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ANALYSIS OF HEAVY DUTY FLEXIBLE PAVEMENT USING FINITE ELEMENT METHOD

S. El-Hamrawy *Minoufiya University*

M. El-Shourbagy *Mansoura University*

G. Moussa *Alex. University*

ABSTRACT

In recent years, decreased fatigue life, increased rutting, and accelerated serviceability loss in flexible pavements have been attributed to the effects of increased wheel loads as well as increased tire pressures. This effect is more significant in subtropical regions.

Thus, the main objective of this research was to evaluate flexible pavement sections under different conditions of axle loads, tire contact pressure and pavement temperatures. Stresses, strains and deflections of different sections were calculated using finite element method. Linear analysis was used to calculate pavement responses of asphalt layers, while non-linear analysis was utilized for granular layers. Moreover, fatigue life of different pavement sections was predicted.

Analysis of the results of this paper revealed that, some pavement sections have high safety criteria for 30 years design period and consequently the thickness of asphalt layers could be reduced and other sections are not acceptable for 30 years design period without increasing the layers thickness. Moreover, it was concluded that the axle loads have a very significant influence on fatigue life and rutting of flexible pavements, while the effect of increasing tire contact pressure has lower influence. Also, it can be concluded that temperature has a very significant influence on flexible pavement responses.

فى الوقت الحاضر ، يرجع نقصان عمر الرصف وزيادة التخدد والنقص المتزايد فى مستوى الخدمة إلى تأثير زيادة أحمال العجلات وأيضا زيادة ضغط الإطارات ، ويكون هذا التأثير أكثر وضوحا فى المناطق الحارة والمناطق شبه الإستوائية.

لذلك كان الهدف الرئيسى من هذا البحث هو تقييم قطاعات من الرصف المرن تحت حالات مختلفة من أحمال المرور وضغط تلامس الإطارات ودرجات حرارة الرصف. وقد تم حساب الإجهادات والانفعالات والترخيم لقطاعات الرصف المختلفة باستخدام طريقة العناصر المحدودة على أساس التحليل الخطى لطبقات الرصف الأسفلتى والتحليل اللاخطى لطبقات الأساس وتحت الأساس الحصوية. أيضا تم حساب عمر الكلال ومعيار الأمان لقطاعات الرصف المختلفة.

من تحليل النتائج وجد أن بعض قطاعات الرصف التى تم تقييمها لها معيار أمان عال لفترة تصميم قدرها ثلاثون عاما وبالتالى يمكن تخفيض سمك طبقات الرصف ، وقطاعات أخرى غير مقبولة لمدة تصميم ثلاثون عاما بدون زيادة سمك الطبقات. أيضا وجد أن أحمال المحاور ودرجة حرارة الرصف لها تأثير واضح جداً على عمر الكلال وعمق التخدد للرصف المرن بينما تأثير زيادة ضغط الإطارات يكون أقل.

Keywords: Finite element, Flexible pavements, Surface deflection, Fatigue life, Permanent deformation, and Tire pressure.

INTRODUCTION

In the recent years an important trend has been established towards the use of heavier highway and aircraft wheel loading. The trend in *Europian Union* now is increasing axle loads of trucks from 11.5 to 13.0 ton [1]. On the other hand, increasing tire pressure leads to a decrease in vehicle operating cost, so it is desired by a lot of drivers. There are various modes in which pavements fail. Cracking of the surface layer and permanent deformation of the pavement system which manifests as rutting on the pavement surface are the famous modes. The effect of increased truck tire pressures on flexible pavement performance has become a subject of great concern. Various researchers have used analytical methods to attribute decreased fatigue life, increased rutting, and accelerated serviceability loss to the effect of increased tire pressure [2,3,4].

The main objective of this research is to evaluate the different flexible pavement sections of road under this study at different conditions of axle loads, tire pressures and temperatures. The following paragraphs discuss the effect of each factor on the behaviour of pavement sections.

Pavement Responses

For conventional flexible pavements, various researchers [3-4] have identified the following critical pavement responses:

1. Surface deflection;
2. Vertical compressive stress at the pavement surface;
3. Vertical compressive stress at the top of the granular base layer;
4. Vertical compressive stress at the top of the subgrade layer, and
5. Radial tensile strains at the bottom of the asphalt layer.

The first four responses have been related to rutting whereas the fifth response has been related to fatigue cracking. In the following paragraph we will discuss the different models to predict the permenent strain and other pavement responses.

