Combined Effect of Wheel and Thermal Load Conditions on Stress Distribution in Flexible Pavement

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Received on: 21/1/2009
Accepted on:2/7/2009

Abstract

The aim of this research is to study the behavior of flexible pavement under wheel and thermal loading conditions using the finite element program ANSYS V (5.4). The stress states distribution within the asphalt concrete pavement that influence the direction of crack propagation have been investigated. The obtained results from ANSYS finite element program show that a maximum stress intensity factor value obtained at surface and then decrease with depth about (0.75 of asphalt layer thickness) due to reduction in temperature in asphalt layer, which indicates that crack will initiate at surface and extend throughout asphalt layer. The horizontal stress for both top and bottom layers increase with the variation of thermal coefficient expansion factor. High values of stresses at top surface of asphalt layer due to high contact stress were induced under wheel and thermal load conditions. As a result the highway pavement exhibited propagation of surface –initiated cracks. Field observation of cores extracted from asphalt concrete pavement confirmed the obtained results.

Keywords: Flexible pavement, thermal analysis, finite element, stress intensity factor, stress distribution, top cracking.

تأثير الحمل الحراري وحمل العجلة على التبليط المرن

الخلاصة

ان الهدف من هذا البحث هو لدراسة تصرف التبليط المرن تحت تاثير ظروف حمل العجلة والحمل الحراري باستخدام برنامج ANSYS V(5.4). تم التحري عن طبيعة توزيع الاجهادات في التبليط الاسفلتي الكونكريتي الذي بدوره يوثر على انتشار الشقوق. ان النتائج المستحصلة من برنامج العناصر المحددة ANSYS اظهرت ان اعلى قيمة لمعامل شدة الاجهاد تكون على السطح وثم تقل مع العمق بحوالي (0.75 من سمك طبقة الاسفلت) نتيجة نقصان درجات الحرارة بطبقة الاسفلت. وهذا بدوره يوضح ان الشقوق تتولد على السطح وتمتد مع عمع الطبقة. وكذلك ان الاجهادات الافقية لكل من السطح والحافة تزداد مع اختلاف معامل التمدد الحراري. اعلى قيم للاجهادات تكون على سطح الطبقة الاسفلتية نتيجة للقيم العالية لاجهادات التماس التي تتولد تحت تاثير طبيعة حمل العجلة والحمل الحراري. واعتمادا على النتائج فان الشقوق تنشا وتنتشر من سطح التبليط المرن للطرق السريعة. المشاهدة الحقلية لنماذج ماخوذة من مقاطع للتبليط المرن الكونكريتي تتطابق مع النتائج المستحصلة.

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https://doi.org/10.30684/etj.27.12.2
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Introduction

One of the major sources of distress in roads is the cracks that appear on asphalt layer in flexible pavement. Combined vehicle and thermal load induced cracking in the forms of bottom-up fatigue cracking, reflective cracking and top-down fatigue cracking. A finite element model that is able to simulate the initiation and propagation of cracks in asphalt layer is highly desirable. It will provide insights into these distress mechanisms and help improve mechanistic design procedures for cracks.

The aim of this research is to provide a finite element model using the ANSYS finite element program V(5.4) to analyze the flexible pavement under thermal and loading conditions based on combined stress intensity factor due to both vehicle and thermal load which may produce conditions that are favorable for fast fracture. Also investigate the stress states within the asphalt concrete pavement influence the direction of crack propagation. Also the effect of thermal expansion factor has been considered in this study. The stress states within the asphalt concrete pavement influence the crack propagation in terms of stress intensity factor.

2. Literature Review of Related Study

[3] used the single parameter; stress intensity factor K (or equivalently energy release G) or J-integral, depending on the size scale of the yielding in the material: the basis for the use of this approach is that the stress and strain field in the small zone ahead of the crack tip (called fracture process zone, or FPZ) in which fracture occurs is controlled by a signal parameter, the stress intensity factor.

The cracks start as micro cracks that later coalesces to form macro cracks that propagate due to tensile or shear stress or combination of both. Therefore it's necessary to acquire more insight into the crack behavior of asphalt concrete mixture, to obtain better understanding of the cracking mechanism of asphalt pavement, and to have a prediction and reliable system to determine a mixture resistance to crack development and propagation. **[7]** stated that reflection cracks in flexible pavement and composite are top-down cracking.

A combination of finite element modeling and fracture mechanics was selected for physical representation and analysis of a pavement with a surface crack. An approach was developed to model a cracked pavement and predict pavement response in the vicinity of the crack and throughout the depth of the asphalt layer **[6]**.

