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Finite Element Model for Rutting Prediction in Asphalt Mixes in Various Air Void Contents

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Abstract: Asphalt pavement rutting is one of the most commonly observed pavement distresses and is a major safety concern to transportation agencies. Millions of dollars are spent annually to repair rutted asphalt pavements. Researches into improvements of hot-mix asphalt materials mix designs, methods of pavement evaluation and design can provide extended pavement life and significant cost savings in pavement maintenance and rehabilitation. The three objectives of this study are to investigate the rutting behaviour of asphalt mixes with different air void contents, to link these behaviours to an accelerated testing tool using wheel track tester and to develop a finite element model based on creep model parameters. The creep model parameters C1, C2 and C3 were obtained from the dynamic creep test results using multiple regression analysis. The dynamic creep test was conducted at temperature of 40°C using two selected stress levels of 100 and 200 kPa. Five superpave mixes with five levels of air void contents ranged from 2.5-10.5% were used to investigate the rutting behaviour of asphalt mixes. The variation between the value of measured rut depth and the predicted one bye finite element simulation is found to be 4-7%. This illustrates that the developed finite element model can be used in the finite element analysis for giving a good prediction of rutting depth of a bituminous mixture. Three dimensions axisymmetric slice analyses have been used in this study. This study indicated that air void contents have significant influence on the behaviour of rutting under repeated wheel loadings. Finally it can be concluded that creep model based on finite element method can be used as an effective tool to analyze rutting of asphalt pavements.

Key words: Rutting, asphalt pavements, creep model, finite element modelling, viscoplastic

INTRODUCTION

More than 90% of the roadways around the world are flexible pavement constructed with bituminous materials. In spite of this worldwide usage, premature pavement deformation such as rutting and cracking are still very common and causing high maintenance cost. Rutting due to repeated traffic loading is a great sign of permanent deformation of flexible pavement and it frequently occurs after only the first few years following road opening (Roberts *et al*., 1996). Pavement requires very frequent maintenance to protect the pavement and keep it meeting the structural and functional requirements. The ability to predict the amount and extension of deformation in pavement is an important aspect to pavement design and maintenance works (Krutz and Stroup-Gardiner, 1990). Rutting is a result of the plastic movement of the asphalt mixture in high temperature or insufficient compaction during construction stage (Huang, 1993). It is well known that variations in material characteristics are a major factor affecting the deformation resistance of bituminous material (Monismith and Tayebali, 1988). In the last 20 years, a lot of researchers focused their interests on investigating these material characteristics and tried to get accurate predictions on rutting propagation of bituminous pavement. Archilla and Madanat (2001) conducted some studies on investigating how the characteristics of aggregates would affect the mixture resistance to rutting. From the conclusion of the study, it is indicated that the use of naturally angular or crushed aggregates in general can yield satisfactory performance. Along with surface texture and shape of the aggregates, gradation of material is also considered to be a very important factor to provide different degrees of inter-particle friction (Brown and Cooper, 1984). For instance, larger maximum aggregate sizes are believed to perform better in terms of

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rutting resistance, since they usually give lower voids in mineral aggregate (Siddharthan *et al*., 2002). The most important characteristic of the bituminous binder for rutting performance is its stiffness at high temperature (Perl *et al*., 1983). The rate of rutting accumulation is directly related to the magnitude of the shear strain obtained in the simple shear test at constant height (Sousa and Weissman, 1994). The recommendation from these studying is to introduce a well-designed asphalt concrete pavement composing with higher quality materials which can be expected not to show any significant rutting in service. However, the rutting behaviour of bituminous materials depends not only on the individual properties of aggregate and bituminous binder but also on the interaction between each other in a mixture (Ramsamooj *et al*., 1998).

The objectives of this study are to investigate the behaviour of bituminous materials with different air void contents using finite element method. The creep model parameters C_1, C_2 and C_3 were obtained based the dynamic creep test results using multiple regression analysis. Finally comparing of wheel tracking test results with finite element results to verify the simulation results.

