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Journal of Construction Research
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ARTICLE

Rutting Resistance of Asphalt Pavement Mixes by Finite Element Modelling and Optimisation

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ARTICLE INFO

Article history
Received: 14 October 2019
Accepted: 27 December 2019
Published Online: 14 January 2020

Keywords:
Visco-elastic-plastic
Creep
Asphalt pavement
Rutting
Wheel track testing
Finite Element modelling
Design of experiments
Optimisation

ABSTRACT

Asphalt pavement rutting is a major safety concern and is one of the main distress modes of asphalt pavement. Research into asphalt pavement mixes that provide strong resistance for rutting is considered of great significance as it can help provide extended pavement life and significant cost savings in pavement maintenance and rehabilitation. The objectives of this study are to develop numerical models to investigate the rutting of asphalt concrete pavements and to find optimal design of asphalt pavement mix for rutting resistance. Three-dimensional Finite Element models were first developed to simulate both the axial compression and wheel track testing in which a visco-elastic-plastic material model was used to predict the rutting of the asphalt concrete pavements. A strain hardening creep model with the material parameters developed from experimental testing was employed to model the time-dependent characteristics of the asphalt concrete pavements. The results were validated against the previous experimental wheel track test results of different pavement mixes. Finally, optimisation techniques using the Design Of Experiments method were applied to the simulation rutting results by varying creep parameters to identify their effects on rutting resistance in order to obtain an optimal asphalt pavements mixes. The results of this paper clearly demonstrate an efficient and effective experimental-numerical method and tool set towards optimal design for asphalt concrete pavements for rutting resistance.

1. Introduction

Rutting is one of the most serious distresses in asphalt pavements affecting the pavement service life and the handling of vehicles. The most common type of rutting is asphalt rutting caused by the plastic movement or 'creep' of the asphalt pavement, usually under heavy, often slow-moving loading. As traffic loading increases significantly and the recent negative changes in environment and climate also increase, the problem of pavement rutting is anticipated to increase. Therefore, research into methods of pavement evaluation and improvements of asphalt material mix designs is considered extremely necessary to provide extended pavement life and significant cost

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 DOI: https://doi.org/10.30564/jcr.v1i2.1283

savings in pavement maintenance and rehabilitation.

In the last three decades, there have been a lot of studies focused on investigating the material characteristics and prediction of rutting resistance of asphalt pavements. Regarding experimental testing, laboratory rut tests and field testing are usually used to investigate the rutting behaviour of asphalt concrete pavements. Wheel track devices such as Hamburg Wheel Tracking Device (HWTD) have been developed over the years and are now commercially available for evaluation of rutting potential of asphalt pavement in the laboratory[1]. It is recommended as one of the most appropriate tools for accelerated rut-ting resistance testing[2]. However, testing of asphalt mixes in the laboratory and in field are often expensive and time consuming. Therefore, it is impractical to conduct too many tests with varying material mixes in order to develop a new optimal asphalt pavement design for the rutting resistance. In terms of numerical modelling, a wide number of numerical studies for analysing rutting of asphalt pavements with more realistic constitutive models have been conducted that included more practical models in different Finite Element programs such as ABAQUS and ANSYS[3][4][5][6][7]. In [3], a 3-dimensional nonlinear Finite Element analysis with a viscoelastic model for asphalt concrete was used to analyse flexible pavements under moving loads, however, due to computational difficulties, the analyses were conducted for only ten loading cycles. The modelling of asphalt mixes using a viscoplastic model available in ABAQUS was addressed in [4], [8], and a 2-dimensional model to analyze in-service pavements was developed. Recently, 3-dimensional analysis simulated the HWTD testing of asphalt mixes using creep model in ANSYS was developed[6]. In these studies, the creep models used was in the 'time hardening' form and moving loads were treated as a static load, but due consideration was given to the duration of loading. However, as the creep 'time hardening' model was only developed for the assumption of the constant load, it might not be applicable for the moving load situation[9]. In addition, experiments indicated that the strain hardening formulation is to be favoured over the time hardening formulation. In recent years, there has been a significant amount of studies on different Finite Element modelling techniques and material constitutive models on predicting rutting in asphalt pavements under repeated loading conditions[10][11][12]. However, there has been limited investigations on optimal design of asphalt pavement mixes, considering the effects of varying material parameters on the mixes' rutting resistances.

