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A Finite Element Model for Rutting Prediction of Flexible Pavement Considering Temperature Effect

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ABSTRACT

Permanent deformation in asphalt layers which manifestation on pavement surface is named rutting which represents one of the most significant distress of asphalt pavements. Different empirical models have been used to calculate permanent deformations which include traffic conditions and temperature effect. These empirical models were calibrated in a three dimensional finite element commercial software package. Finite element analysis through ANSYS computer software (version 11.0) was used to analyze three dimensional pavement structures and in order to investigate the impact of wheel load on rutting formation and pavement response considering temperature effect. In that model, the asphalt layer was assumed to follow a viscoelastic behavior by depending on dynamic modulus using Timm and Newcomb model. While, granular and subgrade layers were presented as linear-elastic perfectly plastic based on Drucker-Prager model. After insuring the model validation, the study investigated the effect of temperature on the rutting depth and plastic strain as a pavement response. The analysis of results showed that the rut depth and plastic strain increases with increasing the temperature.

Keywords*:* Rutting, Flexible pavement, Temperature, Plastic strain, Ansys.

نموذج عنصر محدد للتنبؤ بأخدود الرصيف المرن مع الاخذ بنظر الاعتبار تأثيردرجة الحرارة

الخلاصة

التشوه الدائم في طبقات القير على سطح الرصيف يسمى اخدود والذي يمثل أحد أهم الجهادات المؤذية لأرصفة القير. استعملت نماذج تجريبية مختلفة لحساب التشوهات الدائمة والتي تتضمن ظروف المرور وتأثير درجة الحرارة. قيمت هذه النماذج التجريبية ببرنامج عنصر ثلاثي الابعاد تجاري. استعمل تحليل العنصر المحدد من خلال البرنامج (Ansys version 11.0) ليحلل منشأت الرصيف ثلاثية الابعاد ولكي يتحرى عن تأثير حمل العجلة على تشكيل الاخدود واستجابة الرصيف مأخوذ بنظر الاعتبار تأثير درجة الحرارة. في هذا النموذج, أفترضت طبقة القير تتبع ,السلوك اللزوجة المرونة بالاعتماد على المعامل الديناميكي بأستخدام نموذج تيم ونيوكمب. بينما

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قُدّمت الطبقتين الحبيبة وتحت الاساس كسلوك خطي - مرن لدن بشكل مثالي بالاعتماد على نموذج دركر- براجر. بعد التأكد من تحقق صحة النموذج, تحرت الدراسة تأثير درجة الحرارة على عمق الاخدود والانفعال اللدن على أستجابة الرصيف. بيّنت نتائج التحليل بأن عمق الاخدود والانفعال اللدن يزدادان بزيادة درجة الحرارة.

INTRODUCTION

Asphalt concrete is a heterogeneous complex composite material of air, binder and aggregates used in modern pavement construction. Most the paved roads in Iraq are flexible pavement built with bituminous materials. Despite this widespread usage, premature pavement failures such as rutting and cracking still very common and inducing high maintenance cost. Rutting due to repeated traffic loading is a major sign of distress of flexible pavement and it often happens within the first few years after road opening. Rutting happens due to the plastic movement of the asphalt mixture in high temperature (i.e. hot weather) or inadequate compaction during construction [10]. Pavement rutting is a concern for at least three reasons: a- Water can accumulate in the rut and penetrate the pavement which will cause damage to the structural integrity; b- A rut may cause the driver to lose control of the steering and this is an important safety issue; and c- Ruts will retain water which leaves the road surface wet and this can promote vehicle hydroplaning, another safety issue [8].

Also, it is well known that temperature variation in pavement layers play an important role in the performance of flexible pavement system. The surface layer is usually made of hot-mix asphalt (HMA), which is a viscoelastic material and its behavior is highly related to its temperature, i. e., HMA responds like an elastic solid under low temperature and strain conditions; on the other hand, it also acts as a viscous material at high temperature in the sence that the deformation due to traffic loading cannot fully recovered within a finite time period under the unloading condition. Therefore, an accurate prediction of the temperature profile in the HMA layer is desired when selecting the asphalt binder and predicting performance [12].

The objectives of this study are

1- To choose the proper analysing models for each layer to be used in finite element analysis and to suggest the proper method to determine the parameter needed for finite element analysis.
2- To establish mechanistic-based rutting model including contributions of all layers in pavement with different temperatures.

VISCOELASTIC MODEL FOR HOT MIX ASPHALT

The viscoelastic model can be used for asphalt layer analysis in our case because it is more realistic for modeling of the asphalt layer than the elastic model.