A model that is able to simulate the initiation and propagation of cracks in asphalt layer is highly desirable. It will provide insights into these distress mechanisms and help improve mechanistic design procedures for cracks. For cracking problem, a natural solution would be to use fracture mechanics **[2].**

[8] presented a numerical modeling scheme for asphalt concrete based on micromechanical simulation using the finite element method. The load transfer between the aggregate plays a primary role in determining the load carrying capacity and failure of such complex materials. **[9]** observed that the shear stress and displacement are proportional until the shear stress equals the shear strength and the interface fails. After failure, a friction model may be used to represent the interface condition. Three parameters are considered to completely describe the interface behavior, the interface reaction modulus, k, which is the slope of the shear stress-dependent curve, the shear strength, S_{max}, and the friction coefficient after failure, m_u, the constitutive model for the asphalt concrete layer interface as represented in Figure (3.2) **[9]**.

3. A Finite Element Model

The finite element program ANSYS (V 5.4) has been used in this study to simulate the flexible pavement under mechanical loads (traffic load applied) and thermal load conditions (temperature field). A schematic representation of flexible pavement is shown in Figure (1) which consists of three layers: asphalt layer, base and subgrade layer.

The finite element working was carried out through three stages:

1. Generation of finite element mesh and defining load ,boundary conditions and material properties as shown in Figure (2). It is preferable to use finite element in places were high stress or strain gradients are expected, therefore the mesh consists of fine mesh close loaded area and at the asphalt layer interface, the left and right vertical boundary are constrained to move only in vertical direction whereas those on bottom boundary are all fixed, the rest of the nodal point including those on surface are unconstrained as shown in Figure (2).
2. Computing strains, stresses, displacements and stress intensity factor and finally converted the obtained results into graphical outputs for ease understanding and discussions as shown in next section.

The layers are modeled as elasto-plastic material (plane strain condition) based on Darger –Parger model with isotropic material. A plane 42, 2-D structural solid has been adopted in this research. The element can be used as a plane element (plane strain or plane stress) or as an axisymmetric element. The element is defined by four nodes having two degrees of freedom at each node, translations and the nodal x and y directions. The element has plasticity, and large strain capability. Therefore a stiffness elastic modulus (E) and Poisson’s ratio (v), cohesion (C), angle on internal friction are used to represent their behavior. The coefficient of thermal linear expansion is used to model thermal behavior. Temperature dependent stiffness modulus is used for the asphalt layer.

The load case studied is a rectangular domain representation with uniform distribution within the rectangular. For uniform stress distribution analysis, a contact radius of .136 m (5.35 inch) is assumed for a single tire. The radius is based on 80 kN (18 kip) single axle load with a contact pressure of 690 kPa (100

psi).The temperature gradient was assumed to be ($1/F^{o}$ /inch).
The parameters used for asphalt layer in finite element program are listed in Table (1).

4. Results and Discussions

The finite element analysis was carried out to study the effect of design parameters on the behavior of flexible pavement under traffic and thermal conditions. The study examines the factors that affect the flexible pavement performance such as coefficient of thermal expansion for asphalt layer, and also investigates the stress states within the asphalt concrete pavement influence the crack propagation in terms of stress intensity factor.

Figure (3) shows the stress intensity factor distribution (which is represent the stresses near crack zone that generated due to loading) in pavement layers, it appears that a maximum value at surface and then decrease with depth due to reduction in temperature in asphalt layer. And also this indicates that crack will grow at top and extended through asphalt layer.

Figure (4) and Figure (5) indicate the horizontal and vertical stresses distribution respectively in flexible pavement due to both loading and thermal conditions. It can be shown from the figure that the maximum horizontal stress at the top of asphalt layer is greater that at the bottom with stress ratio of 1.205 as shown in Figure (6), which is represent the stresses generated due to thermal loading. The high stresses at the surface will result in the pavement cracking from the top and this is confirmed with Figure (3) of stress intensity factor distribution in flexible pavement layers.

Figure (7) shows the shear strain distribution within flexible pavement layers and it appears from the figure that maximum thermal strain at the asphalt surface and decrease with depth to insignificant values. This can be attributed to the reduction of temperature with depth of asphalt layer. The distributions of horizontal and vertical displacement are shown in Figures (8) and (9), respectively.

Figure (10) shows the effect variation of thermal coefficient expansion on the horizontal stress at top and bottom of asphalt pavement layer. It can be seen from this figure that horizontal stress for both top and bottom increase with the variation of thermal coefficient expansion factor.