In this paper, 3-dimensional Finite Element models to simulate the laboratory testing of asphalt mixes in triaxial compression and HWTD tests were developed. The triaxial repeated load creep and creep recovery test results have been used to obtain the associated creep parameters for asphalt concrete mixes. The calculated material properties determined in this manner were employed in the Finite Element models and validated against the HWTD test results. A general multi purposes Finite Element program, ANSYS, was used for this study. A creep model of the 'strain hardening' form was employed to represent the time-, stress- and temperature-dependent behaviour of asphalt pavement materials. A practical optimisation process using the Design Of Experiments using a response surface was undertaken to examine the influence of some selected parameters on rutting performance and to propose an optimal designed asphalt mixes for rutting resistance.

2. Experimental Testing

Experimental testing data of a previous study[4] was used in this study. Three asphalt mixes which were selected to represent a wide range of applications, from high traffic freeways to low volume municipal roads. The mixes included HL 3: conventional dense graded Marshall surface course mix; SMA L and SMA G: two Stone Mastic Asphalt 12.5 mm surface course mixes.

The triaxial repeated load creep testing was carried out in the Interlaken machine with the triaxial cell and pneumatic pressure system for the confinement [Interlaken Technology Company 2004]. The samples used were 100 mm diameter and 150 mm height cores obtained from the SGC cylinders. The triaxial repeated load creep and creep recovery tests were conducted in which each loading cycle consisted of two equal periods. During the first loading period, a constant loading deviatoric stress was applied. At the end of this period the load was removed, and a creep recovery was followed for the second period. The testing was carried out at a constant temperature of $50 \pm 0.5^{o}C$. The test results to investigate the visco-elasto-plastic behaviour of the asphalt mixes and to develop the material parameters used in the Finite Element modelling.

The Hamburg Wheel Tracking Device (HWTD) testing general view and diagram are shown in Fig. 1. The wheels were of solid rubber, 50 mm wide, and the load applied to the wheels is 710 N. The test path is 230 mm long and the average speed of each wheel is approximately 1.1 km/h (53 ± 2 wheel passes per minute). All the HWTD testing was carried out at a temperature of $50^{o}C$. Samples were 300 mm and typically 80 mm thick slabs. The number of

  DOI: https://doi.org/10.30564/jcr.v1i2.1283

wheel passes being used was typically 20,000.

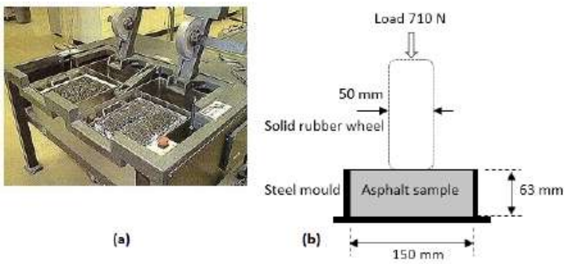

Figure 1. General View (a) and Testing Diagram (b) of the Hamburg Wheel Tracking Device.

3. Material Characterisation

In this analysis, the elastic modulus of asphalt mix material was obtained from the triaxial repeated load creep test[4]. The triaxial repeated load creep test done at a temperature of 50ºC and at a frequency of 1 Hz. The Poisson's ratio was calculated using the following equation given in the Mechanistic-Empirical Pavement Design Guide[13]:

$$\mu_{ac} = 0.15 + \frac{0.35}{1+e^{-1.63+(3.84\times10^{-6})E_{ac}}} \quad (1)$$

Where μ_{ac} is the Poisson's ratio of asphalt mix at a specific temperature, E_{ac} is the elastic modulus of asphalt mix at a specific temperature.

