Evaluation of Rutting Distress for Asphalt Concrete Mixture Using Abaqus Program

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ABSTRACT: Rutting or permanent deformation is one of the most significant problems associated with asphalt pavement performance. It is characterized by a permanent change in the shape of the pavement or pavement layers due to cyclic wheel loads. Quality of asphalt mix (HMA) is one of the main factors that affect the flexible pavement performance. Use of poor quality mix and finding their consequences through pavement performance evaluation is often too costly. Therefore, the remedy is to evaluate the quality of the mix at the design stage of a project. Use of the finite element method (FEM) and other advanced analysis techniques is suitable for evaluation of pavement response and performance. This research describes a method of predicting the behavior of various asphalt mixes (surface coarse and binder coarse mixes) and linking these behaviors to an accelerated performance testing tool (Wheel Track test). The Wheel Track device is used in this research for asphalt laboratory accelerated rutting resistance testing and for calibration of material parameters developed in uniaxial repeated load creep and creep recovery testing. The ABAQUS program is used in this research for the finite element simulation. Two and three dimensional finite element models were developed and utilized in order to predict rut depth of the mixtures. Result of this research is a practical framework for developing finite element model to predict rutting potential of asphalt concrete mixtures.

KEY WORDS: Rutting, wheel track, creep model, abaqus.

1 INTRODUCTION

Pavements represent the largest component of public investment in transport. At the present most pavements in Iran are asphalt pavements. These pavements deteriorate with time due to traffic loading and environmental exposure. Pavement deterioration process is complex and involves not only structural fatigue but also many functional distresses of pavement. It results from the interaction between traffic, climate, material and time. Deterioration is used to represent the change in pavement performance overtime. The ability of the road to satisfy the demands of traffic and environment over its design life is referred to as performance (White 2002).

Asphalt pavement rutting is one of the most commonly observed pavement distresses. Millions of dollars are reportedly spent annually to repair rutted asphalt pavements. As traffic loading increases significantly and more frequent periods of hot weather due to global warming, the problem of pavement rutting is anticipated to escalate. Improvements of hot-mix asphalt materials, mix designs and methods of pavement evaluation and design including laboratory and field testing is considered necessary to provide extended pavement life and significant cost savings in pavement maintenance and rehabilitation (White 2002).

In the past subgrade deformation was considered to be the primary cause of rutting and many pavement design methods applied a limiting criterion on vertical strain at the subgrade level. However recent research indicates that most of the rutting occurs in the upper part of the asphalt surfacing layer (European Commission 1999). Therefore in this research finite element modeling is used to predict rut depth in asphalt layer of pavement.

2 DEFORMATION OF ASPHALT CONCRETE MIXTURES AND CREEP MODEL

Asphalt is a visco-elasto-plastic material with behavior depending on temperature and rate of loading. Perl considered the elastic, plastic, viscoelastic and viscoplastic strain components of asphalt mix behavior in his research on the permanent deformation of the asphalt mixes (Perl 1983). Contribution of each component in mixture performance depends on temperature of the mixture and rate of loading. At low temperatures, asphalt mix can be considered to behave like a linear viscoelastic material, but the higher the temperature, the more important and significant are the response components which describe the viscoelastic and viscoplastic components (Perl 1983).

At elevated temperatures and constant stress or load, asphalt mix will continue to deform at a slow rate. This behavior is called creep (Spencer 1988). At a constant stress and temperature, the rate of creep is approximately constant for a long period of time. After this period of time and after a certain amount of deformation, the rate of creep increases, and fracture may occur. A creep power law is available in a finite element program namely ABAQUS that was used in this research. The creep power law model can be used in its “time hardening” form or in the corresponding “strain hardening” form for pavement rutting ABAQUS simulation. The time-hardening form of the creep model was used in this research (Abaqus 2004):

$$\dot{\varepsilon}=A\sigma^{n}t^{m} \tag{1}$$

Where:

$\dot{\varepsilon}$ = creep strain rate, σ = the uniaxial equivalent deviatoric stress, t = the total time and
A, m, n= parameters related to material properties

The above function is defined as a power law equation and its use assumes that viscoplastic strain is the sole contributor to permanent deformation. An instantaneous plastic strain is neglected in this model (Huang 1995). In this study resilient modulus test was used for determining the elastic properties of asphalt mixtures and dynamic creep test was used for determining the material creep parameters. Also, results of the wheel track test on mixtures were used for calibration of the finite element models.

