main criteria used for DBC determination which are air void determination, lower limit determination and upper limit determination.

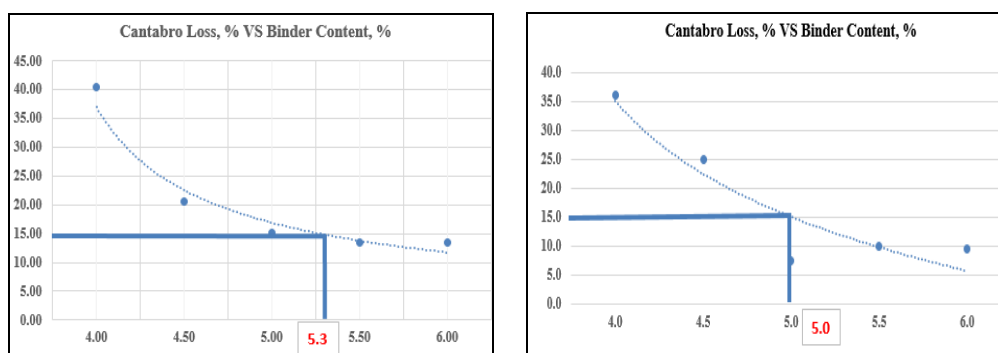
3.1.1. Air void determination .Air void content of bituminous material is significant to control the quality of asphalt binder for being laid and compacted in the field especially in constructing porous asphalt pavement. G_{mm} and G_{mb} were calculated to determine value of air void. For PA Grading A (PA-GA), the air voids for 4.0, 4.5, 5.0, 5.5 and 6.0 % of binder were 19.54, 19.40, 19.91, 21.13 and 20.97 % respectively. For PA-GB, the air void values were 19, 18, 16, 18 and 18 % respectively. Thus, all the design mixtures in this study met the requirement stated by PWD Malaysian Specification for PA. Table 3 shows the summary of air void value for both PA-GA and PA-GB. From the result, air void value for each binder percentages were in the range of the requirement stated in PWD Malaysia's Specification for Road Works which was in between 18 to 25 %.

Table 3. Air void values.

Percentage of Binder (%)	Air Void (%)	
	GA	GB
4	19	19
4.5	19	18
5	20	16
5.5	21	18
6	21	18

3.1.2. Cantabro loss test. Fifteen numbers of samples per grading were prepared and tested using LA drum without steel balls subjected to 300 revolutions. The weight losses after the test were calculated in terms of percentages as Cantabro Loss value. The highest value of Cantabro loss for PA-GA and PA-GB were obtained at 4.0% binder content with 40.37% and 36% respectively. PWD Malaysian Specification stated that the average loss of mass in the Cantabro Test should not exceed 15%. Based on the result recorded, only 5.0% to 6.0% binder content met the requirement for both grading. The result pattern for PA-GB was also almost the same with PA-GA where the value of Cantabro Loss drop rapidly due the increment of binder percentage. In addition, at 5%, 5.5% and 6% binder content, the Cantabro loss values passed the minimum requirement.

The lower amount of losses indicates the stronger bond between aggregate and binder. Thus, this test was conducted to indicate the lower limit of binder content to obtain design binder content (DBC) of PA based on PWD Malaysian Specification. To obtain the lower limit of DBC using graph, the maximum value of average loss of Cantabro Test which is 15% was used by intersecting with graph plotted down to the binder content. From figure 3, the lower limit of DBC for PA-GA and PA-GB were 5.3% and 5.0% respectively.

**Figure 3.** Cantabro loss (PA-GA & PA-GB).

3.1.3. Binder draindown test. For this test, loose mixes of both grading were prepared and placed into wire basket in an oven for 3 hours. According to PWD Malaysian Specification, binder draindown value of porous asphalt should not exceed 0.3% by weight of the total mix. From the result shown in table 4, the binder draindown obtained for 4.0, 4.5, 5.0, 5.5 and 6.0 % of binder content for PA-GA were 0.114, 0.157, 0.228, 0.415 and 0.326 % respectively, while 0.155, 0.123, 0.265, 0.486 and 0.323 % respectively for PA-GB. The occurrence of binder draindown would reduce the permeability of PA mix. A maximum draindown of 0.3 % by weight of total PA mix is typically the maximum allowable value for PA mix draindown. Thus, only 5.5% and 6% binder content exceeded the limit for both grading. This maximum value was used to determine the upper limit of DBC as shown in figure 4.