Prediction of Permanent Strain

To predict the amount of permanent strain that would occur after a given number of wheel load applications, the following models were used:

Deformation of asphalt layer

$$\varepsilon_p = 57.5 * \frac{\sigma_d}{|E|} * \left(\frac{n}{1000 * f}\right)^k \quad \text{.................(1)}$$

The models for calculating plastic strain and load cycles of asphalt layer were suggested as follows [6]:

$$n = 1000 * f\left(\frac{\varepsilon * |E|}{57.5 * \sigma_d}\right)^{\frac{1}{k}} \quad \text{...................(2)}$$

where:

εp	[-]	plastic strain
σ_d	[kPa]	deviator stress
E	[kPa]	Elastic Modulus
n	[-]	Number of repetitions
f	[Hz]	frequency
k	[-]	parameter based on material properties

Deformation of Granular Base Course

Plastic strain in granular base course could be calculated based on the equation after WERKMEISTER [7] as follows:

$$\varepsilon_p = A * \left(\frac{n}{1000}\right)^B \quad \text{..............................(3)}$$

$$n = 1000 * \left(\frac{\varepsilon_p}{A}\right)^{\frac{1}{B}} \quad \text{............................(4)}$$

$$A = a_1 + a_2 * \sigma_3^{a_3} + a_4 * \sigma_1^{a_5} \text{.....(5)}$$

$$B = b_1 + b_2 * \left(\frac{\sigma_1}{\sigma_3}\right)^{b3} + b_4 * \sigma_3^{b5} \text{......(6)}$$

where a_1 to a_5 and b_1 to b_5 are parameters based on material properties as porosity, gradation, max & min grain size, ...etc.

Deformation of Subgrade

Plastic deformation (ε_p)of subgrade could be determined as follows:

$$\varepsilon_p = \varepsilon_{el} * (a + b * \log(n)) \text{..........(7)}$$

$$n = 10^{\frac{Sp - a.\varepsilon el}{b.\varepsilon el}} \quad \text{..........................(8)}$$

a, b parameters ranging between 0 and 0.7

ε_{el} elastic strain (deformation)

Tested Sections in the Present Reseach

The road sections are constructed on different subbase thicknesses. Bituminous surface course consists of two layers, 5.0 cm wearing course and 6.0 cm binder course. Base course constructed from 7.0 cm bituminous macadam above 50.0 cm compacted crushed dolomite (30.0 cm for section 2). Sand subbase was variable according to the criteria of subgrade and its height differs from 0.0 to 150 cm. Pavement sections 3 and 4 are similar in asphalt overlays and base course. The difference is only in thickness of subbase. While asphalt packet of sections 1 and 2 are the same and the difference is in base and subbase thickness. Table 1 shows the thickness of different sections under this study that were chosen according to German specifications [1].

Table1: Layers thickness of different sections

Pavement Layers	Thickness, cm			
	Sec 1	Sec 2	Sec 3	Sec 4
Asphalt wearing course, [cm]	5.0	5.0	5.0	5.0
Asphalt binder course, [cm]	6.00	6.0	6.0	6.0
Asphalt base course, [cm]	0.0	0.0	7.0	7.0
Base course (crushed dolomite), [cm]	50.0	30.0	50.0	50.0
Subbase (natural sand), [cm]	0.0	50.0	100.0	150.0
Subgrade (infinite thickness)	Infinite	Infinite	Infinite	Infinite

Effect of Temperature

The asphalt mixture stiffness is a function of temperature and time of loading (frequency). In general asphalt material display non-linear stress/strain behavior with increasing the stiffness and/or with increasing stress amplitude.

For determination of the modulus of elasticity E, a constant frequency of 0.1 s (10 Hz; speed of 60 km/h) was considered. The temperature gradient was determined using POHLMANN Nomograph [8] that calculates the variation of temperature with pavement depth.

Finite Element Program

Using Finite Element computer program FENLAP, axial symmetrical stress and deformation behavior could be calculated for the different layers of the pavement. The program uses eight knots rectangular elements, in which every knot available is of two degrees of freedom (vertical and horizontal), and all element angles are 90 ° (geometric linearity). Fig.1 shows the mesh of finite element model.

In FENLAP there are different non linear elastic models already implemented plus the linear elastic *Hook's* law, among this also the elastic Dresden model [9]. The subgrade has been modeled as linearly elastic and had an E-value of 45 MPa and a μ-value of 0.49. Asphalt layers were calculated as linear elastic (μ = 0.35) even at high temperatures. Modulus of elasticity E was determined as a function of pavement temperature and time of loading (frequency). Dresden Model as well as parameters of base course granular materials are discussed [9,10,11,12].

