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Article

Structural Design and Sensitivity Analysis of Semi-Rigid Pavement of a Motorway

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Abstract. This paper presents application of mechanistic-empirical methods in design of semi-rigid pavement for a section of a motorway in Poland. The stage construction was assumed. Three fatigue criteria were applied in the design. For asphalt fatigue cracking and subgrade soil the criteria from the Asphalt Institute (1981) were applied. For fatigue cracking of cement stabilized bases the Dempsey (1984) and De Beer (1992) criteria were applied. In the analysis it was assumed the cement stabilized layers will work in two phases: before and after cracking. To calculate stresses and strains software BISAR (1989) was used, which multilayer elastic theory utilized. Additional study was carried out to find the sensitivity of design thickness of asphalt layer related to several design factors. The most significant factors were (a) load transfer through shrinkage and reflective cracks, (b) high summer temperature which causes decrease of asphalt layers stiffness and increase of tensile stresses in cement stabilized bases, and (c) the effect of overloaded vehicles. The performed sensitivity analysis which included several interrelated factors, indicated that thickness of asphalt layers should be increased by about 4 cm as compared with preliminary design.

Keywords: Semi-rigid pavement, stage construction, mechanistic-empirical design, sensitivity analysis

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1. Introduction

This paper presents application of mechanistic-empirical methods in design of semi-rigid pavement for two sections of a motorway in Poland, with a total length 88 km. The main design data and assumptions were the following: (a) For economic reasons the design strategy assumed that pavement structure would be constructed in two stages - the first stage design for 7 mln standard axle loads 115 kN and the second stage design for subsequent 14.6 mln standard axle loads 115 kN. (b) Pavement structure in the first construction stage would consist of asphalt surfacing and two cement stabilized layers (base and subbase course) placed on drainage layer. (c) The second construction stage would consist of recycling of the top of existing asphalt layers and adding new 5 cm wearing course. (d) To minimize reflective cracking in semi-rigid pavement several alternative solutions were considered. (e) Due to various subgrade soils which mostly consist of clays and sandy clays, subgrade would be stabilized in situ to reach required modulus at the formation level below pavement structure. The choice of stabilization method was left to the contractor. (f) Minimum thickness of pavement structure was 75 cm due to frost heave protection.

The fatigue criteria from The Asphalt Institute (1981) [1] were applied for asphalt layers and subgrade soil. The Dempsey (1984) [2] and De Beer (1992) [3] criteria were applied for cement stabilized bases. All fatigue criteria used in this work were analyzed by Judycki (1997) [4]. The permanent deformation criteria (subgrade strain) were checked in the design process and it was found out that the semi rigid pavement in question is resistant to permanent deformation. The plastic deformation of asphalt layers were the subject of the appropriate asphalt mix design. Software BISAR [5] developed in 1989 year by Shell Petroleum Company were used for stress and strain analysis. After preliminary design additional studies were carried out to find the sensitivity of design thickness of asphalt layers in relation to several design factors.

2. Pavement Analysis

The model of pavement structure used in the design was a semi-infinite multi-layer elastic system presented in Fig. 1. Each layer was defined by thickness, elastic modulus and Poisson's ratio presented in Table 1. Initial pavement analysis was performed at average equivalent annual design temperature +12°C. The full bond between layers was assumed, except the interlayer between two cement stabilized layers. For this interlayer three cases were analysed: full bond, partial bond and no bond. Two levels of modulus of improved subgrade were assumed: E=45 MPa and 60 MPa. It was assumed that cement stabilized layers will work in two phases. First phase takes place before fatigue cracking and second phase after fatigue cracking. For the second phase it was assumed that after fatigue cracking cement stabilized base forms large blocks. Respectively different moduli of elasticity were assumed for pre-cracked and after-cracked state (Table 1). Reflective cracks, which are inevitable in semi-rigid pavements, were considered in stress analysis by application of Load Placement Effect Factor (LPEF). This approach was used after Castigan and Thompson (1986) [6], Dempsey *et al.* [2], Otte (1979) [7] and Otte *et al.* (1982) [8]. This paper presents design analysis for the first construction stage only.

