Analysis of rigid pavement by using finite element

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In the present study, an attempt has been made to propose an alternative method for design of rigid pavements using Finite Element using ANSYS package. 2-D plane strain and axisymmetric conditions are considered. The computed values of flexural stresses have been compared with the results of Portland Cement Association (PCA) method. Results show that the computed flexural stresses under axisymmetric condition are in close agreement with PCA results rather than under plane strain condition. An illustrative example is presented to indicate as how the Finite Element Method (FEM) can be a versatile alternate in the field of rigid pavement analysis and design.

خلال هذه الدراسة تم عمل محاولة باستخدام طريقة العناصر المحددة لاقتراح طريقة بديلة لتصميم الرصف الصلب باستخدام برنامج (ANSYS) حيث تم إفتراض أن المشكلة ذات بعدين وتم إيجاد الحل تحت ظروف التماثل حول محور وكذلك ظروف الانفعال المسقطى.وقد تم حساب الاجهادات من خلال برنامج (ANSYS) تحت تأثير كلا الظروف. كما تم حساب الاجهادات باستخدام طريقة هيئة الأسمنت البورتلاندى المستخدمة بالكود المصرى لأعمال الطرق الحضرية والخلوية لتصميم الرصف الصلب. وقد أظهرت النتائج أن الاجهادات المحسوبة تحت ظروف التماثل حول محور تتفق إلى درجة كبيرة مع المحسوبة باستخدام طريقة هيئة الأسمنت البورتلاندى. كذلك تم عرض مثال رقمى توضيحى حيث تم التاكيد من خلاله كيفية إستخدام طريقة العناصر المحددة كطريقة سهلة ومرنة ومتنوعة لتصميم الرصف الصلب.

Keywords: Rigid pavements, Finite element, Flexural stresses, Portland Cement Association (PCA)

I. Introduction

Due to the steep rise in the cost of the construction of bituminous roads, there is a general motivation towards the use of concrete pavements. Also, this type of pavement has long service lives and is usually less expensive to maintain than the flexible pavement. Rigid pavements have some flexural strength that permits them to sustain a beamlike action across minor irregularities in the underlying material. Thus, the minor irregularities may not be reflected in the concrete pavement.

The theories of design of rigid pavements are different from those of flexible pavements. While a flexible pavement basically distributes the load gradually to the layers underneath, a rigid pavement acts as a structural element (a rigid plate) resting on an elastic foundation. In reality, the numerous so-called theories of rigid pavement design are arising from a single theory, the theory of elasticity. There are three categories of plate bending: thin plates with small deflections, thin plates with large deflections and thick plates. Since, the deflection of pavement slabs is small compared with their thickness; they can belong to the first category, [6].

Westergaard's work, [7, 10] gave the world a sound mathematical presentation for stresses in concrete pavements. He considered corner, edge and interior loading cases for his analysis. The basic assumptions in his analysis were: the slab has infinite dimensions and the foundation is a dense liquid, i.e., it is made up of springs. The first assumption casts doubt over the validity of the Westergaard's formulae for the slabs with smaller dimensions. However, the second assumption was justified form the practical point of view, [6]. Pickett (1951), developed formulae for the case of corner loading with two conditions; protected and unprotected corners, [9].

Finite Element Method (FEM) has the advantage of analyzing concrete pavements of various shapes and sizes that are encountered on straight as well as on curves under simple and multiple wheel loading conditions.

2. Design of rigid pavements

Most rigid pavements design techniques for both highways and airfields are based upon theoretical stresses in elastic slab, modified by field experience and appropriate safety factors. The safety factors that will be applied depend to a large extent upon the type of failure. In general, stresses are developed in rigid pavements as a result of several factors, including the action of wheel loads, the expansion and contraction of the concrete due to temperature changes. For example, wheel loads will induce flexural stresses that are dependent on the location of the vehicle wheels relative to the edge of the pavement. The following factors are basic parameters in the design of rigid pavements. Simultaneously, the considered values of these parameters in the present study are also illustrated.

2.1. Modulus of subgrade reaction

The strength of the subgrade is given in terms of the Westergaard modulus of subgrade reaction "k_s" which can be obtained by conducting a plate load test in accordance with the AASHTO test designation T222 using a 75 cm diameter plate. Estimates of "k_s" values can also be made either from experience or by correlating with other tests.