The results obtained indicated high values of stresses at top surface of asphalt layer due to high contact stress induced under wheel and thermal load conditions. As a result the highway pavement exhibited propagation of surface – initiated cracks. Field observation of cores extracted from asphalt concrete pavement as shown in Appendix (1) confirmed the obtained results.

5. Conclusions

Finite element analysis of flexible pavement under combined wheel and thermal load conditions have been considered to study the stress states within the asphalt concrete pavement that influence the direction of crack propagation. The following concluding remarks are obtained:

1. A maximum stress intensity factor value obtained at surface and then decrease with depth due to reduction in temperature in asphalt layer. Which

indicates that crack will initiate at surface and extended throughout asphalt layer.

2. Maximum horizontal stress at the top of asphalt layer is greater that at the bottom with stress ratio of 1.205.

3. The horizontal stress for both top and bottom increase with the variation of thermal coefficient expansion factor.

4. The results obtained indicated high values of stresses at top surface of asphalt layer due to high contact stress induced under wheel and thermal load conditions. As a result the highway pavement exhibited propagation of surface –initiated cracks.

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Table (1) Parameters Used in Finite Element Analysis for Asphalt Layer.

PARAMETER	*VALUE*
n	0.35**[5]**
C(kPa)	158 **[4]**
(degree) f_1	
Coefficient of thermal expansion	$4\times10^{-4^{0}}C^{-1}$ 1-

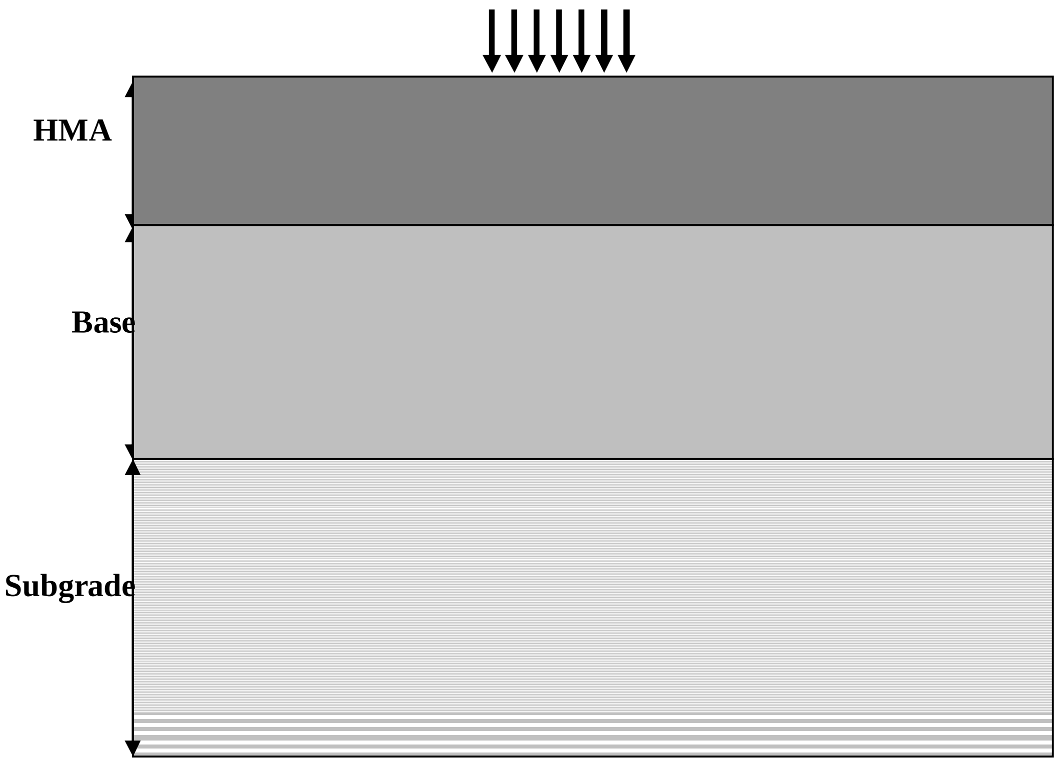


Figure (1) Schematic Representation of Flexible Pavement Layers.