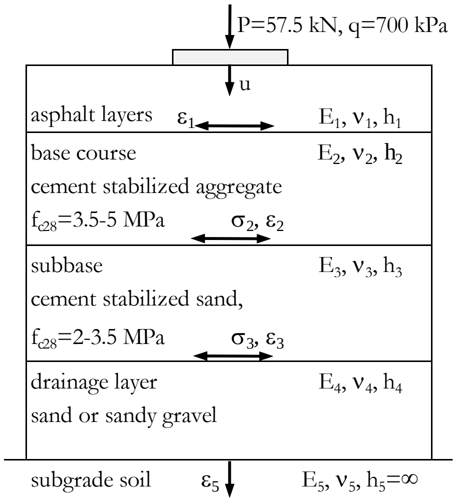

Fig. 1. Model of pavement structure (first construction stage).

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Table 1. Properties of pavement materials.

Nos.	Layer	Material	First phase before fatigue cracking of cement stabilized layer		Second phase after fatigue cracking of cement stabilized layers (large blocks)	
			E (MPa)	ν	E (MPa)	ν
1.	Wearing course	Asphalt concrete (Stiffness at T = +12°C, time of loading t=0.02 sec)	9000	0.3	9000	0.3
2.	Asphalt base course					
3.	Base course	Cement stabilized aggregate f_{c28}=5 MPa	4500	0.25	1200	0.3
4.	Subbase	Cement stabilized sand f_{c28}=3.5 MPa	3300	0.25	800	0.3
5.	Drainage layer	Sand or sandy gravel	80	0.35	80	0.35
6.	Improved subgrade	Soil stabilized in situ (alternatively with cement, lime, fly ash or other chemicals)	45 or 60	0.35	45 or 60	0.35

Note: f_{c28} – maximum compressive strength after 28 day of curing

As it can be seen in Table 1, the elastic moduli of cement stabilized bases decrease a few times in the second phase of the pavement behavior, in the after-cracked state. Stresses and strains were calculated with use of BISAR software. The design axle load was 115 kN, single wheel load 57.5 kN, contact pressure 700 kPa. Fatigue criteria were used to determine fatigue life of bound layers. The Miner law was applied to consider the two phases of cement stabilized layers (before and after cracking). The thicknesses of pavement layers which resulted from preliminary design of the first construction stage are presented in Table 2.

Table 2. Preliminary design of pavement structure for the first construction phase (subgrade modulus E=60 MPa; assumed fatigue life 7 mln standard 115 kN axle load applications).

Nos.	Layer	Material	Thickness, (cm)
1.	Wearing course	Asphalt concrete	5
2.	Asphaltic base course	Asphalt concrete	10
3.	Base course	Cement stabilized aggregate f_{c28}=5 MPa	20
4.	Subbase	Cement stabilized sand f_{c28}=3.5 MPa	20
5.	Drainage layer	Sand or sandy gravel	20
6.	Improved subgrade	Soil stabilized in situ (with cement, lime, fly ash or other chemicals)	-
		Total thickness:	75

Note: f_{c28} – maximum compressive strength after 28 day of curing

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Table 3 presents results of calculation of fatigue life of preliminary pavement structure layers calculated with use of The Asphalt Institute [1] criteria for asphalt layers and Dempsey [2] and DeBeer [3] criteria for cement stabilized layers.

Table 3. Results of calculation of fatigue life of preliminary pavement structure.

Nos.	**Fatigue life**	**No. of 115 kN axle load applications (in millions) to reach particular fatigue cracking**	
		Dempsey criterion	**DeBeer criterion**
1.	Fatigue cracking of cement stabilized base	7.39	7.58
2.	Fatigue cracking of cement stabilized subbase	7.45	8.03
3.	Fatigue cracking of asphalt	12.25	12.62

The results in Table 3 were achieved with assumption that only partial bond exists between two cement stabilized layers. Values of LPEF, selected after Castigan and Thompson [6], Dempsey *et al.* [2], Otte [7] and Otte *et al.* [8], was equal to 1,25 for upper layer and 1,3 for lower layer of cement stabilized base and subbase.

It can be seen in Table 3 that fatigue cracking first occurs in cement stabilized base (upper layer) due to partial bond between stabilized layers, and almost immediately after that in stabilized subbase (lower layer). Fatigue cracks in asphalt layers will occur after cracking of stabilized base into blocks which decreases its stiffness and consequently tensile strains in asphalt base course increase. Fatigue cracks in asphalt will first occur in the vicinity of reflective transverse cracks. The calculations indicated that fatigue life of cement stabilized bases would be close to 7 mln 115 kN standard axle load applications. This number indicates moment when cracks in stabilized layers will develop in the vicinity of transverse shrinkage cracks, where stress concentration will take place. In the middle of a slab, between two transverse shrinkage cracks, fatigue life of the stabilized layer will be much longer. The two applied criteria - Dempsey and DeBeer - gave similar results.

