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Predication of nano-silica modified porous asphalt under dynamic creep by using finite element analysis

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Abstract. In areas with heavy rainfall, the conventional pavement may not be suitable due to low drainage capability. This will cause to a storm failure. To solve this, Porous asphalt (PA) is one of the innovative asphalts that can significantly overcome the issue of storm-water problem. The high air voids content characteristic of PA compares with conventional pavement in Malaysia is very suitable in managing the storm-water. However, PA suffers a few problems such as decrement of strength and tensile strength due to high air voids content which lead to permanent deformation. In order to enhance the performance of PA against the permanent deformation an additive material used to increase the strength of the PA called Nano-silica particles. Therefore, the purpose of this study is to evaluate the dynamic creep of Nano-silica modified PA by developing a finite element analysis (FEA) model. Moreover, this study the dynamic creep performance of porous asphalt with different proportion of Nano-silica particles 0%, 2% and 4% was predicted. A finite element model will be simulated by using ABAQUS 6.14 software for the PA sample in order to achieve the objectives of the study. From this study it was concluded that, the develop model was reliable use to predict the performance of PA in terms of dynamic creep and the utilizing of Nano-silica in PA mixture result changes in the rheological properties of the asphalt binder which lead to an enhancement of its performance against the permanent deformation.

1. Introduction

Small percentage of fines in porous asphalt will increase the amount of the air void content as compared to the conventional type of asphalt. Porous asphalt normally contains higher than 18-20% air voids [1]. In general, the utilisation of porous asphalt in storm-water management is most suitable due to its larger air void contents (AV) that permits the flow of water. It can also be used for drainage purposes. There are several benefits of this asphalt mix such as increasing friction, vision sight improvement while raining, and noise reduction [2]. Despite the benefits, there are some downside of porous asphalt which may influence both its performance as well as service life [3]. Some of the downside of porous asphalt are permanent deformation that occur due to the presence of large air void. Static, dynamic creep and wheel tracking are among the test that can be used to assess the permanent deformation. However, static test isn't capable to be considered a true indicator of permanent deformation of modified mixture. Meanwhile, one of the best test methods to assess the permanent deformation of asphalt mixture is by dynamic creep test [4]. Nanoparticles can add to the mixture to escalate the robustness of the PA as well its reliability in resisting the permanent deformation. Nonclay, Nano silica and Nontitanium are among the nano materials that has the capability to be utilised to modify asphalt [5]. Nano-silica has advanced its usage in medicine and engineering. For the enhancement of asphalt performance Nano-silica can be utilised as an asphalt modification due to its essential properties such as large surface area, strong adsorption, good dispersal ability, high chemical purity, and excellent stability [6]. It is also reasonable in terms of cost. In a nutshell, this study shows the utilization of Finite Element Method (FEM) to predict the dynamic creep test of Nano-silica modified porous asphalt in accordance to solve the problem of evaluation process of PA. Finite element method can be used as a tool for modelling and analysing various types of structures [7]. Thus, the findings of this research provided an insight on how the finite element model used to predict the dynamic creep of porous asphalt.

2. Materials

2.1 Nano-silica

In order to enhance the performance of PA, modification additives such as Nano materials known as the Nano-silica are utilised in form of colloidal particle with an average size ranging from 10 to 15 nanometer (nm). In this study, we will illustrate the enhancement of the Nano-silica as a modified of PA in term of dynamic creep. A different proportions of Nano-silica is added with the Asphalt Binder and simulated separately starting with the control which is 0% of Nano-silica, 2% and 4% in order to achieve this. The properties of the Nano-silica illustrated in Table 1.

Table 1. Properties of The Nano-Silica [8]

Parameter	**Specification value**
Appearance	Slight milky transparent to translucent liquid
SiO_2 (wt%)	30±1%
Na_2O (wt%)	0.5%
pH (20°C)	8.5-10.5
Density (20°C, g/cm^3)	1.19-1.22
Particle size (nm)	10-15

2.2 Asphalt binder

One of the most crucial elements in PA is known as the binder. 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 an average size of 10-15 nm. Table 2 shows the properties of asphalt binder.

Table 2. Properties of asphalt binder [9]

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

2.3 Aggregate

The aggregates were graded between ranges of 14 mm to 0.075 mm. The nominal maximum aggregate size for PA Grading B is 14mm. The aggregate for every specimen weighted 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) [10]

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

3. Finite Element Analysis

This study finding focuses on a series of three-dimensional (3D) models by using the Finite Element Method based software ABAQUS 6.14 in order to attain the main goals of this study. Due to its large-scale library of elements, Abaqus is a prominent engineering simulation program-based tool whereby its analysis consists of three distinct stages such as pre-processing, simulation\ solving, and post-processing that can be used to design any geometry virtually.

3.1 Pre-processing

This stage is a process that commences with generation of model up to the stage of model completion (completes the application of loads and materials) whereby the properties of materials such as density, mechanical and thermal properties are defined in Property Module. Properties of material will be allocated to the sections, and the sections will further allocate to the model geometry. ABAQUS software requires several data input of the main parameters for the materials such as Density, Elastic Modulus and Poisson Ratio to represent the behaviour of material mechanically and physically. The material input was further divided into two groups. The first group is Nano-silica asphalt binder and the data input for this material is shown in Table 4. The second group is PA mixture and the data input for this material is shown in the Table 5 and each of this group will be associated with a specific mechanical and physical properties.