3 MATERIALS

Two mixes of aggregate combination and bitumen were used in this study. Coarse aggregate and fine-filler are all from local supplier. For the production of the asphalt concrete mixture a 60/70 penetration grade bitumen was used. The characteristic properties of the two materials are shown in Table 1 and Table 2.

Table 1: Physical characteristics of the materials used in the project

Test	Test method	Description	Test Results		
			Coarse Aggregate	sand (0-6 mm)	Filler
Sand Equivalent Test	AASHTO-T176		-	48	-
Resistance to Degradation by Abrasion and Impact in the Los Angeles Machine	AASHTO-T96	Gradation Type	B	-	-
		Number of Round	500	-	-
		Abrasion Percentage	13	-	-
Determining the Plastic and Plasticity Index Limit	AASHTO-T89,90	Plastic Index	-	N.P	N.P
Percentage of Fractured Particles	ASTM-D5821	One side	96	-	-
		two side	87	-	-
Coating and Stripping of Bitumen-Aggregate Mixtures	AASHTO-T182		> 95	-	-
Methods for determination particle shape of	BS-812	Elongation index	-	-	-
		Flakiness index	26	-	-
Soundness of Aggregate by Use of Sodium Sulfate	AASHTO-T104	Coarse aggregate	-	2.5	-
		Fine aggregate	0.4	-	-

Table 2: Properties of bitumen (PG 60/70)

Properties	Test method	Unit	Value
Specific gravity (25°c)	ASTM-D70	g/cm3	1.008
Penetration (25°c)	ASTM-D5	0.1mm	67
Softening point	ASTM-D36	°c	49.6
Ductility (25°c)	ASTM-D113	cm	>100
Solubility in Trichloroethylene	ASTM-D2042	%	99.1
Flash point	ASTM-D92	°c	312
Kinematic Viscosity (120°c)	ASTM-D2170	centistokes	723
Kinematic Viscosity (135°c)	ASTM-D2170	centistokes	323
Kinematic Viscosity (160°c)	ASTM-D2170	centistokes	151

4 MIX DESIGN AND MARSHALL PROPERTIES

4.1 Aggregate Gradation

The aggregate gradation for the dense Asphalt Concrete mix with maximum nominal size 25 mm (AC-25) and 19 mm (AC-19), used in this study are as shown in Table 3.

Table 3: Gradation of mixtures

AC-25			AC-19		
Sieve size(mm)	Passing (%)	Lower-upper limits	Sieve size(mm)	Passing (%)	Lower-upper limits
25	100	100	25	100	100
19	95	90-100	19	100	100
12.5	---	---	12.5	95	90-100
9.5	68	56-80	9.5	---	---
4.75	50	35-65	4.75	59	44-74
2.36	36	23-49	2.36	43	28-58
0.3	12	5-19	0.3	14	5-21
0.075	5	2-8	0.075	6	2-10

4.2 Optimum Binder Content

The Marshall method was used in order to determine the optimum binder content of the asphalt mixtures, which was found to be 5.1% and 5.5% by weight of mix for AC-25 and AC-19 respectively. Table 4 shows the volumetric properties of the mixtures at the optimum binder content.