One of the moduli that represent the viscoelastic behavior is the complex modulus. The absolute value of the complex modulus is usually called the dynamic modulus. It is basically an elastic modulus taken from a viscoelastic model which integrates many factors such as loading rate, temperature, grain size characteristics and bitumen viscosity [3]. In this study, the modulus of elasticity was depended to the equation adopted by Timm and Newcomb [11], they suggested the relationship between the asphalt concrete modulus and pavement surface temperature as the following equation:

$$= 16693.4 \cdot \quad \frac{(T \quad 26.2)^2}{1459.7} \qquad \ldots (1)$$

Where:

E_{AC} = asphalt concrete modulus, MPa

T = asphalt concrete surface temperature, ^{o}C.

DRUCKER-PRAGER MODEL FOR BASE AND SUBBASE LAYERS

There are several plasticity models that can be picked to simulate the stress-strain behavior of frictional material such as Mohr-Coulomb model, Drucker-Prager model, Lade-Duncan and Mastuoka-Nakai models and Hoek-Brown model [14]. It is suggested that Drucker-Prager model is used to simulate the stress-strain behavior in base and subbase layer because of its simplicity since it only depends on elasticity modulus andangle of internal friction. In favor of modeling the yielding frictional material, Drucker-Prager introduced the following function.

$$= \quad \overline{} - \qquad - \quad = 0 \qquad \ldots (2)$$

Where a and k are the material constants

I_1 = First invariant of stress tensor.

J_2 = Second invariant of deviatoric stress tensor.

On a deviatoric plane, the previous equation can be drawn as a circle as shown in Figure (2). However in principle stress space, it can be plotted as a cone as shown in Figure (3).

The Drucker-Prager yield surface is matched with Mohr-Coulomb yield surface to decide the material constants a and k for analysis, Figure (1) such as match. Mathematically, this condition demands the following equations [4]:

$$a = \frac{2 \times \sin f}{\sqrt{3} \times (3 - \sin f)}, k = \frac{6 \times c \times \cos f}{\sqrt{3} \times (3 - \sin f)} \qquad \ldots (3)$$

Where ϕ = frictional angel and c = cohesion.

PERMANENT DEFORMATION

The growth of permanent deformation in an asphalt layer, due to the repetitions of traffic loads, is caused by the combination of volumetric reduction and shear strain. Several studies have indicated that plastic deformations in asphalt layers are mainly due to excessively high binder content and low voids volume. Deformations may be also caused by deficiencies in layers densification during construction, or by plastic movement of the asphalt mix subjected to high temperatures [7]. Mixture factors that causing rutting including: (1) aggregate gradation, (2) aggregate absorption, (3) aggregate affinity for asphalt, (4) aggregate size, (5) coarse aggregate shape, (6) coarse aggregate texture, (7) fine aggregate shape (angularity), (8) mineral filler properties, (9) asphalt content, (10) performance grading, (11), plastic fines in the fine aggregate, (12) low air voids and (13) performance graded asphalts [1].

The relationship used to predict rutting in asphalt mixtures is based upon a field calibrated statistical analysis of laboratory repeated load permanent deformation tests. The selected laboratory model is of the form [9]:

$$- \quad = -3.1555 + 0.3994l \qquad + 1.734 \qquad \ldots (4)$$

in which, ε_p is the permanent strain, ε_r is the resilient strain and T is temperature (^oF).

The relationship between rutting failure and compressive strain at the top of subgrade is represented by the number of load applications as suggested by Asphalt Institute [9] in the following form:

$$= 1.365\,x\,10 \qquad -^{4.4} \qquad \ldots (5)$$

Where, ε_c = vertical compressive strain at the top of subgrade. Carvalho [5] recommended an equation describes the relationship between rut depth and number of load repetitions is as follows:

$$RD = 0.00265N^{0.} \qquad \ldots (6)$$

Where, RD = rut depth at the center of the wheel path (mm).

LOAD MODEL

Load in the pavement is caused by repeated vehicle passes. The passes do not follow the same path, but rather have a transverse distribution that is called transverse wheel path distribution or wheel wander. This makes it hard to dynamically simulate the entire loading process on a pavement because the exact sequence of load passes cannot be determined. In addition, the results of a specific loading sequence may not suit the need of this study because the focus of the study was to find the general characteristics of pavement surface profiles. Therefore, in this study, the load was represented as quasi-static uniform distribution load with a transverse distribution so that the resulting pavement deformation was equivalent to that of dynamic loading [6]. A standard axle ranges from 80 to 90 kN. In this study, a load of one set of dual tires of 40 kN is considered. It is assumed that this load is transferred to the pavement surface through a contact pressure of a single tire. The tire contact pressure on the road is equal to the tire pressure [3]. In this study, the uniform tire pressure is assumed to be 600, 700 and 800 kPa.