It was expected that some reflective cracks could occur few years after construction. Till now there is no proven method to eliminate reflective cracking in semi-rigid pavements completely. However, it was specified in the design specifications that as a preventing measure to minimize number of reflective cracks, cutting of stabilized base course into short slabs, would be applied during construction.

Figure 2 presents horizontal stresses in pavement structure, induced by 115 kN axle load, calculated for the pre-cracked and after-cracked state of cement stabilized base course. For analysis of the pre-cracked state of cement stabilized layers greater values of elastic moduli of stabilized layers were used. For analysis of the after-cracked state lower moduli of stabilized layers were used, as given in Table 1. It can be seen that in the pre-cracked state asphalt layer works under compression with slight tension at the bottom. After cracking of the base course intensive tension occurs in asphalt which results in fatigue cracks. The factor which significantly influence pavement behavior is bond between cement stabilized layers. In no-bond state tension in cement stabilized layers is much greater.

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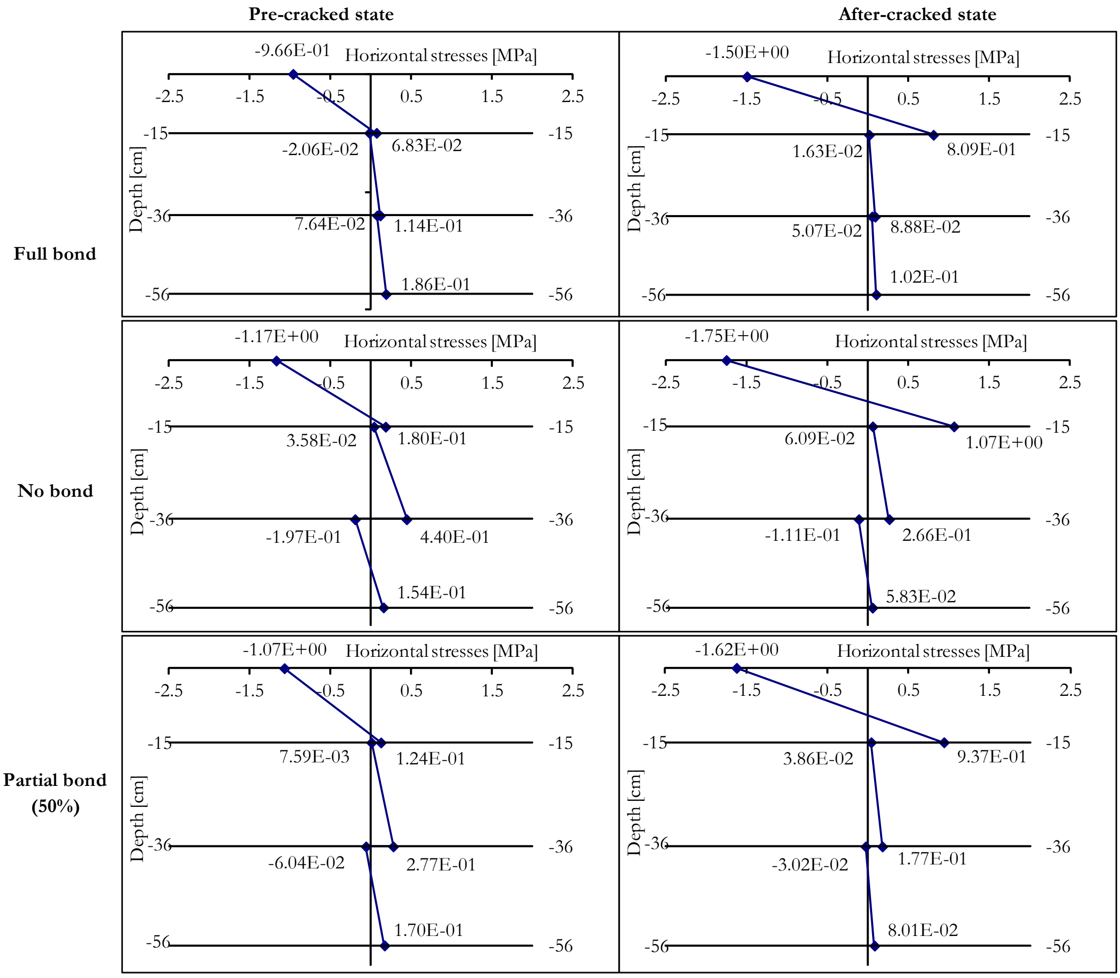

Fig. 2. Horizontal stresses in pavement layers ("-" compression, "+" tension) for pre-cracked and after cracked state in relation to bond between cement stabilized layers.

