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Computer Simulation of Low Volume Roads Made from Recycled Materials

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***Abstract*—**Low volume roads are widely used all over the world. To improve their quality the computer simulation of their behavior is proposed. The FEM model enables to determine stress and displacement conditions in the pavement and/or also in the particular material layers. Different variants of pavement layers, material used, humidity as well as loading conditions can be studied. Among others, the input information about material properties of individual layers made from recycled materials is crucial for obtaining results as exact as possible. For this purpose the cyclic-load triaxial test machine testing of cyclic-load performance of materials is a promising test method. The test is able to simulate the real traffic loading on particular materials taking into account the changes in the horizontal stress conditions produced in particular layers by crossings of vehicles. Also the test specimen can be prepared with different amount of water. Thus modulus of elasticity (Young modulus) of different materials including recycled ones can be measured under the different conditions of horizontal and vertical stresses as well as under the different humidity conditions. Using the proposed testing procedure the modulus of elasticity of recycled materials used in the newly built low volume road is obtained under different stress and humidity conditions set to standard, dry and fully saturated level. Obtained values of modulus of elasticity are used in FEA.

***Keywords*—**FEA, FEM, geotechnical materials, low volume roads, pavement, triaxial test, Young modulus.

I. Introduction

PAVEMENT structures in Czech Republic including low volume roads are designed according to the technical recommendation [1]. The traditional design method is based on the knowledge of traffic load and material characteristics of particular materials. These parameters are defined empirically or are obtained from traditional laboratory tests which unfortunately are not able to respect the real behavior of pavements. Therefore it is very difficult and time consuming to put new materials (including recycled materials) into practice or to change traditional thickness of structural layers, see e.g. [2]-[4].

To improve the quality of low volume roads the computer simulation of their behavior using FEM model is proposed. To obtain the most accurate results from such a model it is necessary to work with the exact values of the modulus of elasticity of individual materials. Generally, the values presented in standards and regulations are not the desired values of the modulus of elasticity, but rather different deformation moduli. The reason is simple - the traditional standard tests used in geotechnical as well as pavement design practice are not able to determine the desired modulus of elasticity.

Cyclic-load triaxial testing is an innovative laboratory test method. By simulating both the vertical loading and the matching horizontal pressure caused by individual crossings of vehicles as well as self-weight of the structure, the real stress conditions in corresponding layers of the structure can be obtained. Although the method was included in Eurocode [5] in 2004, it has not been used in practice very often up till now. The success of the proposed test method in a practical use is dependent on the knowledge of loading effects. The vertical and horizontal stresses produced in particular layer materials are necessary inputs. The horizontal stress cannot be obtained experimentally by long-term measurements on real pavements because it is both time and money consuming process with a low efficiency.

The mechanical properties of materials are dependent not only on the stress conditions but also on the humidity conditions. The test specimen can be prepared with different amount of water and thus the humidity influence can be studied too.

The proposed testing method is used for obtaining modulus of elasticity of recycled materials used in the newly build low volume road under the different stress as well as humidity conditions. The plane (2D) FEM numerical model of a pavement structure is created. The model enables determining the stress as well as deformation conditions in any point of the particular material layer. The values of modulus obtained from triaxial testing are used as input values for FEA of the pavement behavior under different humidity conditions.

II. Cyclic-Load Triaxial Test

The cyclic-load triaxial test is able to simulate the real traffic loading and stress conditions in a pavement during its whole lifetime. As a car moves, the wheel produces horizontal, vertical and shear stresses, see Fig. 1.

The triaxial test consists of repeating short-time vertical pulses together with constant or variable confining horizontal pressure on a cylindrical specimen. The vertical pulses on the specimen simulate passing of wheels and confining pressure simulates the horizontal stress conditions in particular layer of a pavement. The specimen is placed in the triaxial chamber between two porous slabs which drains off the water, see Fig. 2. The specimen is made from one type of material. In the case of sub-grade and base layers its dimensions are 200mm high and 100mm diameter. The specimen deformations are

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measured by linear variable displacement transducers (LVDT). The deformation in vertical direction is measured by three LVDTs in order to measure a possible tilt of the specimen. The horizontal deformations are measured by two mutually perpendicular LVDTs to deal with possible anisotropic deformations.