METHODOLOGY

The mechanical (analytical) design methodology is based on predictions of pavement performance. There are many components and subsystems involved in making these predictions: inputs such as traffic loading, environmental conditions and material properties. The design of flexible pavements is largely based on empirical methods. However, there is currently a shift underway towards more mechanic design techniques, while layered elastic analysis and two-dimensional finite element (FE) methods have been generally used to determine stresses, strains and displacements in flexible pavements, they suffer several limitations. To overcome these difficulties, three-dimensional (3D) FE analysis must be used to analyze pavement structures [13]. This study focuses on exploring the use of 3D FEM to examine the response of flexible pavements.

Assume in this study, the model consists of an asphalt course layer with a thickness of 0.20 m and an isotropic granular course layer with a thickness of 0.40 m. The contact area dimensions were 0.2 x 0.2 m. Alex [2] mentioned that the nodal radial strains were assumed to be negligible at approximately 10 times R (radius of loaded area) from the area applied wheel load. Also, the nodal stresses and displacements were assumed to be negligible at 20 times R below the pavement surface. Therefore, the width and the length of the model were set at 6m, and the thickness of an isotropic sub grade is 5.40 m Figure (3). The properties of the materials used in the analysis are summarized in Table (1).

FINITE ELEMENT MODELING

The model developed and calibrated in this research was implemented in ANSYS (version 11.0), a commercial finite element package widely employed in pavement engineering research. The objective was to have a robust but simple to use tool for analyzing permanent deformations in pavements under moving wheel loads. The three dimensional 8-noded brick element SOLID185 (its behavior as viscoelastic)) is selected to represent the asphalt course and 8-noded brick element SOLID45 to represent the granular course and subgrade. The contact among asphalt course, granular course and subgrade are represented by TARGE 170 and CONTA 173 elements. Table (2) shows the statistics of elements. The boundary nodes along the pavement edges are horizontally constrained, but are free to move in the vertical direction. The mesh of model is shown in Figure (4).

RESULTS

The results FEA of the principle stresses, vertical stress, elastic strain and the vertical displacements for pressure of 700 kPa and temperature of 30 ^{o}C are shown in Figures (5-9). This study sets out to compare flexible pavement performance using FEM and equations (4 to 6). Comparisons of the output were made to determine the governing distress and deterioration models. The results of the analysis which performed on the investigated pavement cross section using FEM and equations 4 to 6 are presented in Figures (10 and 11) for pressure of 700 kPa and temperature of 30 ^{o}C. Good agreement between the FEM and Equations (4 to 6) results is achieved.

TEMPERATURE EFFECT

In order to study the effect of temperature on the behavior of flexible pavement, different values of (T) have been considered. The selected values for this study are 10, 20, 30, 40 and 50 ^{o}C. Figures (12-19) show the rutting depth-pressure and plastic strain-pressure relationships obtained from the FEM for the selected values of temperature.

The rutting depth and plastic strain obtained from this study for pressure of 700 kPa are listed in Table (3). The table shows that the increase of the temperature from 10 ^{o}C to 50 ^{o}C leads to an increase of 740 % in the rutting depth and an increase in the plastic strain of 673 %.

CONCLUSIONS

In this study, the main concluding remarks that have been achieved from the test results may be summarized as follows:-

1- The use of viscoelstic model for pavement course and a linear-elastic perfectly-plastic, Drucker-Prager model for granular course and subgrade gave acceptable results.
2- The increase in the applied pressure causes an increase in the value of rut depth and plastic strain.
3- Nonlinear finite element solution by ANSYS package program using three dimensional elements for modeling the flexible pavement gives acceptable agreement with the equations which predicted from some researchers.
4- The finite element analysis shows that the increase in the temperature from 10 ^{o}C to 50 ^{o}C causes an increase of 740 % in the rutting depth and an increase in the plastic strain of 673 %.

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Table (1) Material Properties for Road Layers.

Layer	**Modulus of Elasticity (E) (MPa)**	**Poisson's ratio (ν)**	**Cohesion (c)**	**Angle of internal friction (ϕ)**
AC	Variable with temperature (Eq. 1)	0.35	-	-
Granular course	160*	0.40	0	40
Subgrade	72*	0.40	0	30

*Reference [11]

Table (2) Statistics of Elements.

