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FLEXIBLE PAVEMENT DESIGN CRITERION BASED ON OCTAHEDRAL SHEAR STRESSES

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Abstract

The judicious pavement design is the key factor in achieving the longest service life and the lowest maintenance and rehabilitation costs. It is based on the consideration of the phenomena in which the pavement structures are subjected to exploitation and the limitation of their destructive effects.

The aim of this study is to verify the possibility of implementing in the flexible pavement structures design practice of another design criterion based on limiting the bituminous mixtures creep phenomenon and that to be called: *The criterion of admissible octahedral shear stresses in the bituminous layers*.

Estimation of octahedral shear stresses is done with a calculation model based on finite element method, and hereafter referred to as **2D ASFEM** (**2D A**xi-**S**ymmetric **F**inite **E**lement **M**odel). The paper presents the results obtained by modeling several specific calculation assumptions for the behaviour of flexible pavement structures in service.

The study underlines the fact that the **O**ctahedral **S**hear **S**tresses **R**atio (**OSSR**) can be an additional design criterion to be taken into account when designing flexible pavement structures alongside other established criteria.

Keywords: flexible pavement structures, octahedral shear stresses, permanent deformation

Résumé

La conception judicieuse des structures de chaussée est le facteur clé pour atteindre la durée de vie la plus longue et les coûts d'entretien et de réhabilitation les plus bas. Il est basé sur la prise en compte des phénomènes dans lesquels les structures de chaussée sont soumises à l'exploitation et la limitation de leurs effets destructeurs.

Le but de cette étude est de vérifier la possibilité de mettre en œuvre dans la pratique de conception de structures de chaussées flexibles un autre critère de conception basé sur la limitation du phénomène de fluage des mélanges bitumineux: *Le critère des contraintes de cisaillement octaédrique admissibles dans les couches bitumineuses*.

L'estimation des contraintes de cisaillement octaédriques est faite avec un modèle de calcul basé sur la méthode des éléments finis, et désigné ci-après par **MEFAS 2D** (**M**odèle des **É**léments **F**inis **A**xi-**S**ymétriques **2D**). L'article présente les résultats obtenus en modélisant plusieurs hypothèses de calcul spécifiques pour le comportement des structures de chaussées flexibles en fonctionnement.

L'étude souligne le fait que le **R**atio de **C**ontraintes de **C**isaillement **O**ctaédrique (**RCCO**) peut être un critère de conception additionnel à prendre en compte lors de la conception de structures de chaussées flexibles parallèlement à d'autres critères établis.

Mots-clés: structures de chaussées flexibles, contraintes de cisaillement octaédriques, déformation permanente

1. INTRODUCTION

The judicious pavement design is the key factor in achieving the longest service life and the lowest maintenance and rehabilitation costs. It is based on the consideration of the phenomena in which the pavement structures are subjected to exploitation and the limitation of their destructive effects.

The aim of this study is to verify the possibility of implementing in the flexible pavement structures design practice of another design criterion based on limiting the bituminous mixtures creep phenomenon and that to be called: *The criterion of admissible octahedral shear stresses in the bituminous layers*.

Estimation of octahedral shear stresses is done with a calculation model based on finite element method, and hereafter referred to as **2D ASFEM** (**2D A**xi-**S**ymmetric **F**inite **E**lement **M**odel) [1].

The concept of octahedral shear stresses is not a novelty, the first concerns being recorded in the 1980s (Freeman and Carpenter, 1986 [2]). In our country the possibility of using it for the flexible pavement structures design has been underlined for the first time by Răcănel (2002) [3].

This study is a continuation of these concerns, and the results obtained confirm the usefulness of *"The criterion of admissible octahedral shear stresses in the bituminous layers"* for the design process of flexible pavement structures.

The difference from the previous studies (Răcănel, 2002 [3]) consists in the method of estimating the octahedral shear stresses values and in the deepening of the study. Thus, in the present study, the finite element method underlying the 2D ASFEM model is used and various specific calculation hypotheses have been modeled for the behaviour of flexible pavement structures in service.

1.1. The general context

In the case of flexible pavement, asphalt layers play one of the most important roles in bearing traffic and climate loads. Thus, it is particularly important to know the mechanics of flexible pavement in general and bituminous mixtures from asphalt layers in particular.

At the present moment it is known that the correct design of the bituminous mixture recipe, which must have good behaviour at the same time for two important phenomena, fatigue and creep (Răcănel, 2002 [3]), depends the subsequent behaviour of asphalt layers within pavement structure.