Visco-elasto-plastic model in the form of power law creep model was used to represent the asphalt mix material. To model primary and secondary stages of creep characteristics, the power law creep model[14] in the form of 'strain hardening' was used in this research and it can be written in the form of creep strain rate which is expressed as a function of stress, strain and temperature. The material is assumed to be isotropic and the basic solution technique used is the initial-stiffness Newton–Raphson method as in the following equation:

$$\dot{\varepsilon}_{cr} = C_1 \sigma^{C_2} \varepsilon_{cr}^{C_3} e^{\frac{C_4}{T}} \quad (2)$$

Where $\dot{\varepsilon}_{cr}$ is the creep strain rate, σ is the equivalent stress, ε_{cr} is the creep strain at the time t, T is temperature and C_1, C_2, C_3, and C_4 are the creep parameters that are functions of state of stress, material type and temperature. As the temperature in the test is fixed at 50°C, the parameters C_1, C_2, C_3 are developed from the triaxial repeated load creep test at 50°C and the modulus of elasticity and Poisson's ratio determined at the same temperature. As C_4 is much smaller than T, $e^{\frac{C_4}{T}}$ is considered as 1. The elastic parameters modulus of elasticity and Poisson's ratio and creep parameters C_1, C_2, C_3 are required for the Finite Element model in order to calculate the rutting for various mixes under a wheel load of 710 N or a uniform loading pressure of 500 kPa.

The creep parameters C_1, C_2, C_3 are material-related parameters and were first determined from the triaxial repeated load creep test and then calibrated based on the rutting measured in the HWTD. Each asphalt mixture has a unique set of C_1, C_2, C_3 that defines the time-dependent behavior of that mixture. The elastic and final creep parameters used in the simulation are shown in Table 1.

Table 1. Material Parameters of Asphalt Mixes

Mix	Material parameter				
	Elastic		Creep		
	E_{ac} (kPa)	μ_{ac}	C_1	C_2	C_3
HL 3	950000	0.41	2.691×10^{-5}	4	-1.703
SMA L	800000	0.42	2.837×10^{-8}	4.727	-3.545
SMA G	800000	0.42	2.284×10^{-7}	6.238	-3.762

4. Numerical Modelling

Finite Element simulations were conducted using ANSYS (ANSYS software, version 2018) to simulate both the triaxial repeated compression loading and wheel track loading tests. The samples were presented by 3D solid elements of the type SOLID45; this element is defined by eight nodes having three degrees of freedom at each node translation in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. The element size is of approximate size of 10 mm and 20mm in the triaxial and HWTD models, respectively (a mesh dependency study was carried out for different mesh sizes to select these meshes, however, results are not shown here). Under the constant pressure in both models, the axial deformation of the sample increased depending upon testing time due to the materials' visco-elasto-plastic (creep) behaviour. A full Newton-Raphson method was used for the iterative procedure and an implicit, static analysis was employed.

4.1 Triaxial Test Finite Element Modelling

Fig. 2 illustrates the FE model setup for the triaxial repeated load creep test which also shows the mesh. The cylinder test sample was modelled with 100 mm diameter and 150 mm height. The sample was modelled by 3D solid elements of approximate size of 10 mm. Compression load was applied on the top of the sample in the form of a uniform axial pressure, and the confining pressure was uniformly applied to the sides of the sample. In the case of verifying the model against the theoretical axial compression creep model (under constant stress) the confining pressure was assumed to be zero. The bottom of the sample was fixed but allowed some small movement in horizontal direction by using the option 'Remove

 DOI: https://doi.org/10.30564/jcr.v1i2.1283

Displacement' in ANSYS. Strain hardening creep model was used for asphalt material in which the creep parameters C_1, C_2, C_3 were determined from the triaxial repeated load creep test as presented in Table 1.

