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Propagation Mechanisms for Surface Initiated Cracking in Composite Pavements

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Abstract:

The primary objective of this study was to identify the mechanisms for the development and propagation of longitudinal cracks that initiate at the surface of composite pavement. In this study the finite element program ANSYS version (5.4) was used and the model worked out using this program has the ability to analyze a composite pavement structure of different layer properties. Also, the aim of this study was modeling and analyzing of the composite pavement structure with the physical presence of crack induced in concrete underlying layer. The results obtained indicates that increasing the thickness of the asphalt layer tends to decrease the stress intensity factor, which may be attributed to the rapidly decrease of horizontal tensile stress in the asphalt layer. The cracks initiate at the surface due to high vertical stress and shear stress from wheel loads tends to propagate downward due tensile stress generated at the bottom of the asphalt layer or near crack tip, and the whole process occur at the same location of the existing cracks in underlying concrete layer rather than travel up from existing crack. As the load position varies from the crack zone, this result in tensile stresses or tension at the crack tip, leading to increase the stress intensity factor and intern result in crack propagation further into the depth of the pavement.

Key Words: *Finite element; pavement model; crack propagation; composite pavement; stress intensity factor; stress distribution; crack initiation; horizontal tensile stress.*

1. Introduction

Cracking of road pavements is one of a major source of distress in roadways. A model that is able to simulate the initiation and propagation of cracks in asphalt layer is highly desirable. It will provide an insight into these distress mechanisms and help improve mechanistic design procedure for cracks.

The primary objective of this study was to identify the mechanisms for the development and propagation of longitudinal cracks that initiate at the surface of bituminous pavements. Also investigate the stress state (horizontal tensile stress and vertical stress within composite pavement structure), and how affect on the direction of crack propagation. Moreover, the aim of this study was modeling and analyzing of composite pavement structure with the physical presence of crack induced in concrete base layer, which result in the critical condition for top-down crack propagation.

2. Literature Review

For cracking problems, a natural solution would be to use fracture mechanics *(Anderson, 1995)*. The single parameter could be either stress intensity factor K (or equivalency energy release G) or j integral, depending on the size scale of the yielding of 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 zone , or FPZ) in which fracture occurs is controlled by a signal parameter, the stress intensity factor *(Canga et. al.,2001)*.

The traditional fatigue approach and the distortion energy approach both implement analysis of a homogeneous continuum pavement.

The distortion energy approach is being used by some researchers (Kim et.al., 1997). The fatigue life of asphalt mixtures under cyclic loading conditions was found from relationship between pseudo-stiffness and number of loading cycles. The damage mechanics model can then predict damage growth for local load conditions with different loading rates and rest periods; however, in reality, it attempts to simulate the conditions for a cracked pavement. The physical presence of the crack is omitted, and the stress redistributions that result from crack growth are not captured.

Definition of the traditional fatigue approach to pavement evaluation has been cited in some publications (Huang, 1993; Yoder and Witzak, 1975). The existing approach to performance prediction is broad and classifies pavement failure types that have been studied several times. The theories reviewed included the traditional fatigue approach, distortion energy approach, damage mechanics and fracture mechanics. Although it would possible to use any of the methods examined for predicting failure, it was determined that the combination of using finite element modeling and fracture mechanics was most appropriate for best analysis the behavior of crack growth and critical conditions at crack tip (Collop and Cebon,1995).

Analysis of cracked asphalt pavement has been studied using the ABAQUS finite element computer program and show that the mechanism of crack failure was tension. Also the load position and base stiffness for flexible pavement affect on crack propagation and confirmed observation of crack growth in the field (Leslie et. al., 2001).

3. Description of Finite Element Model for Composite Pavement Structure

The finite element numerical analysis allows for physical representation of cracks and discontinuities in pavement structure. In this study the finite element program ANSYS version (5.4) was used. The model worked out using this program has the ability to analyze a composite pavement structure of different layer properties. A typical schematic of composite pavement structure is shown in Figure (1) was analyzed to investigate the possible mechanisms of cracking initiation and propagation. The entire composite pavement system (i.e., asphalt layer, old concrete layer, base and subgrade) was modeled, loaded with measured contact stresses and analyzed for pavement response. The input material properties for composite pavement layers are shown in Table(1).