Label	**Number**	**Name**
SOLID185	900	3-D 8-NODE STRUCTURAL SOLID
SOLID45	1700	3-D STRUCTURAL SOLID
TARGE170	500	3-D TARGET SEGMENT
CONTA173	1300	3-D 8-NODE SURF-SURF CONTACT

Table (3) Values of Rut Depth and Plastic Strain for Variable Temperatures.

	Temperature ^{o}C				
	10	**20**	**30**	**40**	**50**
RD (mm)	2.31	4.42	9.54	12.30	19.40
ε_p (x 10^{-3})	1.92	2.41	6.42	8.33	14.84

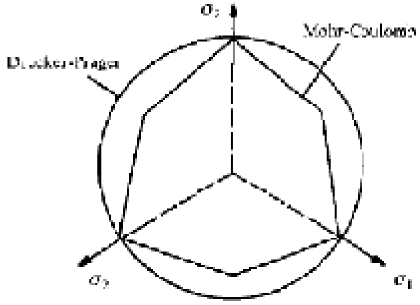


Figure (1) Drucker-Prager's and Mohr-Coulomb Yield Surface on a Deviatoric Plane.

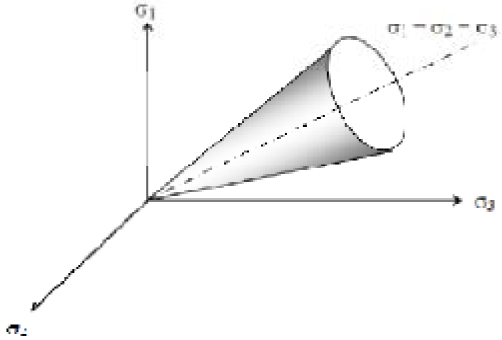


Figure (2) Drucker Prager's Yield Surface in Principle Stress Space.

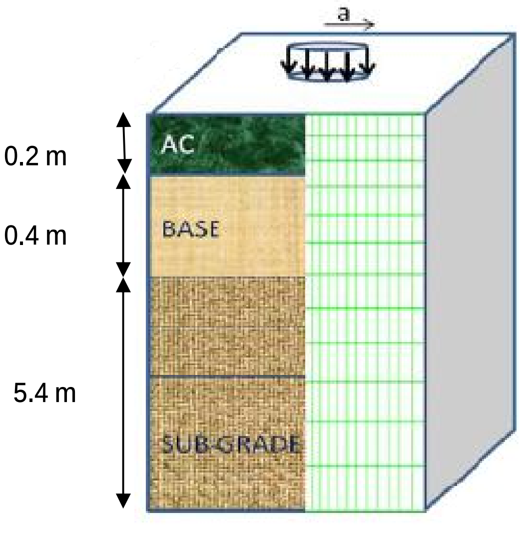


Figure (3) The Model Layers (without scale).

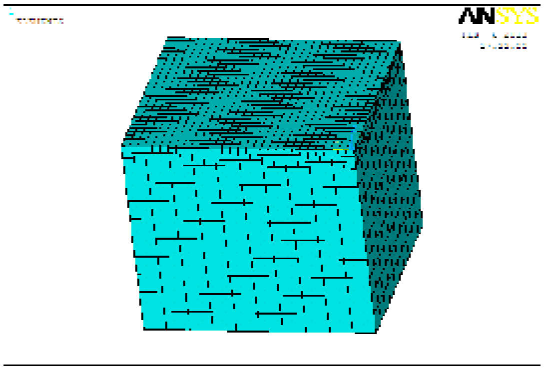


Figure (4) Brick Element Mesh.

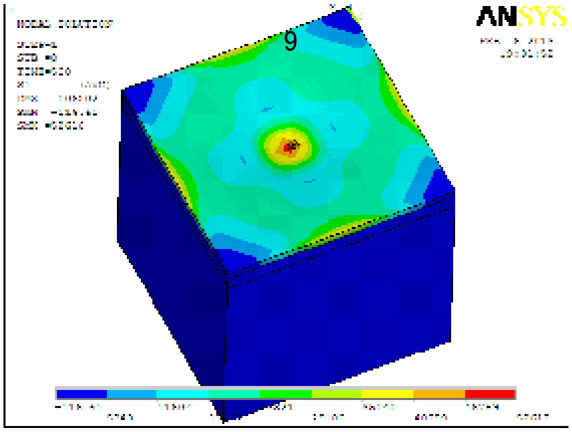


Figure (5) Contour Plot for 1st Principal Stress (σ_1) (kN/m^2).

