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Analysis of Asphalt Pavement under Nonuniform Tire-pavement Contact Stress using Finite Element Method

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Abstract: Tire-pavement contact stress is traditionally assumed to be uniformly distributed over a circular contact area. In this study, the tire-pavement contact pressure has been modeled to be nonuniform. A new tire model is developed for the analysis based on the geometry of the tire footprint because the contact area between the tire and the pavement is not exactly rectangular or circular. The objective of this study is to develop a finite element model based on viscoplastic theory for simulating the laboratory testing of asphalt mixes in Hamburg Wheel Rut Tester (HWRT) for rutting and to model in-situ pavement performance. The creep parameters C_1, C_2 and C_2 are developed from the triaxial repeated load creep test at 50°C and at frequency of 1 Hz. Viscoplastic model (creep model) is adopted and a commercially available Finite Element (FE) program, ANSYS, is used in this study, in order to predict the rutting for in-situ pavement under nonuniform contact pressure. In the simulation, the used element has an eight-node with a three degrees of freedom per node translations in the nodal x, y and z directions. Dual wheel system of a standard axle load of 80 kN is used in the 2D pavement in-situ performance analysis. Reasonable agreement has been obtained between the predicted rut depths and the measured one. Moreover, it is found that creep model parameter C_1, strongly influences rutting than the parameter C_3. Finally it can be concluded that creep model based on finite element method can be used as an effective tools to analyze rutting of asphalt pavements.

Key words: Nonuniform pressure, rutting, creep model, finite element modelling, viscoplastic, isotropic

INTRODUCTION

Finite element method is wide common used now days. Zaoui *et al.* (2008) presented a contribution to the reinforced concrete beams modelling using the Castem 2000 finite element software. Finite element method is evaluated as a useful approach to recognize the critical points and fatigue life time of the reciprocating components such as connecting rod (Omid *et al.*, 2008). The fatigue life prediction was carried out by Rahman *et al.* (2008) study using finite element based fatigue code. Lots of money is spend on the maintenance of asphalt pavements roads (Awwad, 2007), rutting is one of the wide common deformations for flexible pavement roads. For proper pavement design and better understanding of materials behaviours it is necessary to predict asphalt pavement rutting. Rutting phenomenon is the longitudinal depressions along the wheel paths caused by the movement of asphalt pavement materials under high traffic loading based on consolidation or plastic flow (Suo and Wong, 2009). Excessive amount of asphalt cement is one of reasons for plastic flow (Walker *et al.*, 2004). Rutting in asphalt pavement is mainly occurs due to its nonlinear viscoplastic nature (Uzarowski, 2007). The high wheel loads and high tire pressures are the main cause for Increasing of asphalt pavement rutting phenomenon (Mukhtar, 2006). Magdy (1996) presented three rutting mechanisms wear rutting, structural rutting and instability rutting. This study deals with the last type, which is the most dangerous type of surface rutting. An eight-node, three-dimensional stress displacement element was used in the finite element analysis. Pirabarooban *et al.* (2003) developed a finite element model to simulate the laboratory testing of asphalt mixes in Asphalt Pavement Analyzer (APA) test for rutting and to relate the test results to basic material properties, a visco-elasto-plastic model (creep model) has been used to represent the time-dependent characteristics of the asphalt mixture. The objective of this study is to develop a finite element model to simulate the laboratory testing of asphalt mixes in (HWRT) for rutting and to develop a finite element

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model to analyze in-situ pavement performance. Nonuniform contact pressure for dual wheel system of a standard axle load of 80 kN is used in the 2D pavement in-situ performance analysis. The nonlinear viscoplastic behaviour analysis of asphalt mixes was adopted in this study. It was found that creep model parameters C_2 and C_1 have a strong relationship with rutting. However, among these two the parameter C_1 strongly influences rutting than the parameter C_3.

ASPHALT VISCOPLASTIC BEHAVIOUR

The hot-mix asphalt materials plays a major role in asphalt pavement rutting. Most paving materials are not elastic, but if the load is small compared to the strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recoverable and can be considered elastic (Huang, 2004). The recoverable (elastic and viscoelastic) and nonrecoverable (plastic and viscoplastic) strain components are determined in the analyses. The viscoplastic strain component is the major contributor to the asphalt mixture rutting and only this component is used in the development of the material creep parameters. If the creep model is used to describe the time dependant material behaviour, the repeated loading and continuous loading have the same effect on the predicted creep strain as long as the total loading times are the same (Texas DOT, 2003).