Normally, for the rigid pavement analysis, the k_s -value is required but for the proposed analysis by FEM, the modulus of elasticity of the soil subgrade is required (E_s-value). Bowles, [4] presented a correlation between the k_s and E_s values as given in eq. (1).

$$k_s = E_s / [B(1-\mu^2)], \qquad (1)$$

where:
- k_s is the modulus of subgrade reaction,
- E_s is the modulus of elasticity of the subgrade soil,
- B is the width of the concrete slab, and
- μ is Poisson's ratio for the subgrade.

In the present analysis, k_s -values of 13.5, 27, 54 and 81 kPa/mm are considered and subsequently, the related E_s -values required for the FE analysis were calculated based upon eq. (1).

2.2. Slab Dimensions

The lane width for highways may range between 2.75 m (9 ft) and 3.75 m (12 ft) and it can vary between 3.05m (10 ft) and 7.62m (25 ft) for airfield pavements according to the width of taxiways, runways and terminal aprons. In the present study, a slab width of 3.66m (12ft) was adopted to decrease the expected number of trucks that will run over the corners of the slabs with their wheels.

2.3. Wheel loads

Wheel loads produce high bending stresses near the corners, along the edges and to a lesser extent, at the center of the slab. Therefore, tire pressure, contact pressure and tire imprint are basic parameters concerning the design of rigid pavements. Puttappa et al., 2002 reported that the effect of the tire wall is ignored, [2]. Thus, the contact pressure between the tire and pavement must be equal to the tire pressure. For low tire pressures, contact stress under the tire wall may be greater than that at the center of the tire. However, for high tire pressures, the reverse is true. In the present analysis, the radius of contact area was calculated using the equivalent single wheel concept.

2.4. Placement of wheel loads

Stresses in a rigid pavement depend upon the load position. The findings of Portland Cement Association revealed that for a rigid pavement with 3.66m (12ft) lane width and well maintained shoulder, the most critical case of loading when the axle (what ever its configuration) is at the outside pavement edge, [7]. The maximum flexural stresses will be at the bottom of the slab and are parallel to the outside edge. In the present study, the case of loading was taken similar to a static plate load test at the center line of the lane width which is equal to the width of the slab.

3. Flexural stress analysis using ansys (illustrative example)

ANSYS is one of the numerous finite element softwares, which perform finite element analysis of a complicated geometry in an easy way. It is a general- purpose program and more flexible since it has options to perform analysis in the fields like structural, Thermal, Fluid Mechanics and Electro magnetics. Kamel (2004) has validated the ANSYS program to be used for the analysis of pavements, [5]. A solved example was worked out for an airfield pavement to illustrate the proposed analysis of rigid pavements using FEM. Further, for comparison, the same input data was used for finding out the flexural stresses under the concrete slab using the PCA design charts of airfield pavements.

3.1. Input data

Thickness of slab:	It will vary from 25 to 50 centimeters
Load:	$2 * 10^6$ kN
Tire pressure:	980 kPa
Axle configuration:	Single axle with dual wheels of spacing 24 inches (center to center)
Modulus of subgrade reaction:	13.5, 27, 54 and 81 kPa/mm
Modulus of elasticity:	For concrete: 28,000,000 kPa. For subgrade: it will vary with the modulus of subgrade reaction " k_s"
Poisson's ratio	For concrete: 0.15 For subgrade: 0.25
Proposed dimensions	As shown in fig. 1

3.2. The used FE model

A two-layer pavement system as shown in fig. 1 was considered. A pressure "ρ" equals to the tire pressure is assumed to be applied at surface and distributed over a circular area with radius of contact equal to "a".

A 2-D analysis was considered and the problem was analyzed two times as plane strain and axisymmetric problem for comparison. The 8-noded structural solid element (PLANE-82) in ANSYS program was used in the modeling.

