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Resilient modulus prediction of nano-silica modified porous asphalt using Finite Element Analysis

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Abstract. Repetitive traffic load is the most important factor influencing porous asphalt (PA) performance. The performance of asphalt is mostly influenced by the loading magnitude of heavy vehicles. In order to improve the service performance of PA under heavy traffic conditions. the decrement of stiffness is one of the failures that occur on the PA which mainly caused by the repeated load from a large number of different types of vehicles which leads to reduce the characteristic of PA in terms of stiffness and durability. Moreover, to enhance the performance of PA against the stiffness reduction an additive material used to increase the strength of the PA called Nano-silica particles. Thus, the aim of the study to investigate the resilient modulus of Nano-silica modified PA and develop a finite element analysis FEA model to predicate the resilient modulus. In this study, three different Nano-silica contents 0%, 2% and 4% by weight of PA mixture were investigated. To achieve this, a finite element model was developed and simulated by using ABAQUS 6.14 software for the PA samples to predict the resilient modulus performance. A comparative study was done among the unmodified and modified PA mixtures considering the resilient modules value. The result showed that Nano-silica is recommended as an additive in PA mixture, as the result of the modified PA mixture with 2% of NS was 4357Mpa while the unmodified was 3001Mpa. Thus, the addition of NS to PA mixture Capable in increasing the strength and quality of asphalt mixture.
Keywords: Porous asphalt, Nano-silica, Finite Element, Resilient Modules

1. Introduction

Porous asphalt with coarse aggregate structure has an open structure that allows wastewater and rainwater with faster liquidity and eliminates the problem of accumulations (Figure 1). This mixture is formed by about 30-20% of the air pores in the absence of rainwater. PA is an alternative solution to the problem of parking storm-water runoff and other areas of low traffic intensity. In operation, this type of asphalt allows early rainfall and local runoff to soak through the pavement surface course of namely open-graded asphalt which has been used as a wearing surface since the 1950s. Its first major use in Australia was about 1973 and in Japan was about 1987 and the application of PA in Malaysia was started in the 1990s. One of the main reasons for using porous asphalt is the improved skid resistance under wet conditions.

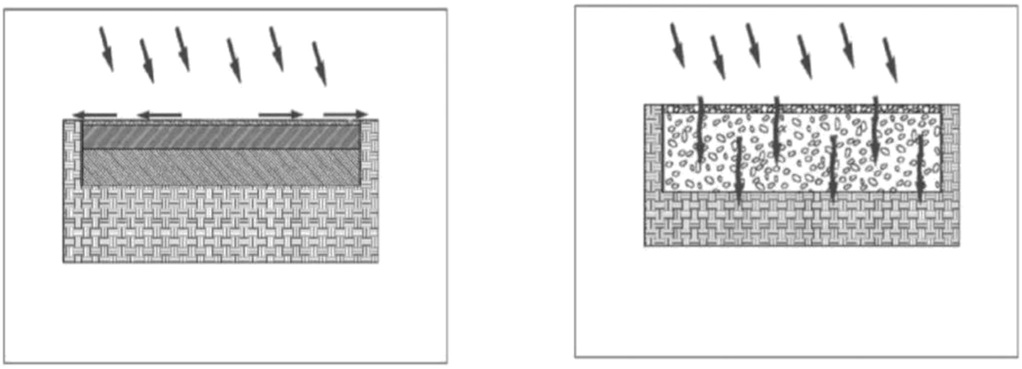

Figure 1. Rain on traditional asphalt (left) and porous asphalt (right)

Taking a rougher path of wear will increase the frictional properties. Porous asphalt friction properties were contrasted with dense graded asphalt in Oregon. Accumulated evidence showed that porous asphalt mixes in dry conditions had slightly improved friction properties and much better friction properties in rainy conditions when free water was present on the pavement [1]. Even so, PA is exposed to traffic (i.e., load frequency, intensity, and axle and tire functionality) and, due to the loads applied by vehicle axles and tires, are mainly responsible for asphalt problems. The modification process of PA has been used in long term with additives that have been commonly used for enhancing its strength and durability in porous asphalt such as DBS, fibers and hydrated lime [2]. Another approach that has recently gained attention to improving the asphalt binder characteristics is changing the asphalt binder with nanomaterials [3]. Nanomaterial refers to a material with the size of less than 100 nm in at least one dimension. Because of the extremely small scale and the immense surface area, the properties of nanomaterials vary significantly from normal-sized materials. Moving these nano-sized particles to another material will transcend monolithic limitations, and asphalt binders are no exception [4]. This research illustrates the participation of the Finite Element Method (FEM) to anticipate the Nano-silica modified porous asphalt under resilient modules test in order to overcome the PA evaluation process problem. Finite element method is being used as a tool for modelling and predicting different types of structures [5]. Thus, the outcomes of this study will provide an overview into how the model of finite elements can be used to predict the resilient modules for porous asphalt in the future and further enhance the estimation of resilient modules.