HAMBURG WHEEL RUT TESTER

The Hamburg Wheel Tracking Device (HWTD) is well known in Canada as the Hamburg Wheel Rut Tester employed The HWRT for asphalt mix accelerated performance testing in terms of its rutting resistance. The wheels can be either steel 47 mm wide or solid rubber 50 mm wide and the load applied to the wheels is 710 N (FHWA, 2002). The customary temperature for the HWRT test in Canada and the United States is 50°C; this temperature is also typically used in Europe for a climate close to a Superpave high temperature PG of 58. The test path is (230 mm) long and the average speed of each wheel is approximately 1.1 km h^{-1} (53±2 wheel passes per min). All the HWRT testing was carried out at a temperature of 50°C. Five asphalt mixes were used by Uzarowski (2007); these mixes present a wide range of applications, from high traffic to low volume roads. All five mixes were obtained from paving projects in Ontario. In total, about one ton of asphalt mixes was used in the research and the designs for all five mixes were provided by the contractors who supplied the mixes. The mixes incorporated the aggregate types and asphalt cements listed in Table 1.

LOADING TIME CALCULATING

The footprint of the HWRT solid rubber wheel on the surface of asphalt mix samples, measured at a testing temperature of 50°C, is shown in Fig. 1. 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 710 N applied in the HWRT testing, a uniform loading pressure of 500 kPa is used in the analysis. The test path in the HWRT is 230 mm long and typically, 53±2 passes are completed in 1 min. For the average wheel footprint length of 28.5 mm, the time of loading in one pass is about 0.14 sec. The time of loading conversion described by Hua (2000) and shown in Fig. 2 is used in this research. The T1-T2 time is 0.14 sec. And the T0-T1 and T2-T3 time periods are 0.07 sec. The converted loading time in one pass is 0.21 sec. The time of loading for 20,000 passes is 4,200 sec. ANSYS simulations are completed for 4, 10, 20 and 30 million ESAL's traffic loading. The assumed average speed of commercial vehicles is 60 km h^{-1}. The effective time of loading in one tire pass for the 175 mm long outside tread areas, is 0.0126 sec. For the traffic loading of 30 million ESAL's applied over 20 years, the total loading time is 156,000 sec.

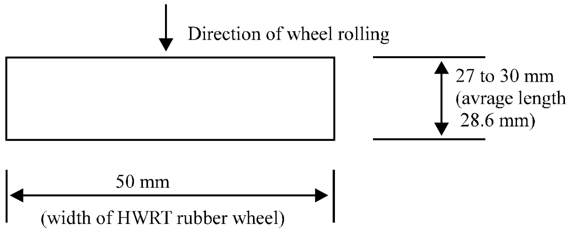


Fig. 1: Footprint of HWRT solid rubber wheel

Table 1: Asphalt mix ingredients (Uzarowski, 2007)

	Aggregate			
Mix	Course	Fine	Additives	Asphalt cement grade
HL 3	Crushed gravel (40%)	Asphalt sand (45%) and screening (15%)	-	PG 58-28
SMA L	Traprock (79%)	Traprock (13%) and mineral filler (8%)	Cellulose fibre (0.3%)	PG 70-28 PM*
SMAG	Traprock	Traprock and mineral filler	Cellulose fibre (0.3%)	PG 70-28 PM*
SP 19 D	Crushed rock (39%)	Screenings (10%) and manufactures (51%)	-	PG 64-28
SP 19 E	Crushed rock (63%)	High stability sand (37%)	-	PG 70-28

*Both PG 70-28 PM asphalt cements were polymer modified

Table 2: Loading time used in pavement *in-situ* performance simulation

	Loading time (sec)	
Traffic loading (ESAL'S)	Step1	Step2
4,000,000	21, 000	3, 200
10,000,000	52, 000	8, 000
20,000,000	104, 000	16, 000
30,000,000	156, 000	24, 000

As the three middle areas are longer by about 15 percent, an additional loading time of 24,000 sec is used for these areas. The loading time used in the ANSYS simulations are given in Table 2.