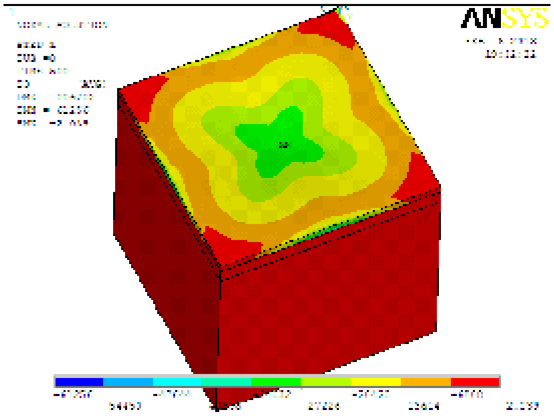


Figure (6) Contour Plot for 3rd Principal Stress (σ_3) (kN/m^2).

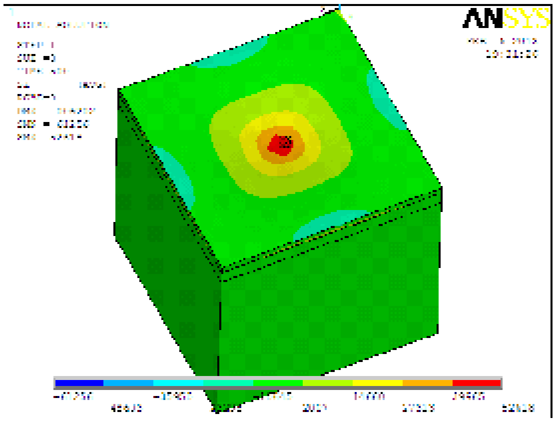


Figure (7) Contour Plot for Vertical Stress (kN/m^2).

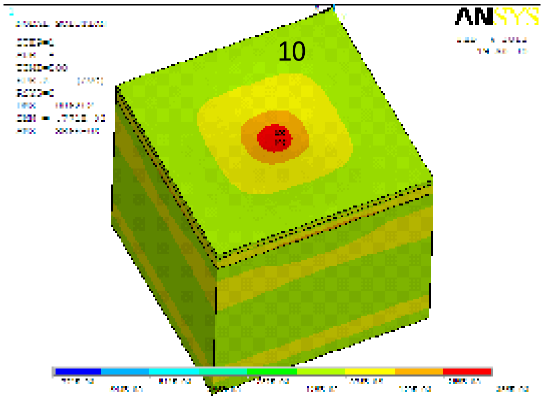


Figure (8) Contour Plot for Vertical Elastic Strain

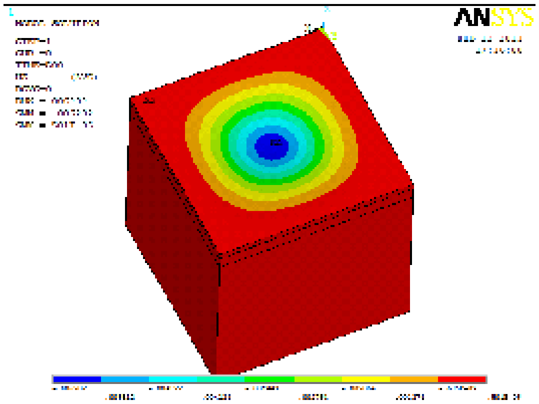


Figure (9) Contour Plot for Vertical Displacement (m).

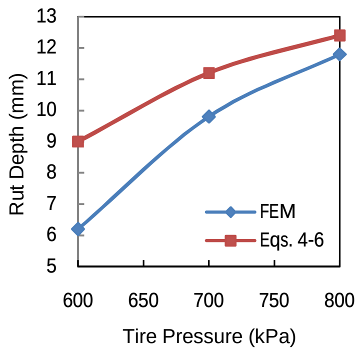


Figure (10) Variation of Rut Depth with Pressure at T=30 °C.