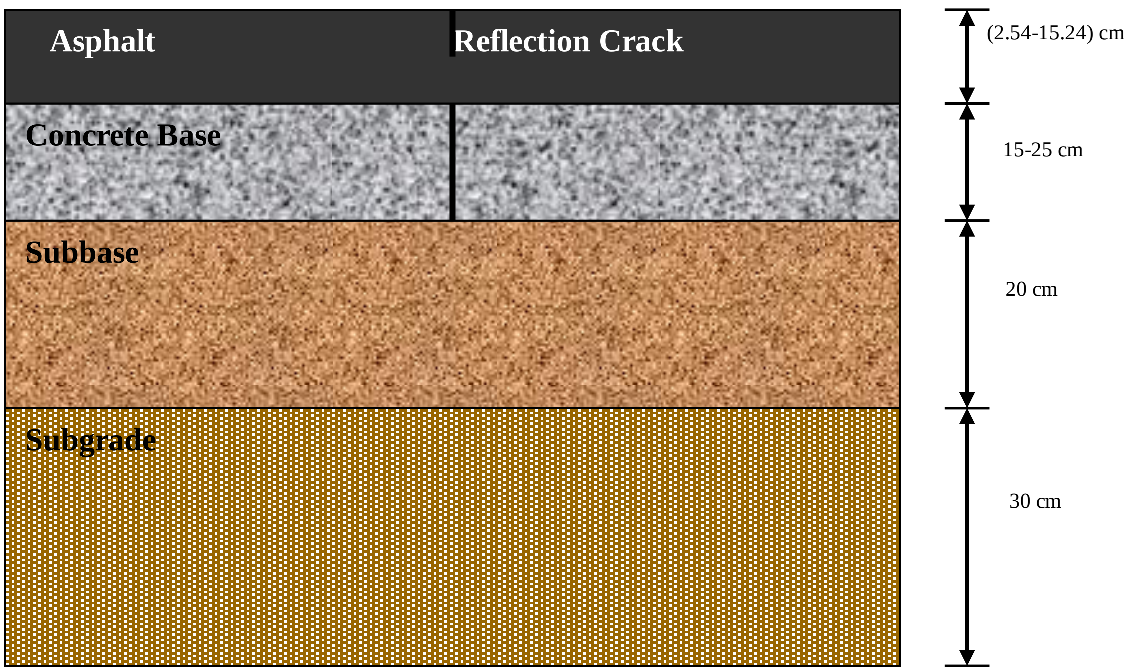

Fig. 1. Schematic Representation of Composite Pavement Structure.

Table 1,
Input Material Parameters for Composite Pavement Layers.

PARAMETERS	LAYERS			
	Asphalt layer	*Concrete layer*	*Base Layer*	*Subgrade Layer*
ν	0.35	0.2	0.35	0.4
C(kPa)	158	16.8	9.2	5.7
ϕ_1 (degree)	26.3	10	30	25

The analysis procedure was repeated for each time of different loading position, asphalt layer thickness and crack length. Also, to represent the reflective cracking in composite pavement a crack have been induced by applying a space gap in concrete in the underlying concrete layer equal to crack length to investigate the effect of reflection crack that appears at top pavement surface.

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.

4. Results and Discussions

The structural model and the finite element mesh of composite pavement is described in Figure (6) to investigate the possible mechanisms of cracking in asphalt layer taking into consideration the effect of pavement structure and load spectra.

Generation of finite element mesh and defining load ,boundary conditions as shown in Figure (6). It 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 layers 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 (6).

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).

Computing strains, stresses displacement and stress intensity factor and finally converted the obtained results into graphical outputs for ease understanding and discussions as shown in next section.