CREEP MODEL PARAMETERS

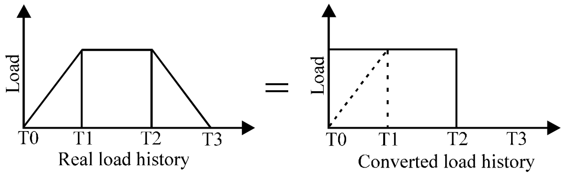
Five material parameters may affect the rutting predicted by the finite element method. These parameters include three creep model parameters (C_1, C_2 and C_3) and the elastic parameters, modulus of elasticity and Poison's ratio. However, predicted rut depth is not sensitive to modulus of elasticity and Poison's ratio since these two factors only define the elastic behavior which is not directly related to the permanent deformation, therefore, the sensitivity study was kept limited to the creep model parameters (Pirabarooban *et al*., 2003). In this analysis, the modulus of elasticity obtained from the triaxial repeated load creep test based on Uzarowski (2007) study has been used. The triaxial repeated load creep test done at a temperature of 50°C and at a frequency of 1 Hz. The creep parameters C_1, C_2 and C_3 have been calibrated based on the rutting measured in the HWRT. The parameter is stress related. The rut resistance testing in the HWRT is conducted at a constant loading stress of 500 kPa, the C_3 parameter is fixed at the initial level shown in Table 3. Parameter C_1 is the value of the y-axis intercept while parameter C_2 is related to the slope of the strain-time relationship curve in a log-log scale. The elastic and final creep parameters used in the simulation are shown in Table 3 and the same parameters are used in the modeling of the *in-situ* pavement performance.

ANSYS MODELING

ANSYS is a suite of powerful engineering simulator based on the finite element method. Many researcher have been used ANSYS in their studies. The finite element based software ANSYS models are employed to evaluate the transient temperature and the residual stress fields during welding. Also, in this study the variations of the physical and mechanical properties of the material with temperature have been taken into account (Vakili-Tahami and Sorkhabi, 2009). ANSYS has an extensive library of finite elements and an extensive list of material models. Analysis in ANSYS includes two stages, starting level and processing level, Starting level includes converting a mechanical problem to Finite Element Model (FEM). Processing level includes three steps Pre-processing, Solve and Post-processing. The geometry of problem, material properties, element type and boundary conditions has been defined in Pre-processing step. While in the solve step, the type of analysis have been chosen. Finally the result of solving the problem has been observed in the Post-processing step (ANSYS, 2004). There are lots of equations embedded in commercial finite element analysis software (ANSYS). In order to model primary and secondary stages of creep characteristics, the presented creep model used in this research can be written in the form of creep strain rate. The material is assumed to be isotropic, and the basic solution technique used is the initial-stiffness Newton-Raphson method as in Eq. 1:

Table 3: Asphalt mix elastic and creep parameters

	Material parameter				
	Elastic		Creep		
Mix type	Modulus kPa	Poisson's ratio	C_1 ($\times10^{-8}$)	C_2	C_3
HL3	950,000	0.41	41	1.48	-0.63
SMAL	800,000	0.42	509	1.04	-0.78
SMA G	800,000	0.42	138	1.31	-0.79
SP 19 D	1,600,000	0.39	66	1.20	-0.68
SP19 E	1,400,000	0.40	72	1.20	-0.64



Real load history

Converted load history

Fig. 2: Load duration conversion (Hua, 2000)

$$\dot{\varepsilon}_{cr} = C_1 \sigma^{c2} t^{c3} \tag{1}$$

where,ε_{cr} is the creep strain rate, r is the equivalent stress, t is the time at end of sub-steps. C_1, C_2 and C_3 are the parameters related to material properties. As the temperature in the analysis is fixed at 50°C, the parameters C_1, C_2, and 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. The elastic parameters modulus of elasticity and Poisson's ratio and creep parameters C_1, C_2, and C_3 are required for finite element simulator (ANSYS) in order to calculate the rutting for various mixes under a uniform loading pressure of 500 kPa.