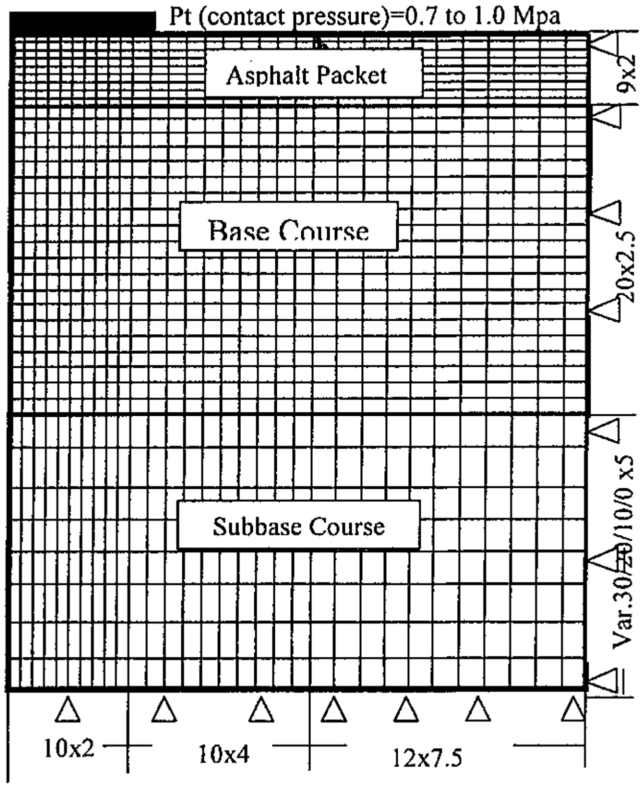

Fig. 1 Finite element mesh

Fatigue Stresses and Safety Criteria

The safety criterion is related to the fatigue stresses. In the present research the following modules is used to calculate this property in the different layers:-

1-Subgrade and Base Course

The allowable number of load cycles to define the safety criteria was calculated based on *HEUKELOM's* equation [9] as follows:

$$N = 10^{\frac{1}{0.7}\left(\frac{0.00875 * E_{velast}}{\gamma * \sigma_z} - 1\right)} \quad ....(9)$$

where

N [-] number of load cycles

E_{velast} [MN/m2] dynamic deformation module

σz [kPa] vertical stress at the top of layer

γ [-] factor of safety that indicates the criteria of safety

2-Asphalt Layers (Asphalt Packet)

$$N = 10^{\frac{2,633(\lg E + 1)}{(\gamma * 10 * \sigma_r)^5}} \quad ....(10)$$

where;

N [-] number of load cycles

E [MN/m2] E-Modul at the bottom of asphalt packet σr [kPa] bending stress at the bottom of asphalt packet

γ [-] factor of safety that indicates the criteria of safety

The last formula calculates safety criteria based on the cracks at the bottom of asphalt packet. The stiffness of asphalt mixture is extremely low at high temperatures. Damage condition is corresponds to factor of safety γ =1.0. When value of γ is too high this means that the section is more safe and when it is less than 1.0 it means that the section isn't safe.

ANALYSIS OF RESULTS

1-Vertical Stress at bottom of Asphalt Layer

Figures 2 and 3 show the relation between vertical stress at the bottom of asphalt layer and the horizontal distance (radius) from load center for different pavement sections at –5 °C and 45 °C respectively. It should be noted that at –5°C this relation isn't clear up to 20 cm radius. The cause is disturbance through loading and low stiffness at the edge of the loading area. Vertical stress goes almost constant and then decreases with increasing the horizontal distance for all pavement sections.

On the other hand, at 45°C, vertical stress decreases rapidly with increasing the horizontal distance. Vertical stress reaches zero at a radius of 0.60 m for Section 1. This stress increases with increasing pavement thickness up to 1.30 m for Section 4. The loading area on base course becomes always smaller with increasing pavement temperature and consequently vertical stress markedly increases. Thus at 45 °C, vertical stress on base course of Section 1 is about 10 times higher than that for Section 4.

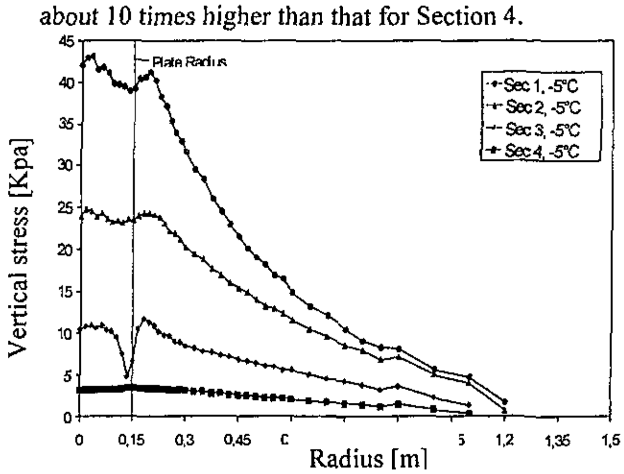

Fig. 2 Vertical stress at bottom of asphalt layers versus horizontal distance for different pavement sections at –5 °C

