

Evaluation Of Rutting Potential In Asphalt Mixes Using Finite Element Modeling

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ABSTRACT

Quality of asphalt mix (HMA) is one of the main factors that affects 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. In recent years, performance-based testing has gained popularity so that problematic mixes can be identified and eliminated. Asphalt Pavement Analyzer (APA) has been successfully used in recent years for evaluation of permanent deformation or rutting in both hot mix and cold mix asphalt specimens. However, testing of asphalt mixes in the APA is often expensive and time consuming. Also, a small-scale model with only one layer of asphalt is usually tested in APA while a typical pavement cross section is made up of several layers. In view of layered pavement systems encountered in practice, three-dimensional finite element models (FEM) can be used to relate the APA test results with the in-service performance of the pavement. The primary objectives of this study are to develop a finite element model to simulate the laboratory testing of asphalt mixes in APA for rutting and to relate the test results to basic material properties. The APA tests results have been used to obtain the associated material parameters through simulation of the rut vs loading cycle response. These material parameters can be used to simulate rutting in an actual pavement using a three-dimensional finite element model. A visco-elasto-plastic model (creep model) has been used to represent the time-dependent characteristics of the asphalt mixture. Factors having significant effects on rutting potential of asphalt mixes have been identified. A commercially available finite element program, ABAQUS, is used in this study. FEM results show that the ABAQUS-based model can adequately account for cyclic loading and other factors and, as such, it can be used effectively to evaluate the rutting potential of in-service pavement.

INTRODUCTION

The ability to predict the amount and growth of permanent deformation or rutting in flexible pavements is an important aspect of pavement design. The evaluation of asphalt concrete mixes for their tendency to rutting has been an important research field for many years. A number of wheel-tracking devices such as Asphalt Pavement Analyzer (APA) have been developed over the years and are now commercially available for evaluation of rutting potential of hot mix asphalt (HMA) in the laboratory (1). However, testing of asphalt mixes in the APA is often expensive and time consuming. Also, a small-scale model with constant thickness and only one layer of asphalt material is usually tested in APA, while a typical pavement cross section is made up of several layers with different thickness. In view of layered pavement systems encountered in practice, finite element models can be used to relate the APA test results with the in-service performance of the pavement (2).

The primary objectives of this study are to develop a finite element model to simulate the laboratory testing of asphalt mixes in APA for rutting and to relate the test results to basic material properties. The APA test results have been used to obtain the associated material parameters through simulation of the rut versus loading cycle response. The calculated material properties determined in this manner were calibrated using additional APA tests. A general purpose finite element program, ABAQUS, was used for this purpose. A visco-elasto-plastic model (creep model) was employed to represent the time-, stress- and temperature-dependent behavior of HMA materials. Also, a sensitivity study was undertaken to examine the influence of some selected parameters on rutting.

DEVELOPMENT OF APA

The APA is based on the pioneering work by the Georgia Department of Transportation (GDOT) and the Georgia Institute of Technology during the mid 80s (1). They developed one of the earlier loaded wheel testers (LWT) in which a rectangular HMA specimen is subjected to a moving load, traveling back and forth on a track, applied through a pressurized hose. The APA is a modified version of LWT, Figure I, in which six cylindrical or three beam specimens or their combination can be tested for rutting or fatigue using multiple wheels (Figure II). By subjecting asphalt specimens to an elevated temperature in a loaded wheel system under repetitive loading conditions and measuring the rutting induced under the wheel path, the rutting susceptibility of a HMA mix can be evaluated.

BRIEF REVIEW OF PREVIOUS STUDIES

Traditionally, structural response of flexible pavements to traffic loading is predicted using the elastic multi layer analysis (3). Computer programs such as ILLI-PAVE, MICH-PAVE, and ELSYM5 have been developed within this framework (4). Although elastic analysis is attractive because of its simplicity unfortunately, asphalt pavement materials in reality are time-, stress- and temperature-dependent (5,6).

Duskov and Scarpas (4) used a three-dimensional finite element program CAPA-3D (Computer Aided Pavement Analysis), developed at Delft University of Technology, to analyze flexible pavements. Pavement materials, including asphalt mixes, were treated as a linear elastic material. Although their study utilized a 3-D finite element idealization to represent a pavement cross-section, it did not address the effect of moving load and time-, stress, and temperature-dependent asphalt materials.

A number of studies conducted at Purdue University have used ABAQUS and utilized its features to characterize the pavement materials with more realistic constitutive models than those used previously (8,9, 10). For example, Zaghoul et. al. (8) used three-dimensional, nonlinear finite element models to analyze flexible pavements. In that study, the asphalt concrete was idealized by a visco-elastic model. Also, the traffic loads were simulated as moving loads, but due to computational difficulties, the analyses were conducted for only ten loading cycles. From application consideration, it is important to examine rutting potential under larger loading cycles. Recently, Huang (9) and Hua (10) addressed the modeling of asphalt mixes using a visco-plastic (creep) model available in ABAQUS, and developed a 2-D model to analyze in-service pavements. However, moving loads were treated as a static load, but due consideration was given to the duration of loading. A more detailed review of the topic in question is given by Pirabarooban (11).

FINITE ELEMENT MODELING OF APA RUT TESTING

The dimensions of beam samples used in APA rut testing are 7.5 cm x 12.5 cm x 30 cm (3 in x 5 in x 12 in). Figure III shows schematic of a beam specimen with pressurized hose under a rolling wheel. Four different finite element meshes with a total of 180, 360, 1080, and 2160 elements were considered in order to examine the convergence of the solution with mesh refinement. Maximum rut depth corresponding to 100 loading cycles for each model was predicted. When the total number of elements in the mesh is increased from 1080 to 2160, the difference between the predicted maximum rut depths is only 2%, while the computation time required increases significantly. Therefore, it was concluded that a finite element mesh with 1080 elements is a reasonably optimum idealization. A typical finite element mesh used is shown in Figure IV.

