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The Effects of Moisture Susceptibility and Ageing Conditions on Engineering Properties of Nanosilica-Polymer-Modified Asphalt Blended with High RAP Contents

Nur Izzi Md. Yusoff [1)], ***Ahmad Nazrul Hakimi Ibrahim*** [2)*], ***Amr Abdulrahman Aziz Salah*** [3)],
Abdul Wahid Mohammed Salah [4)], ***Faridah Hanim Khairuddin*** [5)],
Sri Atmaja P. Rosyidi [6)] ***and Naeem Aziz Memon*** [7)]

[1-5)] Dept. of Civil and Structural Engineering, Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia.
* Corresponding Author. E-Mail: ahmadnazrulhakimi@gmail.com
[6)] Dept. of Civil and Structural Engineering, Universitas Muhammadiyah Yogjakarta, Indonesia.
[7)] Dept. of Civil Engineering, Mehran University of Engineering and Technology, Jamshoro, Pakistan

ABSTRACT

The effects of mixing nanosilica with recycled asphalt pavement (RAP) on the properties of asphalt mixtures with different ageing and moisture susceptibility conditions were investigated. A polymer-modified asphalt (PMA), PG76, was mixed with varying percentages of nanosilica; namely, 0, 2, 4 and 6% by weight of asphalt and 50% RAP by weight of aggregate. Results showed that mixing nanosilica/PMA with 50% RAP improved the characteristics of resilient modulus and dynamic modulus under unaged, short-term ageing and long-term ageing conditions under both dry and wet conditions. The values for indirect tensile strength, resilient modulus and dynamic modulus tests under dry and long-term conditions are higher compared to the values for samples under wet and unaged condition; these values increased when the percentage of nanosilica was increased. The addition of 50% RAP to 6% nanosilica (6%NS/PMA + 50%RAP) was found to be the best combination in improving the performance characteristics of PMA under various conditions.

KEYWORDS: Nanosilica, Recycled asphalt pavement, Dynamic modulus, Indirect tensile strength, Resilient modulu.

INTRODUCTION

The recycling of pavements has been used for many years as a rehabilitation technique in highway industry. The first asphalt pavement recycling project was recorded by van Epps and Garcia in 1915 (van Epps and Garcia, 1980). Since then, various recycling methods have been developed which used various types of equipment and procedures. Various materials, such as soft asphalt, asphalt fractions and commercial recycling agents, were used as rejuvenators. Karlsson and Isacsson (2006) summarized that the methods for recycling asphalt pavement (RAP) can be classified into in-plant asphalt recycling and in-place, or *in-situ*, asphalt recycling methods. Additionally, the Asphalt Reclaiming and Recycling Association (ARRA) has identified five asphalt pavement recycling procedures; namely, cold planning, hot recycling, hot in-place recycling, cold recycling and full-depth reclamation.

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According to the guidelines set by the SuperPave TM Mixtures Expert Task Group, hot-mix asphalt (HMA) design with RAP is conditioned based on a three-tier system (Bukowski, 1997). Almost 15% RAP can be used without altering the grade of virgin asphalt from the project location and the condition selected (Al Qadi et al., 2007). When RAP content is between 15% and 25%, the virgin asphalt temperature, which could be high or low, is reduced by 1 grade in order to account for the effect of stiffening of the aged asphalt (for example, a PG 58-28 could be used in place of a PG 64-22). When over 25% RAP is to be used in HMA, blending charts should be consulted in order to determine the percentage of RAP that should be used with a particular virgin asphalt (Dinis-Almeida et al., 2016; Mcdaniel et al., 2000). In the year 2000, the Transportation Department of Illinois permitted the use of RAP in SuperPave TM HMA with a percentage level between 0 and 30%; the use of a maximum 50% RAP is allowed in HMA shoulders and stabilized sub-bases. Experts are the opinion that future specifications should be set to allow the use of high-class RAP (PMA).

On the contrary, several agencies from the United States adopt a more stringent approach by taking into consideration the increase in the allowable percentage of RAP in HMA in order to take maximum advantage of this efficient technology. For example, almost 80% RAP has been used in some HMA with some acceptable level of performance (Al Qadi et al., 2007). In the United States, almost 453 billion kilograms (500 million tons) of HMA are manufactured and placed annually at the cost of approximately $10.5 billion (Yao et al., 2012). Of the material used, approximately 93% or 421 billion kilograms (equivalent to 465 million tons) are aggregate-related products. The large quantity of HMA used has imposed a strain in ensuring high-quality production as well as naturally occurring aggregate products. As a result, some researchers have shifted their focus to exploring the possible use of more innovative materials (Ahmed, 1991).