Table 4: the volumetric properties of the mixtures at the optimum binder content

Mix	Binder content, per weight of mix, %	specific gravity, (kg/m^3)	Marshall stability, kgf	Air Voids, %	Voids in mineral aggregate, (VMA) %	Void filled with asphalt, (VFA) %	Flow, mm
AC-25	5.1	2231	1350	4	14	72	2.65
AC-19	5.5	2310	1017	3.9	15.4	74.7	2.85

5 PERFORMANCE TESTS ON BITUMINOUS MIXTURES

A series of laboratory tests were designed to assess the fundamental mechanical properties and evaluated deformation resistance of mixtures. All the tests were carried out at optimum bitumen content for all mixtures. Since the wheel tracking test was carried out only at a temperature of 60ºC; therefore, the temperature at the other tests and in the rutting analyses is also fixed at 60ºC.

5.1 Resilient Modulus Test

Resilient modulus of asphalt mixtures was measured by indirect tensile test, is the most popular form of stress‑strain measurement used to evaluate elastic properties. The testing was conducted at 60°C. At this high temperature, resilient modulus of asphalt mixtures was drastically decreased. Specimen dimensions were 100mm diameter by 70mm thick. These specimens were then tested according to the standard of ASTM-D4123. In the test, a pulsed diametric loading force is applied to a specimen and the resulting total recoverable diametric strain is then measured from axes 90 degrees from the applied force. Pulse time was chosen 1000 ms for high trafficked roads volume. Value of 0.35 for poisson’s ratio is used as a constant.

5.2 Dynamic Creep Test

Strength of the bituminous mixtures to the plastic deformation may be determined with the dynamic creep test. Permanent deformation of a cylindrical specimen under a uniaxial, dynamic load is measured as a function of time, the specimen dimensions and test conditions were standardized. Deformation values were measured with time by linear variable transducer (LVDT). Specimen dimensions were 100mm diameter by 70mm thick. These specimens were then tested according to the standard of BS-DD226. Test was carried out for all mixtures at the optimal bitumen content at 60°C during 1800 pulse cycles. The test was conducted three times with different stresses for each sample. AC-25 Samples and AC-19 Samples were exposed to 100, 125, 150 kPa and 75, 90, 100 kPa stresses respectively. Lower stresses were applied to AC-19 samples because of the sample destruction. For each stress, three replicates were tested and the average of three tests was reported.

5.3 Wheel Tracking Test

The wheel tracking tester and Roller Compactor developed by a Japanese company was used in this research (Figure 1). The wheel tracking tester was used according to the AASHTO-T324 test procedure. A contact pressure of 500kPa and total wheel load of 760N was applied to the 300mm×300mm×50mm slab specimen. The slabs were compacted with roller compactor. The wheel tracking tests were conducted at the 60°C of temperature to evaluate the permanent deformation characteristics of bituminous mixtures.

Figure 1: Roller Compactor Wheel Tracking Machine

6 CREEP PARAMETERS DEVELOPMENT

As noted, the time-hardening form of the creep model was used in this research and this function is defined as a power law equation and its use assumes that viscoplastic strain is the sole contributor to permanent deformation. An instantaneous plastic strain is neglected in this model (Huang 1995). It is an indication that the nonrecoverable deformation in the repeated load creep and creep recovery test depends mainly on the viscoplastic strain component, and that the plastic strain can be considered insignificant if larger number of pulses are applied. This confirms the observations by Huang (Huang 1995). Therefore, in this research cumulative permanent strain value that obtained from dynamic creep test is used as a viscoplastic strain to develop creep parameters. The viscoplastic axial strain versus time relationship for all stress levels for the AC-19 mix is shown in Figure 2. Because all of the lines in the plot exhibit similar slope, it can be concluded that the viscoplastic strain ε_{vp} is proportional to t^{β}. The slope β is 0.35. The viscoplastic strain is (Perl 1983):

$$\varepsilon_{VP}(\sigma,t,N)=B(\sigma)\times t^{\beta} \longrightarrow B(\sigma)={}^{\varepsilon_{VP}(\sigma,t,N)}\!\big/_{t^{\beta}} \tag{2}$$

