Jurnal
Teknologi

Full Paper

MECHANICAL PROPERTIES OF POROUS ASPHALT WITH NANOSILICA MODIFIED BINDER

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Article history
Received
2 December 2015
Received in revised form
13 March 2016
Accepted
31 March 2016

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Graphical Abstract

Abstract

This paper evaluates the mechanical properties of porous asphalt (PA) with nanosilica (NS) modified binder in terms of its Abrasion Loss, Binder Draindown, Resilient Modulus and Moisture Susceptibility. These tests are essential to evaluate the performance of NS-PA towards the resistance of moisture induced damage, external loads, abrasion and interlocking structure of PA. Due to porous nature of PA, it is expose to moisture damage and binder draindown. Besides that, raveling is another major problem that closely related to PA. Thus, nanotechnology was promoted in this study in order to enhance the performance of PA. Six different percentages of nanosilica were mixed with PEN 60-70 type of binder in this study. Then, all these blended modified binder were used to prepare PA samples using Marshall Mix Design Method. Nanoparticle used in this study was Nanosilica with the average size of 10 to 15 nanometer. Binder Draindown Test was done using a metal basket with 3mm perforation. Then, abrasion loss value was evaluated using Los Angeles Abrasion Machine without steel ball. In accordance to Public Work Department of Malaysia Specification (JKR/SPJ/2008), it is stated that binder draindown for PA should not be more than 0.3% of total weight of sample, while abrasion loss should not be more than 15% also by weight of total sample. The results for Cantabro Loss Test and Binder Draindown Test indicated that 4% NS was the effective amount of NS to reduce the abrasion loss and binder drained of NS-PA. The maximum resilient modulus value for NS-PA was 4362 MPa while TSR value 91% (2% NS). Meanwhile, for conventional PA (0% NS), resilient modulus value was only 3036 MPa and TSR value 74%. From both tests were also concluded that the optimum amount of NS required for PA to archieved both value was 2%. It can be concluded that with proper concentration, the existence of NS is capable to enhance the physical and rheological properties of asphalt binder and at the same time it dispersed well in asphalt binder. Thus, the performance of PA with NS modified binder is also enhanced.

Keywords: Resilient modulus, moisture susceptibility, binder draindown, cantabro loss, nanosilica, porous asphalt

1.0 INTRODUCTION

Porous asphalt (PA) has been well-known for its advantages in improving skid resistance of pavement during rains, reducing splashing effects, and producing lower riding noise [1]. These criteria made exist due to high porosity possessed by pavement layer which then allows for high drainage capability of surface run-off. PA generally has a total percentage of voids between the ranges of 20 % to 25 % which is relatively high compared to that conventional hot mixed asphalt. The high voids content in PA have been enabled through the use open-graded type of aggregates. Open gradation mainly consists of coarse aggregates with size dimension larger than 2.36 mm (No. 10 sieve) together with small amount of fine aggregates (not more than 15 %) and also mineral filler not exceeding 5 % of the total aggregate weight. Hence, this type of gradation produces relatively high interconnected air voids after compaction.

PA is one alternative [2] solution to the problem of storm water drainage from parking and other low traffic density areas. In operation, this type of pavement allows incipient rainfall and local runoff to soak through the pavement surface course of open graded asphalt concrete mix and accumulate in a porous base consisting of large open graded gravel from which the water would percolate into the natural ground below. They are used in wearing courses and always laid on impervious base course, was promising and effective in enhancing traffic safety [3].

PA has been well distinguished from the conventional asphalt layers due to its high percentage of interconnected air voids content. Porous asphalt has designated air voids content in range of 18 – 25 % and lay out as pavement uppermost layer with surface thickness of 4 – 5 cm [1]. Single-sized aggregate is a major constituent in porous asphalt which comprises 70 – 85 % of the total weight of coarse aggregate [4]. These properties has enabled for the porous asphalt to have excellent surface drainage capability, and therefore, providing better skid resistance (reduce hydroplaning) since no water film exist on the pavement surface during rains [1].