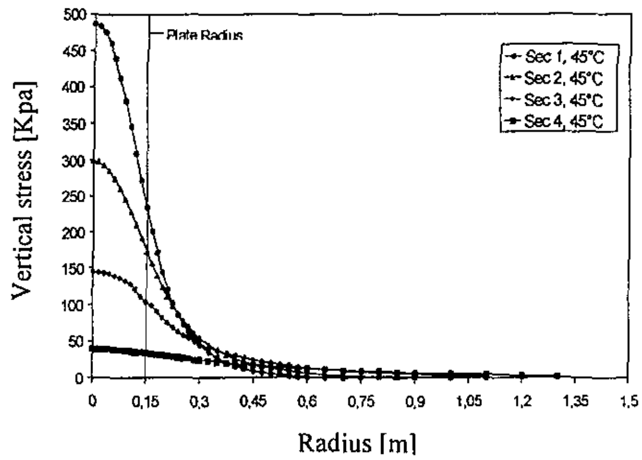

Fig. 3 Vertical stress at bottom of asphalt layers versus horizontal distance for different Sections at 45 °C

2-Radial Stress at bottom of Asphalt layer

From Figs.4 and 5, it should be noted that the bending stress decreases significantly with increasing thickness of asphalt packet. Radial strain at bottom of asphalt packet takes the same shape of radial stress because the linear-elastic model was used for its calculation.

Maximum radial stress occurs at load center and reduces with increasing the horizontal distance. At load center, radial stress is negative (tensile stress) and changes to positive with increasing the distance. The changing point from –ve to +ve depends upon pavement temperature. This point lies at a distance of about 0.45 m at –5 °C and reduces to about 0.20 m at 45 °C pavement temprature.

3-Vertical Stress at Top of Base Course

Vertical stress at top of base course is a result of wheel load distribution on a larger area depending on thickness and stiffness of surface asphalt layers. Fig. 6 shows the relationship between vertical stress and pavement temperature for all pavement sections. Concerning these groups of curves, the following observing can be noted. The increase in vertical stress by increasing pavement temperature is very low up to 20 °C, after that vertical stress increases significantly with increasing pavement temperature. The highest increase of vertical stress is registered for Section 1. The influence of increasing pavement temperature on vertical stress for Section 4 is very small, this is attributed to the extensive height of both asphalt layers and subbase of this section.

The relationship between radial stresses at top of base course with horizontal distance (radius) is shown in Fig. 7 for all sections at 45°C. From this figure it can be noted that the radial stress decreases very rapidly with increasing horizontal distance from load center. The difference of radial stress for different sections is very small at a horizontal distance more than 0.30 m from load center.

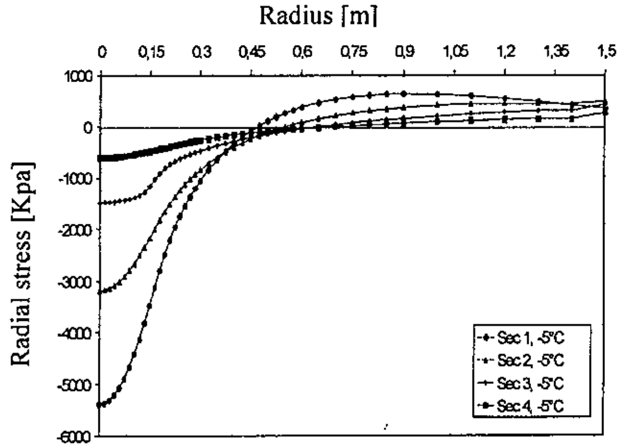

Fig. 4 Radial stress at bottom of asphalt packet with radius for different Sections at –5 °C.

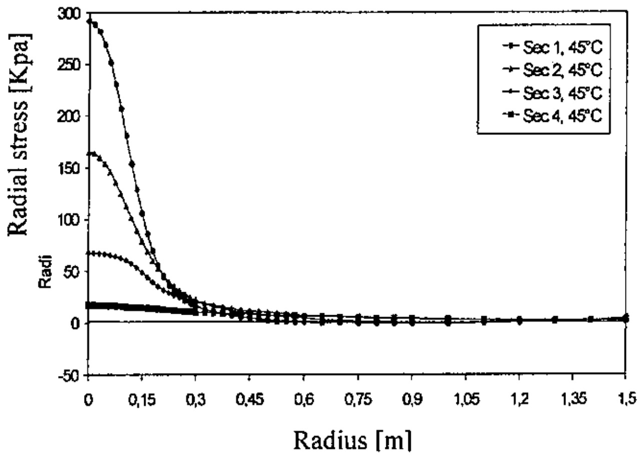

Fig. 7 Radial stress at top of base course versus horizontal distance for different pavement sections at 45 °C