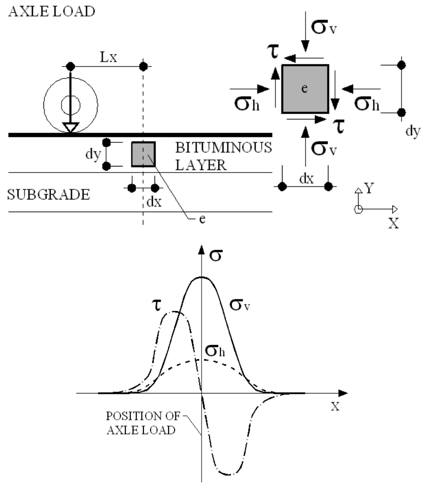


Fig. 1 Stress condition in a layer caused by an axle load

The outputs of triaxial test are resilient modulus, progress of permanent deformation, and Poisson coefficient. Resilient modulus and Poisson coefficient are traditionally used in Czech design method [1]; otherwise the values of traditionally obtained parameters are not comparable with values obtained from triaxial testing. The Eurocode [5] determines the way of testing, data processing and also recommends the methodology of preparing specimens and the suitable measuring equipment.

To make triaxial test of structural materials more reliable we have to know the range of vertical stress and horizontal pressure for particular layer as well as humidity conditions.

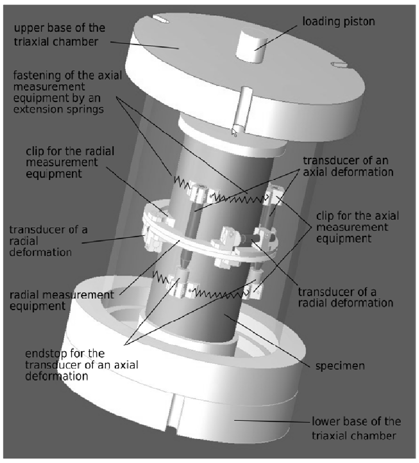


Fig. 2 Triaxial chamber with specimen and measurement equipment

III. Finite Element Model

The analytical model of pavement structure is created in the ANSYS program. The FEM model is 2D model in plane XY, see Fig. 3. Model is fully parametrical, created by means of eight nodes finite element. The finite element has two degrees of freedom at each node - displacements in X and Y axis direction. The geometry of the analyzed pavement structure respects all structural layers including soil.

Model geometry is defined using 14 independent parameters including:

1. Width of pavement layers and soil.
2. Layer thicknesses.
3. General height of soil body with pavement structure.
4. Slope conditions of layers and a mound.
5. Position of design axle load.
6. Position of the section for result evaluation.
7. Location of the evaluation point.

The ideally elastic material model is used to model mechanical properties of materials in layers of pavement structure. According to available information about behavior of connection between layers, the contact between these layers is supposed as bonded. Analyses are performed according to the theory of plane strain as materially and geometrically linear. The influence of self-weight is not included into analyses because of focused on the determination of the axle load influence.

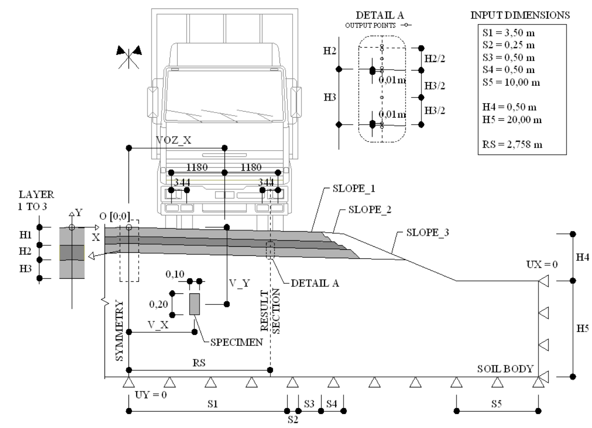


Fig. 3 2D model of pavement structure

TABLE I
Input Values for FEA under Different Humidity Conditions

Material	Layer Thickness [mm]	Poisson Coeff. [-]	Standard Humidity Level E [MPa]	Dry Humidity Level E [MPa]	Saturated Humidity Level E [MPa]
Cover	100	0.3	455	1391	393
Base	150	0.3	150	170	127
Sub-base	150	0.3	500	500	500
Sub-grade		0.25	147	263	66

IV. Low Volume Road Analyzed

For the FEA using input data from the triaxial test the newly built multi-purpose low volume road (forest road and ski track) is used. The road has two lanes (the lane width of

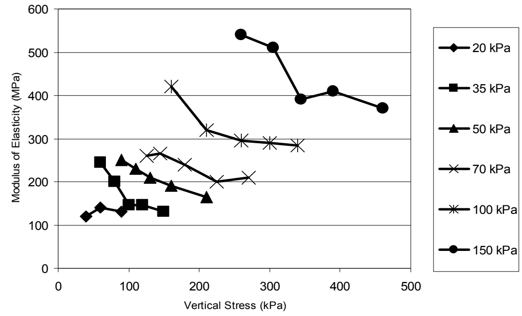
3m) with the total width of 7m, see Fig. 3. It is designed according to Czech Standards [1], [6]. It consists of three structural layers (non-rigid cover, base, sub-base) and the sub-grade soil with no adding binders. For cover as well as base layer the recycled materials instead those from natural resources are used. The cover layer consists of mechanically compacted recycled bitumen material of 100mm thickness, the base layer is made from recycled concrete fractions 0 - 16 of 150mm thickness and the sub-base is made from coarsely crushed natural stone fractions 32 - 63 of 150mm thickness, see Table I.