3. Sensitivity Analysis

Sensitivity analysis was performed to evaluate influence of the following design factors: (a) different design temperatures for four seasons of the year versus average equivalent annual design temperature, (b) effectiveness of load transfer trough shrinkage and reflected cracks, (c) overloaded vehicles, (d) tolerances of thickness of constructed layers.

3.1. Different Design Temperatures for Four Seasons of the Year Versus Average Equivalent Annual Design Temperature

The preliminary design was performed for equivalent annual design temperature +12°C and constant modulus of improved subgrade throughout the year. In the sensitivity analysis more complex data were assumed as shown in Table 4. Temperature and asphalt stiffness for each of four seasons were taken from the Polish Catalogue (1997) [9] of typical pavements. Traffic was assumed either as uniform during entire year or more intense in summer. Higher modulus of improved subgrade was assumed in summer because in Poland in summer moisture content of subgrade soil is lower and its bearing capacity increases.

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Table 4. Data for four season analysis.

Nos.	Data		Seasons of the year		
			Winter	Spring and autumn	Summer
1.	Average design temperature, (°C)		-2	+10	+23
2.	Stiffness modulus of asphalt layers, time of loading t= 0.02 s, (MPa)		18 500	10 000	3 000
3.	Poisson ratio of asphalt layers		0.25	0.3	0.4
4.	Modulus of improved subgrade, (MPa)		60	60	80 or 100
5.	Percentage of traffic loading, (%)	Case 1 (uniform traffic)	25	50	25
		Case 2 (traffic greater in summer)	20	50	30

Figure 3 presents fatigue life of cement stabilized base in relation to thickness of asphalt layers for three analyzed cases. It can be seen that calculated fatigue life of stabilized base is highest in case when average equivalent annual temperature is used in design (line 1). Fatigue life is lower if different temperatures for four seasons of the year are used in design (lines 2 and 3). It results from the fact that higher tensile stresses are developed in the stabilized base in summer, when stiffness and load bearing capacity of hot asphalt layers decreases. If design traffic is more intense in summer the fatigue life of the base slightly decreases (compare lines 2 and 3). When seasonal variation in temperature is considered the designed thickness of asphalt layers is greater by 2 cm as compared with uniform average annual temperature (compare lines 1 and 2, 3).

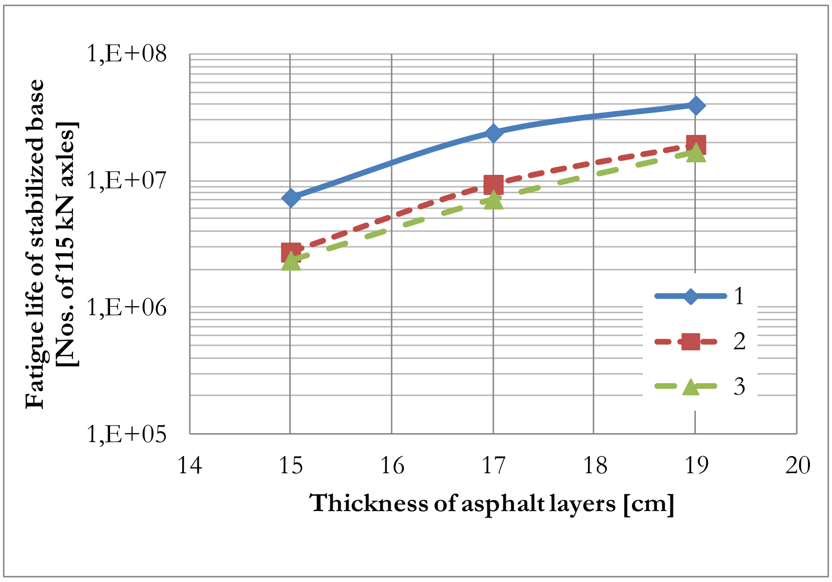

Fig. 3. Fatigue life of cement stabilized base in relation to thickness of asphalt layers; line 1- equivalent annual design temperature +12°C, lines 2 and 3 - design temperatures for four seasons of a year, line 2 – uniform traffic during a year, line 3 – more intense traffic in summer.