One of the innovative materials available in industry is the so-called nanomaterial. However, the use of nano-material in asphalt pavement began quite late. In the field, nano-technology is being used as a kind of tool, system and material at the molecular stage. There are several different types of nano-materials which could potentially be used to modify HMA; among them are: nanosilica, nano-clay, nano-hydrated lime, polymerized powder or nano-sized plastic powder, nano-fibres and nano-tubes (Das and Swamy, 2014; Yusoff et al., 2014). Silica is a ubiquitous compound and is available across the globe; it is used in industries primarily to manufacture silica gels, colloidal silica, fumed silica,… etc. Nano-sized silica is an interesting particle due to its potential for use in emerging areas, such as drug delivery and medicine (Barik et al., 2008). Amorphous nanosilica is suitable for use as nanobio-pesticides. Companies have used silica nanoparticles to strengthen elastomers as a rheological solute (Chrissafis et al., 2009) and cement concrete mixtures (Quercia and Brouwers, 2010). Silica nano-composites have also attracted the interest of some scientific endeavours. The benefits of these nanomaterials are due to their low production cost and high performance quality (Cavallaro et al., 2010).

A small percentage of nanosilica has been found to improve softening point and reduce ductility and penetration values. The use of nanosilica mixed with asphalt also improves resistance towards ageing. The storage stability of modified asphalt has also been observed to decrease when nanosilica content is increased. Nanosilica conversion improves the rheological qualities of asphalt by increasing the stiffness of asphalt mixture and decreasing the phase angle, which means that it enhances elasticity as usually related with asphalt; this could in turn decrease the effects of ageing. For instance, some studies found that adding 2% nanosilica to asphalt could amplify the shear (complex) moduli by as much as 184% (You et al., 2011). This shows that the resistance of rutting asphalt has most likely been enhanced. This material has also been used as secondary modifier to further improve the quality of SBS-modified asphalt performance (Sureshkumar et al., 2010).

Presently, the cost of road construction parallels the cost of crude oil and petrol, which is at all times high without any respite in sight. Since the cost of PMA mixtures is showing an increasing trend, road owners and organizations are consistently looking for suitable techniques to reduce material costs and increase their benefits without compromising their performance. Using RAP in PMA mixtures is one of the most effective techniques in creating innovative technology to incorporate recycled and waste materials. RAP materials could now be used at a specific limited percentage (%) in PMA material layers. Since HMA pavements age with time, asphalt becomes harder and more oxidized, which in turn causes untimely cracking of small pavements. Therefore, the only preventive factor in using a higher percentage of RAP is the stiffness of HMA. Thus, the incorporation of these additives (nanosilica and RAP) into the PMA would allow the use of higher percentages of RAP in the combined product (Ali et al., 2016).

This research aims to investigate the effects of adding varying percentages of nanosilica into new PMA mixtures replaced with 50% RAP and to determine the performance characteristics of the new PMA and RAP mixtures, which have been blended with 0, 2, 4, and 6 % nanosilica, by conducting several tests; namely, binder tests (conventional physical tests and morphological characterization), dynamic modulus, indirect tensile strength and resilient modulus tests under moisture susceptibility as well as ageing conditions. Nanosilica was added at four different modification percentages; namely, 0, 2, 4 and 6% by weight of asphalt and 50% RAP by weight of aggregate. It is likely that the use of a secondary modifier with PMA through the addition of a high amount of RAP material would further improve the performance quality of HMA.

EXPERIMENTAL DESIGN

Binder and Nanosilica

In this study, polymer-modified asphalt, PG-76, was used as the control sample. This binder was subjected to a temperature between 150 and 160°C in a laboratory oven for at least two hours before being mixed to produce the specimen. The bitumen was heated in the oven primarily to increase its fluidity during the mixing process by lowering its degree of viscosity or consistency.