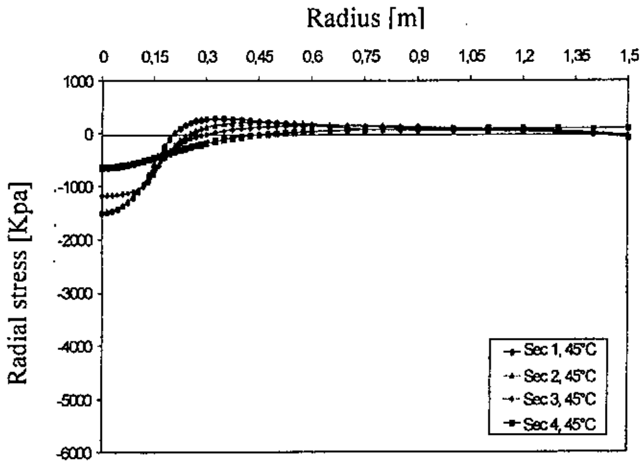

Fig. 5 Radial stress at bottom of asphalt packet with radius for different pavement sections at 45 °C

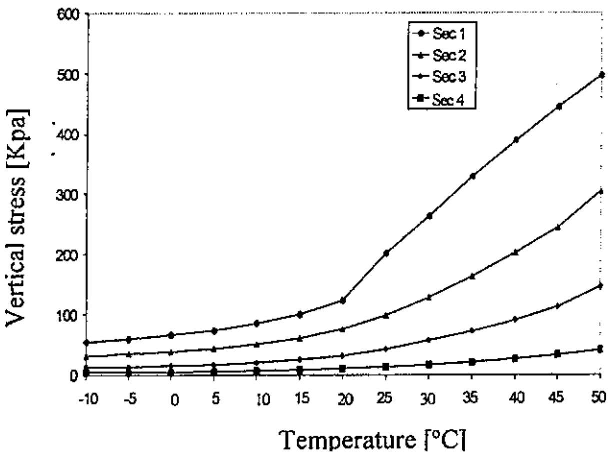

Fig. 6 Vertical stress at top of base course (at load center) versus temperature for different pavement sections

2.4 Pavement Deflection

Fig. 8 illustrates the difference of max deflection with pavement temperature as a function of axle load for Section 4. It is clearly noted that the deflection increases with increasing pavement temperature and /or increasing axle loads. The difference in maximum deflection according to the variation of axle loads increases with increasing pavement temperature. Moreover, the increase of deflection that meets the increase of pavement temperature can be neglected up to 10 °C, after that the increase of deflection is more significant.

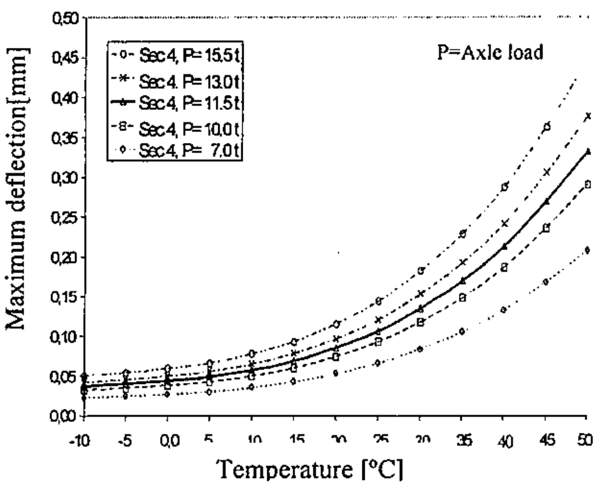

Fig. 8 Maximum deflection versus temperature as a function of axle load for Section 4

Fig. 9 presents the variation of max deflection according to changes of pavement temperature and contact pressure. It may be noted that the increase of pavement temperature has a significant influence on max deflection. For example, increasing pavement temperature from 25 °C (as a normal temperature) to

50 °C leads to an increase of max deflection about 200%, Moreover decreasing pavement temperature from 25°C to -10 °C leads to decrease of max deflection about 70%.

On the other hand, the difference of maximum deflection for the three different contact pressures can be neglected up to 25 °C, then the difference increases with increasing pavement temperature. Increasing contact pressure from 810 kPa to 1000 kPa leads to an increase of deflection only about 6%, this means that the influence of contact tire pressure on pavement deflection is very small compared to the influence of pavement temperature.