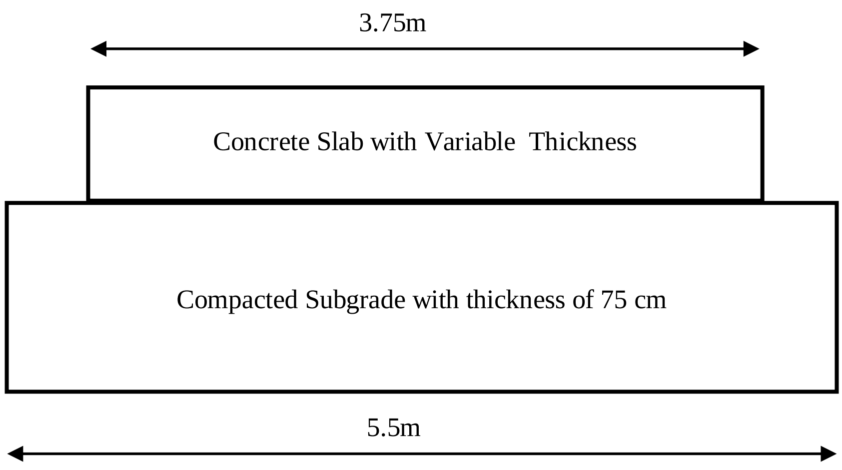

Fig.1. Typical cross section of rigid pavements with proposed dimensions.

For application of FEM in pavement analysis, the layered system of infinite extent is reduced to an appropriate size with finite dimensions. This requires some approximations in the analysis. These approximations will, however have little influence on the stress distributions in the FE model and the support conditions at its boundaries are appropriately selected. Therefore, the following boundary conditions are assumed for the FE model:

a. Clamped (fixed) along the center line to achieve the condition that shear stresses and radial displacements are each equal to zero.

b. Roller support along the ends of the subgrade soil to have negligible deflections in both vertical and radial directions.

c. Fixed along the bottom of the compacted subgrade soil to mainly constraint the vertical movements.

3.3. Results

The problem was solved many for the two cases (plane strain and axisymmetric) for different values of "k_s" which subsequently transformed into E_s –values. For varying thickness of the concrete slab, the flexural stress was obtained for each case using a factor of safety equal 2 i.e, each obtained value from the FE analysis is divided by this factor of safety. Figs. 2 and 3 show the variation of the obtained flexural stresses thickness of slab for plane stain and axisymmetric problems respectively. These figures indicate that higher flexural stresses for concrete reveal lesser thickness. Also, for the same slab thickness, the lesser subgrade strength (in terms of modulus of subgrade reaction) requires higher flexural strength for the concrete. These results are quite reasonable and expected.

3.4. Comparison of results with the PCA design approach

For the same input data, flexural stress can be obtained directly using the PCA charts. fig. 4 shows the variation of flexural stresses and thickness of slab for the different proposed conditions and also those obtained from PCA charts under a value of "k_s" equals to 13.5 kPa/mm. The ratio of the flexural stresses obtained by 2-D plane strain to that of PCA is ranging from 0.93 to 1.20 with average of 1.12 for different subgrade strengths. However, it is ranging from 0.87 to 1.09 with average of 0.98 for different subgrade strength in the case of axisymmetric conditions. This means that the computed flexural stresses under axisymmetric condition are in close agreement with PCA results.

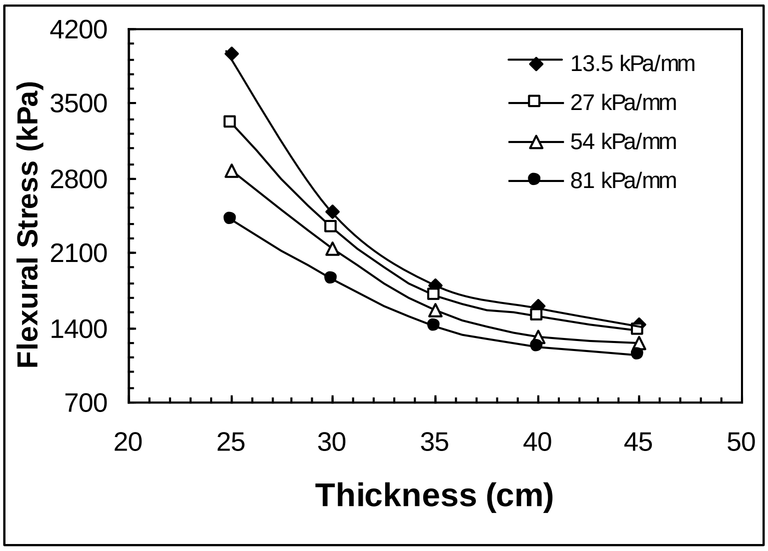

Fig. 2. Variation of flexural stresses with slab thickness under plane strain condition.