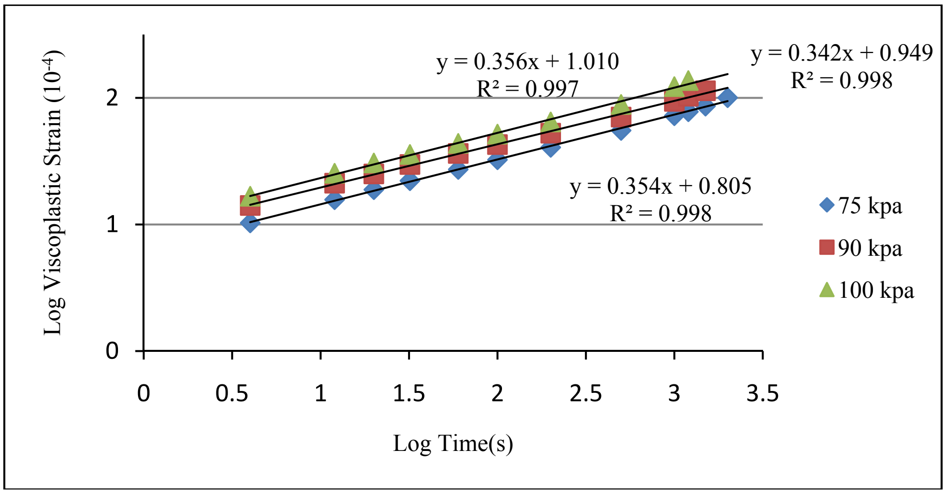


Figure 2: Log scale of viscoplastic Strain versus Time Relationship of the AC-19 mix

The ε_{vp} / t^{β} versus stress relationship for the AC-19 mix is shown in Figure 3. It can be described by a second-order polynomial function (Perl 1983):

$$B(\sigma)=b_1\sigma+b_2\sigma^2 \tag{3}$$

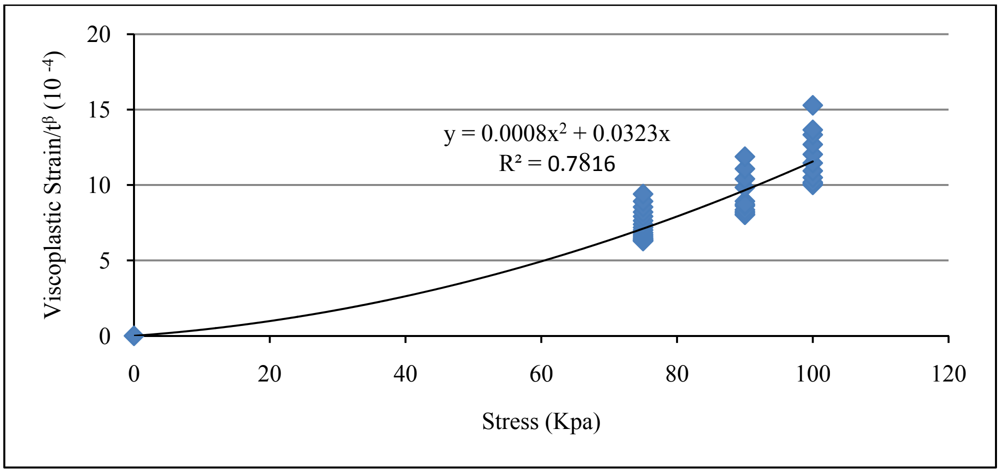


Figure 3: Viscoplastic Strain/t^{β} versus Stress Relationship of the AC-19 mix

Therefore, the rate of the irrecoverable strain can be expressed as (Lai 1973):

$$\dot{\varepsilon}_{vp}(t)=\beta(b_1\sigma+b_2\sigma^2)t^{\beta-1} \tag{4}$$

A creep power law is available in ABAQUS, the finite element program that was used in this research. To define the creep model, the function in Equation 5 is expressed in a power law form. The creep power law model is as follows (Huang 1995, Hua 2000):

$$\dot{\varepsilon}_{vp}=A\sigma^n t^m \quad (5)$$

The A, n and m creep power law parameters for the two asphalt mixtures were developed using regression analysis.