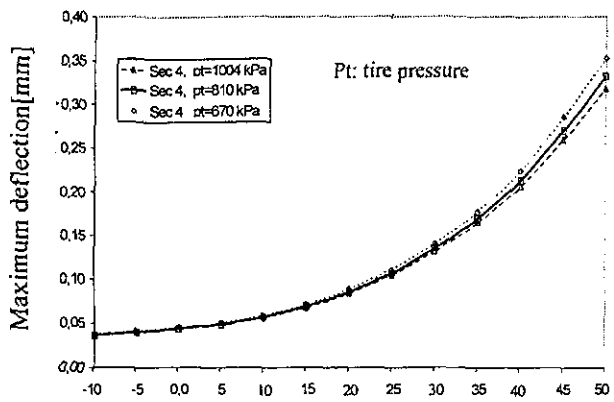

Fig. 9 Maximum deflection versus temperature as a function of contact pressure for Section 4.

2.5 Vertical Strain at bottom of Asphalt Packet

The relationship between vertical strain at bottom of asphalt layer and pavement age for different pavement sections is shown in Fig.10. It should be noted that vertical strain increases with increasing pavement age. Max vertical strain occurs in the first year of pavement age, this returns to the densification of asphalt layers under wheel loads. Also, from the above figure, the relation could be divided into two phases, first phase (rapid phase), that occurs in the first year, and second phase (stable phase). In the second phase the rate of strain (deformation) is lower than that in the first phase, this rate is faster for Section 1. For Section 4, the rate of deformation for the first phase is $1.0x10^{-2}$, while it is $3.1x10^{-4}$ for the second phase. This means that the rate of vertical deformation of second phase is about 3% of the first phase.

2.6 Vertical Strain at Top of Base Course

Fig.11 shows vertical strain at top of base course versus pavement age for different pavement sections. From this figure it can be noted that the lowest vertical strain is obtained for Section 4, since it has highest thickness of both asphalt layers and subbase course. The rate of vertical deformation for this section is nearly constant during 30 years of pavement age. Section 2 gives two stages of vertical deformation, first one is rapid deformation stage, while the second is stable stage. For Section 1, vertical deformation divides into two stages and the rate of increase of vertical deformation is significant in both stages.

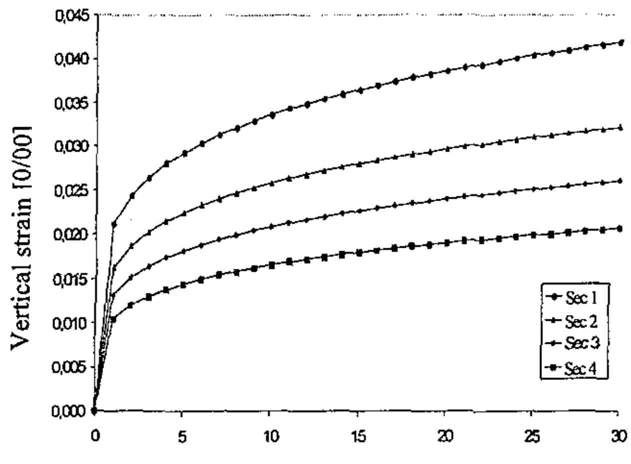

Fig. 10 Vertical strain at bottom of asphalt layers for different pavement sections

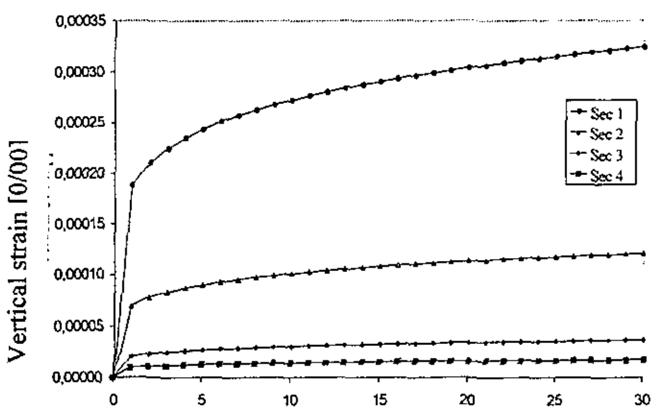

Fig. 11 Vertical strain at top of base course versus pavement age for different sections

2.7 Vertical Strain at Top of Subgrade Layer

The relationship between vertical strain at top of subgrade and pavement age for different pavement sections is clear in Fig. 11. From this figure it can be concluded that this relation is almost similar. That presents the vertical strain at bottom of asphalt layers, yet here the strain is larger. In the second phase the rate of strain (deformation) is lower than that in the first phase for all pavement sections. The highest rate of deformation for the two stages is obtained for Section 1 and the lowest rate for Section 4. The rate of deformation of Section 4 is nearly constant for the second stage.

2.8 Total Surface Deflection

2.8.1 Effect of Axle Load

In this paragraph, the effect of axle load on the total surface deflection will be shown. Fig. 12 shows total surface deflection at load center versus pavement age as a function of axle loads for Section 4. Form this figure it is clearly shown that with increasing axle loads total surface deflection increases. In comparison to the standard axle load of European Union, 11.5 ton [1], with increasing axle load to 15.5 ton surface deflection increases about 130% after 30 years, while with decreasing axle load to 7.0 ton, surface deflection decreases about 140% during the same period of pavement age.