A comprehensive parametric study was conducted to determine the effects of load spectra (magnitude and position) and pavement structure on crack propagation. Different thickness values for the asphalt layer are considered, ranging from lightly trafficked to heavily trafficked pavement (1-6) inch (2.54-15.24) cm. The results of stress and stress intensity factor are obtained using the ANSYS Version (5.4) finite element computer program.

Figure (2) shows the variation of stress intensity factor with the thickness of asphalt layer for top and bottom of asphalt layer. The shape of curve for top is similar to that at bottom of asphalt layer, and the only difference is that the stress intensity factor for bottom crack is less than the surface crack. Increasing the thickness of asphalt layer tend to decrease the stress intensity factor. This can be attributed to the rapidly decrease of horizontal tensile stress in the asphalt layer as shown in Figure (3). And the initiation of cracks is due to high vertical stress applied due to wheel traffic loading at the asphalt surface layer. This is confirmed with results obtained for vertical and horizontal stress distribution in the whole structure of pavement as shown in Figure (4) and (5) respectively.

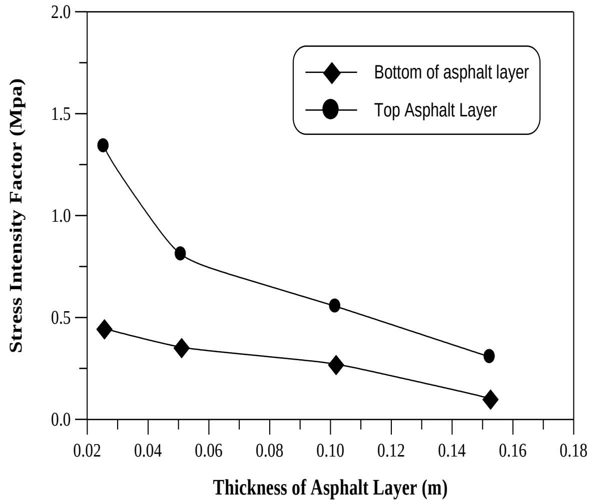

Fig. 2. Variation of Stress Intensity Factor with Thickness of the Asphalt Layer.

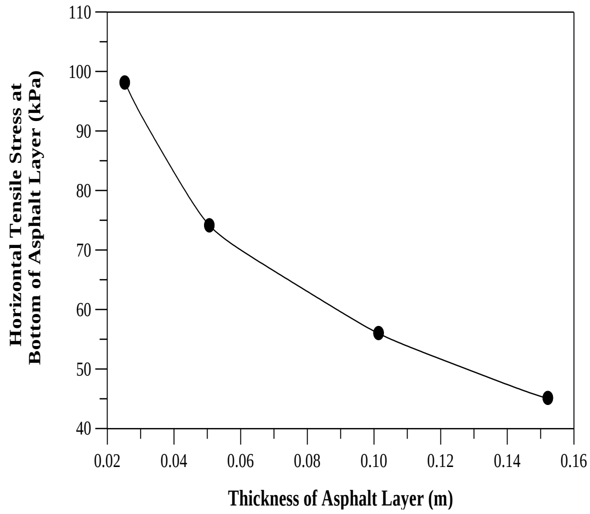

Fig. 3. Effect of Thickness on Horizontal Tensile Stress at Bottom of the Asphalt Layer.