Consequently, the design rules for asphalt mixtures regulate a whole range of features to be considered in order to obtain high quality mixtures.

Regarding the design of flexible pavement structures, the provisions of the norms in force in our country lose sight the bituminous mixtures rutting behaviour and impose design criteria which take into account only their fatigue behaviour.

In this study we first present the theoretical aspects of the rutting phenomenon, the criterion of admissible octahedral shear stresses in the bituminous layers and then the numerical simulation results of the permanent deformation behaviour of the asphalt layers in service under the calculation standard axle load.

1.2. Bituminous mixtures shear resistance analysis

One of the main distress occurring on roads with flexible pavement structures is the ornierage or rutting (permanent deformations), which manifest themselves as irregularities in the longitudinal profile and especially in the transverse profile, by deformations under the wheels traces [3].

The effects of this type of distress on comfort and traffic safety make it necessary to design flexible pavement structures so that road surface characteristics will not fall below certain limits over the projected lifetime of the pavement structure.

In the analysis of the degradation mechanism a distinction has to be made between the part of the degradation that can be attributed to the structure in general and that which can be attributed to each layer. In the first case, we are dealing with structural issues, while in the second case we are dealing with the problems of material composition (characteristics and dosage for constituents) and its execution [4].

Permanent deformations can occur in two stages:

- the *densification* stage that can be considered as a second compacting stage, leading to the development of rutting from consolidation (high void volume);
- the *"shear phase"* stage when the material moves laterally, leading to the development of rutting from plastic flow (low void volume).

Numerous studies have shown that *shear deformation* is the main cause of the rutting. Moreover, it has been shown that having a more compacted material in the layer, shear deformations become smaller.

2. DESIGN CRITERION BASED ON OCTAHEDRAL SHEAR STRESSES

Under the loads given by road traffic, the stresses and strains state is spatial. To simulate this three-dimensional state in the laboratory, triaxial study is used as an experimental support. Thus, by means of the static triaxial compression equipement, the deformation can be determined by shearing a bituminous mixture cylindrical specimen.

Freeman and Carpenter (1986, [2]) used ***the octahedral shear stress theory*** to analyze premature deformations in asphalt layers of a composite pavement structure.

They have determined that the octahedral shear stress in the pavement structure can indicate how close to the break is the asphalt mixture when it is loaded. This sign of the incipient break is given by the ratio of the octahedral shear stress in the pavement structure to the fracture octahedral shear stress resulting from the theory, the ratio named as *rutting potential*.

Ameri-Gaznon and Little (1987, [5], 1990, [6]), continuing the research performed by Freeman and Carpenter, developed the octahedral shear stress theory for a number of typical pavement structures from Texas.

Octahedral shear stress is a scalar parameter that defines the influence of the nine stresses at a certain point. In its general form, this stress is written:

$$\tau_{oct} = \frac{1}{3}\left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + \left(\sigma_z - \sigma_x\right)^2 + \left(\tau_{xy}{}^2 + \tau_{yz}{}^2 + \tau_{zx}{}^2\right)\right]^{1/2} \quad (1)$$

where σ_x, σ_y, σ_z are normal stresses;

τ_{xy}, τ_{zx}, τ_{yz} - shear stresses;

τ_{oct} - octahedral shear stress (invariant).

Octahedral normal stress is defined as this:

$$\sigma_{oct} = \tfrac{1}{3}(\sigma_x + \sigma_y + \sigma_z) \quad (2)$$

If the octahedral shear resistance is assumed to be obtained from the triaxial compression test, for a certain temperature and loading velocity, we can write the expression of *the general equation for the octahedral shear resistance*:

$$\tau_{oct,res} = \frac{2\sqrt{2}}{3 - \sin\phi}\left[\sigma_{oct} \cdot \sin\phi + c \cdot \cos\phi\right] \quad (3)$$

where σ_{oct} is octahedral normal stress;

Φ - internal friction angle;

c - cohesion.

The use of stress invariants is *advantageous* in the tension area, at the bottom of the asphaltic layers, and also in estimating the rutting at certain distances to the symmetry axis of the load.

The advantage of using σ_{oct} and τ_{oct} as stress invariants is that tension stresses and main stresses from outside the symmetry axes can not always be directly reproduced in the triaxial test, but the corresponding values of σ_{oct} and τ_{oct} can be found. The values of σ_{oct} and τ_{oct} can be calculated using ***the multilayer elastic theory*** or using ***finite element programs***.