MIX INFORMATION

The bituminous mixture consists of aggregates of 25, 19, 9.5 and 4.75 mm in size, sand and *in suit* crushed rock filler. The properties of coarse and fine aggregate were determined. The procedures used for the laboratory works were referred to American Society for Testing and Material (ASTM) specifications. The laboratory works can be divided into several stages beginning with the aggregates preparation and distribution into different particle sizes through sieve analyses. Firstly, the quarry aggregates were dried sieve and blended meeting the gradation limit fulfilling the ASTM specification. Washed-sieve analysis that was referred to ASTM C 117 (ASTM International, 1996) to determine the proportion of mineral filler content required in the aggregates gradation. The determination of specific gravity for coarse and fine aggregates was done according to ASTM C 127 and C 128. Based on the ASTM D 3515-96 (D-4), the aggregates were blended as in Fig. 1 and sieved. Aggregates were batched based on the percentage passing on each sieve size.

SPECIMEN PREPARATION

Cylindrical specimens of 100 mm in diameter and 70 mm in height were compacted using Superpave Gyratory Compactor (SGC) at target air void contents of 2.5-10.5%. Slab specimens of the 50 mm in height were prepared using a roller compactor at the same target air void contents. The specimen's air void content is then calculated from the specimen's bulk specific gravity and mixture's theoretical maximum specific gravity (Chen *et al*., 2001). The controlled-density mode was applied during the course of compacting. To ensure that the engineering properties of the compacted specimens in laboratory condition are similar to those of the inplace paving mix, a short-term aging at 135°C for 4 h was applied to the specimen before the mechanical performance tests which aimed to achieve a comparable condition as the compaction process in the field (Chen *et al*., 2004). Specimens are preconditioned at test temperature for 10 h before subject to the creep and rutting tests (Tarefder *et al*., 2003).

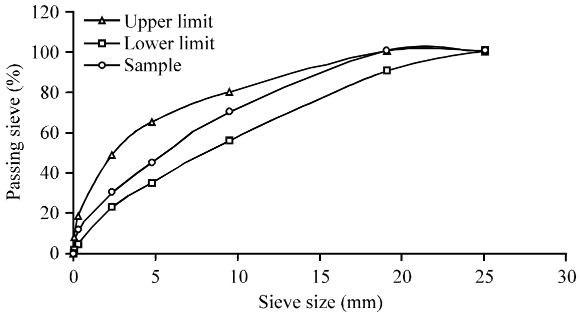

Fig. 1: Gradation graph of mixture

DYNAMIC CREEP TEST USING UNIVERSAL TESTING MACHINE 25 (UTM25)

The dynamic creep tests were carried out using UTM25 to apply repeated axial stress pulse to asphalt specimens measuring the vertical deformation with a linear variable displacement transducer. In servohydraulic UTM25 machine, the stress/load applied to the specimen is feedback controlled, allowing the operator to select a loading wave shape haversin or square pulse, a pulse width duration, a rest period, a deviator stress/load to be applied during each loading pulse and a contact stress/load to be applied so that the vertical loading shaft does not lift off the test specimen during the rest period. Prior to testing, a preload/stress can also be programmed into the testing sequence. To control the ambient temperature of testing samples, the loading mechanism of the UTM machine is placed within an environmental chamber. Figure 2 shows a picture of the sample placed in the container and under the loading setup. As mentioned earlier, input data including dimensions of sample (height and diameter), preload stress, deviator stress, frequency