V. Triaxial Test of Materials

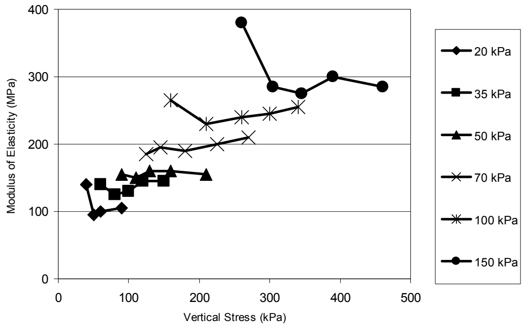
The measurement of elastic behavior of individual materials with help of the triaxial test was performed at a constant chamber pressure (horizontal stress) set to 20, 35, 50, 70, 100, 150 kPa, and 10 000 loading cycles. Testing of one material specimen lasted approximately four hours. After completion of testing, the specimen was removed and from the center of the specimen the humidity was set. Up until now the cover, base and the sub-grade materials testing was finished.

First of all, the modulus of elasticity was determined for the standard humidity level and for different horizontal stress levels (20, 35, 50, 70, 100, 150 kPa). The results are shown in Fig. 4. It is clearly shown how the modulus of elasticity of recycled as well as natural materials significantly depends on the state of stress (horizontal and vertical stress) in which the material is located. As result, for the sub-grade material used in the newly built road the modulus of elasticity can be expected in the interval 120 - 540 MPa, while for the base material the modulus of elasticity can be expected in the interval 100 - 380 MPa and for the cover material the modulus of elasticity can be expected in the interval 90 - 740 MPa. It is also clear that the modulus of elasticity decreases with increasing vertical stress.

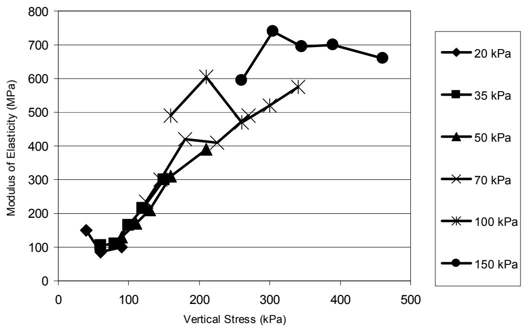
Then more detailed testing of the modulus of elasticity was performed for three different humidity levels and the most probable state of stress, in which the individual material in the structural layer may occur. For example, for the sub-grade material horizontal stress of 20 kPa and vertical stress of 75 kPa are further assumed. Similarly, for the base material horizontal stress of 50 kPa and vertical stress of 150 kPa are assumed and for the cover material horizontal stress of 100 kPa and vertical stress of 250 kPa are assumed. The humidity is now set to standard humidity level (wstd), to dry humidity level (w-) as well as to saturated humidity level (w+). The testing was performed with three samples each time. Results are shown in Tables II-IV.



(a) Sub-grade material



(b) Base material



(c) Cover material

Fig. 4 Modulus of elasticity under different horizontal and vertical stress conditions

TABLE II
Modulus of Elasticity from Triaxial Test – Dry Level

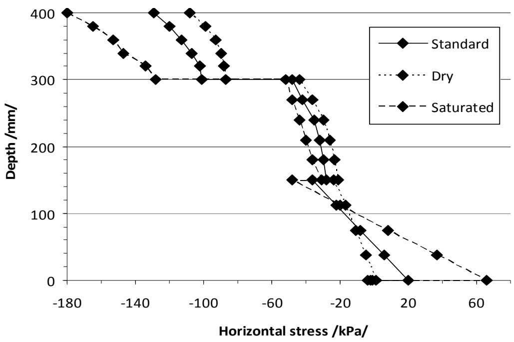
Material	w- [%]	E [MPa]	Mean Value E [MPa]
Sub-grade	1.6	339.0	***263.3***
	1.8	194.0	
	1.8	257.0	
Base	7.4	181.0	***170.3***
	6.4	170.0	
	6.2	160.0	
Cover	0.8	1285.0	***1391.0***
	0.7	1497.0	
	1.0	*2035.0*	