Eight-noded, linear brick element available in ABAQUS were employed in the finite element idealization, having three active degrees-of-freedom per node: U_x , U_y and U_z (displacements along x, y and z directions). In the finite element idealization, the nodes located at the bottom in the finite element mesh were assumed fixed. Since the specimen mold is very stiff compared to the asphalt mixture, the mold was treated as rigid and the movement of nodes along the perimeter of beam was restricted. Therefore, the degree-of-freedom perpendicular to the perimeters was restrained, while the other two degrees of freedom were considered free (Figure V).

Material Model

Creep model (13) was used to represent the asphalt mix. There are two types of creep models available in ABAQUS: power law and hyperbolic sine law (15,16). The power law creep model is attractive for its simplicity. This model can be used either in its “time hardening” form or in “strain hardening” form. In the strain hardening formulation, the creep strain rate is usually expressed as a function of stress, strain and temperature. In the present study, the strain hardening formulation given by Equation I was used because of its attractive features and accuracy (16).

$$\dot{\varepsilon}^C = \left(A \sigma^n \left[(m+1) \varepsilon^C \right]^m \right)^{\frac{1}{m+1}} \quad (I)$$

where ε^C is the creep strain tensor, σ is uniaxial stress, and A , m and n are material constants that are functions of state of stress, material type, and temperature. Since no creep test data are available for the asphalt mixes, these parameters were determined indirectly by finite element simulation of APA results. Details of this simulation and test data can be found in Pirabarooban (11) and Tarefder and Zaman (17).

Simulation of Moving Load

The wheel load applied in the APA is 45 kg (100 lbs). For simplicity, it was assumed that the load is distributed uniformly over the total contact area (contact between hose and beam specimen). The resulting uniform contact pressure is 689 kPa (100 psi), which is equal to the hose inflation pressure (1).

The APA takes approximately two hours and fifteen minutes to apply 8000 loading cycles. A step load function available in ABAQUS was used in the analysis to simulate the moving load in APA. The duration of the step load function is calculated by dividing the length of the wheel print (approximately 2.54 cm or 1 in) by wheel speed (approximately 59.3 cm/second or 23.3 in/second). The step load function is applied at the first set of elements and moved longitudinally to the next set of elements in the wheel path. When the load step is applied to the last set of elements, a single wheel pass is complete. The loading step is then reversed starting from the last set of elements and moved toward the first set of elements. This completes one load cycle. This load cycle can be repeated to achieve the desired number of repetitions.

Model Response

Figure VI shows the deformed shape of the beam specimen after 200 cycles of loading application. Note that the deformation in this figure is magnified by a factor of 500. The deformed finite element mesh shown in Figure VI appears similar to a tested beam specimen, as shown in Figure VII. Figure VIII shows the contours of stress. As expected, the stress concentration close to the wheel path is high and in areas away from the wheel path the stress concentration decreases gradually.

Material Model Parameters

The creep model parameters A , m , and n are material-related parameters. Each asphalt mixture has a unique set of A , m , and n that defines the time-dependent behavior of that mixture. APA test data (rut depth versus load cycle) were used to determine these parameters indirectly. In this parameter determination procedure, creep model parameters were first estimated from information available in the literature (10). These parameters were used in ABAQUS to simulate the APA rut test results. For each case, the total predicted rut depth history for the first two hundred loading cycles was compared with the measured rut depths (17). Based on the quality of the comparison, the creep model parameters were adjusted until the best-fit case is obtained. The values giving the best-fit case are considered the creep model parameters for a given mix. Validity of the parameters thus obtained is checked by using them to predict additional APA tests that were not used in the evaluation of the parameters.

According to Huang (9) and Perl et al. (6), the parameter n is associated with contact pressure. Huang (9) used a value of 0.8 for n for tests with a 655 kPa (95 psi) contact pressure. Since the current study was also conducted with a contact pressure of about 689 kPa (100 psi), the same value of n was utilized. By assuming n equal to 0.8, the other material parameters A and m were estimated by matching the predicted rut depth versus load cycles curves with the measured rut depths versus load cycles curves (17).

Nine different mixes were used in this study. Since the model parameters were different for each mix, different values were obtained for each parameter, one for each mix. The nine mixes were divided into three sets, each set containing three mixes. The first set includes mixes CA1, CA2 and CA3. The second set includes mixes CC1, CC2, and CC3, while the third set includes mixes OA1, OA2, and OA3. Mixes belonging to a given set have the same aggregate gradation, but they differ in asphalt content and air void. The basic properties such as asphalt cement content, percentage of air void, and test temperature for all three sets are given in Table I. The estimated creep model parameters for each of the nine mixes considered are listed in Table II.

Finite Element Model Verification

The three-dimensional (3-D) finite element model developed for the beam specimen was verified in two steps. Since the material model parameters were evaluated by comparing the measured and predicted rut depths corresponding to the first two hundred loading cycles, it was considered beneficial to use the estimated material parameters to predict the rut values for a higher number of loading cycle and then compare the predicted values with the measured rut depths.

The verification study involving a higher number of loading cycles was conducted for the first two sets of asphalt mixes (CA1, CA2, CA3 and CC1, CC2, CC3). The model parameters estimated from the first two hundred cycles of loading, as listed in Table II, were used to predict rut values for large number of cycles. Ideally this effort should have considered 8000 loading cycles, which is the typical maximum loading cycle in an APA test. However, due to computational constraints, the number of loading cycles was limited to five hundred. Even to simulate five

hundred loading cycles, it took about 3 days of computing in the NCSA super computer. Figure IX shows a comparison between predicted and measured rut depths. As can be seen, the predicted rut depths are in excellent agreement with the measured rut depths in an over all sense.