FINITE ELEMENT SIMULATION FOR HWRT

The structure and the auxiliary conditions in the finite element simulation have to be properly odellin to obtain reasonable results. This includes the finite element model's components such as include element type, boundary conditions, load conditions, material properties and geometry of the model As shown in Fig. 3, 150×300 mm (in width) and 63 mm (in height) rectangular bituminous mixture structure was constructed to simulate the Hamburg Wheel Rut Test. The dual wheel loading configurations in the HWRT testing are symmetrical. To reduce the elements number and the required time for each analysis, only one wheel and half of the HWRT sample was included in the finite element modeling. The load magnitude was 710 N with 500 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 triaxial repeated load creep test result. The bottom and the four surrounding vertical boundaries were set to be confined with restricting displacement in all directions except the axisymmetric side which is surrounding is x direction only. SOLID45 is used for the 3-D modelling of solid structures and this element is defined by eight nodes having three degrees of freedom at each node translations in the nodal x, y and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection and large strain capabilities.

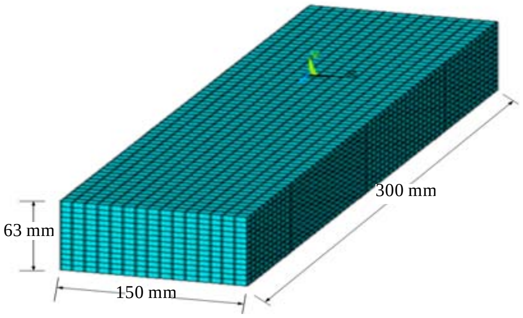


Fig. 3: Geometry of the model and finite element mesh of wheel tracking test specimen

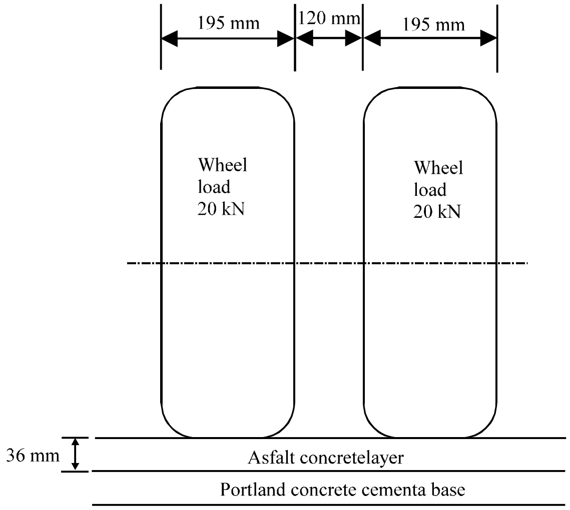


Fig. 4: Dual wheel system used in pavement *in-situ* performance analysis

MODELING PAVEMENT *in-situ* PERFORMANCE

The material parameters developed from the laboratory testing and HWRT testing analysis, shown in Table 3, are used to model pavement *in-situ* performance in ANSYS. It is assumed in the model that a single 63 mm of asphalt placed over a Portland cement concrete base so that rutting could occur only in the asphalt layer. It is also assumed that the layer of HMA is fully bonded with the underlaying Portland cement concrete layer so that no movement of the HMA layer can occur on the surface of the concrete base. A dual wheel system of a standard axle load of 80 kN is used in the pavement *in-situ* performance analysis. The system is shown in Fig. 4 a load of 20 kN is applied by each wheel in the system. Tire-pavement contact stress is traditionally assumed to be uniformly distributed over a circular contact area. The tire modeled in this research is a standard Goodyear G159A-11R22.5 (Fig. 5). The wheel load is applied through the tire treads to the surface of the asphalt layer. A new tire model shown in Fig. 6 is developed for the analysis based on the geometry of the tire footprint, because the contact area between the tire and the pavement is not exactly rectangular or circular. The wheel load is transferred to the pavement through five rectangular areas. The three middle areas are narrower and longer than the two outsideareas. The different lengths of the areas are reflected in the 2D finite element analysis by using a longer time of loading for the middle three areas. The contact pressure is not uniform. It ranges from 517 kPa for the outside areas to 586 kPa for the central area. The pressure in the remaining two areas in the middle is 552 kPa. As the dual wheel system is symmetric, only half of the system is modeled. The distance between the two wheel tires in a dual wheel system is 120 mm. The density of the mesh under the load