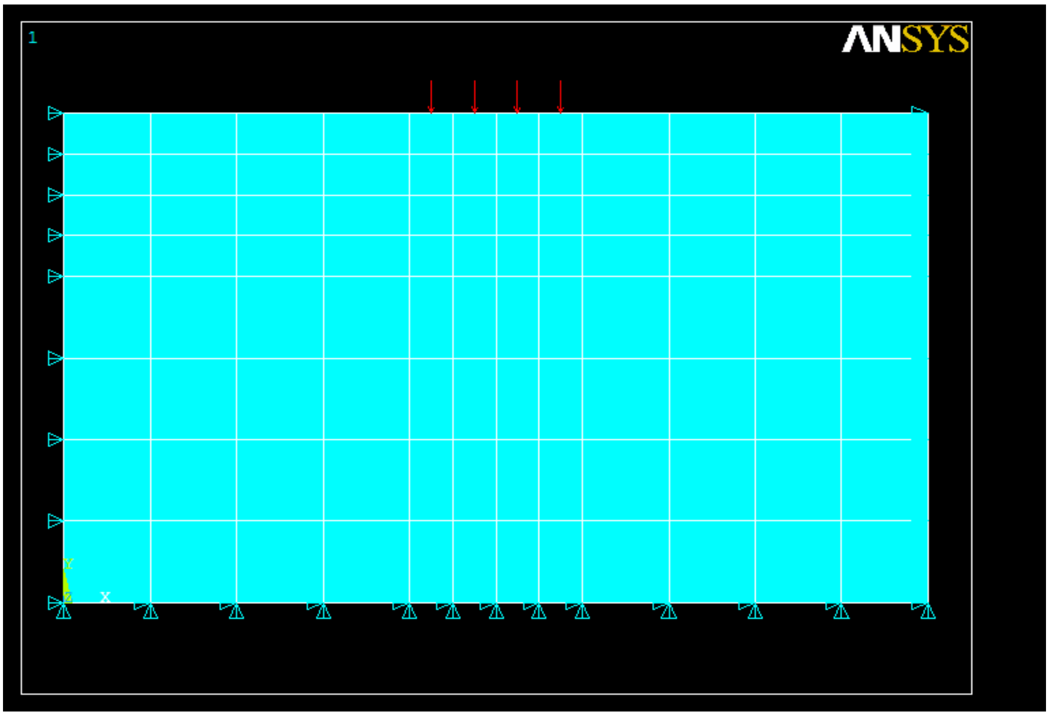


Figure (2) Finite Element Mesh of Pavement Layers.