2. Material

2.1. Nano-Silica

Nano materials are one of the additives used to enhance the PA performance as a modification. The nano-silica used was colloidal particle shaped with an average size varying from 10 to 15 nanometers (nm). In this analysis we will illustrate the enhancement of nano-silica in terms of dynamic creep as a changed of PA. To do that, a difference in the amounts of nano-silica applied with the Asphalt Binder and measured separately beginning with the control which is 0 percent, 2 percent and 4 percent of nano-silica. The Nano-silica properties are presented in the Table 1.

Table 1. properties of the Nano-silica [6]

Parameter	Specification value
Appearance	Slight 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 Asphalt Binder

Binder is one of the most important elements in PA. In this study asphalt binder (PEN 60/70) penetration grade modified different concentration (0% to 4% by the weight of the binder) of nano-silica at average size of 10-15 nm. Table 2 shows the properties of asphalt binder.

Table 2. properties of asphalt binder [7]

Test	Test result
Softening point (°C)	48-56
Penetration (0.1 mm)	60-70
Ductility (cm)	>100

2.3 Aggregate

In this study, the aggregates were graded in the range of 14 mm to 0.075 mm size. Porous asphalt grading B was used, where the nominal maximum aggregate size for this type of PA is 14mm. The weight of aggregate for every specimen was about 1100g. Table 3 shows the PA Grading B blended aggregate gradation in accordance to Public Work Department of Malaysia Standard Specification for road works.

Table 3. PA grading B aggregate gradation (14mm NMAS) [8]

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
Hydrate		2	11

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3. Finite Element Method

A series of three dimensional (3D) models by using the Finite Element Method based software ABAQUS 6.14 are analysed in order to achieve the objectives of this study. ABAQUS is a suite of strong simulation engineering programs focused on the finite element principle, although it includes a vast collection of elements that can model nearly any geometry. A complete ABAQUS analysis usually consists of three distinct stages: pre-processing, simulation\ solving, and post-processing.

3.1 Pre-Processing

It explains phases from model creation to the point when the models (loads, materials added, and meshing) are finished and ready for study. In this stage users in the Property Module describe material properties such as density, mechanical, and thermal properties. The sections are assigned material properties, and the sections are then allocated to model geometry (Fig. 2). Most of the material data inputs needed in ABAQUS software are Length, Elastic Modulus and Poisson Ratio, as it considers the key parameters to describe the behaviour of any material both mechanically and physically. In this model, the material input would be split into two groups, each group having different mechanical and physical properties. The first group is the asphalt binder for nano-silica and the data input for this material is shown in Table 4, while the second group is the mixture for PA and the data input for this material is shown in Table 5.

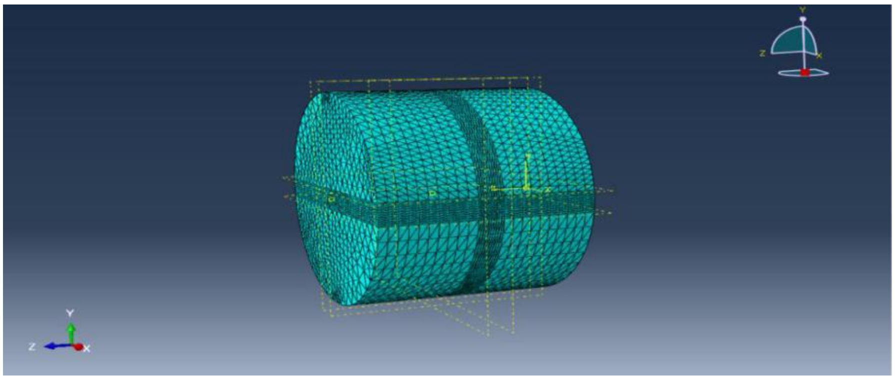

Fig 2: model meshing

Table 4. NS-MB = Nano-silica modified Asphalt Binder

Type	Density (Kg/m^3)	Poisson Ratio	Elastic Modulus (Mpa)
0% NS-MB	1.030	0.25	700
2% NS-MB	1.030	0.25	900
4% NS-MB	1.030	0.25	1200

Table 5. NS-PA-GB = Nano silica modified Porous Asphalt Grading B (14mm NMAS)

Type	Density (Kg/m^3)	Poisson Ratio	Elastic Modulus (Mpa)
0% NS-PA-GB	2.2	0.35	3036
2% NS-PA-GB	2.2	0.35	4362
4% NS-PA-GB	2.2	0.35	2971

3.2 Processing

Processing / solving involves executing model or structure analysis. The time required to solve a model depends heavily on the complexity of the model and the computer specifications used for the analysis.