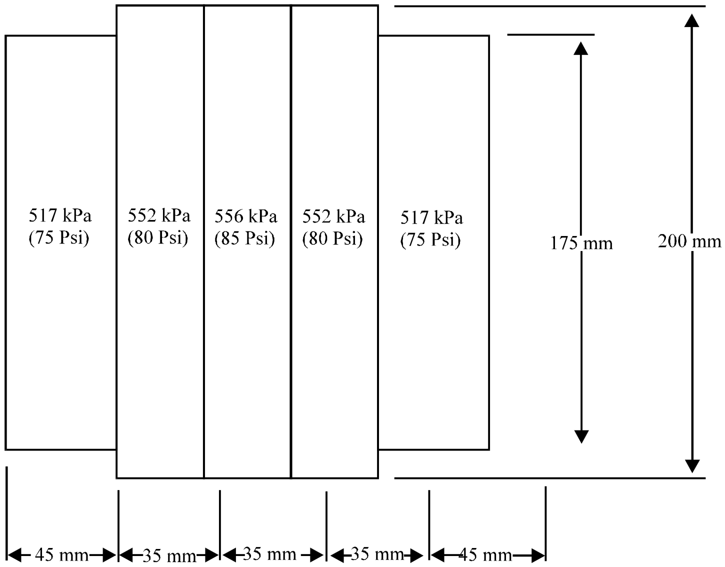


Fig. 5: Wheel tire model used in ABAQUS simulation

and directly next to it is twice the density in the 300 mm wide zone outside the loaded part.

RESULTS AND DISCUSSION

The creep parameters have been used in the 3D simulation, were derived from the triaxial repeated load creep test's results. The simulation results for the HWRT shows different amount of rutting and Different shape of rutting versus time curve for different mixes. Figure 6 shows that dense graded mix, HL3, is the worse mix with higher rutting, there was a good agreement between the finite elemnt results and the measured one. The gap graded mix, SMA L, shows a good resistance to rutting, Fig. 7 shows the rutting versus time for SMA L mix. It's clear from Figure 8 that SMA L mix has a better resistance than SMA G. The SP 19 E mix has significantly higher asphalt cement content than the SP 19 D mix, 4.60 percent and 4.35%, respectively that's why SP 19 D mix has a higher resistance to rutting. Figure 9 shows that SP 19 D mix looked much leaner than the SP 19 E mix which shown in Fig. 10, SP 19 E mix has the beast rutting resistance among all the five mixes as shown in Fig. 10. The difference between the shapes of the permanent deformation curves is clear. Uzarowski (2007) noted that there is a significant difference between the curve's shapes of the gap graded mixes and dense graded mixes. Figure 7 and 8 shows that the densification of the gap graded mixes SMA L and SMA G is high at the beginning of the loading and then the rutting curve flattens to reach the constant slope after about 1500 sec. The densification of the dense graded mixes is gradual, proportionally small at the beginning of the loading and then the deformation

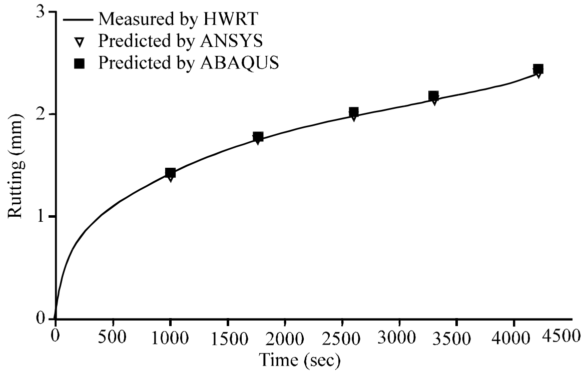


Fig. 6: Rutting measured in HWRT and predicted in ABAQUS and ANSYS for the HL 3 Mix

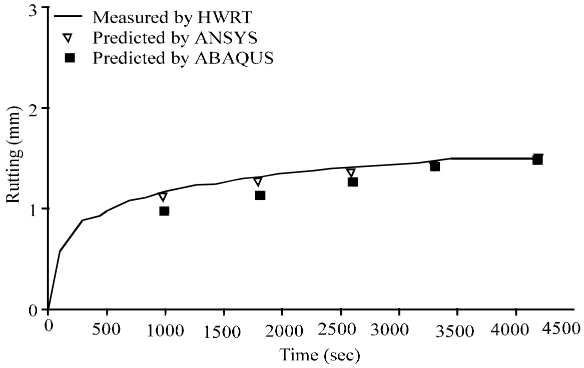


Fig. 7: Rutting measured in HWRT and predicted in ABAQUS and ANSYS for the SMA L Mix