The nanosilica used in this research is in the form of a 32-µm powder. The amount of nanosilica added into the mixture was expressed in percentage (2, 4 and 6%) by weight of modified asphalt. According to Yao et al. (2012, 2013), nanosilica is a material with a large plane area, good dispersal ability, strong adsorption, high chemical purity as well as excellent stability. The binder samples were mixed at 160 °C at a shear rate of 1500 rpm for one hour. The PG-76 which has been added with nanosilica was then blended with rough and fine aggregates using the wet process.

RAP Materials

RAP sources were chosen based on the viscosity of the recovered RAP asphalt. RAP materials used in this study were obtained from the Road Care Company located in Selangor, Malaysia. The sources comprise of a range of high stiffness RAP materials. RAP was added into the mixture in varying proportion of the total aggregate. Fifty percent (50%) RAP was added to the mixed material along with natural aggregate to produce new asphalt mixtures. Assessment of the effect of coarse aggregate on the quality of RAP is based on the percentage of aggregate added to the mixture.

Aggregate Properties and Sample Preparation

The aggregate used in this research was obtained from a mine located in Kajang, Selangor. The gradation of the aggregates along with their specific gravity are given in Table 1. Aggregate gradation was chosen based on the ASTM D 3515-96 (D-4). Since the virgin aggregate has already been sieved and separated according to the size set by the ASTM D3515-96 (D-4), the RAP material was also sieved based on the virgin aggregate gradation limit. Superpave specimens' preparation methods used in this research are congruent with the PP-28-200 and AASHTO T312 specifications.

Table 2 shows the volumetric qualities of the control mixture and NS/PMA mixtures.

Table 1. Aggregate and RAP gradation and specific gravity value

Sieve size (mm)	UL	LL.	Pass %	Virgin Agg %	RAP %	SG (g/cm^3)
25	100	100	100	0	0	0
19	100	90	100	0	0	0
9.5	80	56	76	12	12	2.61
4.75	65	35	51	12.5	12.5	2.6
2.36	49	23	29	11	11	2.61
0.3	19	5	11	9	9	2.58
0.075	8	2	4	3.5	3.5	2.62
Dust	0	0	0	2	2	2.63

Table 2. Volumetric properties of mixes

Mix Properties	**Control Mix**	**50% RAP**	**2%NS+ 50% RAP**	**4%NS+ 50% RAP**	**6%NS+ 50% RAP**	**Criteria**
OBC (%)	6.2	5.65	5.75	5.6	5.62	-
Air Voids (%)	4.00	4.80	4.2	4.50	4.5	-
VMA (%)	18.46	15.64	16.0	16.15	16.02	≥13
VFA (%)	65.83	69.00	66.8	71.2	70.48	65-75

Binder Tests

Both the PMA control sample and NS/PMA-RAP binders were subjected to physical testing; namely the softening point test (ASTM D36) (ASTM D36, 1995), penetration test (ASTM D5) (ASTM D5, 1997) and morphological characterization; X-Ray Diffraction (XRD) was conducted using the Brucker axs-D8 diffractometer utilizing Cu k radiation ($\lambda = 0.15406$ nm; 40 kV, 40 mA). The scanned range was between 5° and 80° in the 2θ with a scanning rate of 0.025°/s.

Indirect Tensile Strength (ITS)

The indirect tensile strength (ITS) test was conducted to assess the asphalt mixtures' resistance against fracture in accordance with the AASHTO T 322, "Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mixture Asphalt (HMA) Using the Indirect Tensile Test Device." The two samples; namely, the unaged and aged samples were investigated at 25°C. A cylindrical specimen was loaded to failure at a deformation rate of 50.8 mm (2 inches). A compressive load was applied across the vertical diametric plane using the Universal Testing Machine (UTM) after the development of tensile stress across the horizontal diametric part (perpendicular to the applied compressive load). Load as well as vertical and horizontal deflections were recorded in continuum during testing. All sample mixtures, which are triplicate, were evaluated for both unaged and aged conditions. In addition, the ageing index, which quantifies the age hardening of asphalt mixtures, was calculated from the ITS outcomes. It is computed by dividing the ITS values of aged specimens by the ITS values of unaged specimens.

Resilient Modulus Test

Resilient modulus is an important variable used to measure pavement response in terms of dynamic stresses corresponding to strains. During the testing period, both the vertical and horizontal deformations were estimated from two sides of the specimen and the resilient modulus was then calculated accordingly. This test was conducted to characterize and compare samples; namely, the PMA control mixture and the NS/PMA at 25 and 40°C. At 25°C, the resilient modulus showed mixture resistance against fatigue, while the resilient modulus at 40°C showed mixture resistance against rutting.