TABLE III
MODULUS OF ELASTICITY FROM TRIAXIAL TEST – STANDARD LEVEL

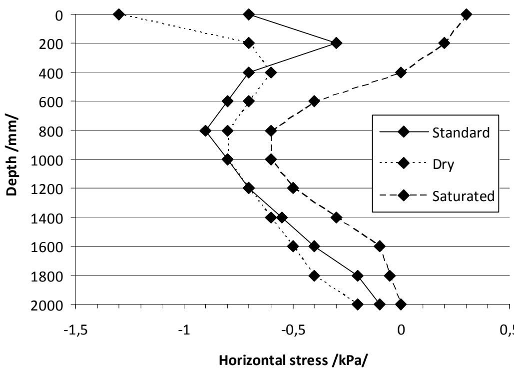
Material	wstd [%]	E [MPa]	Mean Value E [MPa]
	10.0	137.0	
Sub-grade	10.0	158.0	***146.7***
	10.0	145.0	
	10.0	166.0	
Base	10.0	*314.0*	***149.5***
	10.0	133.0	
	3.0	459.0	
Cover	3.0	*1800.0*	***455.0***
	3.0	451.0	

TABLE IV
MODULUS OF ELASTICITY FROM TRIAXIAL TEST – SATURATED LEVEL

Material	W+ [%]	E [MPa]	Mean Value E [MPa]
	11.6	66.0	
Sub-grade	10.5	81.0	***66.0***
	11.0	51.0	
	12.7	126.0	
Base	14.2	156.0	***126.7***
	10.5	98.0	
	3.9	*1040.0*	
Cover	5.0	527.0	***393.5***
	4.0	260.0	



(a) Structural layers



(b) Sub-grade

Fig. 5 Horizontal stress σ_x under different humidity conditions

It could be seen that the modulus of elasticity decreases with increasing humidity and vice versa. It could also be seen that the sunny weather acting on the structural materials of the pavement does not cause as significant changes in the mechanical properties as rain or high moisture in structural layer. It also should be noted, that some values obtained from one specimen (see Tables II-IV) are rather different from two others. These values are excluded from the following calculation.

VI. FINITE ELEMENT ANALYSIS RESULTS

The FEA of the newly built low volume road is performed to analyze the influence of different humidity conditions on the pavement behavior. Horizontal stress σ_x and vertical stress σ_y in materials of the individual structural layers as well as in sub-grade soil are analyzed under the centre of dual wheel, see Fig. 3. Results are shown in Figs. 5 and 6.

Horizontal stress in structural layers is influenced by humidity changes in individual materials in a decisive way especially in cover and sub-base layers. The higher is the humidity, the higher is the horizontal stress and/or the higher are differences of stresses in the layer. Due to different material properties there are generally large stress discontinuities on the contact of individual layers.

The influence of humidity changes on horizontal stress in sub-grade as well as vertical stress in structural layers seems to be marginal.

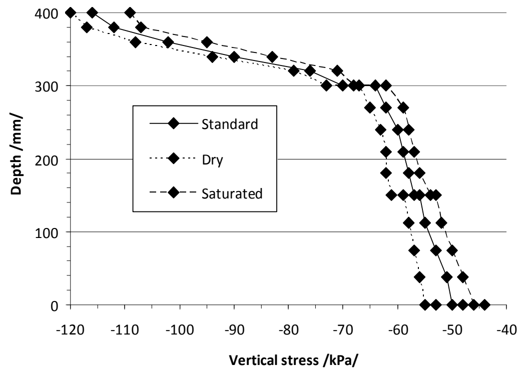


Fig. 6 Vertical stress σ_y under different humidity conditions

VII. CONCLUSION

Testing of materials in triaxial testing machine under different humidity as well as stress conditions allow to obtain the values of modulus of elasticity that respect real conditions in real pavements. Up until now realized tests show that the modulus of elasticity decreases with increasing humidity and vice versa. Also it is found that the dry conditions acting on the structural materials of the pavement generally do not cause as significant changes in the mechanical properties as rain or high moisture.

The proposed FEM model makes it possible to compare various types of pavement structures under different humidity conditions. It provides a wide scale of outputs such as normal stresses, vertical deformation, principal stresses and their orientation etc.

It is found from the analysis of the newly built low-volume road that horizontal stress in structural layers is influenced by humidity changes in individual materials in a decisive way especially in cover and sub-base layers. The higher is the humidity, the higher is the horizontal stress and/or the higher are differences of stresses in the layer. Due to different material properties there generally large stress discontinuities on the contact of individual layers.

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