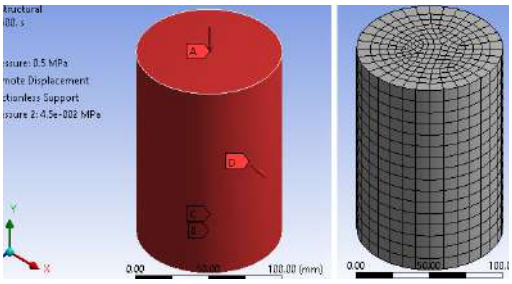

Figure 2. FE Model Setup of the Triaxial Compression Testing Which Shows Loading, Boundary Conditions and Mesh.

4.2 Hamburg Wheel Track Device Test Modelling

The FE model setup for the wheel track test HWTD is shown in Figure 3 which also shows the mesh. The rectangular test sample was modelled with dimensions of 150 mm in width × 300 mm in length × 63 mm in height. The sample was modelled by 3D solid elements of approximate size of 10 mm. The model had 5,760 solid cube elements and 26,725 nodes. The footprint of the HWTD solid rubber wheel on the surface of asphalt mix sample, measured at a testing temperature of 50°C, had a rectangular area of 50 mm in width × 28.5 mm in length, and this was used to calculate the loading time and contact pressure. The test was done after 20,000 loading passes which was about 4,200 seconds. The bottom and the four surrounding vertical boundaries were set to be confined with restricting displacement in all directions. For the load of 710 N applied in this area, it was equivalent to a uniform loading pressure of 0.5 MPa. Different loading techniques including the most realistic moving load model and the equivalent load for the whole wheel path model were simulated and compared for predicting asphalt rutting.

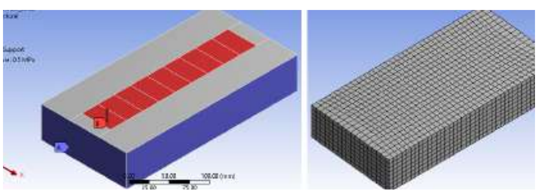

Fig. 3. FE Model Setup of the Triaxial Compression Testing Which Shows Loading, Boundary Conditions and Mesh.

4.3 Optimisation Technique

Mathematically, the objective function of parameters $\vec{X} = [x_1, x_2, x_3, \ldots, x_n] \in D^n$ for the α^{th} application can be expressed as $f_{k\alpha}(\vec{X} \in D^n)$ with $k=1, 2, 3, \ldots, L_\alpha$ and $\alpha=1, 2, 3, \ldots, A$. The best feasible solution for one single objective can be found by $Min\, f_{k\alpha}(\vec{X} \in D^n)$ with the constraint $g_{j\alpha,min} \leq f_{k\alpha}(\vec{X} \in D^n) \leq g_{j\alpha,max}$, $j=1, 2, 3, \ldots, m_\alpha$. In which, n is the total number of design parameters, L_α is the total number of objective functions, is the total number of parameters. Details of the response surface's mathematical forms can be found in ANSYS Documentations (version 2018). A numerical procedure of straightforward direct search was employed to optimize multiple objective functions. The whole design space is first represented by discrete points that were evenly spaced in each dimension. The objective functions and state variables were then mapped to the points, forming the response surface. Planning the Design Of Experiments (DOE) using a response surface model, running multiple simulations, recording the performance of the system at each run and determining material parameter values that gave the target performance. A graphic method was thus used and described as follows: all regions of optimum solutions were plotted together on a matrix of 2-dimensional plots with all possible combinations of two design parameters out of n design parameters. In this study, design parameters are C_1, C_2 and C_3 and the objective function is the rutting depth.

The rutting depths predicted by Finite Element modelling could be affected by any parameter of the five material parameters: two elastic model parameters including elastic modulus and Poison's ratio, three creep model parameters including C_1, C_2 and C_3. However, predicted rut depth was not sensitive to elastic modulus and Poison's ratio since these two factors only define the elastic behaviour, which is not significantly affected to the permanent deformation. Therefore, the DOE study was carried out by varying values of the three creep parameters.