Dynamic Modulus Test

The dynamic modulus assessment, |E*|, was carried out on unconfined specimens as well as the cylindrical test in accordance with the AASHTO T 342, “Main Method of Test for Determining Dynamic Modulus of Hot-Mixture Asphalt.” A sinusoidal compressive stress was applied on samples of unconfined cylindrical specimens in order to investigate the relationship between stress and strain for linear viscoelastic properties under different testing conditions, which could be frequency or temperature. The behaviour of asphalt mixtures is described by a complex number called the dynamic modulus. Phase angle shows the viscoelastic performance of a material, where the value of a phase angle ranges from 0 to 90º. An asphalt mixture as a dynamic modulus is not a measure of strength, because a higher dynamic modulus does not necessarily indicate higher strength. A sinusoidal load has enough strength to generate 100 microns, which is the main vertical strain level imposed on the samples. Strain, deformation and stress were recorded simultaneously for all cycles that were used to estimate the dynamic modulus and phase angle.

Moisture Sensitivity Test

The broadly established test, which is known as the adapted Lottman test (AASHTOT283) and which is approved by the SuperPave system, was used to determine the moisture vulnerability of asphalt mixtures. The specimens were put in steel loading strips (UTM-25) used in the indirect tensile test. A load was applied on the specimens at a constant head rate of 50 mm/min and maximum compressive force until the specimens cracked.

Ageing Procedures

All samples underwent conditioning. Mixture conditioning for volumetric mixture design process was carried out on the laboratory-prepared, loose mixture. The mixture and the pan were put in a forced-draft oven for 2 h ± 5 min. at the same temperature as the mixture’s compaction temperature ±3°C. The mixture was stirred after 60 ± 5 min to ensure uniform conditioning. Short-term conditioning of the mixture for the mechanical property testing procedure was applied to the laboratory-prepared, loose mixture only. The mixture was then put in a pan and spread to a thickness between 25 and 50mm.

RESULTS AND DISCUSSION

Physical Tests

Fig. 1 shows the softening and penetration point values for the PMA control sample and NS/PMA. Results show that increasing the content of nanosilica caused a decrease in the penetration values, while the values for the softening point increased. Therefore, the increase in softening point and the decrease in penetration point indicate an increase in the stiffness of the NS/PMA.

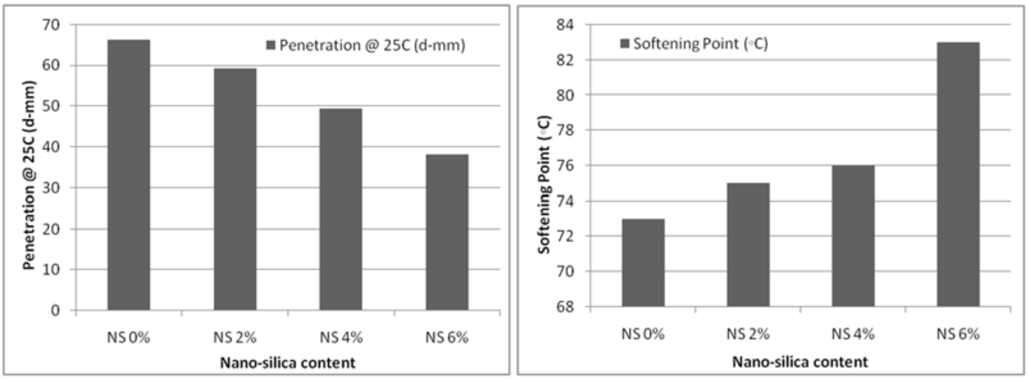

Figure (1): Penetration and softening point of unmodified and NS/PMA mixtures

Molecular Dynamics Results

The result for XRD indicates that the nanosilica particles were uniformly distributed within the asphalt binder matrix. This shows that the blending method used is effective in producing nanosilica particles within the asphalt matrix. Fig. 2 shows the typical XRD peaks for NS/PMA, which indicates an amorphous structure. Hence, nanosilica was well distributed and uniformly dispersed in the mixture.