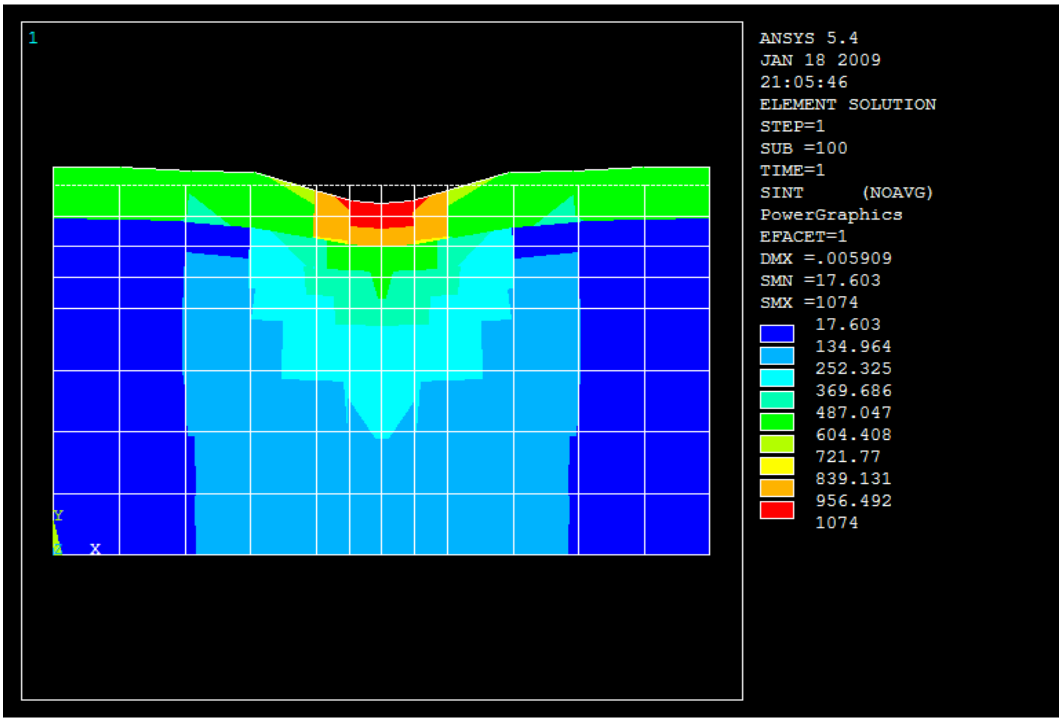


Figure (3) Stress Intensity Factor Distribution

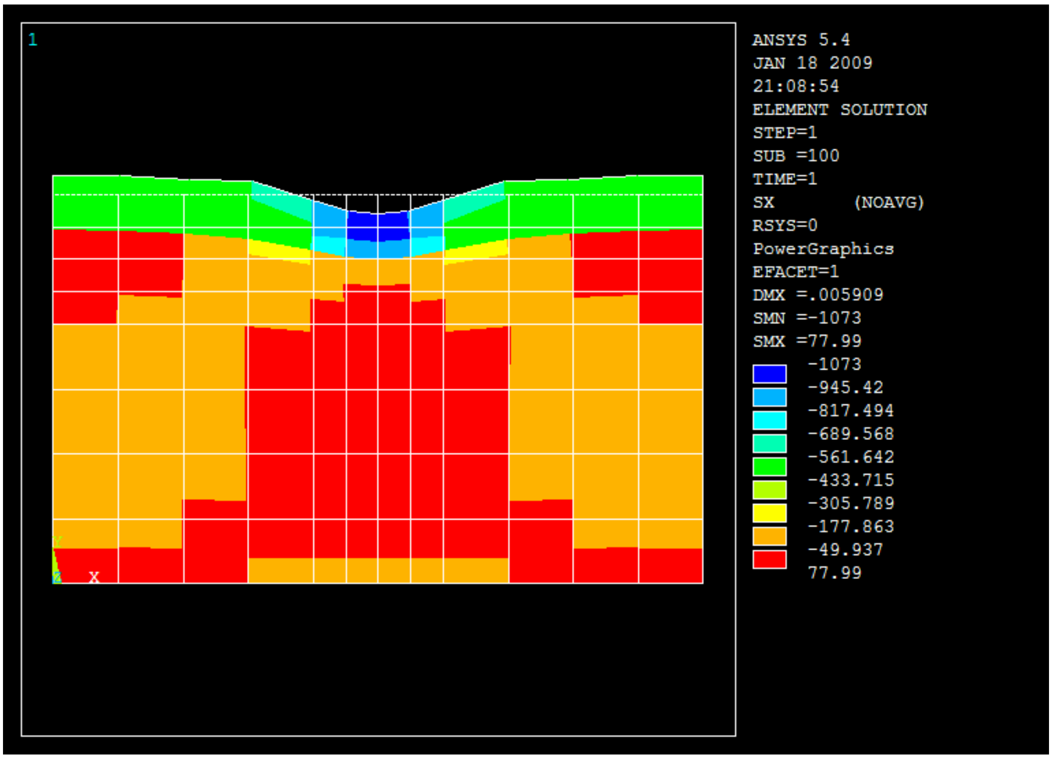


Figure (4): Horizontal Stress (kPa) Distribution within Flexible Pavement