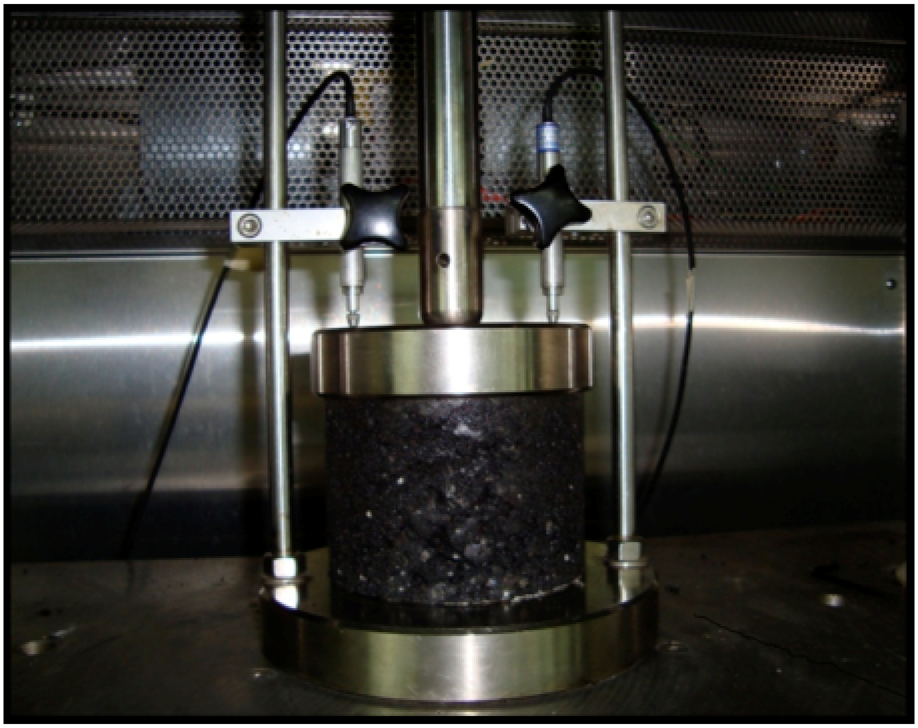

Fig. 2: A sample in UTM25 container under dynamic creep test

of stress application and contact stress are controlled via integrated software. In this study a square pulse wave with frequency of 0.5 Hz (by allocating 500 msec for pulse width and 1500 msec for rest period) was chosen according to Australian code (Australian Standard, 1995). A sample of pulse wave and the measured axial displacements of the specimen for one pulse are displayed in Fig. 3.

Deformation of specimen, as it is manifested in the Fig. 3, starts to increase by application of stress during the pulse width and it climbs up to its highest point as the loading is finalized. During the rest period, considerable portion of deformation which is known as resilient deformation disappears and the remaining deformation is considered to be permanent deformation. Resilient modulus and creep modulus are the most important outputs of dynamic creep test. Based on the definitions suggested by a number of researches and UTM25 software reference manual. Resilient modulus and creep modulus are derived using Eq. 1 and 2, respectively:

$$Mr = \frac{\sigma_d}{\varepsilon_r} \tag{1}$$

$$Mc = \frac{\sigma_d}{\varepsilon(t)} \tag{2}$$

$$\varepsilon(t) = (\varepsilon_e+\varepsilon_p+\varepsilon_{ve}(t)+\varepsilon_{vp}(t)) \tag{3}$$

Where:

σ_d = Deviator stress
ε_e = Resilient deformation at a certain number of load application
ε_d = Total deformation (including elastic, visco-elastic, plastic and visco-plastic deformations) up to a number of load application

Resilient modulus, as derived from the Eq. 1 indicates the sample resistance to resilient deformations and creep modulus indicates its resistance to permanent deformation. By the application of load to samples in each cycle, three sets of diagrams consisting of permanent deformation, resilient modulus and creep modulus versus load cycles are drawn by UTM software.

Based on the information gotten from the dynamic creep tests, the permanent deformations of mixtures with different air void contents are demonstrated in Table 1. The results show that the permanent deformation differs among the mixtures with different air void contents. For example, it is found that the mixtures with 4% air void are the most resistant to permanent deformation. Under an excessive compaction condition, the deformation resistance for the mixture of 2.5% air voids is shown to