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 is a process of analysing the model or structure. The complexity of the model and the descriptions of the computer used for the analysis will have a great impact on the time to solve model which may eventually increase the time

3.3 Post- processing
Post-Processing involves the process of displaying typical results of reaction forces, Von-Mises (Equivalent) Stress & Strains, and Maximum Displacement. These results obtained are then extracted manually and graphs plotted using Microsoft Excel.

4. Result and discussions

4.1 Dynamic creep
As shown in Figure 1 below we can observe the three regions of the creep failure for the 0%NS (control sample). the primary region started from the 0-500 cycle which in this stage the deformation is recoverable and unrecoverable. After that, the permanent strain getting increased with the increasing of the load cycle before it reached to the third stage which more than 3000cycles in this stage the strain increased rapidly up to failure. On the other hand, 2% and 4% of Nano silica in porous asphalt show a great improvement in resisting the creep behaviour and the permanent deformation while the strain had a significant decrease by around 70% in average of the difference of the strain in 1000, 2000 and 3000 cycles obtained from Table 6. Lastly, 2% of nano-silica as a modification of porous asphalt observed to be the optimum percentage as its strain vs load cycle curves recorded as the lowest compared with 0% and 4% respectively. The result also consistent with studies by [11,12].

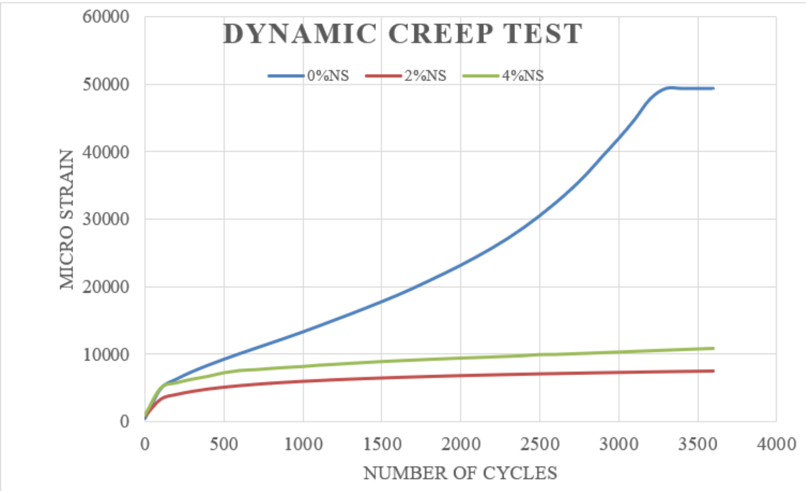


Figure 1. Dynamic Creep Test Result

Table 6. Dynamic Creep Test Result

Mixture Type	Micro strain at 1,000 number of cycles	Micro strain at 2,000 number of cycles	Micro strain at 3,000 number of cycles
0%NS porous asphalt	13225.37	23103.91	41869.1
2%NS porous asphalt	5946.685	6773.753	7238.551
4%NS porous asphalt	8122.001	9362.577	10253.6

4.2 Finite Element Analysis Result

To verify the experimental results for the dynamic creep test of nano-silica modified porous asphalt, it had been simulated the experiment by using the finite element method by ABAQUS software according to the test specification. We applied the repeated load with a magnitude of 100 kPa in the middle of the surface of the specimen as it is applied in the dynamic creep test apparatus. Moreover, we assigned the boundary condition as a fixed support on the bottom surface of the sample similar to the position of the specimen in the real test. Figure 2 shows the model with the applied load and the boundary condition assigned in ABAQUS software.