An indication of the bituminous mixture ***rutting potential*** can be obtained from the assessment and analysis of the ***octahedral shear stress ratio*** (***OSSR***) expressed as the ratio between the critical octahedral shear stress induced in the asphalt layer of a flexible pavement structure, τ_{oct} and the octahedral shear resistance of the asphalt material, $\tau_{oct,res}$:

$$OSSR = \frac{\tau_{oct}}{\tau_{oct,res}} \quad (4)$$

The above relationship (4) is the one underlying the “The criterion of admissible octahedral shear stresses in the bituminous layers” [3].

3. STUDY ON *OSSR* VARIATION FOR EXISTING PAVEMENT STRUCTURES

The study on the ***OSSR*** (Octahedral Shear Stresses Ratio) variation of an existing flexible pavement structure has been carried out for various degradation levels of asphalt layers and subbase course.

The composition of the flexible pavement structure subjected to finite element method analysis as well as the initial characteristics of the materials are presented in Table 1.

Table 1. Initial characteristics of the pavement structure

Material in pavement structure layer	Layer thickness, h, cm	Dynamic elastic modulus, E, MPa	Poisson's ratio, μ
Asphalt concrete, BA 16	4	3600	0.35
Binder, BAD 25	5	3000	0.35
Bituminous concrete, AB 2	8	5000	0.35
Granular material, Ballast	15	300	0.27
Sand (constructive)	10	-	-
Subgrade type P5	∞	70	0.42

To determine the OSSR value of the pavement structure analyzed at various moments during its life time, several numerical simulations will be performed using the 2D ASFEM model.

Thus, in order to simulate the behaviour in time of a pavement structure under the influence of traffic and environmental conditions, various deformability characteristics (Eam – asphalt mixture dynamic elastic modulus) of the existing asphalt layers were adopted in accordance with the requirements of the Normative for flexible pavement structures overlay, indicative AND 550, depending on the level of their technical degradation status, expressed by global degradation index (IG) (Table 2).

Table 2. Mechanical characteristics changing of asphalt layers over time

Stage in the pavement structure life	Stage symbol	Global degradation Index, IG, according to the norm AND 540	Dynamic elastic modulus, Eam, MPa	Observations
The initial stage	FPS D	100	4016	Weighted average modulus
Degradation stage 1	FPS E1	> 85	3300	Minimum calculation values for climate type I and II
Degradation stage 2	FPS E2	65 – 85	3000	
Degradation stage 3	FPS E3	< 65	2500	

In addition, in order to take into account the influence of all the layers in a flexible pavement structure composition, the over time degradation hypothesis of the granular material from subbase course by the variation of the ballast dynamic elastic modulus (Eb) was also imposed.

In conclusion, it has been performed a total number of 16 numerical simulations resulted from the adoption of four hypotheses for the asphalt degradation state, noted as follows:

- FPS D – designed flexible pavement structure with degradation level 0;
- FPS E1 – existing flexible pavement structure, degradation level 1;
- FPS E2 – existing flexible pavement structure, degradation level 2;
- FPS E3 – existing flexible pavement structure, degradation level 3;

combined with other four hypotheses of the degradation state for the ballast subbase, noted as follows:

- I – subbase with degradation level 0, Eb = 300 MPa;
- II – subbase with degradation level 1, Eb = 255 MPa;
- III – subbase with degradation level 2, Eb = 240 MPa;
- IV – subbase with degradation level 3, Eb = 210 MPa.

The 2D axi-symmetric finite element model (2D ASFEM), implemented in the LUSAS program, allowed the fairly fast run of the adopted calculation assumptions, providing the pavement structure response to the standard axle load of 115 kN, expressed in terms of stresses and strains.

The following stresses are of interest for the calculation of the Octahedral Shear Stresses Ratio (**OSSR**):

σ_x, σ_y, σ_z - normal stresses;

τ_{xy} - shear stress;

which could be evaluated by the 2D axi-symmetric finite element model.

For the situation of the designed flexible pavement structure (FPS D), the intrinsic characteristics established in the laboratory for a new asphalt mixture type BA 16 were adopted from the study [3] (Răcănel, 2002) in the admissible octahedral shear stress calculation of the asphaltic material ($\tau_{oct,res}$) as follows:

- internal friction angle, $\Phi = 41.70972^o$;
- cohesion, $c = 0.12027$ MPa.