The second method that was used to calibrate the finite element model employed additional APA test data for rutting. For this purpose, the last three asphalt mixes OA1, OA2 and OA3, listed in Table I, were used. Initially, the creep model parameters for all three mixes were evaluated using the method explained before and listed in Table II. For the verification study, new tests with different geometric configurations were utilized. As noted previously, dimensions of a typical beam specimen used in APA are 7.5 cm x 12.5 cm x 30 cm (3 in x 5 in x 12 in). For these new tests, the sample height was reduced from 7.5 cm (3 in) to 5 cm (2 in), while keeping the width and length unchanged. This was accomplished by placing a steel plate of 2.5 cm (1 in) thickness at the bottom of the mold, called modified mold.

All three mixes were tested for rutting using this modified mold. Except for the specimen geometry (height), all other testing conditions and material properties were kept unchanged. Consistent with the geometry of the modified mold, the thickness of the finite element model was reduced from 7.5 cm (3 in) to 5 cm (2 in).

The measured rut depth for one of the modified tests and the corresponding prediction from the finite element analysis is shown in Figures X. It is observed that overall there is a good agreement between the measured and predicted rut depths from the finite element model. However, the difference between the predicted and measured rut depths before 100 loading cycles is significant. The possible reason for this difference is that the rutting observed before about 100 loading cycles is primarily due to the initial compaction of the asphalt mixes. The creep model used in this study does not account for this initial compaction. And also, the rut values measured at the beginning of a test are prone to errors as the values are small.

It is observed that the difference between finite element model prediction using ABAQUS and measured rut depth is as high as 40% for the first 10 loading cycles and the difference decreases as the number of loading cycles increases. It is noted that rate of reduction in difference is rapid for up to 100 loading cycles and beyond 100 loading cycles, the difference narrows in most cases. In most of the cases considered, it is observed that beyond 100 loading cycles, the difference between the predicted and measured rut depths is between 10 -15%. As the number of loading cycles increases, the contribution from initial compaction decreases, while the contribution from plastic flow increases. Since the creep model is capable of capturing the rutting due to plastic flow, the difference between the predicted and measured rut depth narrows down as the number of loading cycles increases.

SENSITIVITY ANALYSIS

Testing Wheel Speed

HMA mix is a time-dependent material. Therefore, wheel speed, which is directly related to the time of loading, is expected to influence the response of HMA mixes. As would be expected, because of the loading time, rut depth decreases with increasing speed and increases with decreasing speed. Because of this reason, close to intersections and other places where vehicles move rather slowly, significant amount of rutting is observed in the pavement.

Predicted rut depths versus wheel speed corresponding to 200 loading cycles are shown in Figure XI. Wheel speeds from 5km/hour to 120 km/hour (3.1 miles/hour to 74.5 miles/hour) were considered in this study. Maximum rut depth of about 3.3 mm (0.13") is observed when the speed is about 5 km/hour (3.1 miles/hour). When the wheel speed is increased from 5 km/hour (3.1 miles/hour) to 20 km/hour (12.4 miles/hour), rut depth decreases drastically by about 60%. However, when the speed is increased from 20 km/hour (12.4 miles/hour) to 60 km/hour (37.4 miles/hour), the change in rut depth is only 30%. As expected, because of the reduced loading time, rut depth decreases with increasing speed.

Beam Specimen Thickness

Pavement thickness has significant effects on rutting, as expected. Again, the rut depths corresponding to 200 loading cycles were predicted. Specimen thickness from 3.8 cm (1.5 in) to 15.2 cm (6 in) were considered. Figure

XII shows the effect of specimen thickness on rut depth. When the sample thickness is increased from 3.8 cm (1.5 in) to 7.5 cm (3 in), rut depth increases by about 66 %. Similarly, when the thickness is increased from 7.5 cm (3 in) to 10 cm (4 in), rut depth increases by about 70 %. Based on these results, the relationship between the rut depth and specimen thickness could be considered approximately linear.

Creep Model Parameters

There are a total of five material parameters that may affect the rutting predicted by the finite element method. These parameters include: three creep model parameters (A , m and n) and two elastic parameters (modulus of elasticity, and Poisson's ratio). However, predicted rut depth is not sensitive to modulus of elasticity and Poisson'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. Of the three creep model parameters A , m , and n , the parameter n was fixed at 0.8 in accordance with the study conducted by Huang (9). Thus, only two parameters, A and m , were considered in the parametric study.

The original beam model was used to predict rutting after 200 loading cycles with various values of A and m . Figure XIII shows the effect of parameter A on rutting. It can be seen that rutting increases with increasing A values. As it was observed during the material parameter evaluation stage, the predicted rut depth is very sensitive to parameter A . Parameter A increases with increasing asphalt cement content in a mix (Figure XIV). Since A is directly related to the amount of asphalt cement content that influences the amount of rutting in HMA mixes. The relationship between predicted rut depth and parameter A is approximately linear as observed in Figure XIII.

Figure XV shows the effect of creep model parameter m on rut depth. It can be seen that the rut depth (magnitude) and the nature of variation decreases with increasing m values. Note that m is negative. Similar to parameter A , the parameter m also increases with increasing asphalt cement content (Figure XVI). However, the relationship is non-linear.