3.3 Post processing

Post-Processing requires showing the outcomes of the analysis. Reaction forces, Von-Mises (Equivalent) Pressure & Strains, and Total Displacement are common findings shown. Such data were manually compiled, inputted and plotted using Microsoft Excel.

4. Results and Discussions

On completion of the study of PA mixture using a three-dimensional finite element method, a several 3D Finite Element models on the various assumptions stipulated in the methodology to accurately determine the influence of varying input data on PA structures and to determine the differences between modified and unmodified mixture. The result of this study had been obtained and analysed in order to achieve study objectives which include the investigation of adding different percentages of Nano-silica to asphalt mixture of PA under resilient modulus.

4.1 Experimental Result

The resilient modulus was one of the most commonly used methods for measuring the stiffness modulus of PA as the previous study investigates and evaluates that for a various percentage of nano-silica. Universal Testing Machine was used to achieve the total resilient axial deformation that a specimen reacts to. Indirect stress was used to examine the specimen's resilient module. Along with compressive loads, the haversine waveform was introduced in the test [6]. Table 6 shows the data obtained from the Universal Testing Machine (UTM) for a sample with a different percentage (0 %, 2 %, and 4 %) of nano-silica content at 25 ° C. The study was carried out with different cycles including 1000, 2000, and 3000 cycles. This will differentiate and measure the consistency and strength of the asphalt mixture which was integrated with NS. The resilient modulus values are increased by adding the NS to PA mixture (Fig. 3). Adding 2% of NS can see the different the resilient modulus it shows a higher value than the control. But, 4% of NS show a low value than control and 2% NS. So, form this result can conclude that the maximum resilient modulus value was obtained in NS content of 2%. So, by increasing the percentage of NS up to 2% that led to an increase in the values for PA stiffness. This result is consistent by studies by [11, 12].

Table 6: the result of Mr obtained through the study

NS %	**Mean Pulse Repetitive Period (ms)**		
	1000	**2000**	**3000**
0	3036	2938	2880
2	4362	4098	4243
4	2971	2678	2607