2.0 LITERATURE REVIEW

2.1 Binder Draindown

Binder Draindown Test will decide the upper limit of OBC for PA. According to Allex *et al.* [5], PA mixtures typically exhibited an asphalt binder film thickness of higher than the corresponding thickness for dense-graded HMA. This difference and the small fine aggregate content in PA mixtures (as compared to that of dense-graded HMA) lead to higher susceptibility for the asphalt binder to drain off the aggregate skeleton. The irregular distribution of asphalt binder generated by its draindown can lead to raveling in zones with low asphalt binder content and reduction of permeability in zones with accumulation of asphalt binder [5].

Binder draindown is also considered as the major problem of PA, since PA is having high air void content, thus the tendency for binder to flow through those air voids is high, resulting to binder drained off from the mix. This testing procedure entailed measuring the binder lost from the loose mix placed in a draindown basket and conditioned at the mixing temperature for 3 hours with the draindown being measured every hour. A maximum draindown of 0.3% by weight of total mix is typically the maximum value for draindown of a porous asphalt mix [6].

Kimberly and Bradley [6] were also studied the potential for binder draindown due to exposure to elevated temperatures over long periods of time. The specimens were conditioned in a 60°C chamber for 56-days and the porosity and permeability of each specimen was measured at specified intervals (7, 14, 28, 42, and 56 days) to determine the occurrence of binder draindown through the specimen, which would reduce the permeability. During conditioning, each specimen was wrapped using a galvanized steel hardware cloth to prevent deformation or collapse due to the high temperature conditioning. In addition, the top of the specimen remained the top for the entire 56-day conditioning period, so the binder would only be able to flow in one direction [6].

2.2 Cantabro Loss

Cantabro Test will decide the lower limit of OBC for PA. This test was developed to evaluate and control the raveling loss of PA under dry condition and soaked condition. Particle loss is one of the disadvantage of porous asphalt. This is also called raveling which is the loss of particles from the road surface. The raveling of PA is influenced by aging, low temperature, moisture and other factors. Therefore, it is necessary to investigate the raveling characteristic of PA in order to ensure the durability of PA. Cantabro Test is used to evaluate the particle loss resistance of porous asphalt concrete specimens. The test is done using Los Angeles Abrasion Machine without steel ball [7].

Allex *et al.* [8] stated that the Cantabro Test is the laboratory test most commonly used to evaluate durability for mix design and evaluation of PA mixtures In the Cantabro Test, a compacted specimen is placed in the Los Angeles abrasion machine (without abrasive load) and subjected to 300 revolutions. [9] also stated that the sample are placed in the Los Angles testing machine without steel ball and the machine is rotated at a speed of 30 to 33 revolutions per 7 minute for 300 revolutions. The Cantabro loss, expressed in percentage, corresponds to the ratio of lost weight to initial weight of the compacted specimen. The Cantabro loss is considered as an index of the mixture resistance to disintegration [5]. The disintegration resistance of PA has been evaluated using Cantabro Loss Test since many years ago [10].

2.3 Resilient Modulus

Stiffness characteristic of asphalt materials is determined through resilient modulus test. Janoo *et al.* [11] has conducted a standard and large-scale test which successfully proves that resilient modulus as a function of crushed aggregate constituent in asphalt mixture. Resilient modulus is least affected with high constituent of crushed aggregate (more than 75 %) in mixture but severely influenced if crushed aggregate is less than the given percentage. This implies that the application of angular-shaped aggregate is capable of improving resilient modulus of porous asphalt and simultaneously reduces the effect of voids ratio on resilient modulus value. Furthermore, increase in the crushed aggregate constituent can reduce asphalt layer deformation since a tougher mix is created [12].