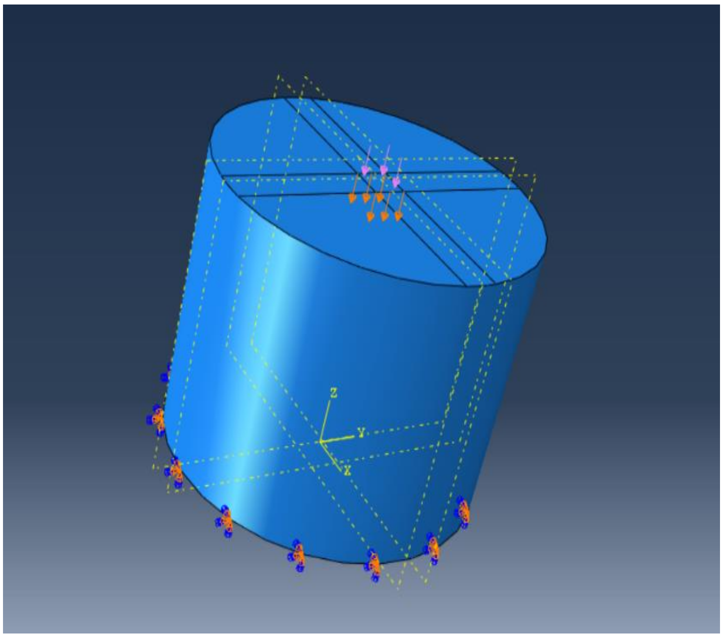
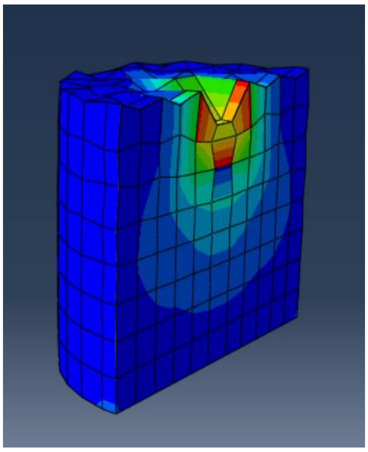
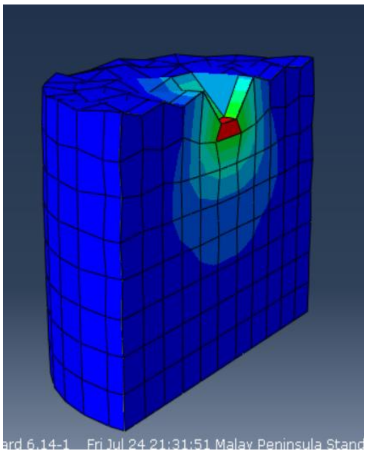


Figure 2. Load applied and the boundary condition in ABAQUS software.

The visual result for the dynamic creep test of nano-silica modified porous asphalt has been obtained in the visualization module in ABAQUS software. Figures 3-5 shows the strain distribution on the cylinder specimen of 0%NS, 2%NS and 4%NS respectively. Firstly, for the 0%NS is shows the maximum strain occurred with increasing of the load cycles. However, with the addition of Nano-silica it is clearly observed that the performance of porous asphalt sample enhanced against the permanent deformation. The 2%NS shows as the optimum percentage of Nano-silica while its visual result shows it has the lowest affection compared with the other samples.





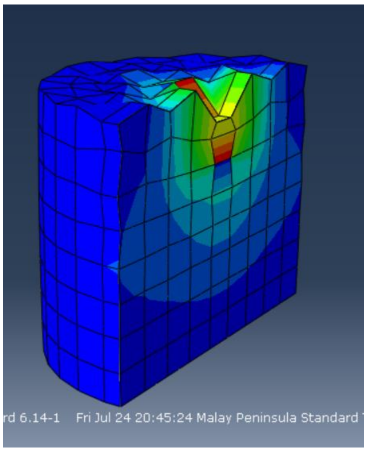


Figure 3. Strain distribution in visualization module for 0%NS.

Figure 4. Strain distribution in visualization module for 2%NS.

Figure 5. Strain distribution in visualization module for 4%NS.

As shown below in figure 6 the result obtained from the numerical analysis of the dynamic creep test for nano-silica modified porous asphalt with the three proportion of nano silica. The graph showed that, 2% and 4% of Nano silica in porous asphalt show a great improvement in resisting the creep failure and the permanent deformation while the strain had a significant decrease compare with the sample with 0% of nano-silica. Lastly, similar with the experimental results, the optimum percentage of nano-silica as a modification of porous asphalt observed to be 2% as its strain vs load cycle curves recorded as the lowest compared with 0% and 4% respectively. Lastly in this study, we have verified the experimental results of dynamic creep test by the numerical results with a range of percentage of error lies between 3-7 %.

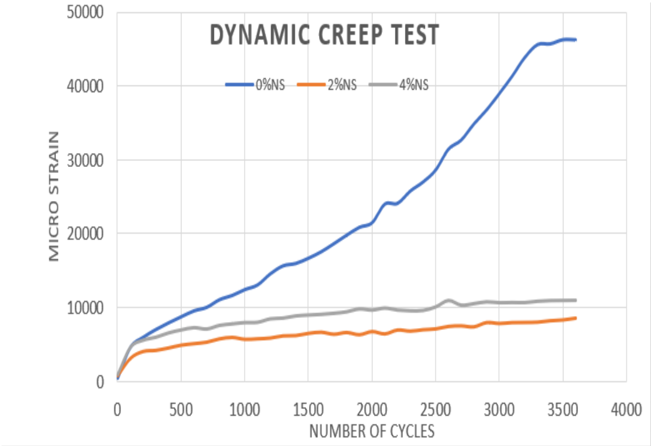


Figure 6. Dynamic Creep Test Result

5. Conclusion

In conclusion, this study evaluated the dynamic creep of nano-silica modified porous asphalt and the experimental results was verified by the numerical results that obtained from Finite element analysis. The results clearly showed that the optimum percentage of nano-silica as a modification of porous asphalt in permanent deformation resistance observed to be 2% as its strain vs load cycle curves recorded as the lowest compared with 0% and 4% respectively. Moreover, by the developed model we conclude that Finite element method eased the evaluation process of PA and provided a precise result of dynamic creep prediction.

6. References

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