CONCLUDING REMARKS

The finite element model developed for APA rut testing was verified by comparing predicted and measured rut depths for new tests that were not used for material parameter evaluation, as well as by comparing predictions for higher number of loading cycles. Excellent agreement was found between the predicted and measured rut depths. The sensitivity study conducted using the finite element model revealed that:

1. The speed of the moving load has a significant effect on predicted rutting.
2. Thickness of the beam specimen influences the predicted rut depth significantly. The relationship between beam specimen thickness and rut depth is approximately linear.
3. It was found that creep model parameters m and A have a strong relationship with rutting. However, among these two, the parameter A strongly influences rutting than the parameter m . The parameters A and m are closely related to the amount of asphalt content and the air void in hot mix asphalt.
4. Overall, from this study it can be concluded that the finite element based models can be used as effective tools to analyze rutting behavior of asphalt pavements including moving loads.

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Table I Asphalt Mixture Properties

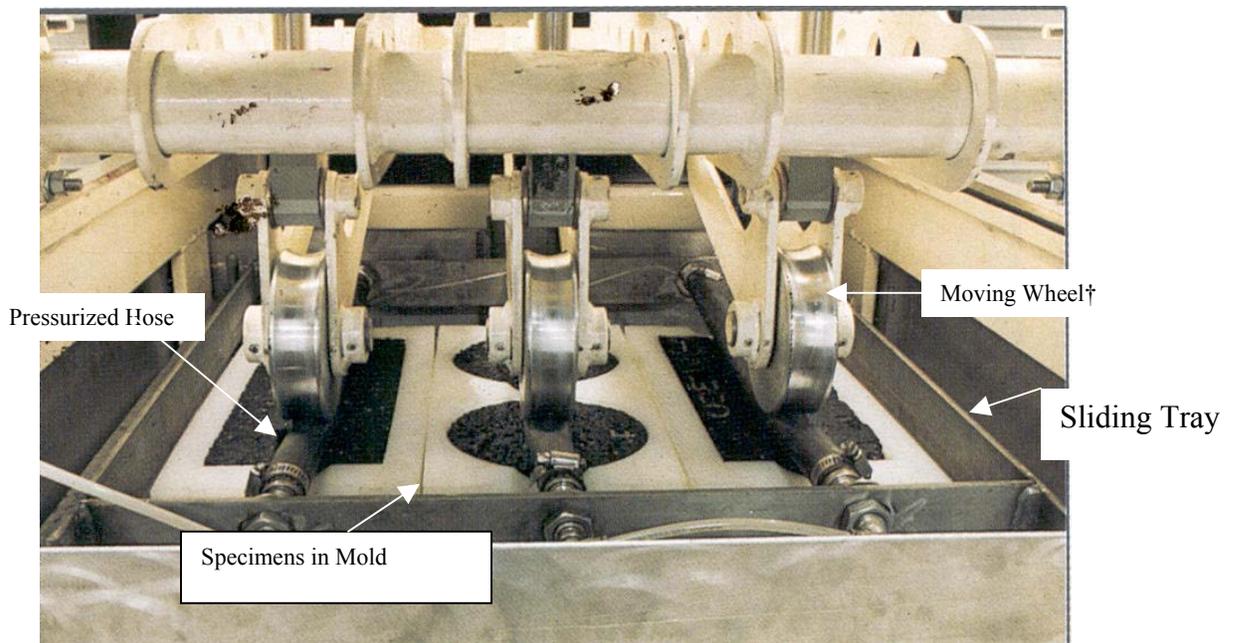
Mixture	Properties		
	Asphalt Content (%)	Air Void (%)	Testing Temperature (°F)
CA1	4.5	6.5	147
CA2	5.0	5.8	147
CA3	5.5	5.6	147
CC1	4.5	6.5	147
CC2	5.0	5.8	147
CC3	5.5	5.6	147
OA1	5.0	5.3	147
OA2	5.5	8.6	142
OA3	6.0	6.4	140

Table II Creep Model Parameters

Mixture	Estimated Creep Model Parameters		
	A ($\times 10^{-5}$)	m	n
CA1	2.95	-0.5	0.8
CA2	3.12	-0.45	0.8
CA3	3.3	-0.43	0.8
CC1	2.1	-0.55	0.8
CC2	1.58	-0.55	0.8
CC3	1.9	-0.5	0.8
OA1	2.93	-0.48	0.8
OA2	3.12	-0.45	0.8
OA3	3.28	-0.45	0.8