Jemere performed the Repeated Load Indirect Tensile Test (RLITT) to determine the resilient modulus of the asphalt specimens [13]. The test is conducted at low stress levels not exceeding 10% of the failure stress to ensure linear response of the materials. Haversine loading 5 pulses with 3000 ms pulse repetition period are applied. The total recoverable diametrical strain is measured from an axis perpendicular to the applied load. The RLITT is performed with a Universal Testing Machine (UTM). The equipment has a temperature controlled chamber for maintaining constant temperature during the test. The specimens are conditioned at the testing temperature for a minimum of 3 to 4 hours before conducting the test. Cylinder shaped specimens with 100 mm diameter and 50 mm thickness are tested [13].

2.4 Moisture Susceptibility

Indirect tensile strength is a measurement on the elasticity behavior of asphalt pavement. It gives indication on how well will asphalt mixture able to resist the formation of failure cracks. In a study on indirect tensile strength properties of two different types of porous asphalt, mixture with high percentage of air voids (compacted in the laboratory) produces a relatively lower indirect tensile strength compared to that which has a more packed and denser aggregate gradation [14]. Furthermore, increase in the air void content causes a reduction in the amount of load cycles to be incurred by asphalt pavement, hence reducing its elasticity against permanent deformation [15]. This implies that particle-to-particle contact gives an enhancement in indirect tensile strength performance of porous asphalt.

The indirect tensile strength (ITS) of each mixture is measured after dry and wet conditioning. Two compacted specimens from each mixture are conditioned in air at 25 °C for 24 hours prior to testing the ITS (ITS dry) and two specimens are submerged in 60 °C water for 24 hours followed by 2 hours in 25 °C water before testing the ITS (ITSwet). Due to the porous nature of the specimens, it is not possible to attain the level of saturation required by typical test procedures similar to AASHTO Standards. Therefore, the saturation step is omitted with the reasoning that the specimen would easily become saturated just by soaking in the water bath. In addition to assessing the strength of the mixtures, the potential for moisture induced damage is also determined based on the tensile strength ratio (TSR). The minimum value for the TSR of porous asphalt mixtures varies by agency, but is typically required to be greater than or equal to 80% [6].

Xin stated that the indirect tensile stiffness modulus (ITSM) test can be conducted to evaluate the load spreading ability of mixtures in pavement [16]. The test results will shows the indirect tensile stiffness modulus. However, the evaluation of moisture susceptibility based on the retained tensile strength ratio (TSR) is recommended for PA mix design. Indirect tensile strength tests (ITS) is carried out to provide an indication of the mechanical performance of PA mixtures [17].

3.0 METHODOLOGY

3.1 Material

Porous Asphalt grading B were used for this study. The weight of aggregate for every samples were approximately 1100 g. PEN 60-70 type of binder was used and those binder was mixed with different proportion of 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). Table 1 below shows the aggregate gradation of the sample Grading B in accordance to PWD Malaysia Standard Specification while Table 2 shows the properties of NS used in this study.

Table 1 PA Grading B Aggregate Gradation

Sieve Size (mm)	Passing (%)	Retained (%)	Retained (g)
20	100	0	0
14	85-100	7.5	82.5
10	55-75	27.5	302.5
5	10-25	47.5	522.5
2.36	5-10	10	110
0.075	2-4	4.5	49.5
Filler		1	22
Lime		2	11

Table 2 Properties of Nanosilica

Properties	Value
Appearance	Slight Milky Transparent
SiO_2 (%)	30%
Na_2O (%)	0.5%
pH	8.5-10.5
Density	1.19-1.22 g/cm3
Particle Size	10-15 nm

To prepare NS modified binder, 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 mixing 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 1% by weight of the binders.