It can be concluded that if seasonal temperatures differ it is important to consider in the design temperature of asphalt layers in every season of a year, especially high temperature in summer. If in a particular area temperature is uniform throughout the year one average annual equivalent temperature can be used.

3.2. Effectiveness Of Load Transfer Though Shrinkage And Reflected Cracks

Load transfer efficiency depends on width of crack, degree of damage of crack, corrosion of the base course at crack (caused by salt used in winter maintenance), grading of stabilized material (coarse or fine), strength of stabilized material and other factors. Stresses in stabilized layer induced by traffic load are higher at a crack than in the center of the slab and increases with lower transfer efficiency. Stresses at crack can be calculated from the formula Eq. (1):

$$\sigma_{crack}=\sigma_{center}\cdot LPEF \quad (1)$$

where: σ_{crack} - stress at crack, σ_{center} -stress in the middle of the slab calculated for infinite layer from BISAR program, LPEF- Load Placement Effect Factor which is related to load transfer efficiency and consequently to the form of the crack. According to Otte at al [8] the LPEF varies as follows: LPEF = 1.0 for no cracking, LPEF = 1.1-1.2 for crack widths less than 0.2 cm, LPEF = 1.25–1.5 for crack widths more than 0.2 cm. Value of LPEF in a range from 1.4 to 1.5 was suggested by some researchers Dempsey *et al* [2] and Otte [7]. Such high values of LPEF are characteristic for degraded cracks and load transfer efficiency in a range of 40-50% according to Costigan and Thompson [6].

It is difficult to predict the state of the crack in a newly designed pavement although it is obvious that degradation will take place with time. The following four values of LPEF were assumed in our sensitivity analyses: LPEF = 1.2(1.3), LPEF = 1.3(1.35), LPEF = 1.35(1.4), LPEF = 1.4(1.45). The first number indicates LPEF for upper stabilized layer and the second number in brackets for lower stabilized layer.

Figures 4 and 5 present result of calculations if form of relationships between fatigue life of cement stabilized base and LPEF for three thicknesses of asphalt layers 15, 17 and 19 cm. Fatigue life of stabilized base decreases strongly if LPEF is greater. The load transfer efficiency depends on the crack maintenance and road repair. To be on a safe side value of LPEF in a range of 1.4 seems to be reasonable. The difference in designed thickness of asphalt layers if LPEF increases from 1.25(1.3) to 1.4(1.5) is about 3 cm.

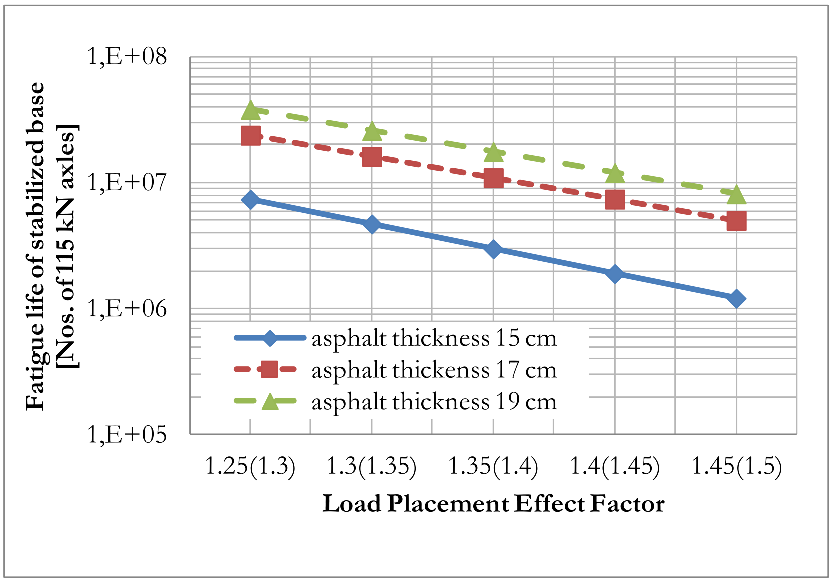

Fig. 4. Fatigue life of cement stabilized base in relation to LPEF and thicknesses of asphalt layers (average annual equivalent temperature +12°C).