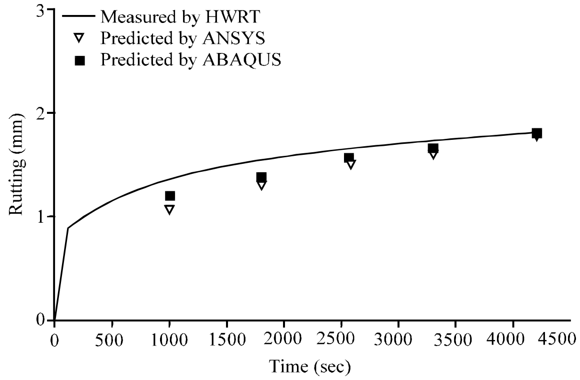


Fig. 8: Rutting measured in HWRT and predicted in ABAQUS and ANSYS for the SMA G Mix

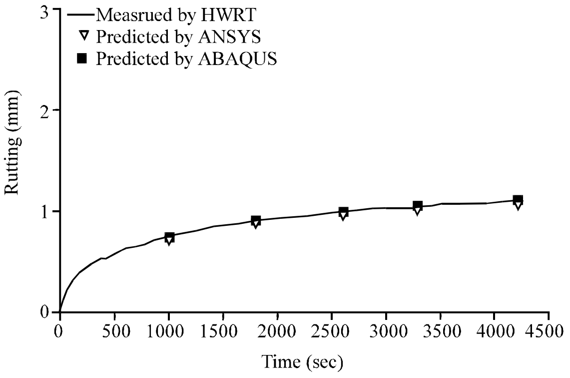


Fig. 9: Rutting measured in HWRT and predicted in ABAQUS and ANSYS for the SP 19 D Mix

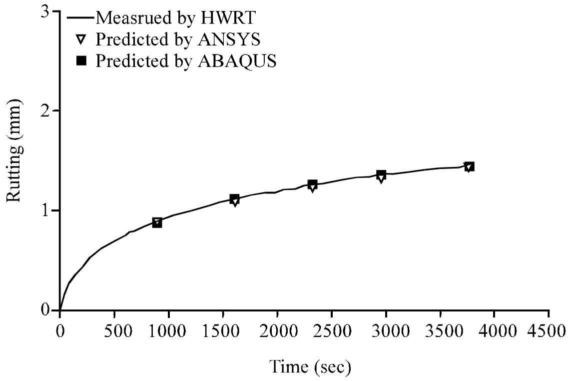


Fig. 10: Rutting measured in HWRT and predicted in ABAQUS and ANSYS for the SP 19 E Mix

reaches a constant slope after about 1700 sec, as shown in Fig. 6, 9 and 10. The measured rut depth versus time is predicted in ANSYS and ABAQUS at the time of loading of 1000, 1800, 2600, 3300 and 4200 sec, the results show that there is a reasonable agreement of the difference between the predicted and the laboratory measured rutting and the comparison between the obtained results from ABAQUS. It's clear that the rutting increasing with the time as the asphalt pavement is time dependent, Yin *et al.* (2007) presented that the loading time has a more significant impact on pavement response in the fixed temperature. The 2D model for *in-situ* asphalt pavement is successfully predicted asphalt pavement rutting. Fig. 11 show the predicted rutting of a pavement versus ESAL for the five mixes. The depth of the rutting for HL3 mix has increased from 3.5 mm for 4 million ESAL's to 9.3 mm for 30 million ESAL's as shown in Fig. 7 while the depth of the rutting for SMA L mix has increased from 1.7 mm for 4 million ESAL's to 2.6 mm for 30 million ESAL's. It is also clear from Fig. 11 that the rutting depth for the mix SMA G has increased from 2.2 mm for 4 million ESAL's to 3.4 mm for 30 million ESAL's, while the depth of the rutting for mix SP19 D has increased from 1.6 mm for 4 million ESAL's to 3.04 mm for 30 million ESAL's. The rutting depth For SP19 E mix increase from 2.5 mm for 4 million ESAL's to 5.3 mm for 30 million ESAL's. Load repetition is an important traffic factor which influences rutting resistance of asphalt pavements (Hofstra and Kolomp, 1972). Phang (1988) stated that rutting accumulates faster as the load repetition increases. There are total of five possible factors which may affect the predicted model response, they are creep model parameters C_1, C_2 and C_3, modulus of elasticity and Poisson's Ratio. Pirabarooban *et al.* (2003) stated that the rut depth (magnitude) and the nature of variation decreases with increasing C_3, values, note that C_3 is negative. Similar to parameter C_1, the parameter C_3 also increases with increasing asphalt cement content. The results of this work simulation shows that the predicted