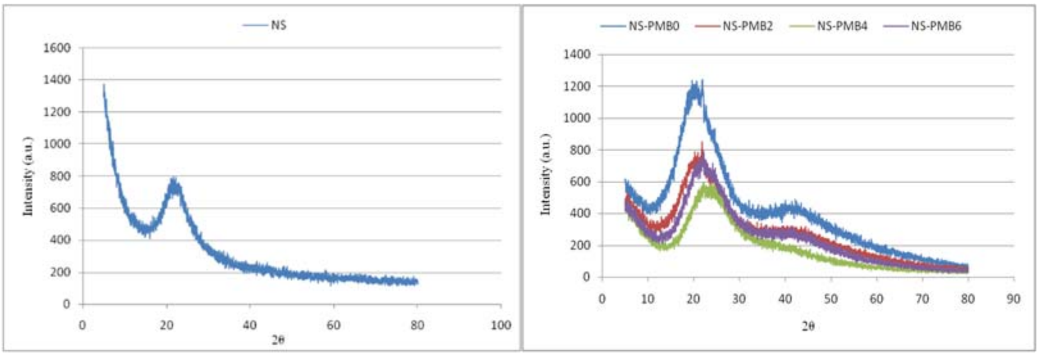

Figure (2): XRD patterns of NS/PMA

Resilient Modulus Test

Fig. 3 shows the result for the resilient modulus test for PMA control mixture and NS/PMA mixtures for unaged, long-term and short-term ageing. The difference in resilient modulus is more apparent when temperature was increased, along with a decrease in stiffness at 40°C. At high temperature, 6% NS/PMA with 50% RAP showed a higher resilient modulus value when compared to the control mixture and other NS/PMA mixtures. The difference in resilient modulus was based on the values at high temperature and shows that the 6% NS/PMA is the least vulnerable to rutting when compared to the control mixture. The result at a pulse moment of 100 (ms) of the resilient modulus test shows that 6% NS/PMA + 50% RAP has the highest rut resistance with the highest resilient modulus value of 3362 MPa for long-term ageing at 25°C and 1303 MPa for long-term ageing at 40°C. This result is in good agreement with an earlier research conducted by Yusoff et al. (2014). Table 3 presents the resilient modulus index (RMI) under various conditions and temperatures. Aged samples show higher levels of stiffness compared to unaged samples, where the highest value was observed for 6% NS/PMA + 50% RAP in long-term ageing. Therefore, it can be said that samples exposed to ageing condition have higher stiffness modulus values.

Moisture damage is a decrease in the values of strength and durability and the stiffness of asphalt mixtures due to moisture. Moisture vulnerability test was carried out on all mixtures at the OBC for each mixture. Fig. 4 shows the results for resilient modulus assessment under dry and wet conditions, performed at 25 and 40 °C. Resilient modulus decreased when temperature was increased. At 40 °C, the value for 2% NS/PMA+50% RAP is 435 MPa and it increased to 510 MPa for 4% NS/PMA+50% RAP and to 575 MPa for 6% NS/PMA+50% RAP. In general, the results for resilient modulus show higher values under dry condition compared to wet condition; the change in temperature also has a significant effect on the result of resilient modulus in that the value increases as temperature decreases.