For hypotheses with degraded asphalt layers (FPS E1, FPS E2 and FPS E3), the intrinsic characteristics values from the *Asphalt Institute Chart for asphalt mixtures* (*) (USA) (Figure 1) were adopted depending to the degradation level (Table 3).

Table 3. Intrinsic characteristics depending to the asphalt mixture quality

Asphalt mixture quality	Stage symbol	Asphalt mixture characteristics (*)	Internal friction angle, Φ, °	Cohesion, c, MPa
Degradation stage 0	FPS D	D	41.70972	0.12027
Degradation stage 1	FPS E1	D	36	0.10
Degradation stage 2	FPS E2	B	32	0.08
Degradation stage 3	FPS E3	B	28	0.06

Typically, the Asphalt Institute Chart [7] is used to determine the quality of an asphalt mixture, knowing its intrinsic characteristics established in the laboratory by triaxial compression test.

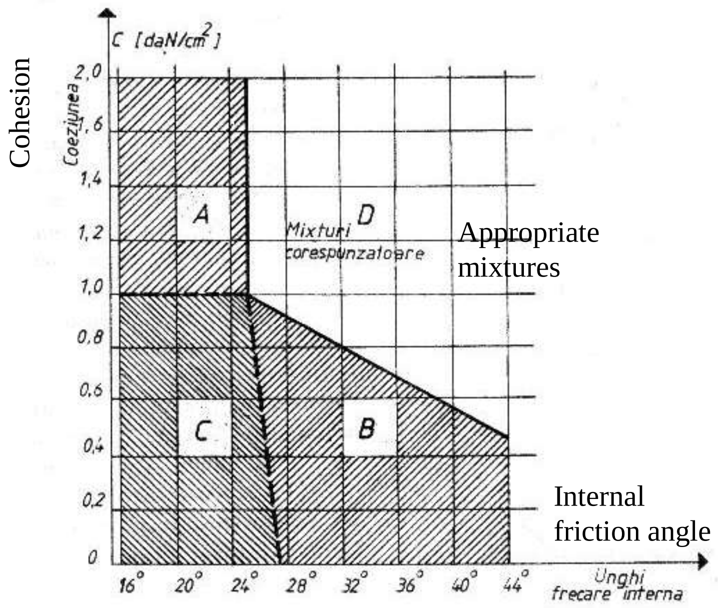

Figure 1. Asphalt Institute Chart for asphalt mixtures [7]

The corresponding areas on the chart correspond to the following characteristics of asphalt mixtures:

A. = insufficient internal friction;

B. = insufficient cohesion;

C. = insufficient cohesion and internal friction;

D. = satisfactory cohesion and internal friction.

In the present study, a qualitative assessment was made to estimate the intrinsic characteristics of the asphalt mixture. It started from some real values obtained in the laboratory for an asphalt mixture type BA 16, and assuming a variation in time under operating conditions of a linear nature, the values of the intrinsic characteristics Φ and c for each degradation stage were determined.

The results of the calculations performed with the 2D ASFEM model in the 16 hypotheses as well as the octahedral stresses and the Octahedral Shear Stresses Ratio (**OSSR**) calculations are shown below in Table 4.

From the analysis of Table 4, it is observed that octahedral shear stresses (τ_{oct}) decrease as the asphaltic layers degradation increases and increase as the subbase course degradation increases. This suggests that a weak subbase course will lead to additional loading of asphalt layers.