The optimal asphalt pavement mix design and finite element simulations, using the HL 3 mix as an example, were carried out in three stages: (1) Developing new asphalt pavement mixes from the existing ones by varying their creep material parameters C_1, C_2, C_3, against the target performance of the mixes, using parametric modelling technique, (2) Planning the Design Of Experiments (DOE) using a response surface model, running multiple simulations, recording the performance of the system at each run and determining C_1, C_2, C_3 values that give the target performance: a maximum rutting resistance, and (3) Simulating the wheel track testing of new optimal asphalt pavement mixes and comparing with recently conducted test results for validation.

5. Results and Discussion

5.1 The Triaxial Load Creep Testing

The FE modelling was first verified by comparing the

DOI: https://doi.org/10.30564/jcr.v1i2.1283

results obtained from the triaxial repeated load creep testing model with the theoretical axial compression creep model as presented in Eq. (2). In the FE model, the creep parameters C_1, C_2, C_3 for each asphalt mix as shown in Table 1 were used. The FE results in term of creep strain are shown in Fig. 4 which also shows the comparison between FE and theoretical results obtained from Eq. (2). It can be seen clearly that the FE model predicted accurately the axial compression and creep behavior of the asphalt mix under axial constant loading.

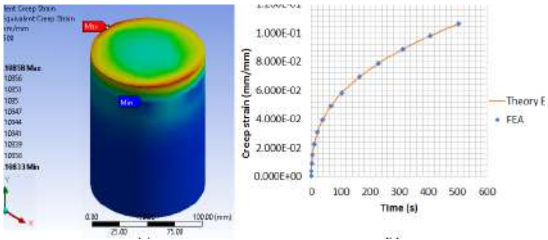

Figure 4. FE Creep Results for Axial Compression Loading (a) and Comparison with Theoretical Axial Compression Creep Model as Presented in Eq. (2), Demonstrating Via the Typical Sample HL 3

5.2 The Hamburg Wheel Tracking Device Testing

The measured rut depth versus time relationship with rutting predicted in FE models for all mixes at any time of loading up to about 4500 seconds are shown in the Fig. 5. It is observed that the difference between FE model prediction and measured rutting depth for sample HL 3 is as high as 4% at around 2250 seconds and 4200 seconds. The maximum differences between the predicted rutting values and the HWTD values for samples SMA L and SMA G are illustrated in the Figs. 6 and 7, respectively. The maximum differences between the predicted rutting values and the HWTD values are about 8% and 16%, respectively. The typical FE predicted deformation shape after 20,000 passes is illustrated in Fig. 8. It shows that the FE model is very capable of capturing the rutting depth due to plastic flow and irrecoverable deformation in the sample.

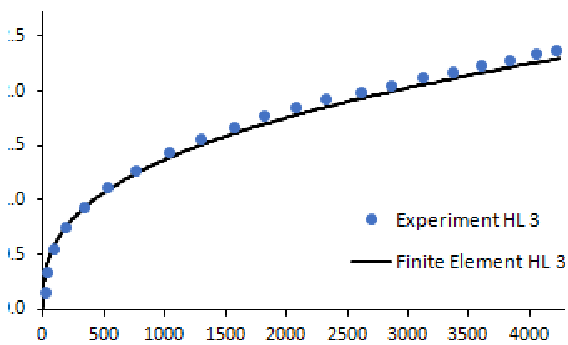

Figure 5. Comparison Between Rutting Depths Predicted by FE Modelling and Measured in HWTD tests for the HL 3 Mix.