Figure I Asphalt Pavement Analyzer



† Referred to as Wheel Tracking/Loading System

Figure II APA Arrangement for a Submerged Test

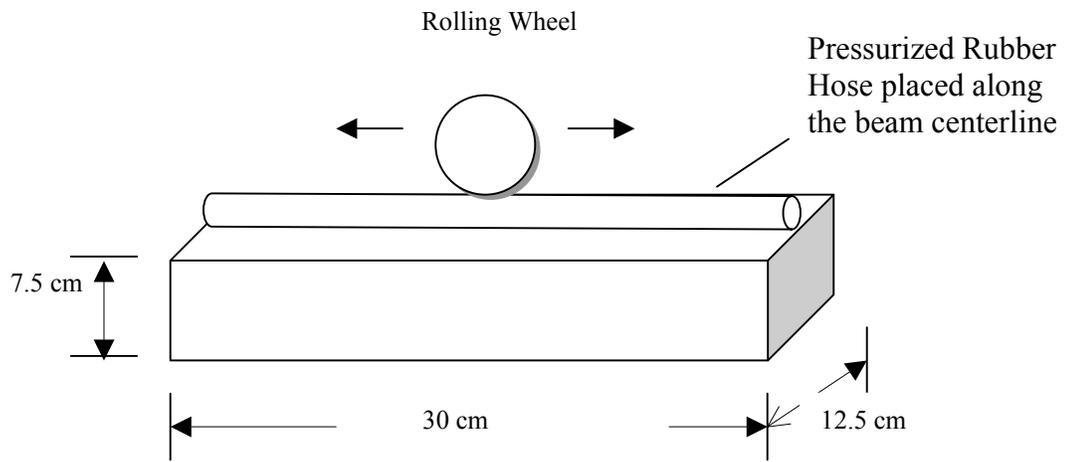


Figure III Schematic Diagram of APA Rutting Testing of a Beam Sample

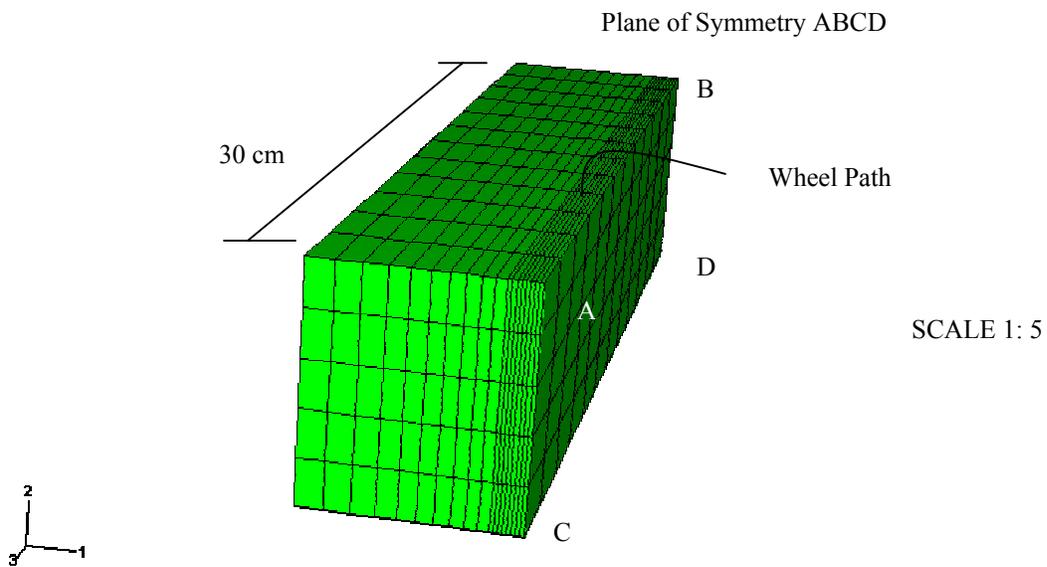


Figure IV Finite Element Mesh of a Beam Sample

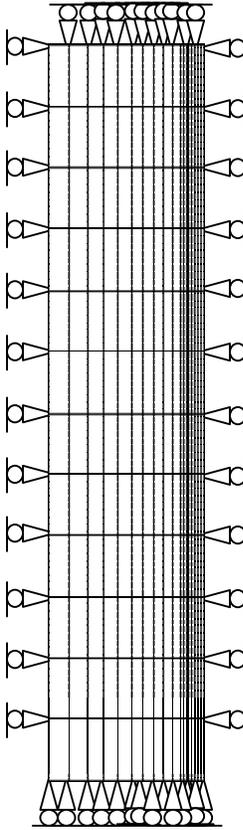


Figure V Boundary Conditions (APA Beam Sample-Plan)