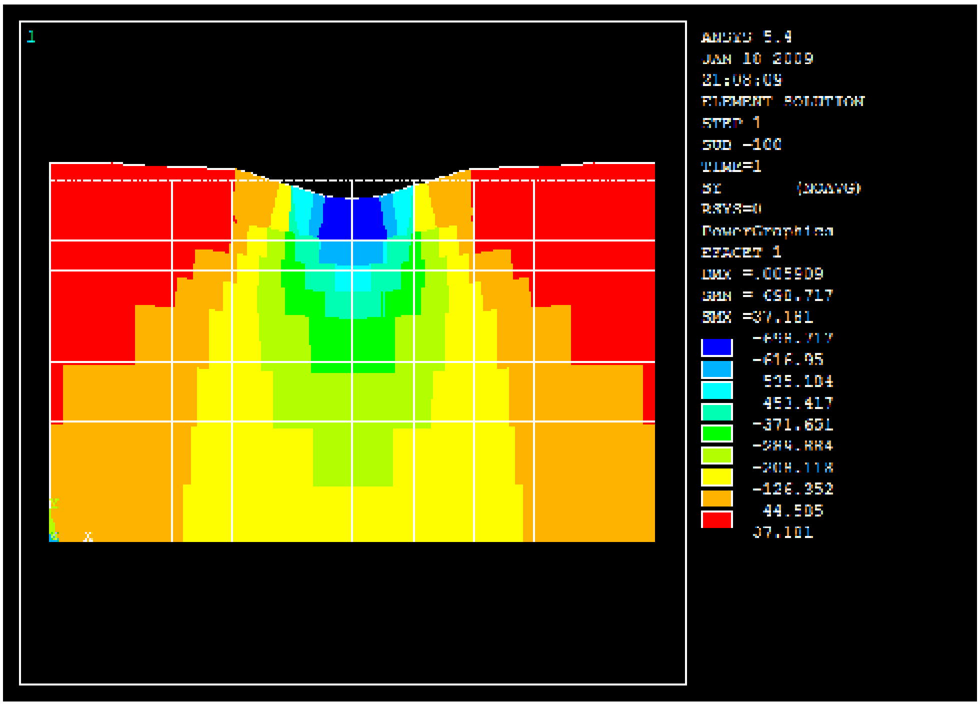


Figure (5) Vertical Stress (kPa) Distribution within Flexible Pavement.

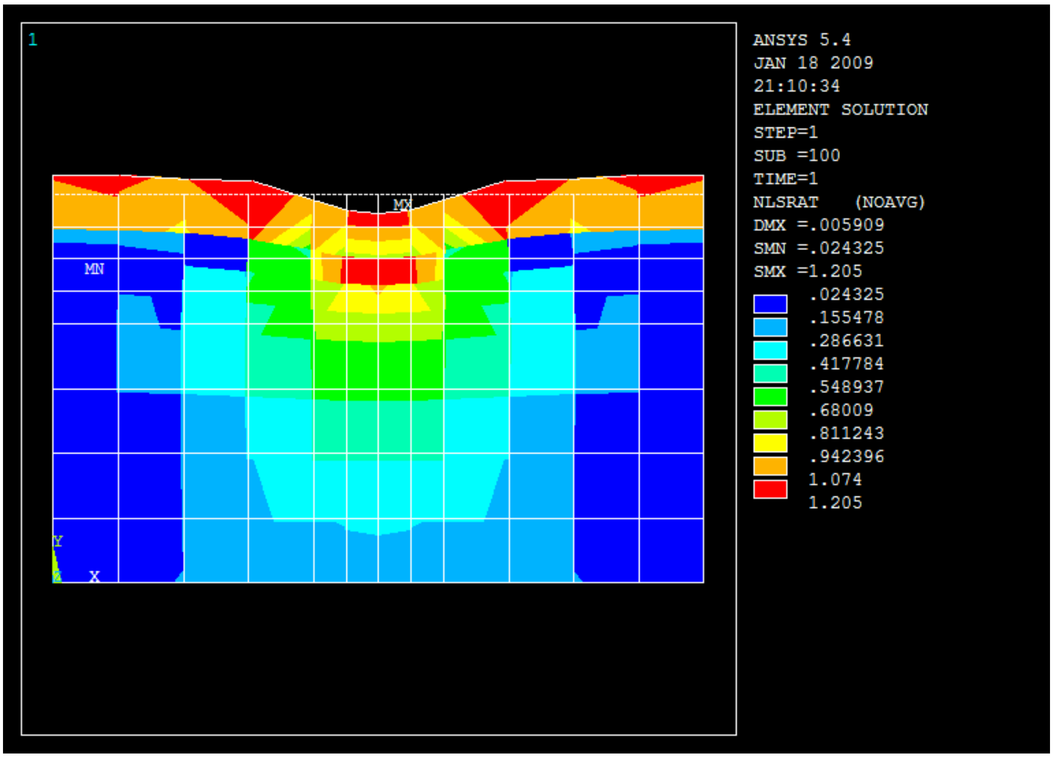


Figure (6) Thermal Stress Ratio Distribution State.