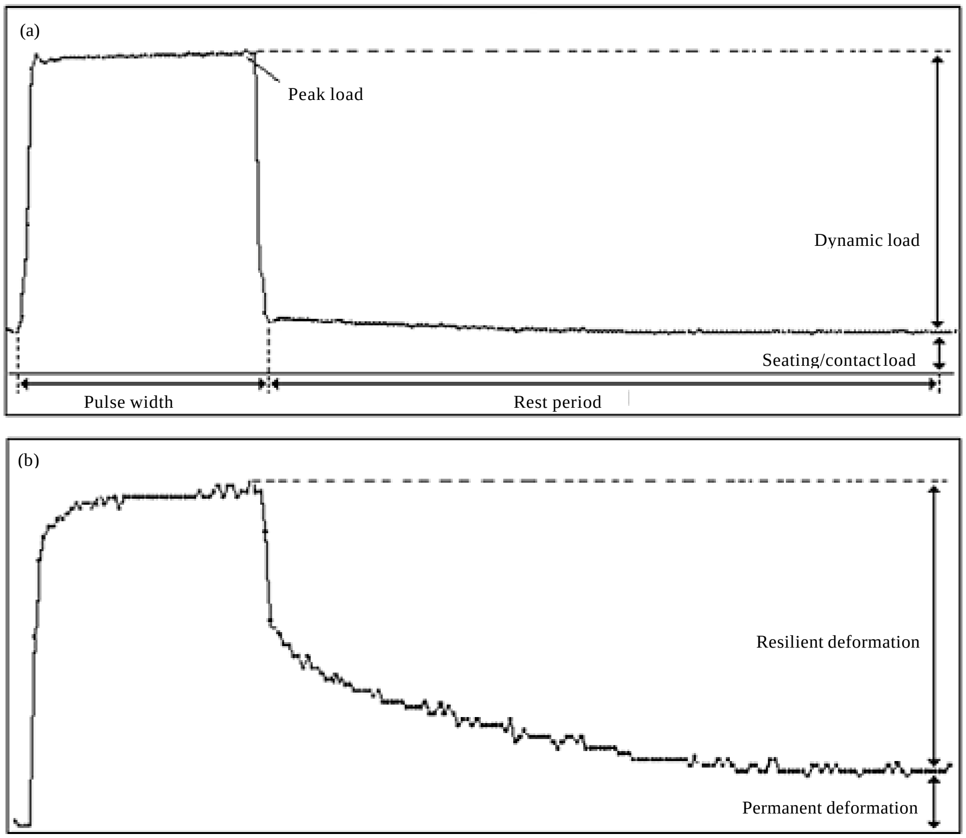

Fig. 3(a-b): A pulse wave and the measured displacement, (a) Typical force and (b) Typical deformation wave shape (square pulse)

Table 1: Results of dynamic creep test with different air void contents

Description	Value
Temperature	40°C
Specimen height	Varies
Specimen diameter	100 mm
Test loading stress	100 kPa
Pulse width	500 msec
Rest period	1500 msec
No. of cycles	3500

drop significantly. This shows that the excessive compaction would lead to a decrease in resistance to permanent deformation. While throughout the poor compaction phase, the permanent deformations of mixtures with air voids of 6.5, 8.5 and 10.5% increase significantly and cause damage to the mixtures' structures.

The permanent deformation curves of bituminous mixtures with different air void contents are presented in Fig. 4. As the curves show, the different mixtures behave differently in the 7200 sec of loading application. It is also found that the materials subjected to intermediate temperature (40°C) and higher stress levels clearly show

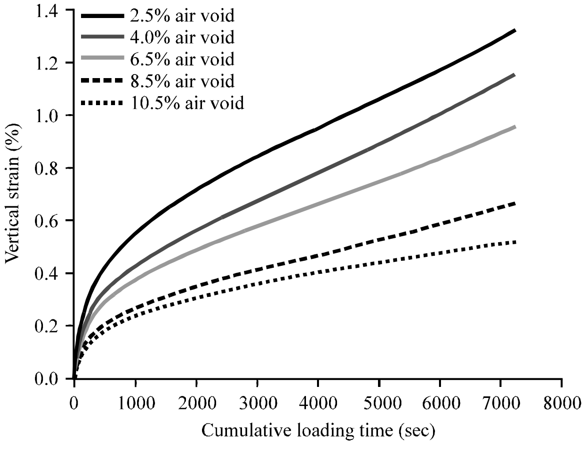

Fig. 4: Permanent deformation curves of bituminous mixtures with different air void contents

three stages of creep, with the first stage lasts for a relatively short period of time. However, under the standard temperature, the creep curves of bituminous materials show that three creep stages do not exist as the creep strain continuously increases with time until failure occurs. On the other side, the test results also show the mixtures with different air void contents have different creep characteristics. Under the condition of low air void content resulting from good compaction, the strong interface could be formed between aggregates. To the mixtures with high air void contents, the interface between aggregates is weak due to inadequate compaction. In the same condition of cyclic compression, the mixtures with different air void contents would bear different behaviours in creep due to different interface structures generated. To verify the performance of bituminous material under different loading conditions, in the research, two stress levels of 100 and 200 kPa were selected for the test conditions. Figure 5 shows the results of the dynamic compressive creep tests (with 4% air void content) under different stress levels. By comparing the two results, it is indicated that higher stress level would generate a higher vertical strain increment rate in the primary stage of creep. In addition, the creep curves are strongly orientation dependent and the creep strain tends to be fairly insensitive to the change in stress level, for example the creep strain increases only by a little amount (i.e., 20%) with a double increase in the stress level during the test at a temperature of 40°C. The details of the dynamic creep test results with different stress levels and different air voids are summarized in Table 2.