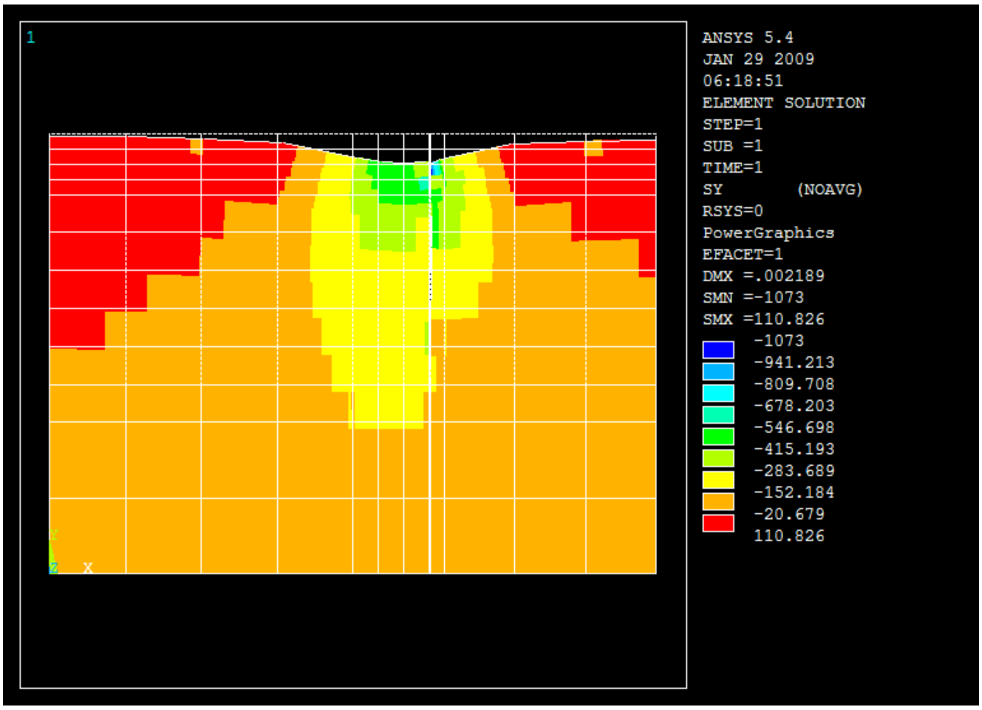

Fig. 4. Vertical Stress Distribution within Pavement Structure.

Finite element analysis of the cracked pavement was conducted to define the critical design conditions at which crack growth will occur. A finite element mesh of the cracked pavement was modeled by induced a gap spacing for crack length at the concrete base layer to simulate the composite pavement structure as shown in Figure (6).

Figure (7) shows the stress intensity factor at pavement surface as a function of crack length already exist in the concrete base layer of the composite pavement. It can be noticed that the increase in crack length result in higher stress intensity factor at the surface of pavement which result in a reflection cracks that appears and exhibit on most composite pavement. Also this can be seen in Figure (8) which shows the stress intensity factor for whole pavement structure. This confirmed the generation of cracks at surface and propagates downward. It may concluded that cracks are initiated at surface due to high vertical and shear wheel stress applied then tend to propagate downward due tensile stress generated at the bottom of asphalt layer.