Table 4. Centralization of in service pavement structures calculations

Subbase degradation: **Var. I**								
Stage symbol	σ_x MPa	σ_y MPa	σ_z MPa	τ_{xy} MPa	σ_{oct} MPa	τ_{oct} MPa	$\tau_{oct,res}$ MPa	**OSSR**
FPS D	0.097	0.120	0.027	-0.300	0.081	0.107	0.174	0.62
FPS E1	0.107	0.123	0.037	-0.289	0.089	0.103	0.156	0.66
FPS E2	0.112	0.125	0.042	-0.283	0.093	0.101	0.134	0.75
FPS E3	0.120	0.130	0.051	-0.273	0.100	0.097	0.112	0.87
Subbase degradation: **Var. II**								
Stage symbol	σ_x MPa	σ_y MPa	σ_z MPa	τ_{xy} MPa	σ_{oct} MPa	τ_{oct} MPa	$\tau_{oct,res}$ MPa	**OSSR**
FPS D	0.089	0.119	0.017	-0.305	0.075	0.110	0.169	0.65
FPS E1	0.098	0.121	0.028	-0.294	0.082	0.106	0.152	0.70
FPS E2	0.103	0.123	0.033	-0.289	0.086	0.104	0.130	0.80
FPS E3	0.111	0.127	0.042	-0.279	0.093	0.100	0.108	0.93
Subbase degradation: **Var. III**								
Stage symbol	σ_x MPa	σ_y MPa	σ_z MPa	τ_{xy} MPa	σ_{oct} MPa	τ_{oct} MPa	$\tau_{oct,res}$ MPa	**OSSR**
FPS D	0.086	0.118	0.014	-0.307	0.073	0.111	0.167	0.66
FPS E1	0.095	0.121	0.024	-0.297	0.080	0.107	0.150	0.71
FPS E2	0.100	0.125	0.029	-0.292	0.085	0.105	0.129	0.82
FPS E3	0.108	0.127	0.038	-0.281	0.091	0.101	0.107	0.95
Subbase degradation: **Var. IV**								
Stage symbol	σ_x MPa	σ_y MPa	σ_z MPa	τ_{xy} MPa	σ_{oct} MPa	τ_{oct} MPa	$\tau_{oct,res}$ MPa	**OSSR**
FPS D	0.080	0.115	0.007	-0.311	0.067	0.113	0.163	0.69
FPS E1	0.089	0.121	0.017	-0.301	0.076	0.109	0.147	0.74
FPS E2	0.093	0.122	0.022	-0.296	0.079	0.107	0.126	0.85
FPS E3	0.101	0.125	0.031	-0.286	0.086	0.103	0.104	0.99

Thus, the results of the study clearly help us to understand the mechanism of bearing the traffic loads by the layers of a flexible pavement structure.

It can be noticed that the admissible octahedral shear stresses ($\tau_{oct,res}$) decrease with the degradation of the pavement structure in service (Table 4).

From the view of the charts provided by the LUSAS program it was observed that the octahedral shear stresses are manifested mainly at the edge of the contact area wheel - carriageway surface and at the interface between the binder course and the base course.

Next, graphical representations of the Octahedral Shear Stresses Ratio (OSSR) variation were developed based on the mechanical characteristics of the pavement structure layers.