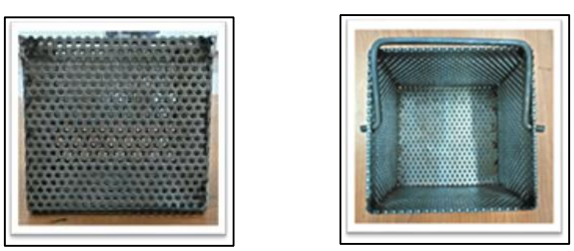
3.2 Binder Draindown

The amount of NS that were blended into binder were in the range of one to six percent (1%, 2%, 3%, 4%, 5% and 6%) by weight of binder. The determination of design bitumen content were performed through Marshall Mix Design Method. For this study, 5.00 % of Design Binder Content (DBC) was used as control sample of PA (0% NS). To obtain DBC, specimen that were tested had variations in the binder content (4 % to 6 % by weight and differ by 0.5 % increment). In each increment of the binder content, 3 specimens were be prepared, thus, making a total of 30 specimens for Cantabro Test and Binder Draindown Test (15 samples each test). For Cantabro Test, each specimen were subjected to 300 revolutions in the Los Angeles apparatus (LAAV) together with steel balls at temperature of 25°C. The analysis on the percentage of mass loss versus binder content reveals the lower limit of bitumen content. For Binder Draindown Test, the wire basket and the aluminum tray were used. The loose sample were tested by putting it into wire basket with 3mm perforation. Then, the samples were put into oven for three hours with the temperature of 180°C. The binder will flow through wire basket and drop onto the aluminum tray. The analysis on the mass retained versus binder content reveals the upper limit of bitumen content. Drained binder is essential to ensure the accuracy and reliability of upper limit DBC for PA [18]. Equation (2) was used to calculate the binder draindown while Figure 1 illustrate the binder basket (100mm×100mm×100mm) with 3mm perforation that was used for this test.

$$\text{Draindown, (\%)} = (D-C)/(B-A) \times 100 \qquad (1)$$

where,

A = Mass of Empty Wire Basket (g)
B = Mass of Wire Basket & Sample (g)
C = Initial Mass of Paper Plate (g)
D = Final Mass of Paper Plate (g)



a) Top View b) Side View

Figure 1 Binder Draindown Basket

3.3 Cantabro Loss

A total of 21 samples were prepared for this test, where 3 samples each for different percentage of NS ranging from 0 to 6 %. Those three samples were tested to obtain the average value of abrasion loss for each different proportion of NS. Those Marshall specimens were kept at a temperature of 25℃ for six hours before testing. The specimens were weighed after it had been kept for the specified time and placed into the Los Angeles machine without the steel balls. Then, the drum was switch on at a velocity between 188 and 208 rad/s and subjected to 300 revolutions without steel ball. The Cantabro Loss was determined using equation (1) and Figure 2 illustrates the Los Angeles Abrasion (LAA) Machine that was used to run this test.

$$\text{Cantabro Loss, (\%)} = (M_0 - M_1)/M_0 \times 100 \qquad (2)$$

where,

M_0 = Initial Mass of Specimen before Testing (g)
M_1 = Final Mass of Specimen (g)

Figure 2 LAA Machine

3.4 Resilient Modulus

Resilient Modulus Test is the test to measure the flexibility of PA. This test was carried out using a Universal Testing Machine (UTM-5P). This test is essential to evaluate the effectiveness of the elastic properties of PA under repeated loading. This test is also provides the stiffness characteristic of pavement construction materials under a variety of temperatures and stress states. It simulates the conditions in a pavement subjected to moving wheel loads. In addition, this test compared the behavior of pavement construction materials under a variety of conditions such as moisture, density, gradation and stress states.

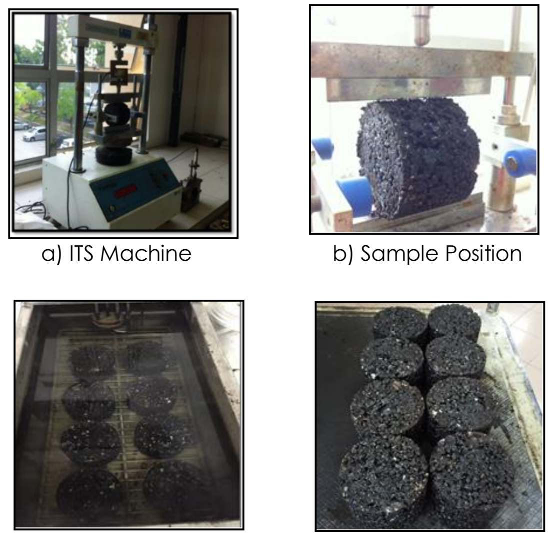
The resilient modulus test was performed on cylindrical PA specimens with 1100g in weight. A total of 12 samples were tested for this test, with 0% to 6% NS concentration were mixed with 2% increment. Each of PA specimen has the dimensions about 100 mm in diameter and 200 mm in height. The PA specimens were prepared using the Marshall Mix Design Method. The test temperature used was 25°C, where all the samples were conditioned for 3 to 4 hours with this temperature before testing. Figure 3 shows the Universal Testing Machine equipment and PA specimen's position for Resilient Modulus Test. During the testing configuration, the UTM applies through the actuator with the force required to reach the desired displacement. Then, the CDAS unit was continuously reads the force applied by the actuator. Forces were increased until the PA specimens bends to the required maximum strain.