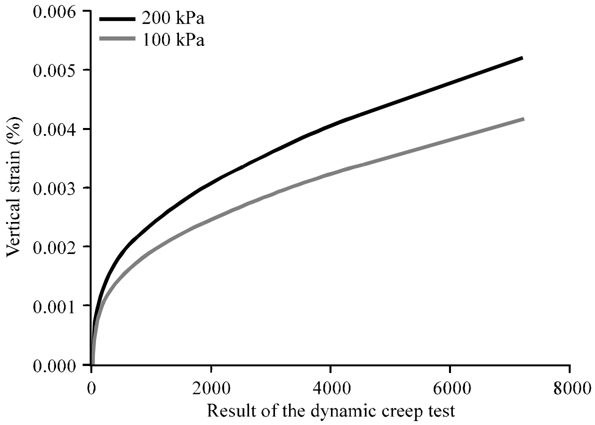

Fig. 5: Results of dynamic creep test under different stress levels for 4% air void content mixture

Table 2: Vertical strains (%) under different stress levels

Air voids content (%)	Strain at different stress levels (kPa) 100	200
2.5	0.7909	0.9530
4.0	0.4150	0.5188
6.5	0.5524	0.6656
8.5	0.8047	1.1497
10.5	1.1576	1.3155

CREEP PARAMETERS DEVELOPMENT

In this study the creep model parameters C_1, C_2 and C_3 are calculated based on dynamic creep test results shown in Table 3. The multiple regression analysis can be used to obtain the creep model parameters. The details of analysis procedure are presented as follows:

- To obtain the measured creep stains of ε_{cr} and draw a graph of creep strain vs. time
- To computing creep strain rate by using:

$$\Delta\varepsilon_{cr}/\Delta t \tag{4}$$

- Input data ($\Delta\varepsilon_{cr}/\Delta t$, σ and t) to the multiple regression analysis base on Eq. 4

Material behaviour at different time stage is the main factor affecting the increment rate of the creep strain. Table 3 shows the results of multiple regressions.

As is the common practice among other researchers, the criteria for goodness of fit of statistical parameters can be based on the value of the coefficient of determination, (R^2). The coefficient of determination is the correlation coefficient squared and it tells the percentage of the variation in the dependent variable (Y) which is explained by the variation in the independent variable (X). The criteria used in this study is shown in Table 4 (Witczak *et al*., 2002).

As shown in Table 1, air voids of 4% and air voids 6.5% have present the best fit results according to R^2>0.9. The parameter values will be used in a finite element model.

FINITE ELEMENT SIMULATION OF WESSEX WHEEL TRACKER

Finite element method can be used as effective tool to analyze rutting in asphalt pavements (Nahi *et al*., 2011).

Table 3: Multiple regression results for creep model

	Air void contents (%)				
Variables	2.5	4.0	6.5	8.5	10.5
C_1	8.44E-7	8.66E-7	8.51E-7	3.46E-7	1.92E-7
C_2	0.228	0.328	0.279	0.399	0.410
C_3	-0.6735	-0.9004	-0.8322	-0.6732	-0.6412
R^2	0.881	0.929	0.921	0.863	0.814

Table 4: Criteria for goodness of fit statistical parameters

Criteria	R^2
Excellent	≥0.90
Good	0.70-0.89
Fair	0.40-0.69
Poor	0.20-0.39
Very poor	≤0.19

Nahi *et al.* (2011)

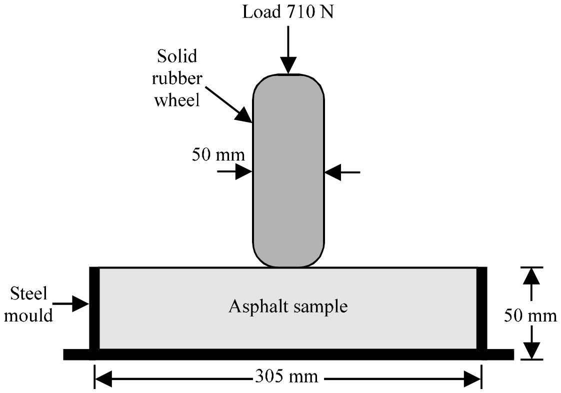

Fig. 6: Rutting resistance testing in the Wessex Wheel Tracker

The objective of the initial model is to describe the impact of Wessex Wheel Tracker on asphalt mixes with various sir voids content. The primary purpose of the model is to define what occurs in the asphalt sample during the Wessex Wheel Tracker test. A general schematic of the used finite element mesh is shown in Fig. 6.