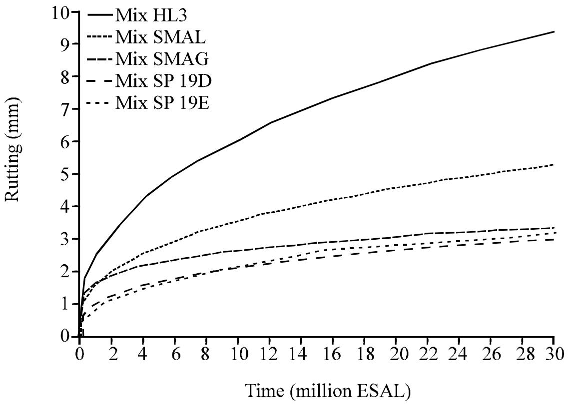


Fig. 11: Predicted rutting depth versus ESAL of a pavement the five mixes by ANSYS

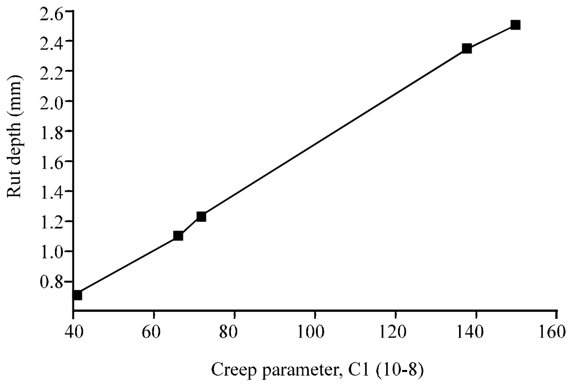


Fig. 12: Effect of varying creep model parameter on rut depth

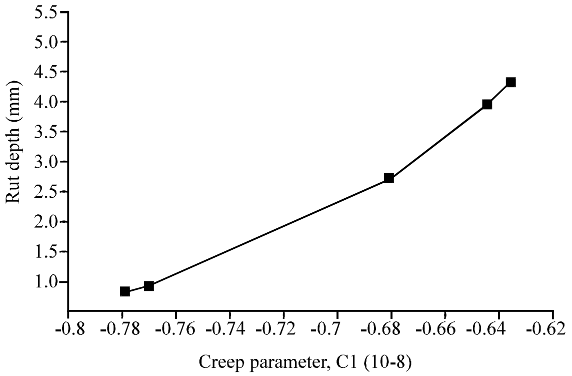


Fig. 13: Effect of varying creep model parameter on rut depth

rut depth is not sensitive to modulus of elasticity and Poisson's Ratio. This expected since these two factors only define the elastic behaviour which is not directly related to permanent deformation. It was clear that the parameter C_1 strongly influences rutting than the parameter . As can be seen from Figure 12, predicted rut depth increases with increasing value. As can be seen from Fig. 13, predicted rut depth increases with increasing value (noted that is in the range from -1 to 0).

CONCLUSION

The 2D model for *in-situ* asphalt pavement is successfully predicted asphalt pavement rutting. A new tire model used for the analysis based on the geometry of the tire footprint and that successfully simulated the tire-pavement contact stress because the contact area between the tire and the pavement is not exactly rectangular or circular and. The finite element model developed for HWRT tester was verified by comparing predicted and measured rut depths and also by comparing the rut depth with ABAQUS result from literature. Reasonable agreement was found between the predicted and measured rut depths furthermore it was found that creep model parameters C_1 and C_3 have a strong relationship with rutting and that the parameter strongly influences rutting than the parameter C_3. It was clear that the predicted rut depth increases with increasing value and with increasing C_3 value. The parameters C_1 and C_3 are closely related to the amount of asphalt content and the air void in hot mix asphalt. Finally it can be concluded that creep model based on finite element method can be used as effective tools to analyze rutting of asphalt pavements.

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