a) UTM Machine b) Sample Position

Figure 3 Resilient Modulus Test

3.5 Moisture Susceptibility

For every NS concentration including the control PA (0%NS), the indirect tensile strength (ITS) of each mixture was measured after dry and wet conditioning. Three compacted specimens from each mixture were conditioned in air at 25°C for 24 hours prior to testing the ITS (ITS_{dry}) and another three specimens were submerged in 60°C water for 24 hours followed by 1 hour in 25°C water before testing the ITS (ITS_{wet}). This test is also known as Modified Lottman Test. Due to the porous nature of the specimens, it is not possible to attain the level of saturation required by typical test procedures similar to AASHTO Standards. Therefore, the saturation step was omitted with the reasoning that the specimen would easily become saturated just by soaking in the water bath. The ITS was measured by loading the specimens across the diametric plane and recording the peak load, then calculating the ITS. The samples were placed between the steel loading strips by loading the samples at constant head rate (50 mm/minute vertical deformation at 25°C) and maximum compressive force required to break the specimens were recorded. In addition to assessing the strength of the mixtures, the potential for moisture induced damage was also determined based on the Tensile Strength Ratio (TSR). The TSR was calculated as the ratio of the ITS_{wet} to the ITS_{dry}. In accordance to AASTHOT283, the minimum value for the TSR of porous asphalt mixtures varies by agency, but it is typically required to be greater than or equal to 80% [19]. Figure 4 illustrates the Modified Lottman Test. The maximum compressive load for every samples were recorded and the tensile strength of PA specimens were calculated using Equation 3. Lastly, the potential moisture induced damage for PA in accordance to its Tensile Strength Ratio (TSR) was obtained from Equation 4. TSR value will indicates the resistance of PA towards moisture damage. 80% TSR was used as the boundary between PA resistant and sensitive to moisture.



a) ITS Machine b) Sample Position

c) Wet Subsets d) Dry Subsets

Figure 4 Modified Lottman Test

$$S_t = 2P/\mu Dt \quad (3)$$

where,

S_t= Tensile Strength (Kpa)
P = Maximum Load (N)
T = Sample Thickness (mm)
D= Sample Diameter (mm)

$$(S_{t\ wet}/S_{t\ dry}) \text{ X } 100 \quad (4)$$

where,

$S_{t\ wet}$ = Average Tensile Strength of Wet Conditioned Subset (Kpa)
$S_{t\ dry}$ = Average Tensile Strength of Dry Subset (Kpa)

4.0 RESULTS AND DISCUSSION

4.1 Binder Draindown

4.1.1 Binder Draindown Vs Amount of NS

Figure 5 presents the percentage of binder draindown with the addition of different percentages of NS. The bar chart shows almost the same pattern as the cantabro loss bar chart. This indicates that the existence of NS enhance the bonding between binder and aggregates. The value of binder draindown was significantly reduced with the addition of 2-5 % NS. However, the addition of 1% NS and 6% NS gave almost similar value with control sample (0% NS). This indicates that the optimum proportion of NS to be mixed was around 2 to 5 % in order to reduce the binder draindown of PA. Figure 6 shows binder draindown value in gram where its ranges from 2 gram to 3.6 gram.