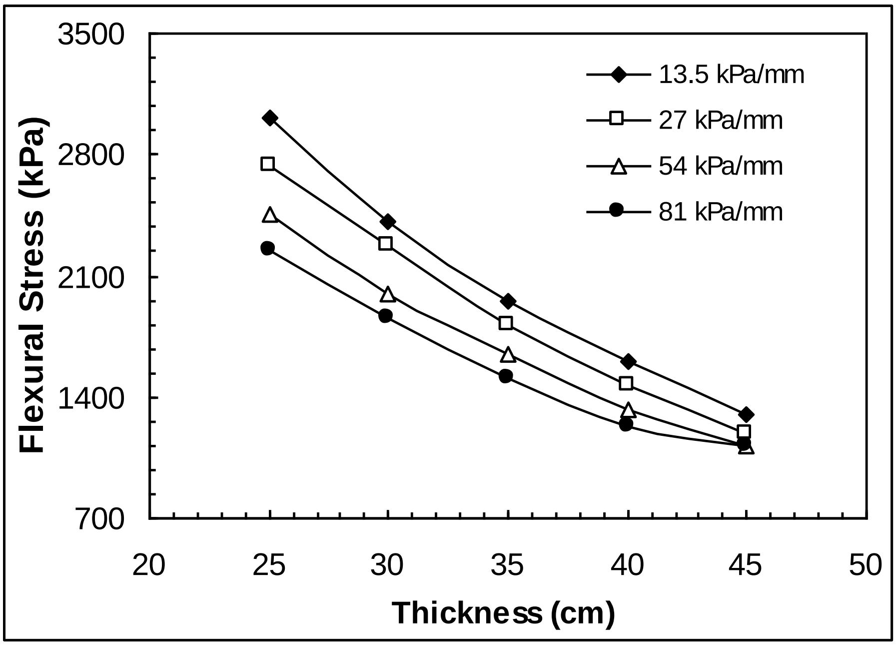

Fig. 3. Variation of flexural stresses with slab thickness under axisymmetric condition.

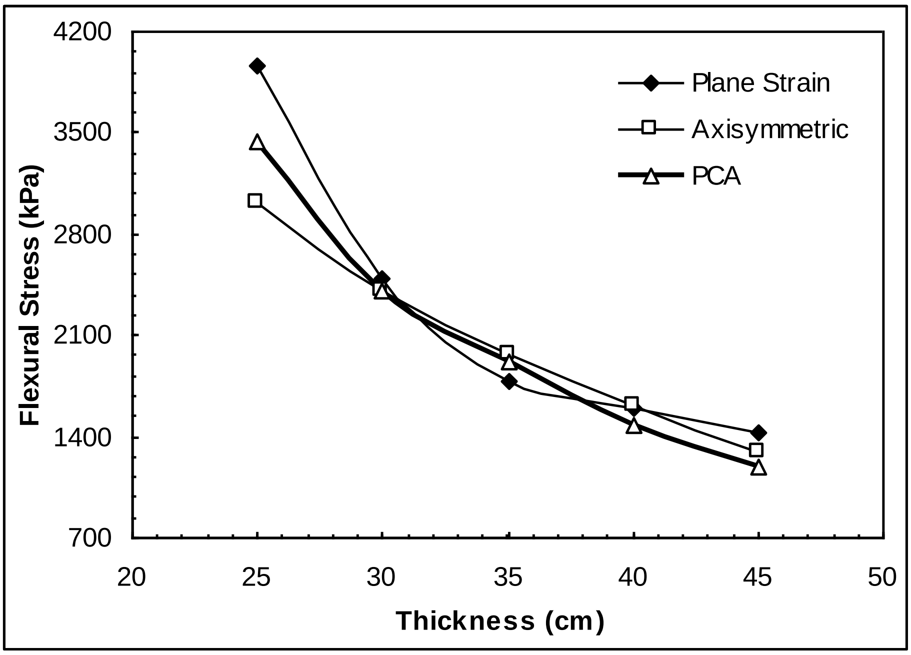

Fig. 4. Comparison between finite element analysis results and PCA design method.

4. Summary and conclusions

An attempt has been made to analyze the flexural stresses of the rigid pavements. The ANSYS package has been used for the same. 2-D plane strain and axisymmetric conditions were considered. The computed values have been compared with the results of PCA method. The variation of flexural stresses obtained by 2-D plane strain to that by the PCA is ranging from 7 to 20% while, it is only from 9 to 13% in case of axisymmetric condition. This indicates that the axisymmetric condition is ideal for the center loading condition of the rigid pavements. This is also showing how the FEM can be a versatile alternate in the field of rigid pavement analysis and design.

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