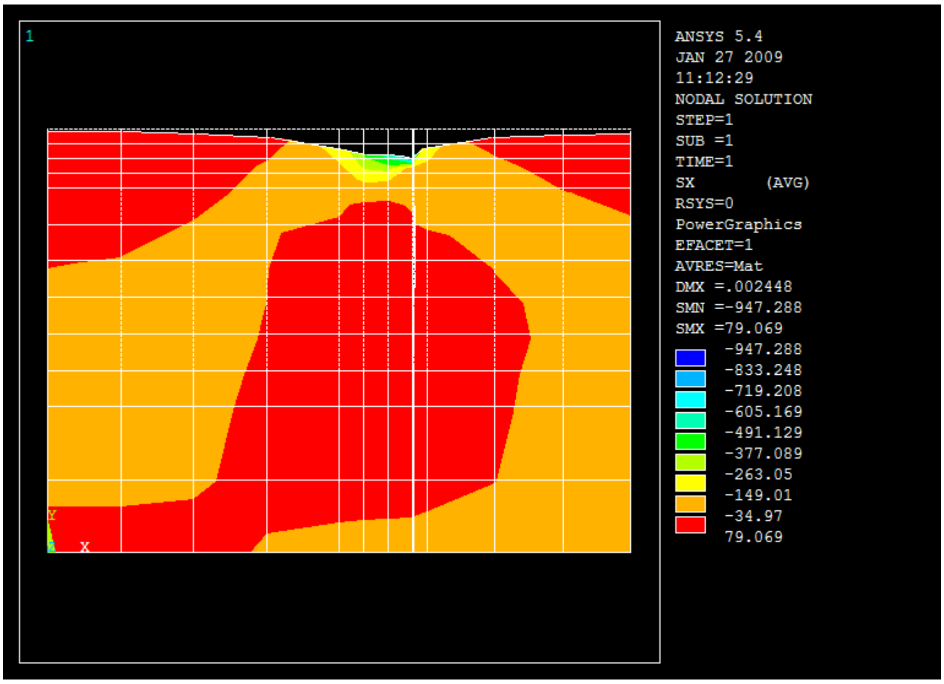

Fig. 5. Horizontal Stress Distribution within Pavement Structure.

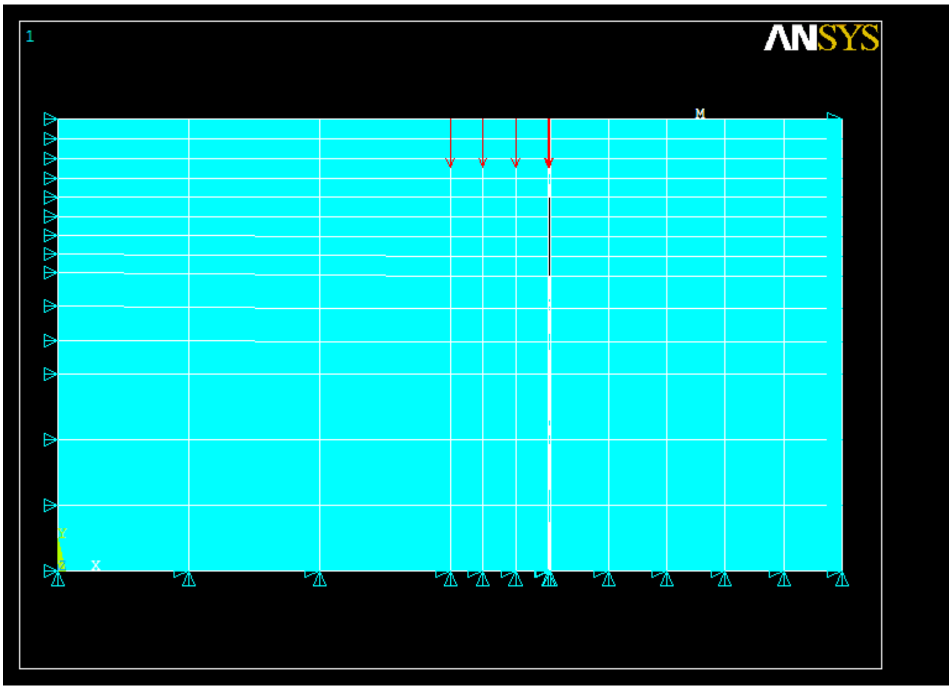

Fig. 6. Finite Element Mesh Induced Crack in the underlying Concrete Layer.