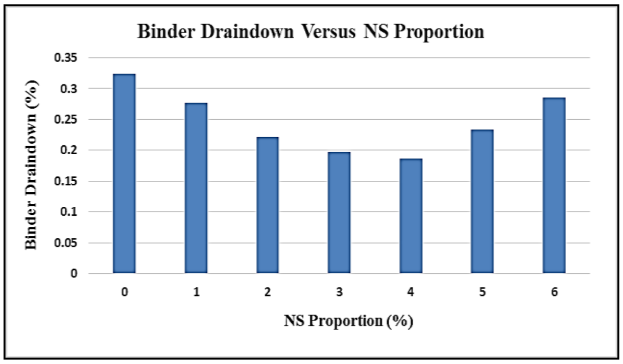


Figure 5 Binder Draindown (%) VS Amoount of NS (%)

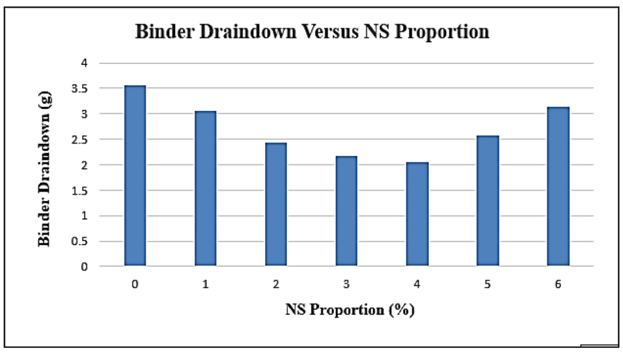
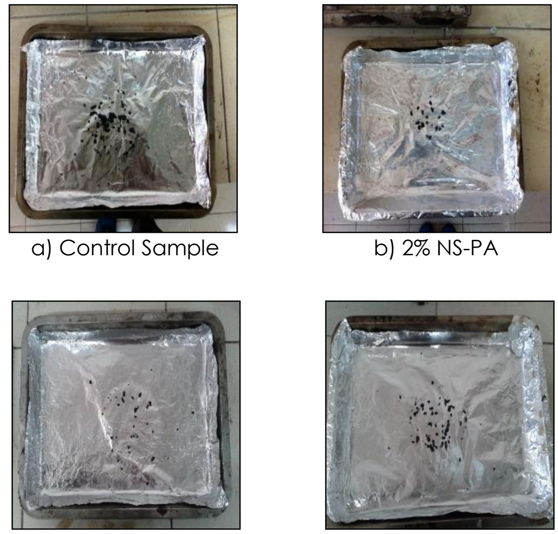


Figure 6 Binder Draindown (g) VS Amoount of NS (%)

4.1.2 Visual Observation

From visual observation, there was a significant difference of binder material drained for different proportions of NS. For control sample (0% NS), binder was drained together with fine particles. A study by Hamzah and Hassan [18] proved that binder was drained together with fine aggregates due to 3 mm perforation used for the binder basket. However, binder drained was lower with the increase in the amount of NS. This is shown in Figure 7, where less binder was drained for NS-PA compared to control sample (0% NS). In addition, based on visual observation, 4% NS was determined as the optimum amount to reduce the binder draindown of PA since a very little binder was drained compared to other samples. The trend was also consistent with the results discussed in the previous section where the addition of more than 6% NS increased the amount of binder drained.



a) Control Sample
b) 2% NS-PA
c) 4% NS-PA
d) 6% NS-PA

Figure 7 Visual Observation of Binder Draindown Test

4.2 Cantabro Loss

From Figure 8, it could be seen that different percentages of NS produced different values of Cantabro Loss. The control sample (0% NS) obtained the highest value of cantabro loss which was 17%, while the lowest cantabro loss value was 9% (4% NS). This happened likely due to the abrasion force between specimens and drum, resulting in disintegrated samples with certain amount loss [10]. The trend pattern of cantabro loss value also indicated that 3 to 5 % NS as the optimum amount to be utilized in order to reduce the abrasion loss of PA. The value of cantabro loss increased after the addition of 4% NS thus indicating that too much addition of NS is not suitable in enhancing the abrasion resistance of PA. Table 3 summarized the overall results for both tests.