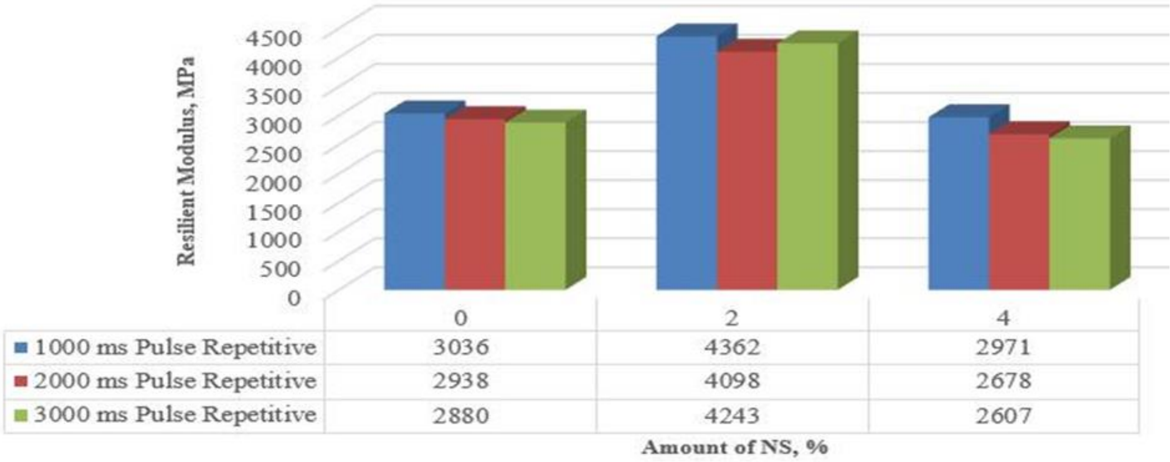

Fig. 3. Resilient modulus VS Content of NS

4.2 Finite Element Analysis Results

PA analysis is performed using a 3-D dimensional finite element model by using ABAQUS (ver. 6.14). Figure 4 and 5 shows the difference between the unmodified and modified PA mixture under the repetitive load applied. The change occurs due to the reaction of loading applied in the model as shown in the visualization mode, we found that the visual effect of the sample for 0% NS is observed the damage and its weakness due to the high loading applied and the structure of PA itself as well. The increase of the percentage of nano-silica to 2%, it's found that the performance of the PA mixture along with elastic strain is enhanced gradually which increase its stiffness. The test is normally performed over a range of temperatures and stresses to simulate the moving of vehicles over a PA mixture on cylindrical specimens with a 100mm diameter and 76mm high for each mixture while the temperatures used was 25°C. The indirect tensile strength was applied to the vertical diameter for control and modified PA. The load application frequency was 1 Hz with load duration of 0.1s representing field conditions and a resting time of 0.9s. Based on Fig 6, PA mixture at 25°C, the high value of resilient modulus of the specimen might be due to the increment in the amount of the additive NS resulted, at 1000ms pulse period, the result of resilient modulus for the origin specimen (0% of NS) was 3001Mpa. The highest Mr value obtained at 2% of NS was 4357Mpa. Nevertheless, the results for other pulse period did not show any trend of increasing. At 4% addition of NS, the resilient modulus value is lower than the previous percentage with an average value of 2800Mpa at 3000ms and 2000ms pulse repetition. Thus, the average value of resilient modulus at 25°C for 2% was 4357Mpa at 1000ms, 4088Mpa at 2000ms and 4213Mpa at 3000ms pulse repetition shows a higher value of Mr rather than the other percentage which prove the enhancement of PA at 2% of NS.

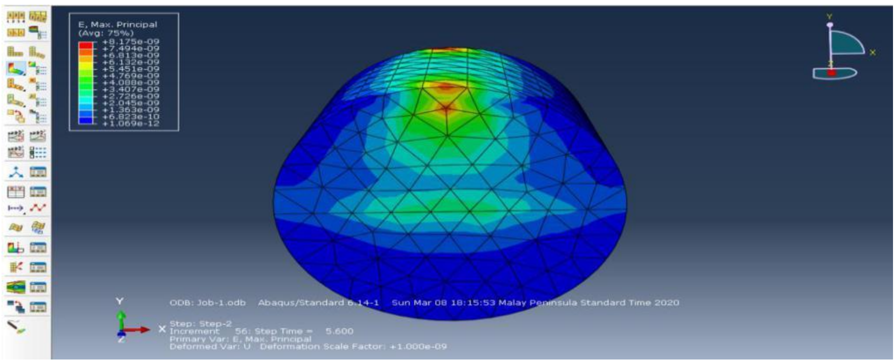

Fig. 4. Visualization of the sample stress of 0% NS

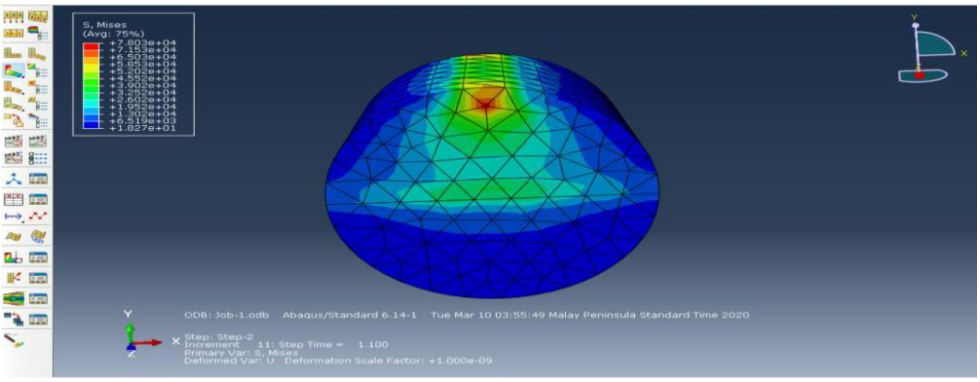

Fig. 5. Visualization of the sample stress of 2% NS

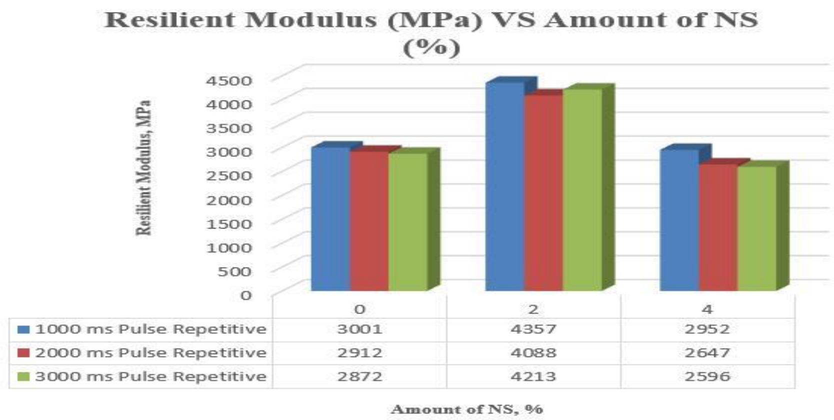

Fig. 6. Resilient modulus VS Content of NS Numerical Result

5. Conclusions

Base on the result of this study that can be obtained, the addition of NS tends to increase the strength and quality of asphalt, by increasing the percentage of NS to 2% lead to increase in the resilient modules. Thus, a 3D FE model of PA demonstrated a good agreement between the deformations predicted by the theoretical model and the deformations measured.

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