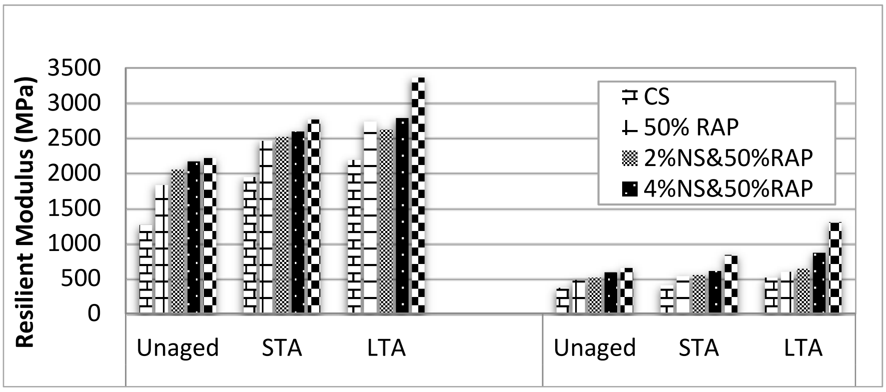

Figure (3): Resilient modulus for unaged and aged NS/PMA mixtures at 25 and 40°C

Table 3. Resilient modulus index at various conditions and temperatures

Sample	Temp (°C)	Ageing index		
		Unaged	STA	LTA
Control mix	25	1.00	1.54	1.73
50% RAP	25	1.00	1.34	1.49
2%NS+50% RAP	25	1.00	1.23	1.28
4%NS+50% RAP	25	1.00	1.2	1.29
6%NS+50% RAP	25	1.00	1.54	1.73
Control mix	40	1.00	1.1	1.41
50% RAP	40	1.00	1.12	1.25
2%NS+50% RAP	40	1.00	1.07	1.24
4%NS+50% RAP	40	1.00	1.03	1.48
6%NS+50% RAP	40	1.00	1.1	1.41

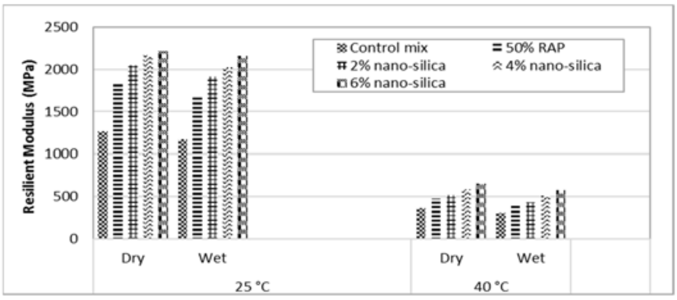

Figure (4): Resilient modulus for dry and wet NS/PMA mixtures at 25°C and 40°C

Indirect Tensile Strength (ITS) Test

Fig. 5 shows that the values for indirect tensile strength change with different ageing periods at 25°C, where the more aged the mixture, the higher its ITS value. The bar chart in Fig. 5 also shows that the tensile strength of 6% NS/PMA+50% RAP is slightly higher than the control PMA. Table 4 shows the difference in ageing index for aged and unaged samples at 25°C. The stiffness modulus values for aged samples are higher than those for unaged samples, with the highest value recorded for 6% NS/PMA + 50% RAP. The index values for ageing shown in the table indicate that vulnerability to oxidative ageing was considerably decreased with an increase in the percentage of nanosilica, particularly with long-term ageing. The addition of nanosilica also enhances the ability of asphalt binders to recover.

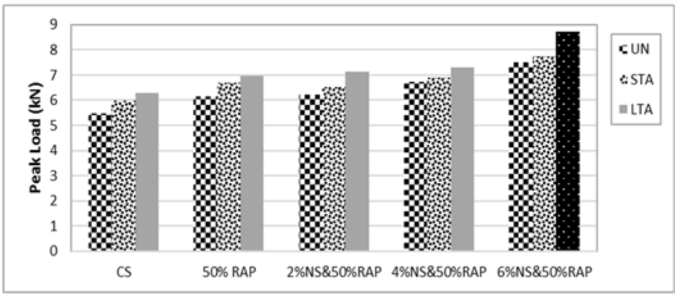

Figure (5): Indirect tensile strength for unaged and aged NS/PMA mixtures at 25°C

Table 4. Indirect tensile strength (ITS) at 25°C

Sample	**Ageing Index (AI)**		
	Unaged	**STA**	**LTA**
Control mix	1	1.09	1.15
50% RAP	1	1.09	1.13
2%NS+50% RAP	1	1.05	1.15
4%NS+50% RAP	1	1.03	1.09
6%NS+50% RAP	1	1.03	1.16

Fig. 6 presents the results for the indirect tensile strength test for moisture susceptibility under dry and wet conditions for PMA and NS/PMA. It clearly shows that the result for indirect tensile strength test for samples under wet condition decreased slightly compared to the samples under dry condition at 25 ºC. The result for wet condition shows that the value increased from 4.567 kN for control PMA to 4.737 kN for 50% RAP, 5.104 kN for 2% NS/PMA + 50%RAP, 5.226 kN for 4% NS/PMA + 50%RAP and 5.348 kN for 6% NS/PMA + 50%RAP. It can be concluded that ITS increased with the increase in the percentage of nanosilica.