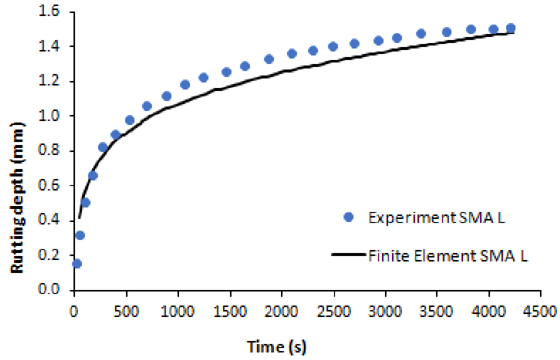

Figure 6. Comparison Between Rutting Depths Predicted by FE Modelling and Measured in HWTD Tests for the SMA L Mix.

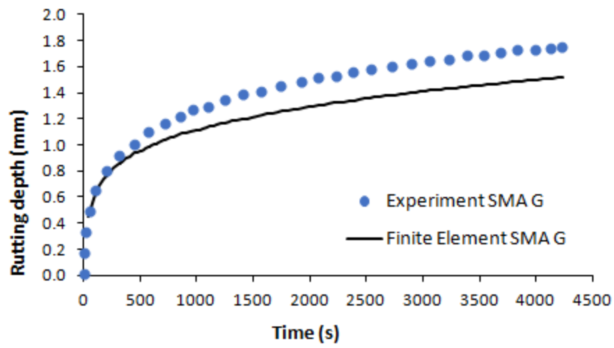

Figure 7. Comparison Between Rutting Depths Predicted by FE Modelling and Measured in HWTD Tests for the SMA G Mix.

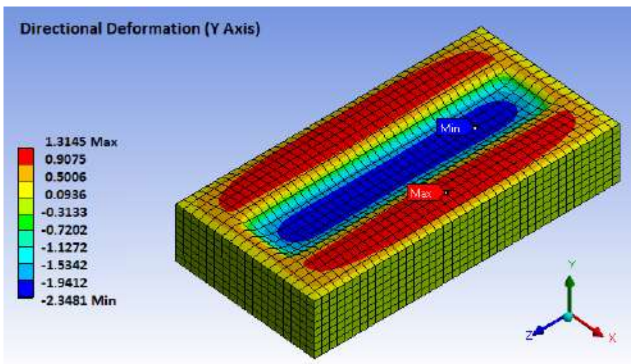

Figure 8. FE Predicted Deformation Shape of the HL 3 Mix After 20,000 Passes (the Rutting Depth is Not in a Correct Scale).

5.3 Optimisation Technique

The validated FE model (of HL 3 mix) was then extended for modelling and developing new asphalt pavement mixes. The rutting performance of the new mixes was examined by changing creep parameters including: Parameter P1 is the creep constant C_1 (2.837×10^{-8} – 2.691×10^{-5}), Parameter P2 is the creep constant C_2 (4 –

 DOI: https://doi.org/10.30564/jcr.v1i2.1283

6.238), Parameter P3 is the creep constant C_3(-3.762 – -1.703). The output target results were rutting depth or Directional Deformation Minimum (mm).

The process of varying all the parameters was carried out in ANSYS under the Analysis System: Optimisation. In which each parameter was assigned 5 different values in the range from min to max value. The target responses selected in this study were the rutting depth in the asphalt pavement specimens under the HWTD testing simulations. Each response was a response surface function of all parameters and was treated as an objective. There were a selected 15 runs integrating all parameters while the applied loads on the specimens were the same for all the runs. These are illustrated in Table 2 below. The response surface which also shows the effects of creep parameters on the rutting depth is shown in Fig. 9.

Table 2. Geometric Parameters and Target Responses Using the DOE Method in ANSYS

Mix	C_1	C_1	C_1	Rutting Depth (mm)
1	1.485E-05	5.119	-2.733	-2.8
2	2.837E-08	5.119	-2.733	-0.6
3	2.968E-05	5.119	-2.733	-3.4
4	1.485E-05	4.000	-2.733	-4.9
5	1.485E-05	6.238	-2.733	-1.6
6	1.485E-05	5.119	-3.762	-5.5
7	1.485E-05	5.119	-1.703	-0.8
8	2.800E-06	4.209	-3.570	-5.0
9	2.691E-05	4.209	-3.570	-8.1
10	2.800E-06	6.029	-3.570	-2.4
11	2.691E-05	6.029	-3.570	-4.0
12	2.800E-06	4.209	-1.895	-1.1
13	2.691E-05	4.209	-1.895	-2.5
14	**2.800E-06**	**6.029**	**-1.895**	**-0.4**
15	2.691E-05	6.029	-1.895	-0.8