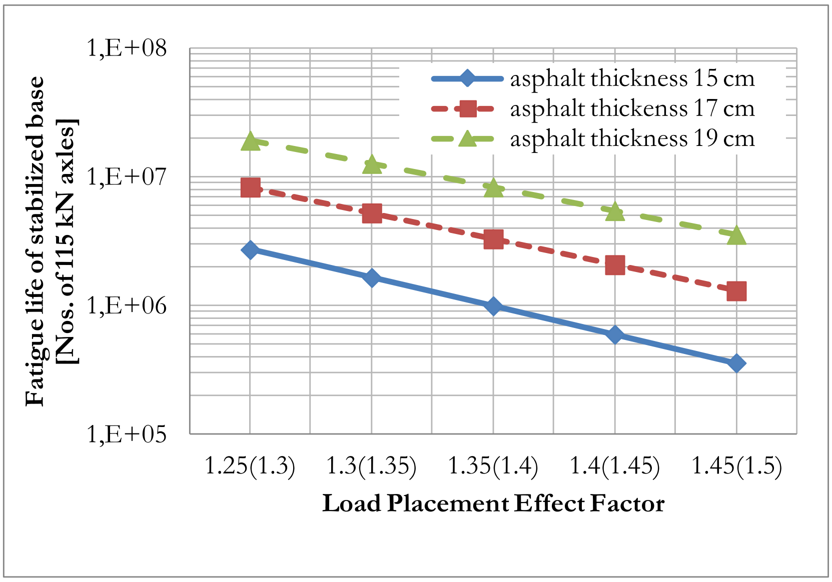

Fig. 5. Fatigue life of cement stabilized base in relation to LPEF and thicknesses of asphalt layers (design temperatures for four season of the year).

It was concluded from the analysis that to be on the safe side the load transfer efficiency through reflective cracks should be included in design by use of the Load Placement Effect Factor equal to 1.4.

3.3. Effect of Overloaded Vehicles

Weighing in motion indicates that on Polish roads there is up to 10% of heavy vehicles which are overloaded with respect to the total admissible weight or axle load. For the purpose of this analysis the following simplified assumptions were used: (a) number of overloaded axles with load greater than 115 kN is 5%, 10% or 20%, (b) average load of overloaded axle is 130 kN, (c) tire contact pressure of overloaded tire is 850 kPa, (d) the rest of heavy traffic, respectively 95%, 90% or 80%, is formed by standard 115 kN axles.

Calculations were performed for: (a) thickness of asphalt layers 15, 17 and 19 cm, (b) average annual equivalent temperature +12°C, (c) different temperatures for four seasons, (d) LPEF = 1.25(1.3); 1.35(1.4). Results of calculations are presented in Fig. 6 and 7. Overloaded axles affect in decrease of total number of axle load applications to cracking of stabilized base. The decrease in fatigue life is especially high when great percentage of overloaded axles coincide with higher value of LPEF. To compensate for 20% of overloaded axles additional 2–3 cm of asphalt layer would be needed. Again, in this case the consideration of seasonal changes in temperature is very important (compare Figs. 6 and 7).

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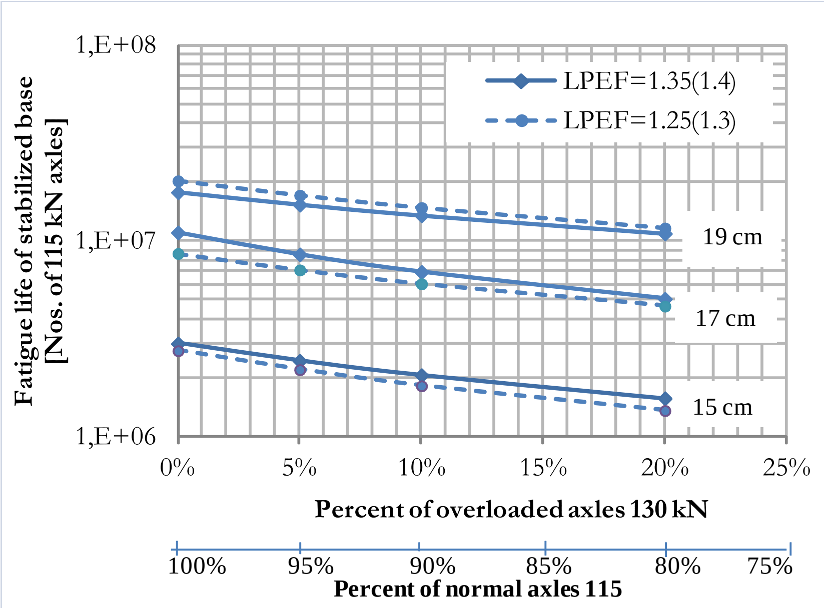

Fig. 6. Total number of axle loads to fatigue cracking of stabilized base in relation to percentage of overloaded axles, thicknesses of asphalt layers and LPEF (average equivalent annual temp. +12°C).