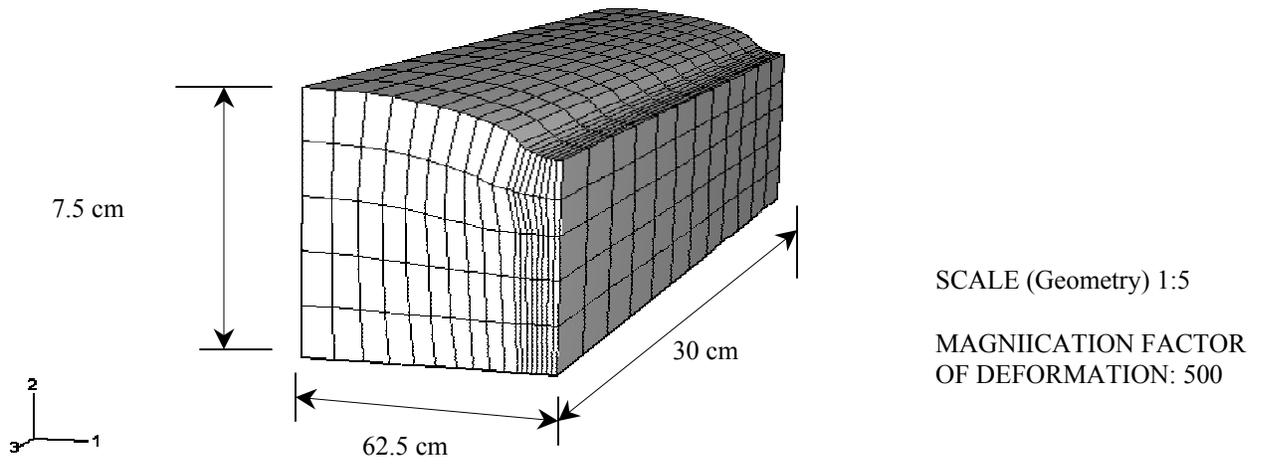


Figure VI Deformed Shape of the Finite Element Mesh



Figure VII Tested Beam Samples in APA

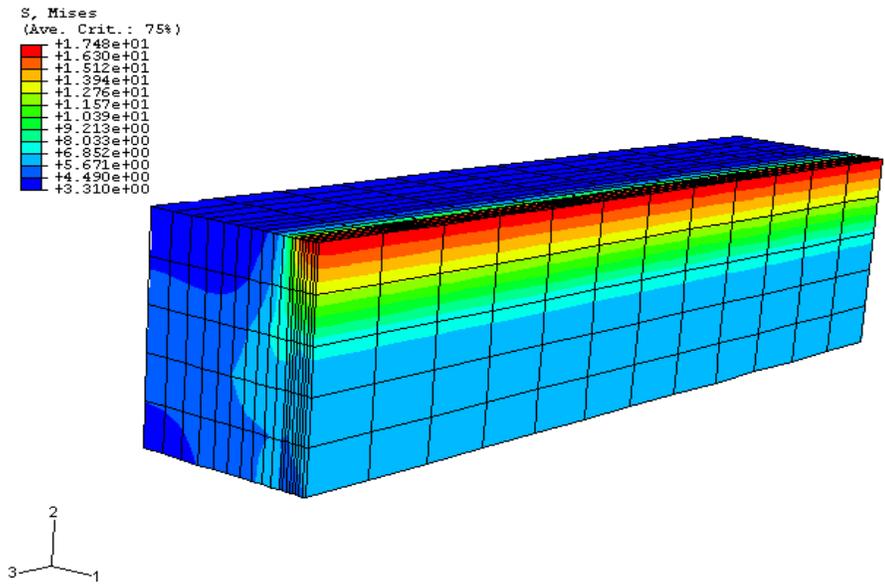


Figure VIII Stress (σ_{22}) Contours After 200 Loading Cycles

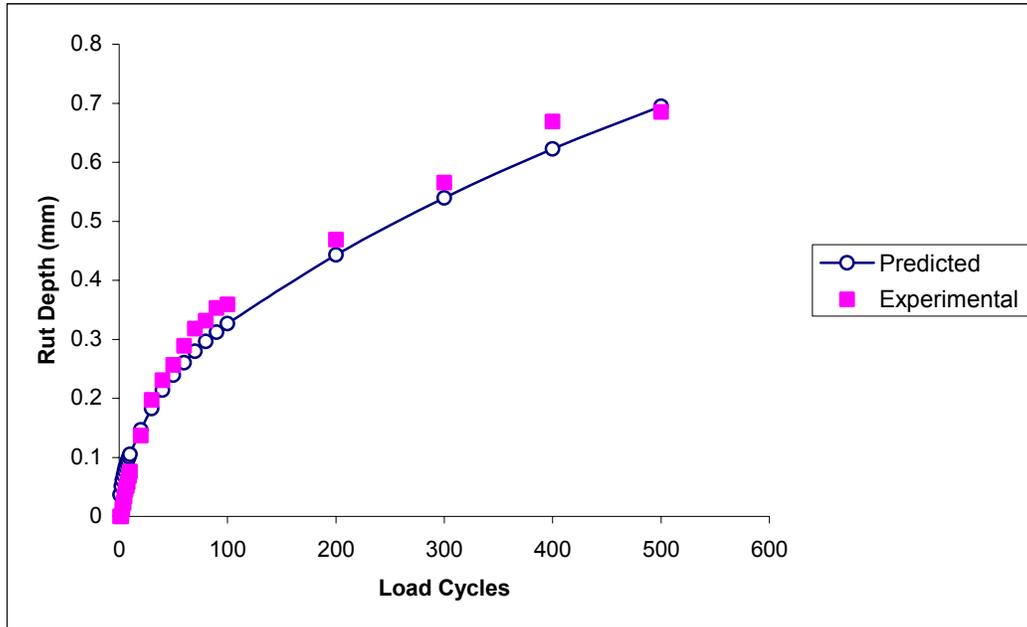


Figure IX Typical Rut Depth Development History