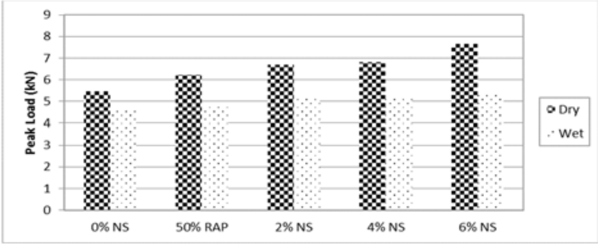

Figure (6): Indirect tensile strength for dry and wet NS/PMA mixtures at 25°C

Dynamic Modulus Test

Rutting Resistance Due to Ageing Condition

The results for the dynamic modulus test at higher temperatures were used to assess the permanent deformation (rutting) features of asphalt mixtures. The rut factor, expressed as E*/sin δ, is calculated using the dynamic modulus, E* and phase angle, δ values at a specific frequency and temperature from the testing condition in order to assess the rutting features of asphalt mixtures. In this research, a temperature of 55 °C and a frequency of 5 Hz were chosen for the calculation of the rutting factor under ageing condition (Witczak et al., 2002); a high rut factor will improve the rutting performance of asphalt mixtures. Therefore, a higher dynamic modulus and a lower phase angle indicate a better resistance to rutting.

Fig. 7 shows the dynamic modulus and rutting elements for the individual mixtures at 55°C and 5 Hz. It is important to note that both the dynamic modulus and the rut factor showed a similar trend. NS/PMA and 50% RAP mixtures show higher dynamic modulus values than their corresponding control PMA mixtures. However, the rut factors for 50% RAP, 2% NS/PMA + 50% RAP and 4% NS/PMA + 50% RAP are slightly lower compared to 6% NS/PMA + 50% RAP. This might be due to the higher phase angle in these mixtures when the PMA mixture is compared to the control mixture. Adding a higher percentage of RAP in relation with nanosilica additive enhanced the performance of PMA mixtures.

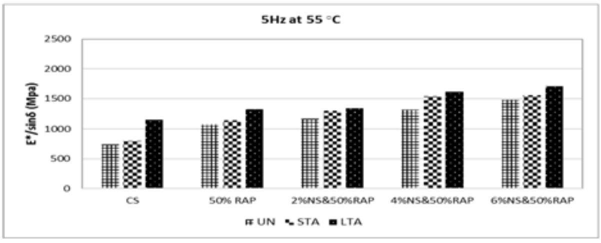

Figure (7): Rutting factor for ageing condition

Fatigue Resistance Due to Ageing Condition

The results of the dynamic modulus test at average level temperature were used to assess the fatigue vulnerability features of asphalt mixtures. The value for fatigue, which is expressed as E* × sin δ, is calculated using the dynamic modulus, E* and phase angle, δ values at a specific temperature and frequency of the testing conditions in order to determine the characteristics of the asphalt mixtures' fatigue cracking. In this study, the factor in fatigue was calculated at a temperature of 35 °C and a frequency of 5Hz (Witczak et al., 2002). If the fatigue factor is low, the fatigue cracking susceptibility of the asphalt mixture is also low. Therefore, a blend with lower dynamic modulus and phase angle values is seen as less vulnerable to fatigue cracking.

Fig. 8 shows the dynamic modulus and fatigue factors for individual mixtures at 35 °C and 5 Hz. It is important that both the dynamic modulus and the fatigue factors go through a compatible trend. All mixtures, except for the PMA control mixture, show equal or lower dynamic modulus values. It was also found that all mixtures show similar fatigue factors which are lower compared to their corresponding control PMA mixture. In general, all PMA mixtures with nanosilica additives and 50% RAP are less susceptible to fatigue cracking than the control sample.

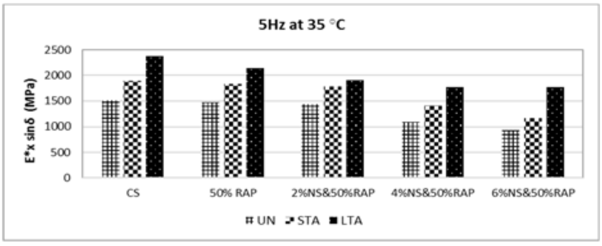

Figure (8): Fatigue factor for ageing condition

Table 5 shows the results for the ageing index for the dynamic creep investigation. Results show that 6% NS/PMA + 50% RAP has a better performance than all other mixtures; therefore, fatigue will decrease with long-term ageing, since ageing condition increases the stiffness of asphalt mixtures. This result is congruent with a previous research carried out by Yao et al. (2013).