7 FINITE ELEMENT MODELING

In the finite element analysis, the structure and other auxiliary conditions have to be correctly modeled to obtain reasonable results. This includes various components of the finite element model such as material properties, load conditions, boundary conditions, element type and geometry of the model.

7.1 Modeling of Wheel Tracking Test

The objective of the model is to describe the impact of wheel track device on various asphalt mixes and define what occurs in the asphalt sample during the wheel tracking test. A schematic of the 3D slice of the wheel track sample is shown in Figure 4. No side confinement was applied in the 3D slice model.

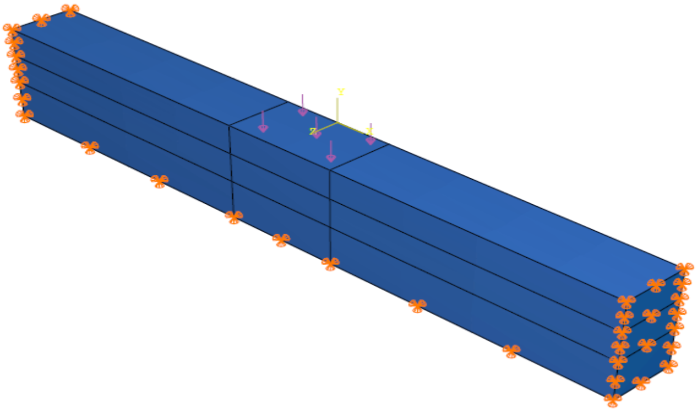


Figure 4: Schematic of the 3D slice of the wheel track sample

As shown in Figure 4, 300mm (in length)×28.5mm (in width) and 50mm (in height) rectangular bituminous mixture structure was constructed to simulate the wheel tracking test. The average length of the wheel footprint of 28.5 mm is used for modeling. A uniform loading pressure of 500 kPa is used in the analysis. The creep model available in the plasticity group of ABAQUS software was used for the rutting simulation and the A, n and m parameters were entered. The modulus of elasticity and Poisson's ratio were also entered for each mix. The Poisson's ratio at temperature of 60ºC is calculated using the following formula given in MEPDG (NCHRP 2004):

$$\mu_{ac} = (0.15 + 0.35)/(1+e^{(-1.63+3.84x10-6Eac)}) \quad (6)$$

Where: μ_{ac} = Poisson's ratio of asphalt mix at a specific temperature

E_{ac} = modulus of asphalt mix at a specific temperature (psi)

Simulating an actual wheel track loading sequence can be a difficult task in finite element modeling. Alternatively, a simplified loading method was introduced and used by Huang (1995) and subsequently by Pan (1997), Hua (2000), and Fang (2000, 2004). With this simple approach, the load is first applied over the entire length of the wheel path. The total cumulative loading time is then estimated using the number of wheel passes and the time required for traversing the tire print of the wheel during a single pass. The time for a single pass is estimated based on the tire print length and the wheel velocity. This simpler approach drastically reduces the computational time the load is applied by using a single step. A series of finite element analyses were performed with decreasing element size to determine the suitable mesh size.