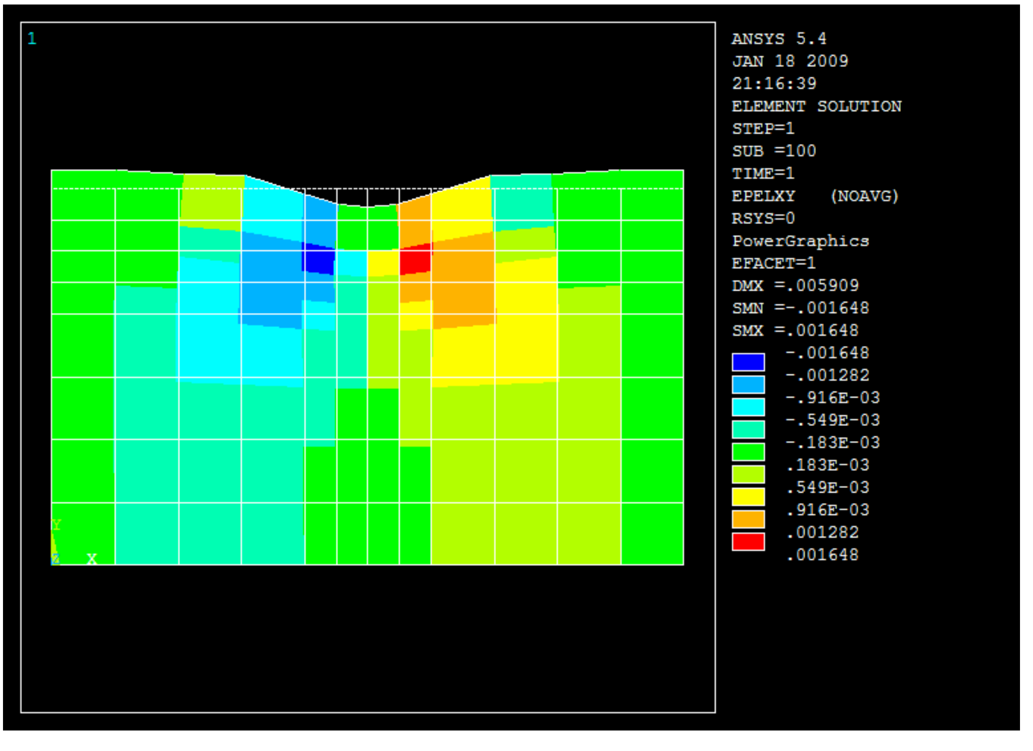


Figure (7) Shear Strain Distribution in Flexible Pavement.

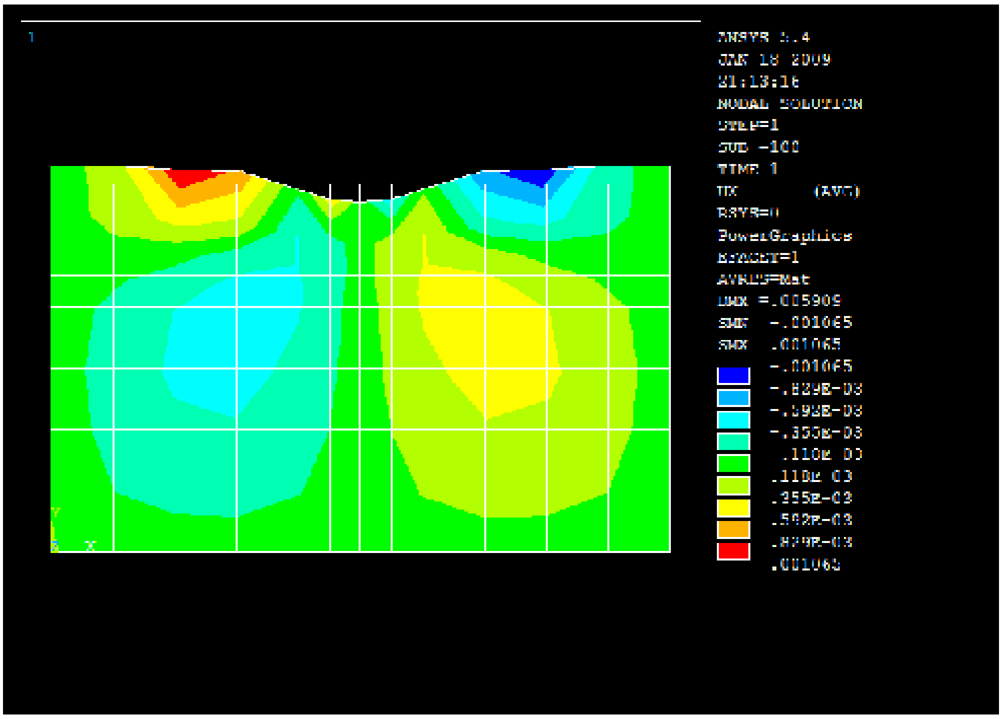


Figure (8) Horizontal Displacement (m) Distribution in Flexible Pavement.