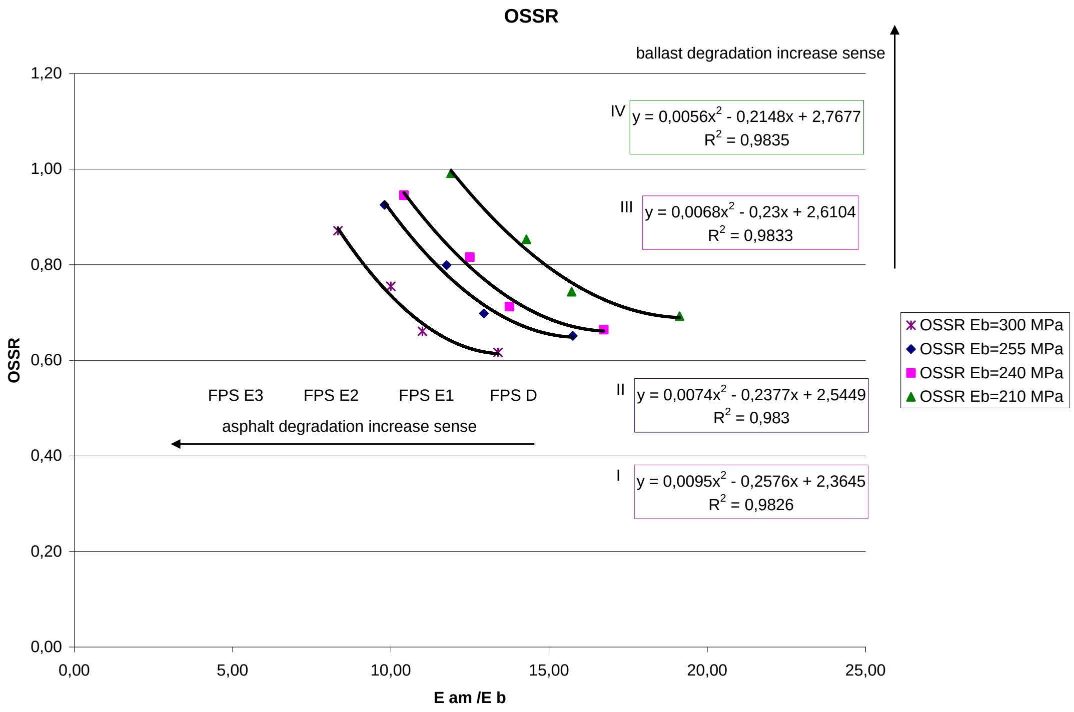

Figure 2. OSSR variation depending to asphalt degradation state

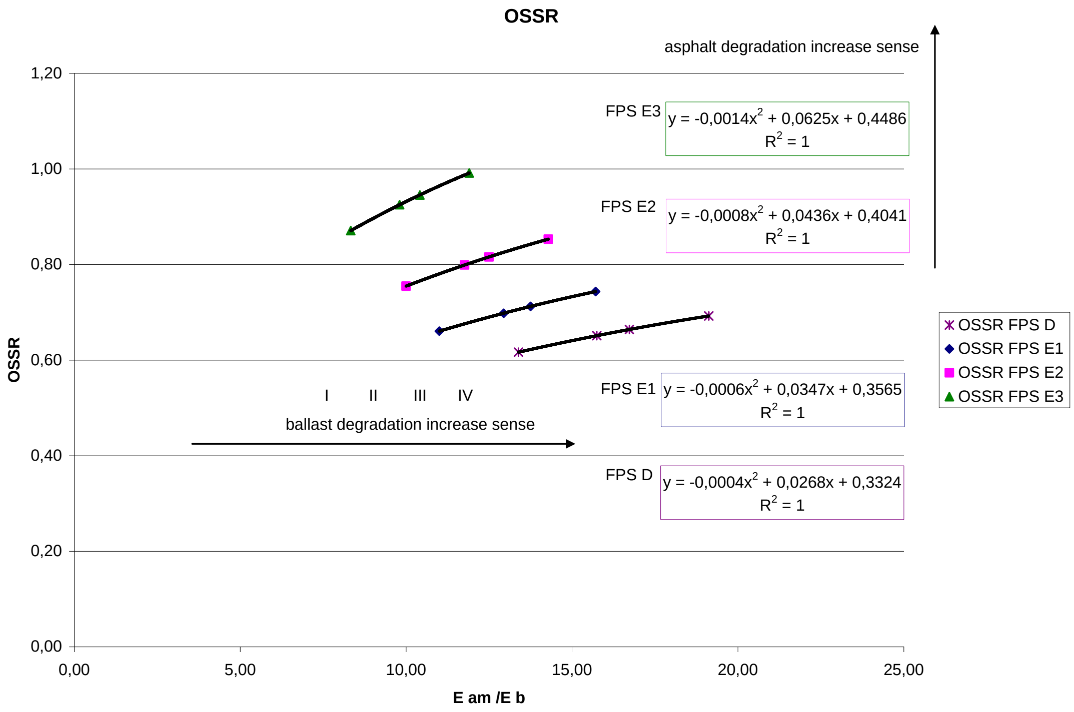

Figure 3. OSSR variation depending to ballast degradation state

From Figures 2 and 3 it is observed that the Octahedral Shear Stresses Ratio (OSSR) increases as the degradation of the asphaltic layers and the ballast subbase course increases.

4. CONCLUSIONS

The octahedral shear stresses provide information about the loading degree of asphalt layers located above the base course, which mainly has to bear tangential stresses from braking and accelerating cars.

It is observed that octahedral shear stresses (τ_{oct}) decrease as the asphaltic layers degradation increases and increase as the subbase course degradation increases.

Thus, we can understand the mechanism of bearing the traffic loads by the layers of a flexible pavement structure.

It has been found that the octahedral shear stresses are manifested mainly at the edge of the contact area wheel - carriageway surface and at the interface between the binder course and the base course, these being the main cause of the permanent deformation phenomenon.

The study shows that the Octahedral Shear Stresses Ratio (OSSR) increases as the degradation of the asphaltic layers and the ballast subbase course increases.

In conclusion, the study underlines the fact that the Octahedral Shear Stresses Ratio (OSSR) can be an additional design criterion to be taken into account when designing flexible pavement structures alongside other established criteria.

For the future, it would be interesting to extend the study by taking into account also the subgrade mechanical characteristics influencing on the pavement structure response, in particular on the asphalt layers behaviour.

In addition, since the present paper is of a more theoretical nature, it would be necessary to carry out some laboratory studies to find out the real change in time of the asphalt layers intrinsic characteristics as well as mechanical ones under exploitation conditions.

To obtain accurate regression laws, it would be preferable to use asphalt samples taken from an experimental sector.

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