Based on this figure, the upper limit of DBC for PA-GA and PA-GB were 5.4 % and 5.1% respectively. From both tests, DBC values for PA-GA and PA-GB were 5.35% and 5.05% respectively. Cantabro Loss Test and Binder Draindown Test were repeated to obtained the DBC values for 2%, 4% and 6% NS-PA. Table 5 summarises the DBC values for all the NS-PA mixes that were used in this study.

Table 4. Binder draindown values.

Percentage of Binder (%)	Binder Draindown (%)	
	GA	GB
4	0.114	0.155
4.5	0.157	0.123
5	0.228	0.265
5.5	0.415	0.486
6	0.326	0.323

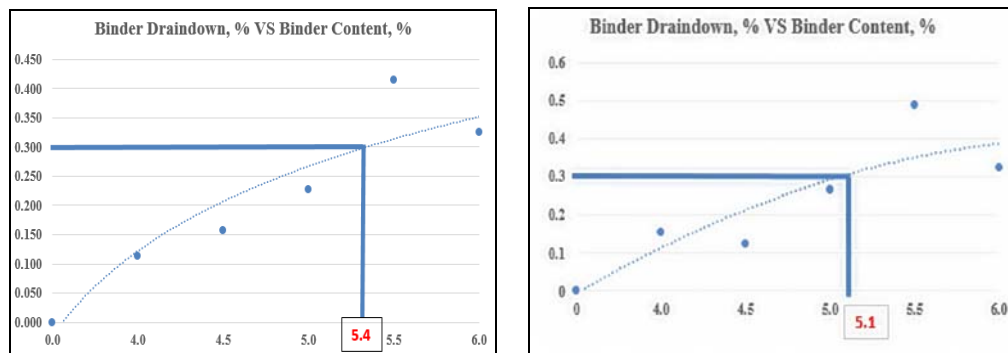


Figure 4. Binder Draindown (PA-GA & PA-GB).

Table 5. Summary of DBC values.

NS-PA	Design Binder Content (%)	
	GA	GB
0	5.35	5.05
2	5.22	4.93
4	5.16	4.87

3.2. Dynamic SPT test

The dynamic modulus evaluation of NS-PA with various frequencies and temperatures was conducted using Simple Performance Test (SPT) machine. This test is essential to evaluate the effect of stiffness characteristic for NS-PA at different temperatures. Dynamic modulus is a mechanically based laboratory test that is carried out to characterise the strength and load resistance of hot-mix asphalt (HMA) mixes including PA mixtures. This test was carried to further analyse the performance, PA mixture characteristics and also identify any possible relationship between the other performance tests of PA with the dynamic modulus values of NS-PA mix.

In this test, five test temperatures (25°C, 30°C, 35°C, 40°C and 45°C) at six different frequencies for each temperature level (20 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz and 0.1 Hz) were performed for both NS-PA grading A and B with various amount of NS (0%, 2%, 4% and 6% NS).

Figure 5 and 6 illustrate the Dynamic Modulus graph versus frequency for all NS-PA at 25°C and 45°C for NS-PA Grading A and NS-PA Grading B respectively. The dynamic modulus values for all mixes show a similar trend of decreasing value as the frequency decrease at increasing test temperature. In terms of different grading, both NS-PA-GA and NS-PA-GB produced almost the same maximum dynamic modulus values which were 7442 MPa and 7102 MPa respectively. In addition, all modified NS-PA (2%, 4% and 6% NS-PA) produced higher dynamic modulus values compared to unmodified specimens (0% NS-PA). This shows that the addition of NS was capable in enhancing the resistance of PA towards distresses and permanent deformation such as rutting and fatigue cracking.

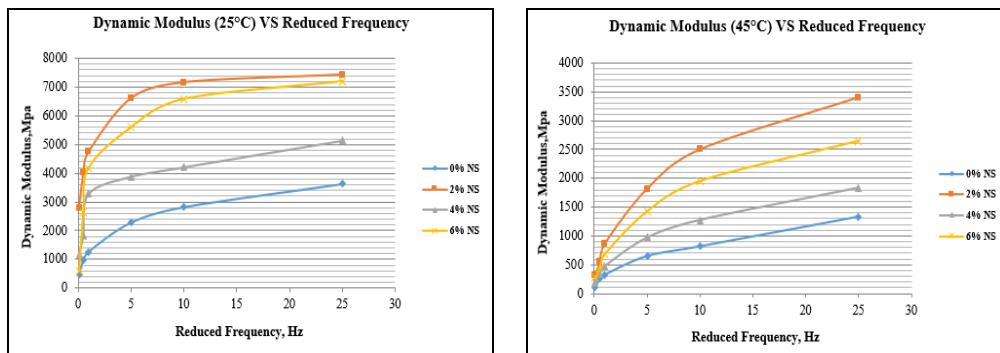


Figure 5. Dynamic modulus for NS-PA-GA.