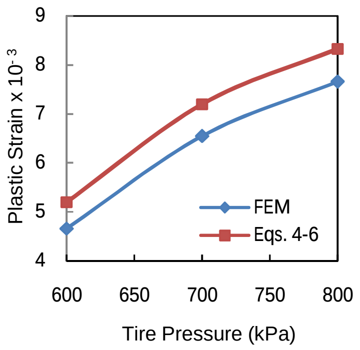
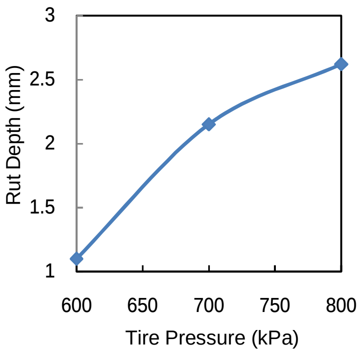


Figure (11) Variation of Plastic Strain with Pressure at T=30 °C .



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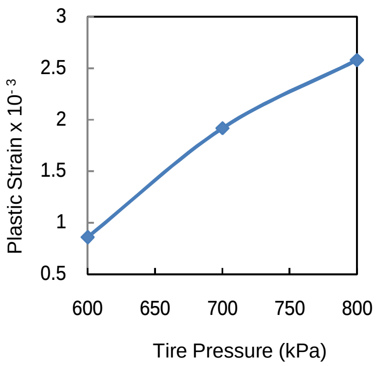
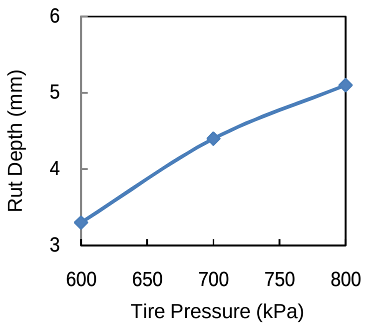


Figure (12) Variation of Rut Depth with Pressure at T=10 °C.

Figure (13) Variation of Plastic Strain with Pressure at T=10 °C .



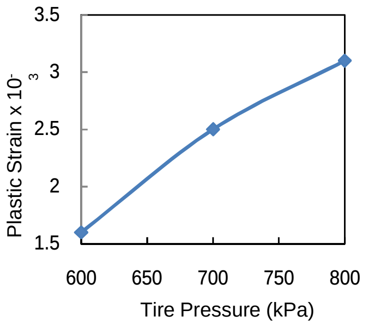


Figure (14) Variation of Rut Depth With Pressure at T=20 °C.

Figure (15) Variation of Plastic Strain With Pressure at T=20 °C .

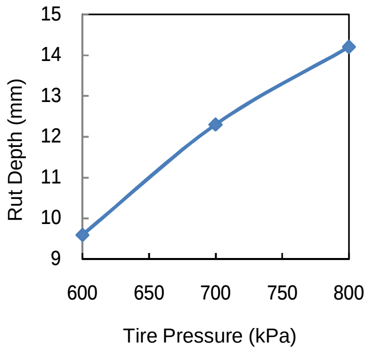


Figure (16) Variation of Rut Depth with Pressure at T=40 °C.

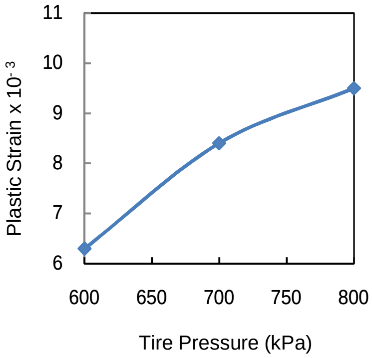


Figure (17) Variation of Plastic Strain with Pressure at T=40 °C.

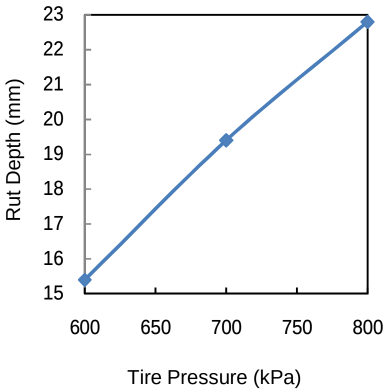


Figure (18) Variation of Rut Depth with Pressure at T=50 °C.

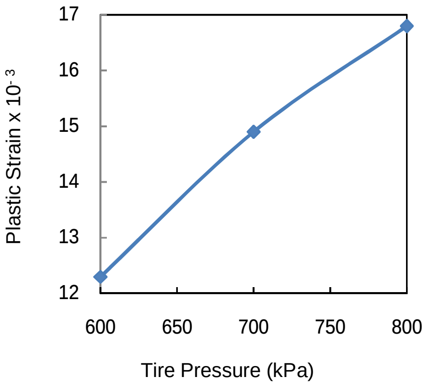


Figure (19) Variation of Plastic Strain with Pressure at T=50 °C.