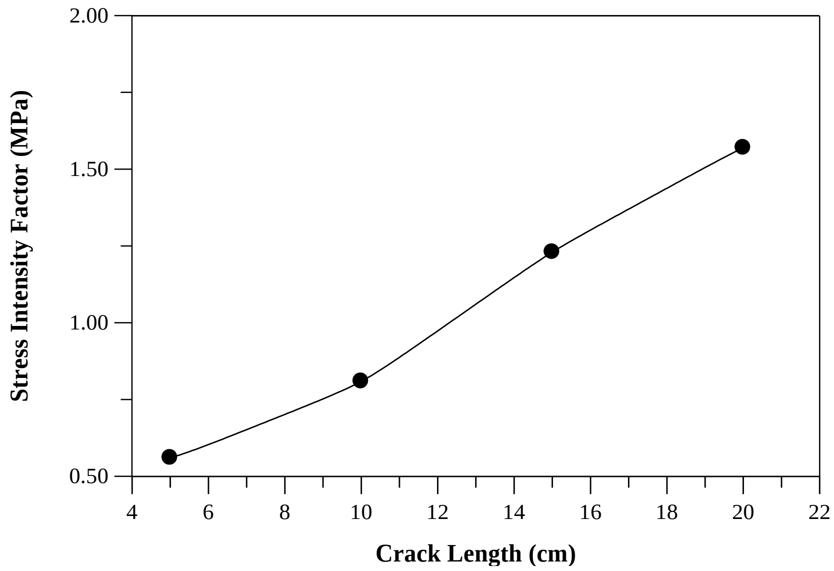

Fig. 7. Variation of Stress Intensity Factor at Pavement Surface with Crack Length.

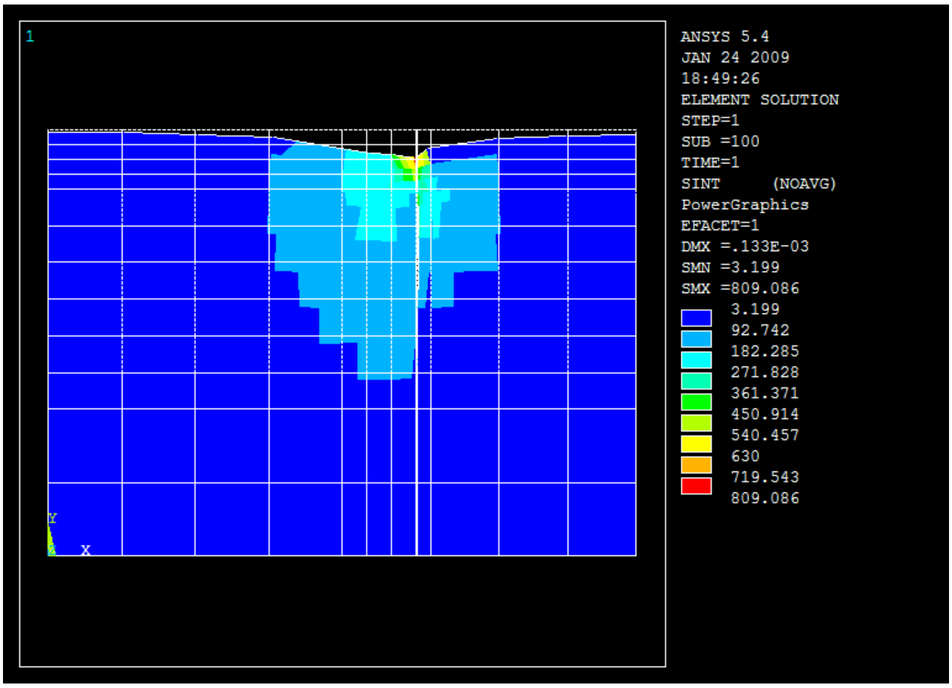

Fig. 8. Variation of Stress Intensity Factor within Pavement Structure.

Also it can be concluded that reflection cracks initiate and propagate at the same location of the existing cracks in underlying concrete layer since its represent the weak zone in pavement structure rather than travel up from down crack.

To study the effect of load spectra, different load positions are considered in this study, which they are important factors to induce critical stress and strain. The finite element model was analyzed at four different loading positions as shown in Figure (9), relative to crack location (tire's widest rib over crack, 25, 40, 50, and 70) cm and the obtained results for stress intensity factor are shown in Figure (10). It can be seen from figure that intensity factor increases with radial distance from load positions, which can be attributed to the horizontal tensile stresses that generated near the crack zone as shown in Figure (11). As the load position varies from the crack, this results in tensile stresses or tension at the crack tip, leading to increase the stress intensity factor and intern result in crack propagation further into the depth of pavement. And throughout the asphalt layer depth, the crack propagate straight down into the pavement by tension then after the direction or crack propagation change due to stress state change with depth.