7.2 Calibration against Measured Rutting in Wheel Tracking Test

The n parameter is stress related. As the rut resistance testing in the wheel track device is conducted at a constant loading stress of 500 kPa, the n parameter is fixed at the initial level shown in Table 5. Parameter A is the value of the y-axis intercept while parameter m is related to the slope of the strain-time relationship curve in a log-log scale (White 2002). Initially only parameter A is adjusted to match the rutting depth measured after 8000 passes. After adjustment of the parameter A, if the rutting predicted in ABAQUS was not overlapped the measured rutting, the adjustment of parameter m, controlling the slope, is also required. Figure 5 compare the measured rut depth versus number of cycle relationship with rutting predicted in ABAQUS for the AC-25 mix at the cycle of loading of about 250, 500, 1000, 2000, 4000, 6000 and 8000. Table 5 shows the final elastic and creep parameters.

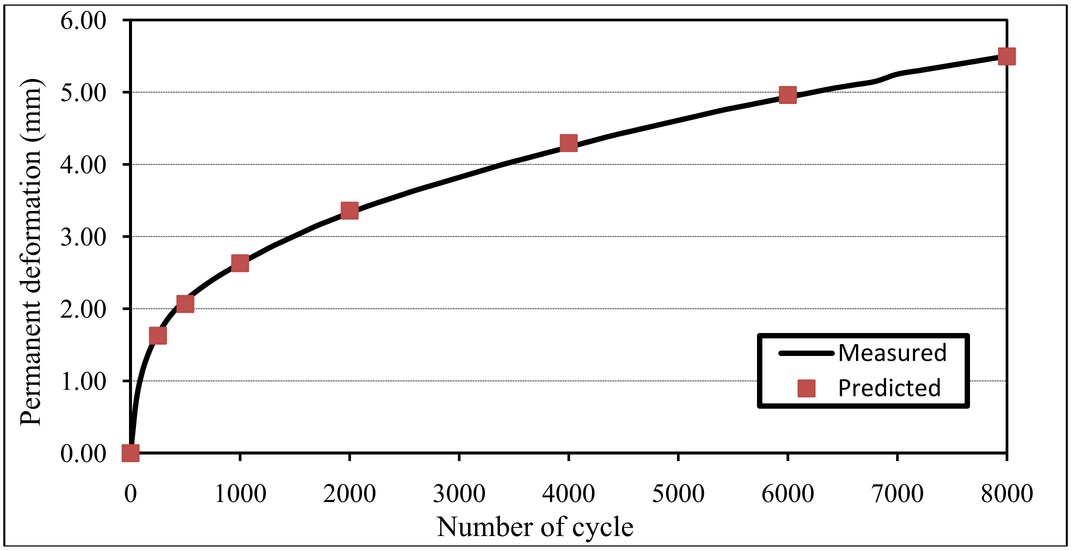


Figure 5: Rutting measured in wheel track and predicted in ABAQUS for the AC-25 Mix.

Table 5: Final elastic and creep parameters of mixes

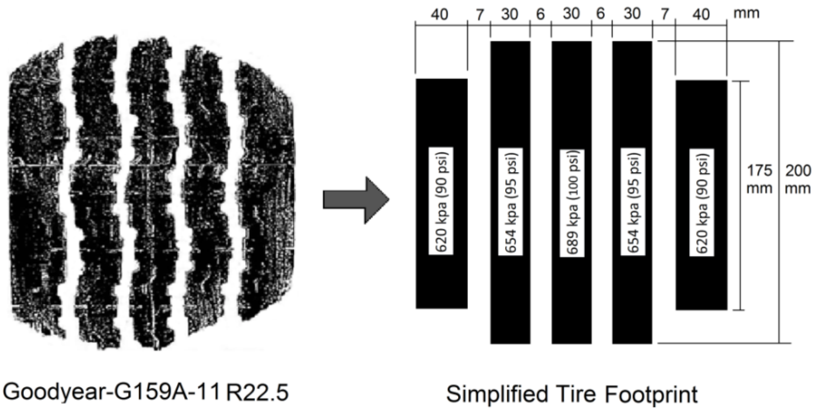
Mix	Material Parameters				
	Elastic		Creep		
	Modulus (Kpa)	Poisson`s Ratio	A ($\times 10^{-8}$)	n	m
AC-25	197000	0.43	14	1.62	-0.63
AC-19	136000	0.43	17.48	1.71	-0.67

7.3 Simulation of Asphalt Concrete Layers of Pavement and Rut Depth Prediction

It is assumed in the model that a single 50 mm layer of AC-19 asphalt wearing course is placed over the double 70 mm layers of AC-25 asphalt base course 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 layer so that no movement of the HMA layer can occur on the surface of the base layer.