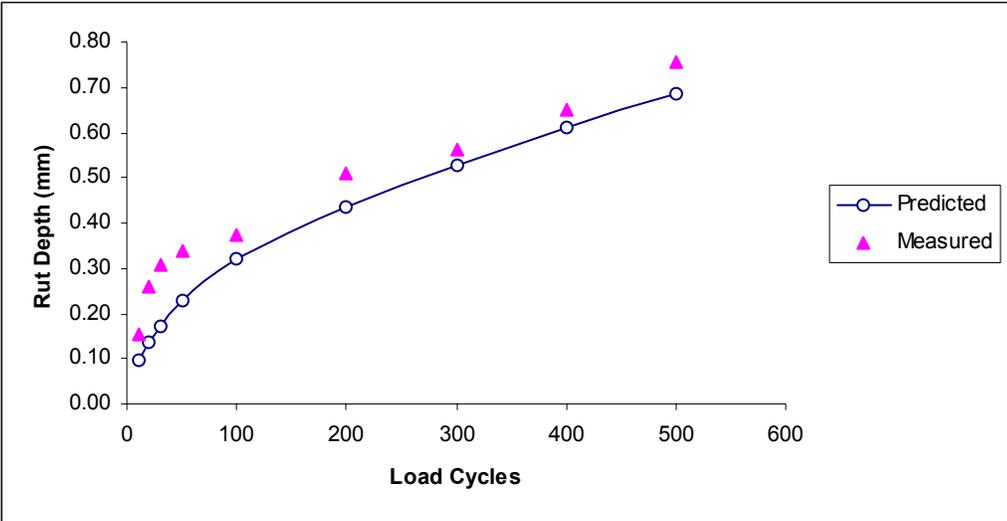


Figure X Predicted and Measured Rut Depths for Mix OA1

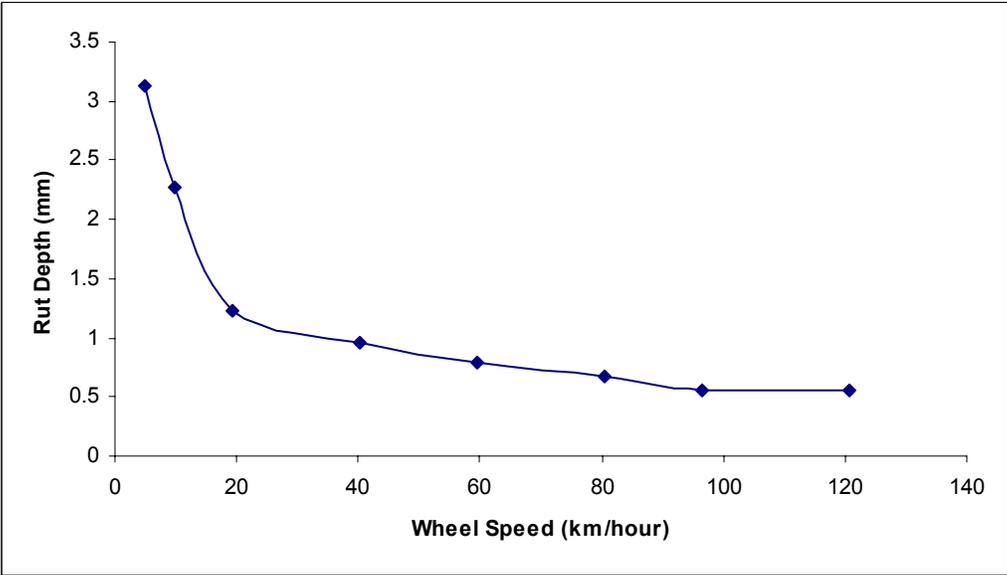


Figure XI Effect of Wheel Speed on Rut Depth

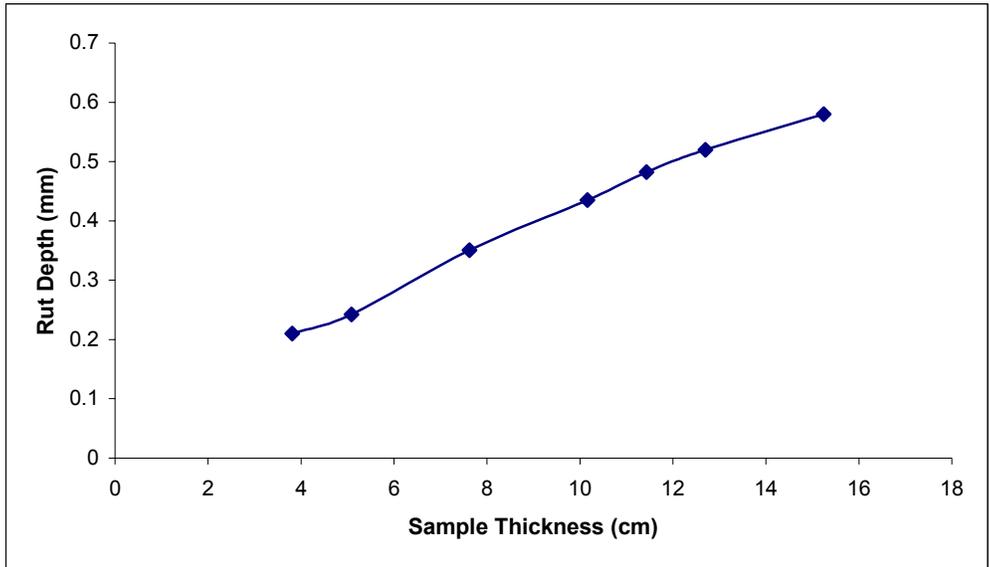


Figure XII Effect of Sample Thickness on Rut Depth

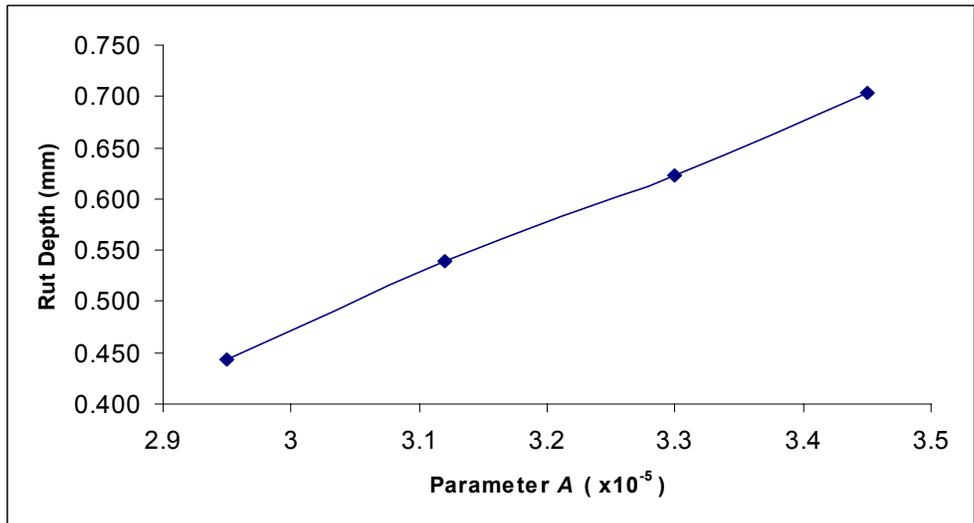


Figure XIII Effect of Creep Model Parameter *A* on Rut Depth