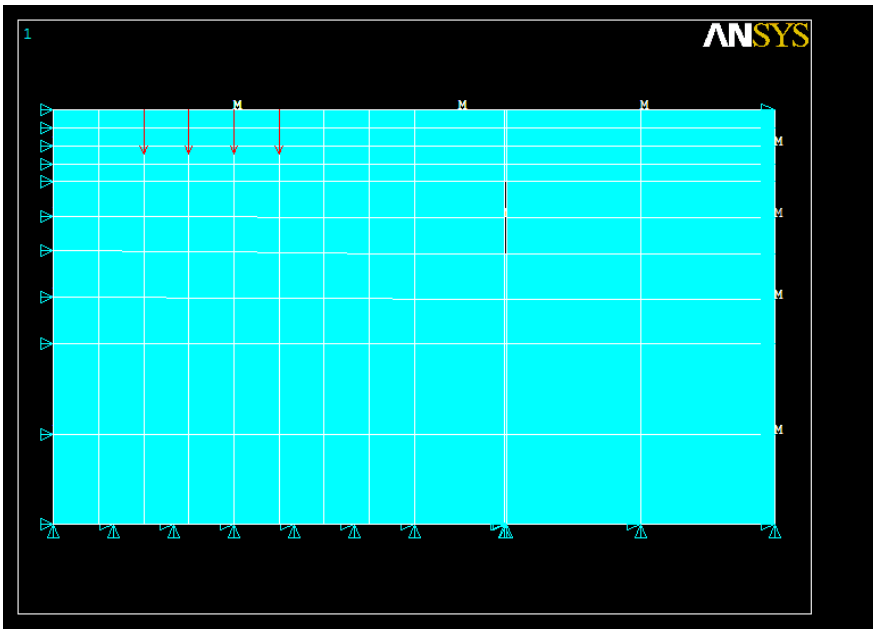

Fig. 9. Finite Element Mesh Induced Crack in the underlying Concrete Layer for Different Loading Positions.

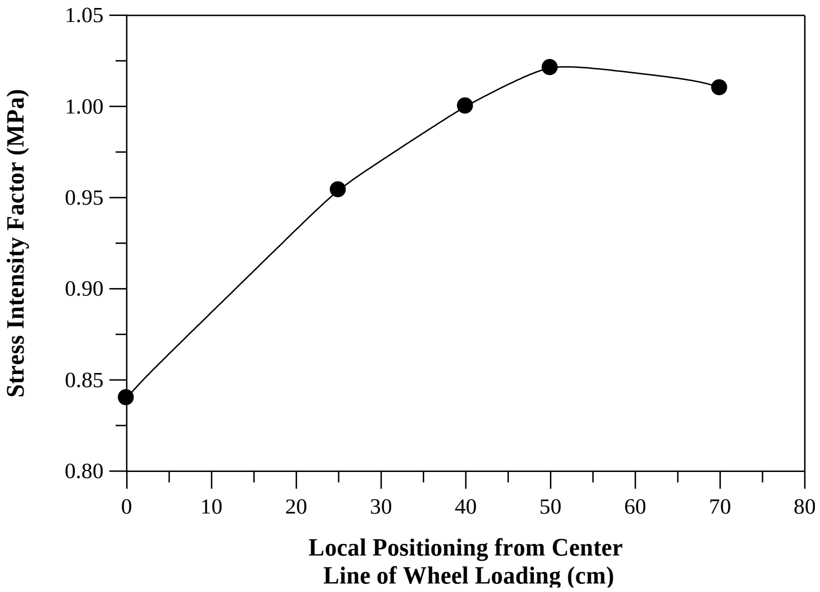

Fig. 10. Variation of Stress Intensity Factor with Loading Position.