In this study load was modeled using Goodyear G159A 11R22.5 tires in a dual-tire configuration with an 80 kN standard axle load and a 620 kPa tire inflation pressure. In this configuration, each tire carries a load of 20 kN because there are four tires on an axle. Figure 5 shows the simplified contact area for a single axle with dual tires. Contact stresses are assumed to be constant within a given rectangular area (White 2002).

The asphalt mixes' elastic and calibrated creep parameters, shown in Table 5, are used in the modeling of the asphalt concrete layers performance. Similarly for the wheel track modeling the time of loading is calculated. ABAQUS simulations are completed for 5 million and 10 million ESAL's traffic loading. The assumed speeds of commercial vehicles are 60, 70 and 80 km/hour. It is also assumed that, asphalt pavements may rut during summer period with the starting point being at the end of spring and the rutting period can last potentially 4 months ending at the beginning of fall. 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 contact pressure is as shown in the tire model in Figure 6.



Goodyear-G159A-11 R22.5

Simplified Tire Footprint

Figure 6: Simplification of tire footprint

As the three middle areas are longer by about 15 percent, an additional loading time is used for these areas. The loading is applied in two steps. In Step 1, the contact pressures shown in Figure 5 are applied over the entire tire width for a period of time based on the length of the outside areas of the tire model. In Step 2, the contact pressure is applied only in the three middle areas of the tire for an additional period.

As the wheel tire wanders within the wheel path, it causes the upheaval outside the tire to migrate away from the wheel path (White 2002). In a National Pooled Fund Study (PFS) at the Indiana Department of Transportation/Purdue University Accelerated Pavement Test Facility, rutting for the single-wheel-path loading (i.e. with no wander) was about 1.7 times that of rutting with 250 mm wander (White 2002). A wander rut depth reduction factor of 1.7 is assumed in this research. Table 6 shows a summary of the predicted pavement rutting with wander reduction, downward rut depth, height of the upheaval and the total rut depth of pavements with all five mixes.

8 CONCLUSIONS

In this research a method of predicting the behavior of various asphalt mixes was described and linking this behavior to an accelerated performance testing tool (wheel track test) and pavement performance. Various laboratory test methods of determining asphalt mix characteristics were examined in terms of their use in performance prediction. Detailed analysis completed in this research indicates that asphalt rutting occurs mainly due to its nonlinear viscoplastic nature. A finite element method (FEM) was selected to be used in this research as it allows for the evaluation of nonlinear viscoplastic behavior of asphalt mixes. The result is a framework for developing material parameters in laboratory testing that can be used in FEM modeling of accelerated performance testing and pavement performance. The relationship between the predicted rut depth in ABAQUS and field measurement was good and between the predicted value and measured value was not much difference.

Table 6: Summary of Predicted Total Pavement Rutting

Traffic Loading (million ESALs)	Speed (km/h)	Pavement Rutting Predicted in ABAQUS (mm)			Total Predicted Pavement Rut Depth with Wheel Wander Reduction (mm)
		Downward Rut Depth (-)	Upheaval Rut Depth (+)	Total Rut Depth	
5000000	60	18.6	7.1	25.7	15.1
	70	17.7	6.6	24.3	14.3
	80	16.9	6.3	23.2	13.6
10000000	60	22.7	9.2	31.9	18.8
	70	21.8	8.6	30.4	17.9
	80	21	8.2	29.2	17.2

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