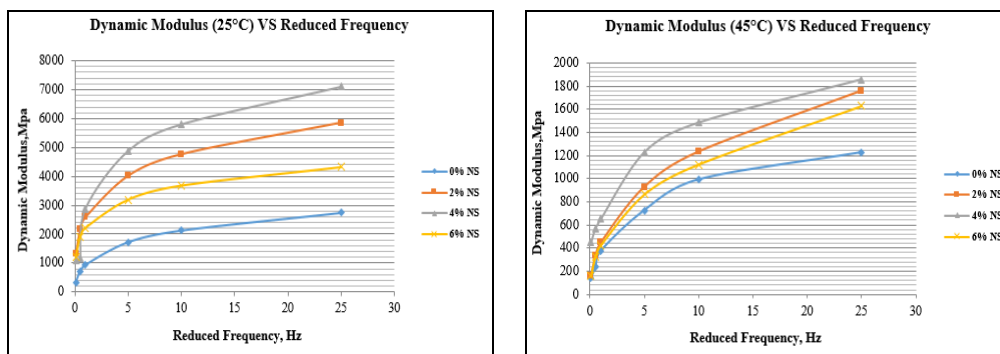


Figure 6. Dynamic modulus for NS-PA-GB.

The values of dynamic modulus for all NS-PA were decreased at high temperatures (35°C to 45°C) especially for NS-PA-GB where the values of dynamic modulus decreased more than 50%. This finding proved that PA mixture was very prone to high temperature. This may be due to the softening of the asphalt binder that cause the reduction of stiffness for NS-PA mixtures. When the stiffness decreases, the PA structure become unstable and reduce the resistance towards distresses. Hence, the dynamic modulus value will drop. Figure 7 shows the dynamic modulus values with different test temperatures.

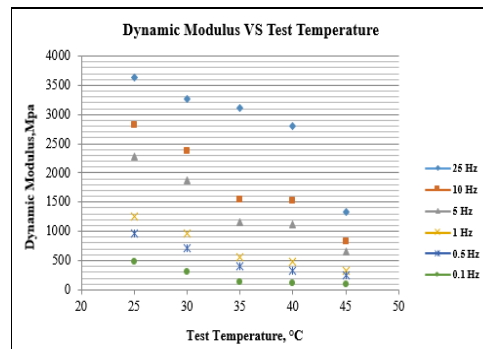


Figure 7. Dynamic modulus vs test temperatures.

4. Conclusion

Based on Dynamic SPT Test, the existence of NS was capable in enhancing the stiffness properties of PA, thus increasing the resistance towards permanent deformation. The results showed that the addition of NS was capable in increasing the dynamic modulus value for about 50% for both gradation of PA. This shows that NS was capable in providing PA with adequate rutting resistance.

5. References

- [1] Liu Q and Cao D 2009 Research on material composition and performance of porous asphalt pavement, *J. of Mater. in Civil Engineering* **21**(4) 135–140
- [2] Xie J, Wu S, Lin J, Cai J, Chen Z and Wei W 2012 Recycling of basic oxygen furnace slag in asphalt mixture: Material characterization & moisture damage investigation, *Constr. Build. Mater.* **36** 467–474
- [3] Goh S W and You Z 2012 Mechanical properties of porous asphalt pavement materials with warm mix asphalt and RAP, *J. of Transportation Engineering* **138**(1) 90–97
- [4] Marasteanu M O and Clyne T R 2006 Rheological characterization of asphalt emulsions residues, *J. of Mater. in Civil Engineering* **18**(3) 398–407
- [5] Brown B E R, Kandhal P S K, Lee D Y and Lee K W 1996 Significance of tests for highway materials, *J. of Mater. in Civil Engineering* **8**(1) 26–40
- [6] Apeagyei A K 2011 Rutting as a function of dynamic modulus and gradation, *J. of Mater. In Civil Engineering* **23** 1302-1310
- [7] Zhu J, Birgisson B and Kringos N 2014 Polymer modification of bitumen: Advances and challenges, *European Polymer Journal* **54** 18-38
- [8] JKR/SPJ/2008 2008 *Standard Specification for Road Works* (Kuala Lumpur: Public Works Department)

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