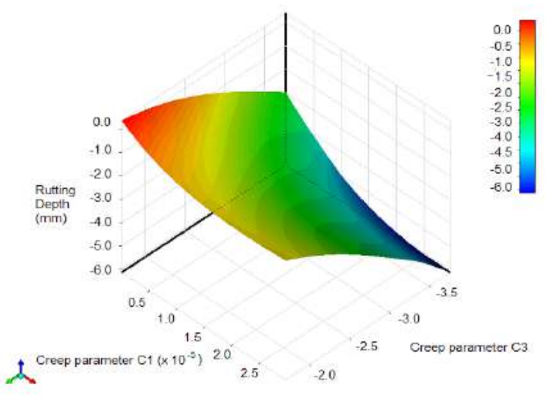

Figure 9. Response Surface for the Effects of Creep Parameters on the Rutting Depth.

It can be seen from Fig. 9 that the rutting depth was very sensitive with C_1, and increased with increasing values. That could be due to C_1 was directly related to the amount of asphalt cement content, and C_1 increased with increasing asphalt cement content in a mix that influenced the amount of rutting in the asphalt mixes. The rutting depth increased with reducing C_3 values as C_3 was decreased with increasing asphalt cement content. Similarly, the rutting depth increased with reducing C_2 values (graph not shown). Local sensitive analysis showed that C_1 had negative effects whilst C_2 and C_3 had positive effects on the rutting deformations, and the magnitude of sensitivity on the rutting deformations reduced from C_3 to C_2 and to C_1, as from 48% to 28% and to 20%, respectively.

The DOE results in Table 2 indicated that the asphalt pavement mix no. 14 with C_1=2.8×10^{-6} , C_2 =6.029, and C_3 =-1.895 could be the optimal mix for rutting resistance (with a rutting depth of 0.4 mm).

6. Conclusion

In this paper, the Finite Element models were developed to simulate the laboratory testing of asphalt mixes in triaxial compression and HWTD tests. The associated creep material parameters for asphalt concrete mixes were obtained from the triaxial repeated load creep and creep recovery test results. The FE models employed the characterised creep parameters associated with 'strain hardening' creep models were first verified against the theoretical creep model for the axial compression loading on asphalt cylinder sample. The characterised material properties determined in this manner were employed in the Finite Element models and validated against the HWTD test results for three different asphalt mixes. Very good agreement was found between the FE predicted and HWTD measured rutting depths.

This paper has also presented the design and development of new asphalt pavement mixes by using a combined approach of the finite element analysis and optimization using DOE method to simulate the HWTD rutting responses and obtain the optimum design for the mixes. The creep parameters of the asphalt pavement were defined as input parameters in FE modelling and assigned a range of values so that a wide range of FE results was obtained. A response surface model was then used for the results to determine parameter values that achieve the rutting resistance as the target optimised performance. The optimisation study conducted using the FE models gained more understanding on the influences of creep parameters to the rutting resistance of asphalt mixes. It can be

DOI: https://doi.org/10.30564/jcr.v1i2.1283

concluded that the Finite Element simulations can be used to effectively evaluate and optimise the rutting resistance of asphalt concrete pavements.

Acknowledgement

This study is part of the FIRST project 'The development of numerical simulation and optimization technologies for optimal performance of concrete asphalt pavements taking into account the traffic and climate conditions of Vietnam' (35/FIRST/1a/UTC). We acknowledge FIRST Project, Ministry of Science and Technology, Vietnam, for sponsoring this project.

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