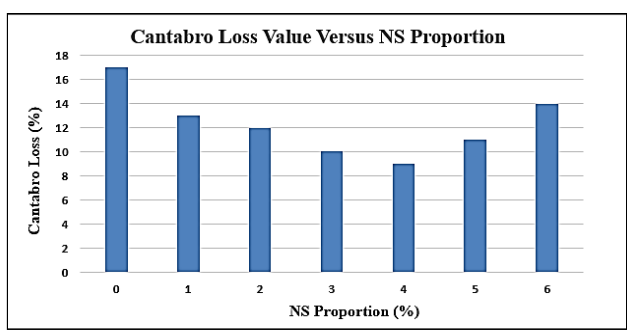


Figure 8 Cantabro Loss (%) VS Amount of NS (%)

Table 3 Result Summary

NS (%)	Cantabro (%)	Draindown (%)	Draindown (g)
0	17	0.324	3.564
1	13	0.277	3.047
2	12	0.222	2.442
3	10	0.197	2.167
4	9	0.186	2.046
5	11	0.234	2.574
6	14	0.285	3.135

4.3 Resilient Modulus

Based on the results, three mean values of Resilient Modulus (M_r) were obtained, based on three different testing points and pulse repetitions. Higher M_r value obtained at 1000 ms pulse repetitive period, where 2% NS-PA gave the highest value which was 4362 MPa, compared to control sample where M_r value was only 3036MPa. At 4% NS-PA and 6% NS-PA, the value of M_r were lower than 2% NS-PA which were 2971 MPa and 3728 MPa respectively. It shows that 2% NS-PA is the optimum amount of NS required to increase the Resilient Modulus of PA. Table 4 and Figure 9 represent the summary of the result for Resilient Modulus Test for PA different amount of NS.

Table 4 Mean Resilient Modulus, M_r

Sample	Point	Mean Pulse Repetitive Period (ms)		
		1000	**2000**	**3000**
0%	A	2992	2750	2658
	B	3283	3036	3070
	C	2833	3028	2913
	Mean Mr	**3036**	**2938**	**2880**
2%	A	5098	5154	5799
	B	4100	3285	3291
	C	3888	3856	3638
	Mean Mr	**4362**	**4098**	**4242**
4%	A	2943	2670	2597
	B	3760	3934	3623
	C	2211	1431	1602
	Mean Mr	**2971**	**2678**	**2607**
6%	A	2338	2383	3316
	B	4085	4080	4257
	C	4761	1815	2259
	Mean Mr	**3728**	**2759**	**3277**

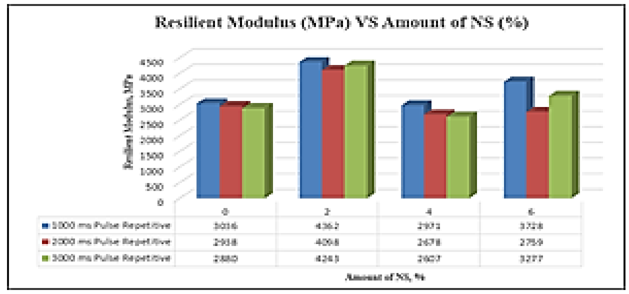


Figure 9 Resilient Modulus (MPa) VS Amount of NS (%)

4.4 Moisture Susceptibility

From Modified Lottman Test, the value of Maximum Applied Load (P) for every samples of PA was obtained, then this value was used to calculate the ITS and TSR values. From Figure 10, the highest ITS value for dry condition was at 6% NS-PA which was 477 kPa, followed by 4% NS-PA (450 kPa), 2% NS-PA (381 kPa) and the lowest value from control sample (0% NS-PA) which was only 298 kPa. The same trend also obtained from ITS value for wet condition, where the highest ITS at 6% NS-PA (388 kPa), followed by 2% NS-PA (347 kPa), 4% NS-PA (318 kPa) and again the lowest value was at 0% NS-PA (222 kPa). Theoretically, tensile strength indicates the cracking potential of PA, where higher tensile strength represents PA can withstand higher strain before failing, thus providing better crack resistant. From the ITS result, the value for wet condition samples were significantly lower compare to dry condition samples for every PA mix. This indicates that the existence of moisture reduce the tensile strength of PA, thus exposing the PA mix with cracking. It is also proved that the existence of moisture affect the performance of PA.