The footprint of the Wessex Wheel Tracker solid rubber wheel on the surface of asphalt mix samples, measured at a testing temperature of 40°C. The average length of the wheel footprint of 28.5 mm is used to calculate the loading time and the contact pressure. For the load of 520 N applied in the Wessex Wheel Tracker testing, a uniform loading pressure of 365 kPa is used in the analysis.

In the finite element analysis, the structure and other auxiliary conditions have to be correctly modelled to obtain reasonable results. This includes various components of the finite element model such as include material properties, load conditions, boundary conditions, element type and geometry of the model (Witczak *et al*., 2002; Suo and Wong, 2009; Rahman *et al*., 2008; Vakili-Tahami and Sorkhabi, 2009). As shown in Fig. 4 and 5,305×305 mm (in width) and 50 mm (in height) rectangular bituminous mixture structure was constructed to simulate the wheel tracking test. A single axle with single wheel was used to provide the loading condition. The load magnitude was 520 N with 365 kPa tire pressure. The material creep model discussed above was used to characterize the permanent deformation properties of the bituminous mixture. The parameters used in the creep model were derived from the creep test result shown in Table 2. The bottom and the four surrounding vertical boundaries were set to be confined with restricting displacement in all directions. An eight-node, three-dimensional stress-displacement element was used in the finite element analysis (Fig. 7). The size of the finite element mesh was varied according to loading effect. The finest mesh was used on the wheel path to improve the precision of calculation.

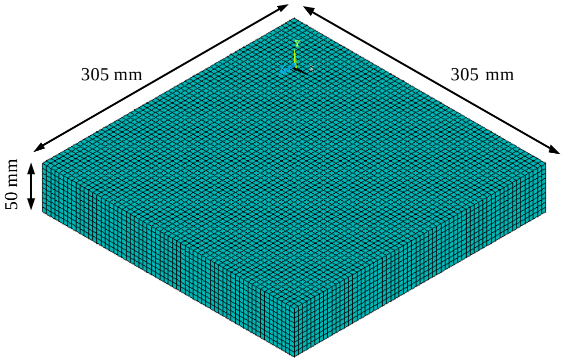

Fig. 7: Finite element mesh of wheel tracking test specimen

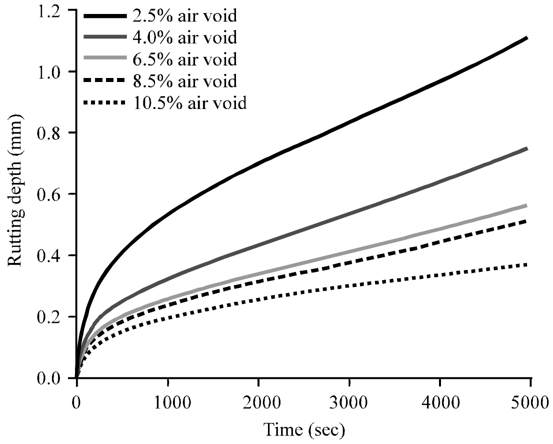

Fig. 8: Comparison of rutting depth versus time with different air void contents in finite element

Figure 8 shows the predicted rutting profiles of a specimen under the wheel tracking by using the creep model. Figure 9 shows the measured rutting profiles of a specimen in wheel tracking test. The variation between measured rut depth value and the predicted one bye finite element simulation is 4-7% as shown in Fig. 10. This illustrates that the developed creep model can be used in the finite element analysis for giving a good prediction of rutting depth of a bituminous mixture.