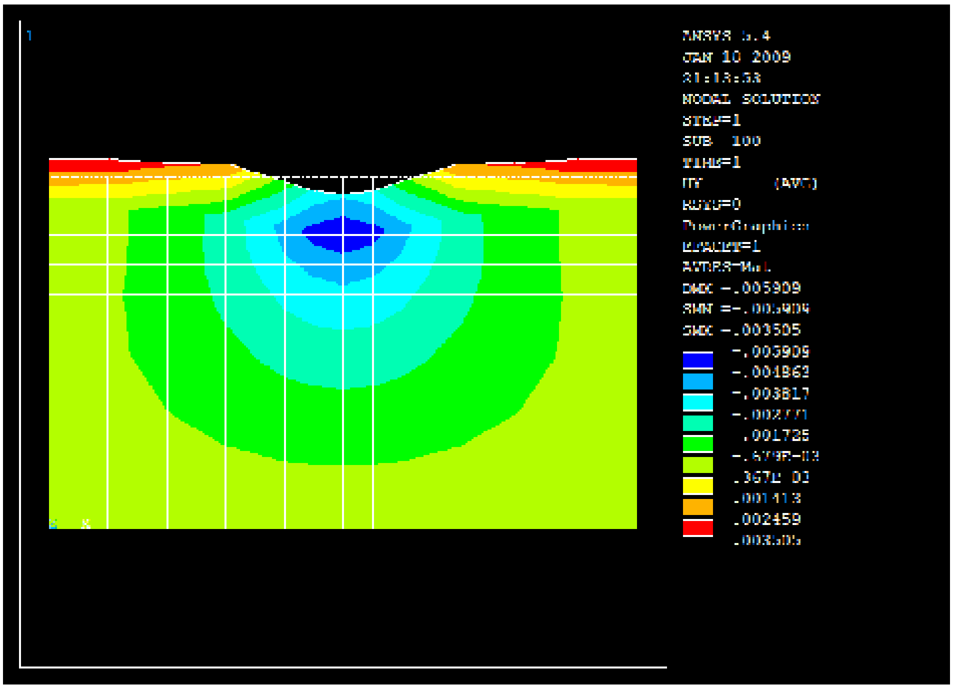
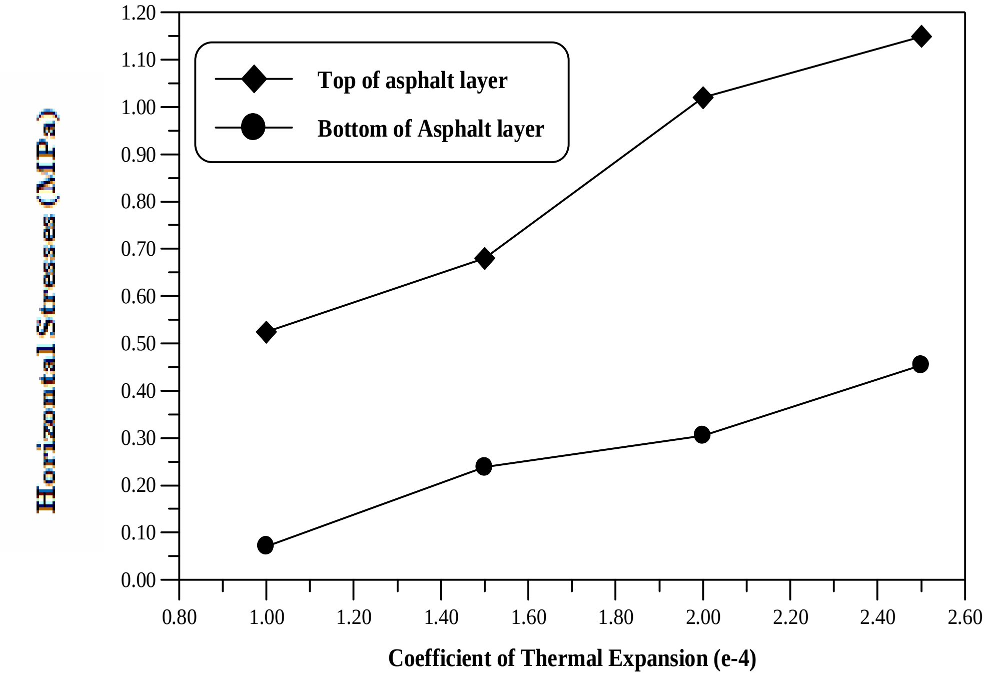


Figure (9) Vertical Displacement (m) Distribution in Flexible Pavement.



(1/C^0)

Figure (10) Effect of Thermal Expansion Factor on Horizontal Stress under the Center of Loading.

Plate (1) Field Core Extracted From Asphalt Concrete Pavement