2.8.2Effect of Contact Pressure

The relationship between total vertical deflection at pavement surface and pavement age as a function of tire contact pressure will be studied in the present research. This relation is clearly shown in Fig. 13 for section 4. From this figure it can be noted that Increasing tire contact pressure leads to an increase of total surface deflection. The curves consist of two stages, the first stage happens in the first year and the second stage in the remaining pavement age. Increasing tire contact pressure from 810 kpa to 1000 kpa leads to an increase of surface deflection about 70% at the end of first stage and about 130% at the end of second stage.

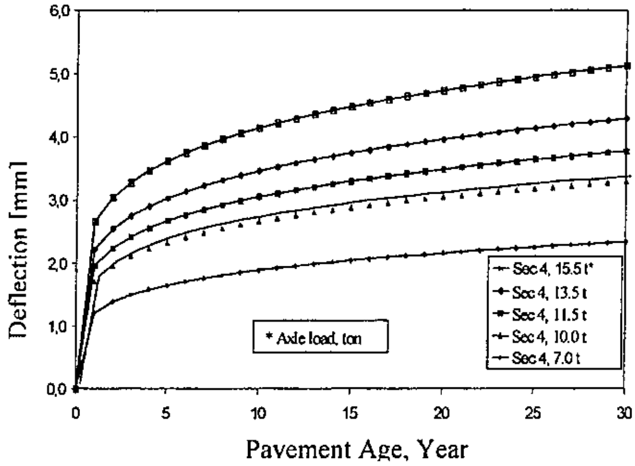

Fig. 12 Deflection at pavement surface versus pavement age as a function of axle load for Section 4.

2.9 Safety criteria

2.9.1 Safety Criteria at Different Pavement Sections

Safety criteria was calculated according to Equations 9 and 10 for different pavement sections. Fig.14 shows safety criteria of different pavement sections. It is clearly shown that Section. 4 has the highest values of safety criterias. By decreasing the layers thickness, safety criteria decreases. For sections 2, 3 and 4, safety criteria lies above the damage condition (γ=1.0). For Section 1 (without subbase), safety criteria lies under the damage condition for both asphalt course and base course.

Also, it may be concluded that the pavement sections 3 and 4 achieve high safety criteria for 30 years design period and consequently the thickness of asphalt layers could be reduced. On the other hand, the pavement of Section1 isn't acceptable for 30 years design period without increasing the layer thicknesses.

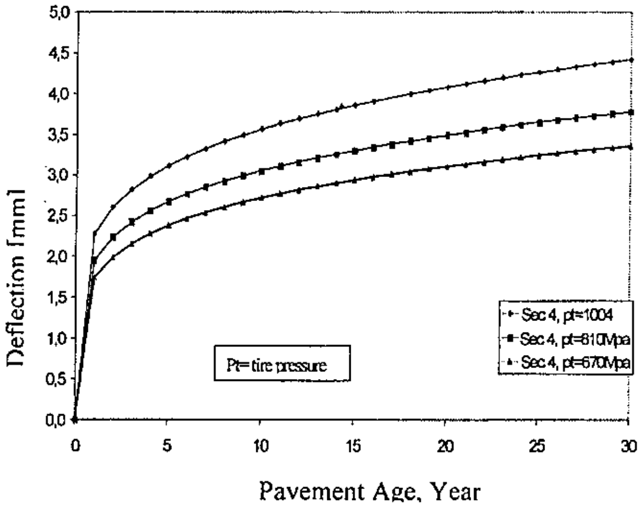

Fig. 13 Deflection at pavement surface versus pavement age as a function of contact pressure for Section 4

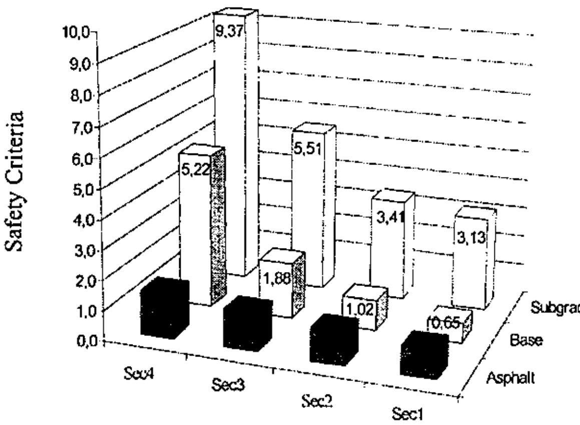

Fig. 14 Safety Criteria for different pavement sections

2.9.2 Comparison of Different Axle Loads

Safety criteria of different axle loads for Section 4 is shown in Fig.15. In general, safety criteriaa reduces with increasing axle load. For example, safety criteria decreases 11.0% with increasing axle load from 11.5 ton to 13.0 ton.