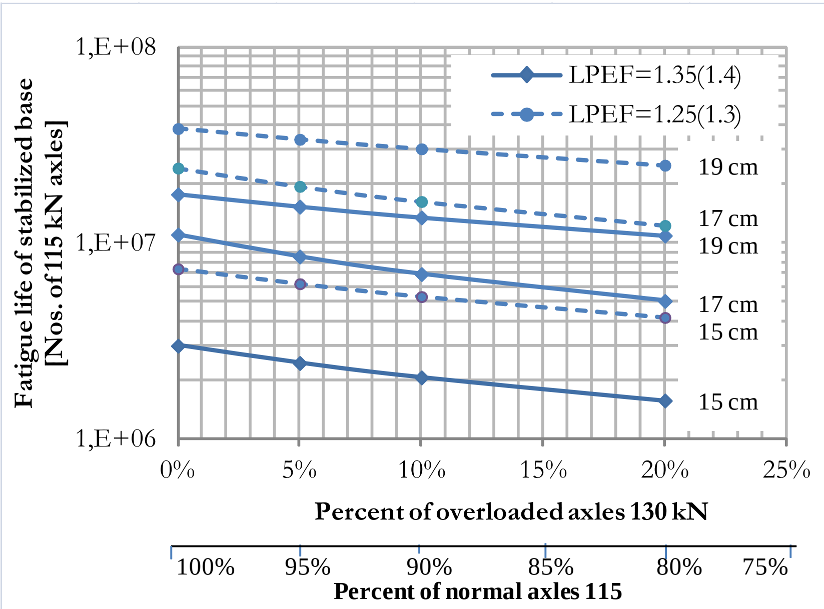

Fig. 7. Total number of axle loads to fatigue cracking of stabilized base in relation to percentage of overloaded axles, thicknesses of asphalt layers and LPEF (different temperatures for four seasons).

3.4. Tolerances of Thicknesses of Constructed Layers

Thicknesses of layers are predominant factors influencing the fatigue life of pavement. It can be seen in all figures included in this paper. Therefore it was proposed that the design thicknesses determined by the analytical design methods should be treated as an absolute minimum during construction.

4. Conclusions

The pavement design and analysis indicated that:

1) The mechanistic – empirical method is a useful and effective tool for analysis and design of a

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motorway pavement. Presented method is especially useful in the stage construction design.

2) The Dempsey (1984) criterion for design of cement stabilized bases produced lower fatigue life than the DeBeer criterion (1992).
3) For semi-rigid pavement, when in a particular area seasonal temperatures during a year vary significantly, it is important to consider design temperatures for each season. In summer time, when stiffness of asphalt layers decreases, much higher stresses occur in cement stabilized layers. Fatigue life is lower if different temperatures for four seasons of the year are used in the design instead of one annual equivalent temperature. When seasonal variation in temperature is considered the designed thickness of asphalt layers is greater by 2-3 cm as compared with uniform average annual temperature.
4) Shrinkage and reflective cracking are inevitable in semi-rigid pavements. Therefore, load transfer through cracks has to be considered in the design. The transfer efficiency will decrease with age of pavement and can be analyzed with use of Load Placement Effect Factor. Fatigue life of stabilized base decreases strongly if LPEF is greater. The difference in designed thickness of asphalt layers if LPEF increases from 1.25(1.3) to 1.4(1.5) is about 3 cm. Which value of LPEF factor is the most appropriate is still disputable.
5) The consideration of overloaded axles is important in the design. Overloaded axles affect in decrease of total number of axle load applications to cracking of stabilized base. If it is assumed that number of overloaded axles (in a range from 115 kN to 130 kN) is 20% additional 2–3 cm of asphalt layer would be needed.
6) The performed sensitivity analysis which included several interrelated factors, indicated that thickness of asphalt layers should be increased by about 4 cm as compared with preliminary design.

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