Rutting depths are shown to be small at air voids between 4 and 6.5%. However, the rutting depth increases

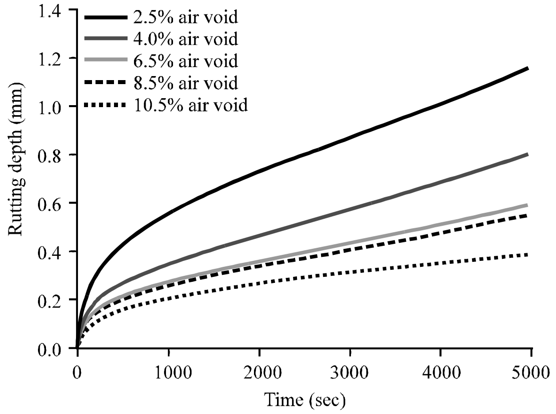

Fig. 9: Comparison of rutting depth versus time with different air void contents in Wessex Wheel Tracking test

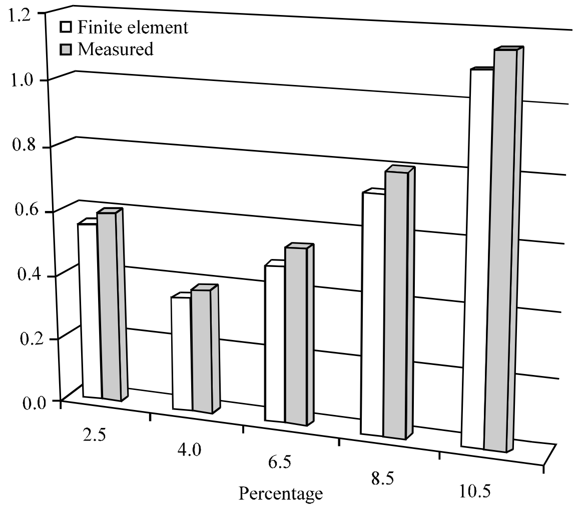

Fig. 10: Comparison of the prediction of rutting between measured value and finite element simulation value with different air void content

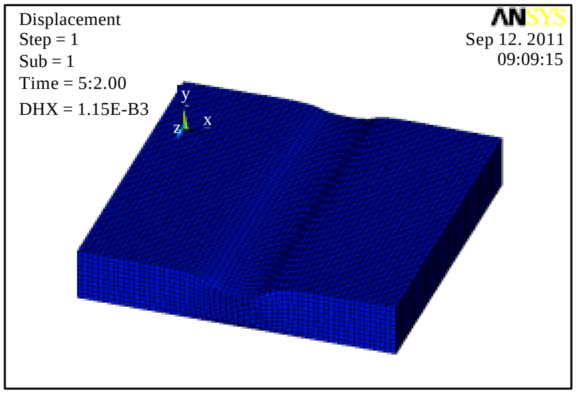

Fig. 11: Deformed shape for a sample in the end of loading time predicted in 3D finite element simulation

concentration of stress level in mixture components and a specimen with higher air voids also would bear an inhomogeneous bituminous binder-aggregate structure. For very low air void content, the cause may due to the excessive compaction applied to the mixture. The excessive compaction energy may damage or fracture the coarse aggregates. Since, for mixture with higher amount of fine aggregate components, the stability of the specimen structure would be weakened and thus the rutting potential of bituminous materials would be when the air void falls either below or above this range. For higher air voids (i.e., >8.5%), air replaces larger volume of bituminous binder and aggregates that increases the increased. Figure 11 shows deformed shape for a sample in the end of loading time predicted in 3D finite element simulation.

CONCLUSION

Testing in the Wessex Wheel Tracker is a suitable method for determining the rutting potential of asphalt mixes. It can be used to define the nature of rutting and to investigate rutting behavior of bituminous materials with different air void contents. The dynamic creep tests for bituminous materials with different air void contents under different stress levels were carried out. The characteristics of orientation dependency, rates dependency and air voids effects were studied. A number of material parameters of bituminous materials were also obtained. A specimen under wheel tracking was then simulated by using a finite element model to verify the rutting propagation of a real asphalt concrete mixture. The creep parameters C_1, C_2 and C_3 are developed based on dynamic creep test using multiple regression analysis and used for finite element simulations. From the finite element analysis results it was found that air void contents have significant influence on the behavior of rutting under wheel loadings. For the air void contents within the range of 4-8.5%, the rutting depth changes very little when it is subject to the change of applied stress. However, for air void contents below or above this range, the reduction in rutting resistance resulting higher rutting depth is noted. This may due to the fact that the lower and higher air void of the mixture may be caused by the excessive and poor compaction, respectively. The variation between measured rut depth value and the predicted one bye finite element simulation is 4-7% which is illustrates that the developed creep model can be used in the finite element analysis for giving a good prediction of rutting depth of a bituminous mixture.

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