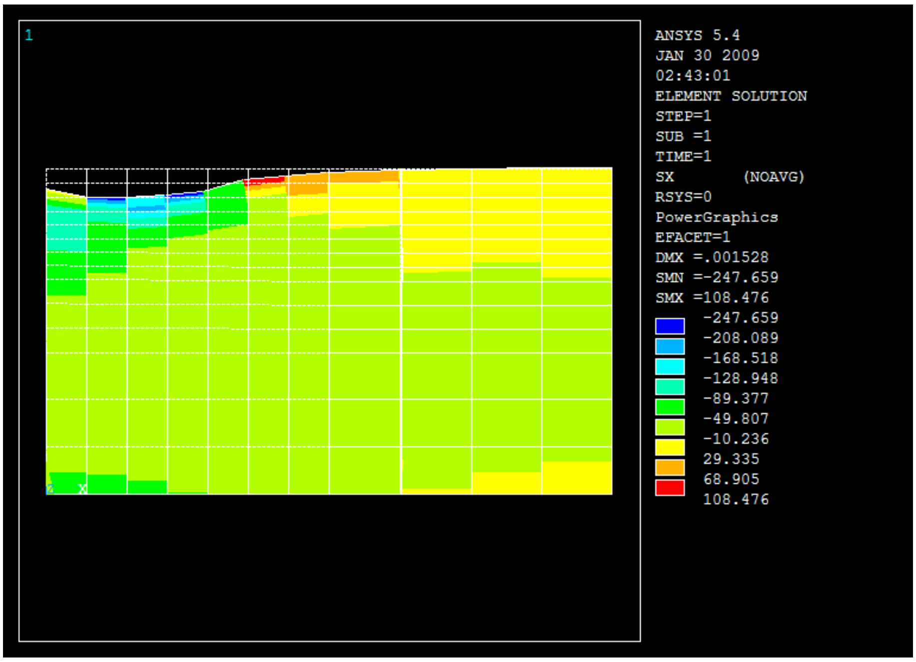

Fig. 11. Horizontal Stress Distribution within Pavement Structure (Local Positioning From Center of Loading 50 cm).

5. Conclusions

The main concluding remarks can be summarized as follows:

1. Increasing the thickness of the asphalt layer tends to decrease the stress intensity factor. Which may be attributed to the rapidly decrease of horizontal tensile stress in the asphalt layer. And the stress intensity factor for bottom crack is less than the surface crack.
2. The generation of cracks at the surface and propagate downward. It's initiate at surface due to high vertical and shear wheel stress applied then tend to propagate downward due tensile stress generated at the bottom of asphalt layer or near crack tip. Also the crack initiate and propagate at the same location of the existing cracks in underlying concrete layer rather than travel up from down crack.
3. As the load position varies from the crack zone, this result in tensile stresses or tension at the crack tip, leading to increase the stress intensity factor and intern result in crack propagation further into the depth of the pavemen

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ميكانيكية انتشار الشقوق في التبليط المركب

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الخلاصة

ان الهدف الاساسي من هذه الدراسة هو لتعيين الميكانيكية لتولد وانتشار الشقوق الطولية التي تنشا في سطح التبليط المركب. في هذه الدراسة تم استخدام برناج العناصر المحددة ANSYS الذي له القابلية على تحليل تركيب التبليط المركب باختلاف خواص طبقاته. الهدف من هذه الدراسة كان عمل موديل تحليلي لتركيب التبليط المركب مع وجود او انشاء شق في طبقة الكونكريت التحتية. ان النتائج التي تم الحصول عليها تضمنت ان زيادة سمك طبقة الاسفلت يودي الى نقصان معامل شدة الاجهاد والذي يعزى الى نقصان اجهادات الشد في طبقة الاسفلت. ان الشقوق تنشا في سطح التبليط نتيجة الاجهادات العمودية واجهادات القص الكبيرة المتولدة من احمال العجلة المسلطة ثم تستمر اسفل بسبب اجهادات الشد المتولدة اسفل طبقة الاسفلت او بقرب حاف الشق وان هذه العملية تحدث بنفس مكان الشق القديم الموجود في الطبقة الكونكريتة التحتية بعكس ما هو معروف بان الشقوق تستمر من الاسفل الى الاعلى. ايضا اختلاف موقع الحمل مع منطقة الشقوق يسبب اجهادات شد في حافة الشق ويؤدي الى زيادة معامل شدة الاجهاد وبدوره يسبب استمرار تولد الشقوق فى عمق التبليط.