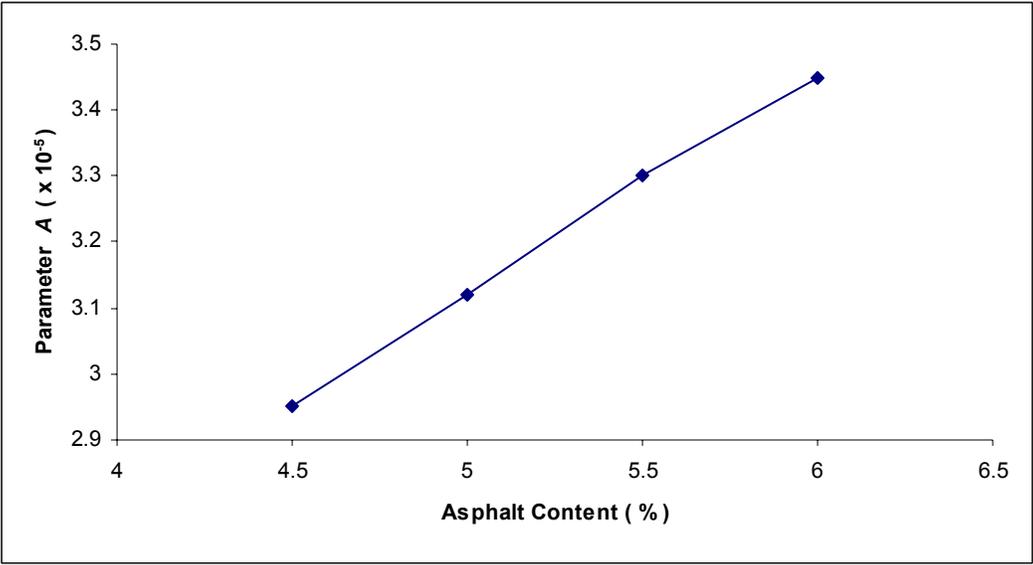


Figure XIV Effect of Asphalt Content on Creep Model Parameter *A*

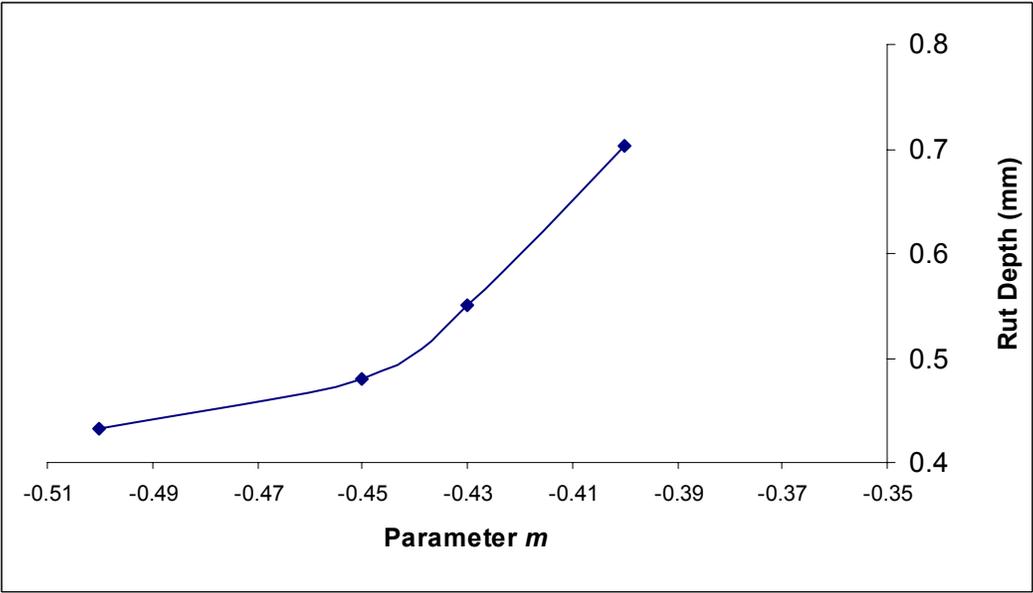


Figure XV Effect of Creep Model Parameter *m* on Rut Depth

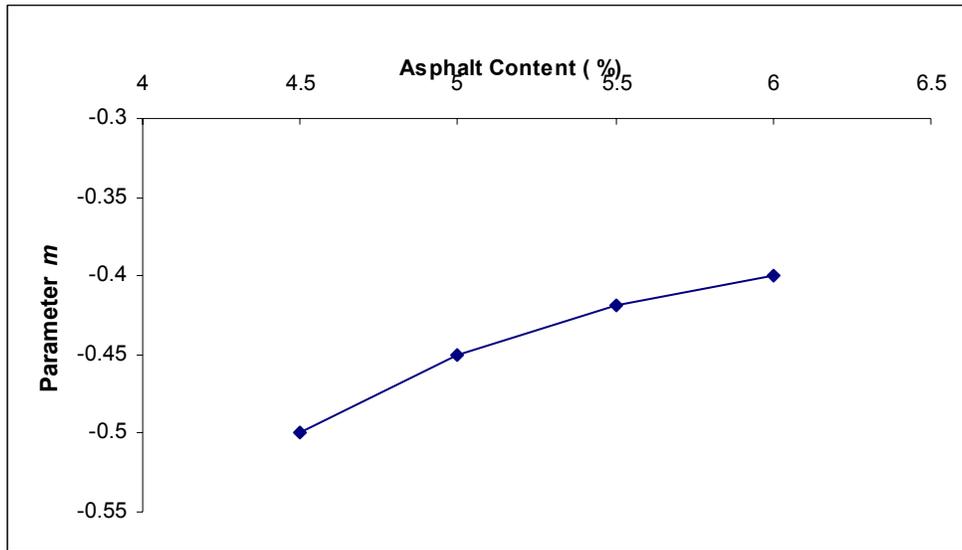


Figure XVI Effect of Asphalt Content on Creep Model Parameter m