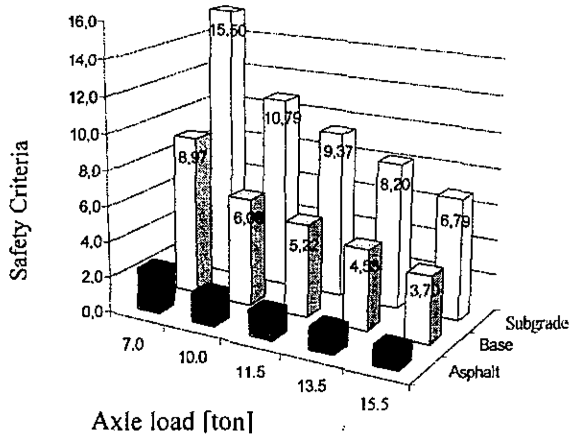

Fig. 15 Safety criteria for different axle loads of Section 4

2.9.3 Comparison of Different Tire Contact Pressure

Fig.16 shows the safety criteria for various contact pressures of Section 4. It should be noted that safety criteria increases with decreasing contact tire pressure. Effect of variation of tire pressure on safety criteria isn't significant compared to the influence of axle load variation. For example, increasing contact pressure from 810 kPa to 1004 kPa leads to an increase of safety criteria less than 3% for asphalt layers.

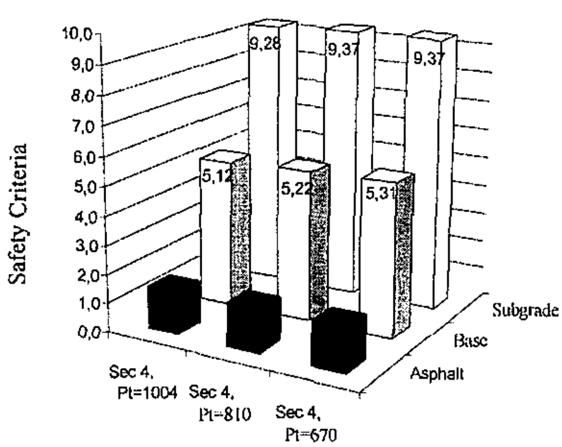

Fig. 16 Safety criteria for different tire contact pressure of Section 4

3. CONCLUSION

The main objective of this paper is to evaluate four pavement sections under different conditions. These conditions are axle loads, tire contact pressure and temperatures

The following points could be observed:

1- At load center, radial stress is negative (tensile stress) and changes to positive with increasing the horizontal distance. Changing point from –ve to +ve depends on pavement temperature which lies at a distance of about 0.45 m at –10 °C and reduces to about 0.15 m at 45 °C pavement temp.

2-The increase in vertical stress by increasing pavement temperature is very low up to 15 °C, after that vertical stress increases significantly with increasing pavement temperature. The highest increase of vertical stress is registered for Section 1. The influence of increasing pavement temperature on vertical stress for Section 4 is very small.

3-Surface deflection increases with increasing pavement temperature and/or increasing axle load. The difference in max deflection according to the variation of axle loads increases with increasing pavement temperature. The increase of deflection that meets the increase of pavement temperature can be neglected up to 5 °C

4- The difference of max deflection for the three different contact pressures can be neglected up to 25 °C, then the difference increases with increasing pavement temperature. Increasing contact pressure from 810 kPa to 1000 kPa leads to an increase of deflection about 6%

5- Vertical strain increases with increasing pavement age. Max vertical strain occurs in the first year of pavement age. Varying flexible pavement responses as strain and deflection with pavement age could be divided into two phases, first phase (rapid phase),that occurs in the first year, and second phase (stable phase). In the second phase the rate of deformation is lower than that in the first phase

6- Total surface deflection increases about 130% after 30 years with increasing axle load from 11.5 ton to 15.5 ton, while with decreasing axle load from 11.5 ton to 7.0 ton surface deflection decreases about 140% at the same period of pavement age

7- Increasing tire contact pressure from 810 kpa to 1000 kpa leads to increase of surface deflection about 70% at the end of first stage and about 130% at the end of second stage

8- Safety criteria reduces with increasing axle loads as well as with decreasing pavement thickness, while variation of tire pressure on safety criterias isn't significant.

9- Finally, from the above results, it can be concluded that FE-program FENLAP can be used successfully to calculate the flexible pavement responses and to evaluate the behaviour of pavement sections under different conditions of pavement layer thickness, axle loads and tire contact pressure. This program offers linear and non-linear calculations.

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