Table 5. Dynamic modulus index at various conditions and temperatures

Sample		**Aging Index (AI)**			
		35 °C		**55 °C**	
	Unaged	**STA**	**LTA**	**STA**	**LTA**
Control mix	1.00	1.1	1.22	1.04	1.19
50% RAP	1.00	1.19	1.3	1.09	1.24
2%NS+50% RAP	1.00	1.01	1.05	1.12	1.21
4%NS+50% RAP	1.00	1.26	1.18	1.13	1.23
6%NS+50% RAP	1.00	1.27	1.29	1.16	1.24

Rutting Resistance Due to Moisture Condition

This test was conducted to investigate the difference between rutting factor of mixtures with complete-dry conditioning and incomplete-dry conditioning as well as mixtures with moisture conditioning and without moisture conditioning. As expected, results show that mixtures from each set exhibit a gradually decreasing value for dynamic modulus due to moisture condition (wet sample) compared to without moisture condition (dry sample). However, Fig. 9 shows that the rutting factors for the 2% NS/PMA + 50% RAP and 4% NS/PMA + 50% RAP mixtures under moisture condition were slightly lower compared to 6% NS/PMA + 50% RAP. This could be attributed to the higher phase angles in these mixtures when compared to the control PMA mixture.

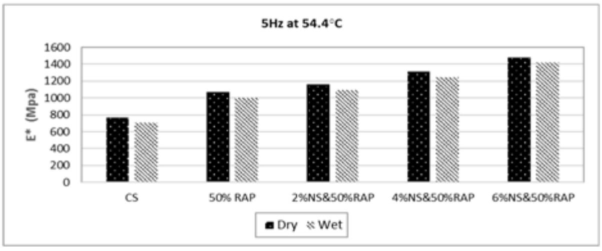

Figure (9): Rutting factor for moisture condition

Fatigue Resistance Due to Moisture Condition

This test was conducted to investigate the difference between fatigue resistance of mixtures with complete-dry conditioning and incomplete-dry conditioning as well as mixtures with moisture conditioning and without moisture conditioning. Fig.10 shows that, as with the results for the rutting factor test, the mixtures from each set exhibit a gradually increasing trend of fatigue factor compared to the results for rutting factor and this is due to the decrease in temperature. The fatigue factors for the 2% NS/PMA + 50% RAP and 4% NS/PMA + 50% RAP mixtures under moisture condition are slightly lower compared to 6% NS/PMA + 50% RAP. In relation to rutting outcomes, this could be due to the higher phase angles in these mixtures when compared to the control PMA mixture.

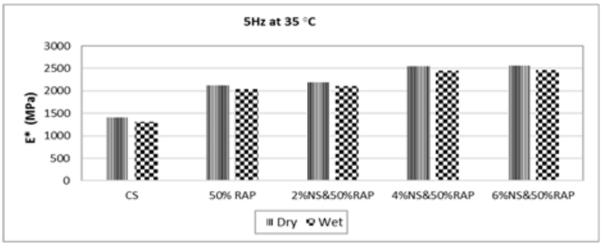

Figure (10): Fatigue factor for moisture condition

CONCLUSION

The conclusion for this study is made based on the outlined objectives, which were set during the early stage of the study. PMA mixtures could be designed with a 50% RAP content. The addition of 50% RAP with 6% nanosilica (6% NS/PMA + 50% RAP) proved to be the best mixture to enhance the performance characteristics of PMA under different circumstances. The addition of nanosilica to fresh mixed PMA with the replacement of 50% RAP materials enhances the performance of the asphalt mixtures as shown by the result for the resilient modulus test, while 6% NS/PMA + 50% RAP is the least vulnerable to rutting compared to the control mixture. The results of the ITS test showed that aged samples have higher stiffness modulus than unaged samples and that 6% NS/PMA + 50% RAP has the highest value for long-term ageing. This indicates that vulnerability towards oxidative ageing is considerably decreased when the nanosilica content was increased, especially in long-term ageing. This study shows that adding RAP into virgin PMA could reduce up to 50% of virgin PMA materials used in road asphalt pavement. The benefit of RAP is very dependent upon project size and location.

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