Tensile Strength Ratio is an essential indicator for PA whether PA can withstand moisture susceptibility or sensitive to it. Moisture susceptibility is also known as moisture induce damage or stripping. For PA, 70% TSR is acceptable due to its drainage capability. From Figure 11, the highest TSR value obtained at 2% NS-PA which was 91%, followed by 6% NS-PA 81%. For control sample (0% NS-PA) and 4% NS-PA, TSR value obtained were below 80% which were 74% and 71% respectively. But due to porous nature of PA, those value still acceptable. Thus, all the PA mix tested met the requirement and resist from moisture induce damage. Based on TSR value, the optimum amount of NS was 2%. It can be concluded that with proper concentration, the existence of NS in PA can significantly enhance the performance of PA especially in terms of moisture susceptibility. This is due to NS dispersed well inside binder, strengthened the interconnecting bonds between binder molecules, thus enhancing the cohesion and adhesion properties of PA mix.

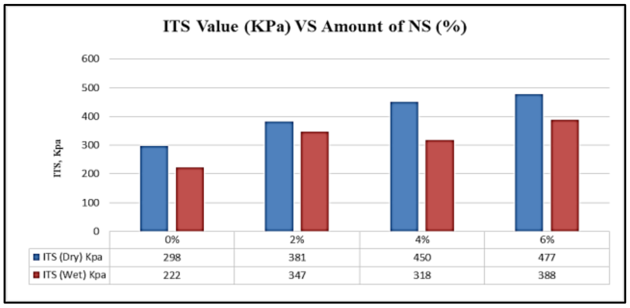


Figure 10 ITS Value (KPa) VS Amount of NS (%)

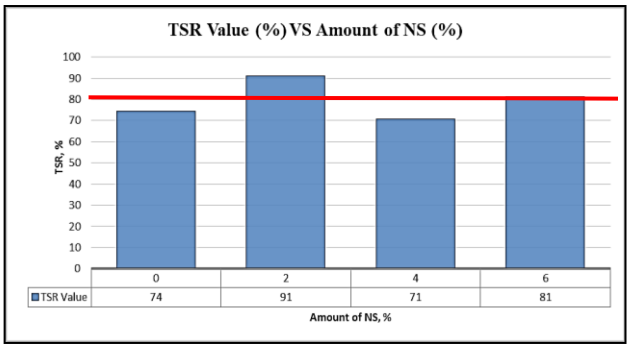


Figure 11 TSR Value (%) VS Amount of NS (%)

5.0 CONCLUSIONS

The findings of this study indicate that the existence of nanoparticle is capable of enhancing the performance of PA in terms of its abrasion resistance, binder draindown, Resilient Modulus and Moisture Susceptibility. Thus, the performance of PA with the addition of NS in the binder is also enhanced. From the results for all the tests conducted, a few conclusions have been made;

i. All 4 tests proved that 2% to 4% NS are considered as the effective amount of NS to be mixed with binder.
ii. The existence of 2% NS is capable in enhancing the Resilient Modulus of PA, where the percentage improvement was about 44%.
iii. Based on ITS value for NS-PA, the difference between wet and dry condition samples were insignificance, thus proved that Nanosilica was capable to provide PA with adequate resistance towards moisture damage.

Acknowledgement

The authors would like to acknowledge FRGS Research Grant, RMC, Uitm Shah Alam that has funded this study and that enables this article to be written. A sincere appreciation is also express to all the technicians and colleagues of Highway Engineering Laboratory at the Faculty of Civil Engineering, Uitm Shah Alam, Selangor.

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