ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com
International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 3, Special Issue 2, March 2016

EFFECT OF PAVEMENT STIFFNESS ON THE SHAPE OF DEFLECTION BOWL

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ABSTRACT

The paper introduces a new method for calculating the elastic moduli of pavement layers. The method requires only two input parameters: the thickness of the upper „bound" layer and the Falling Weight Deflectometer (FWD) or Improved Benkelman Beam Apparatus (IBBA) measurement data. The authors developed a continuously differentiable regression function, which can be applied to describe the shape of the deflection bowl. Additional parameters of the deflection bowl (e.g. radius of curvature, position of inflexion point) can be calculated based on the regression function. FWD measurements were simulated running the BISAR (Bitumen Stress Analysis in Roads) software on different pavement variations. Outputs of the simulations were further processed with self-developed software. As a result, a series of diagrams were elaborated, by which the elastic moduli of the pavement layers can be determined.

Keywords: Stiffness / pavement layers / elastic module / deflection bowl / BISAR

INTRODUCTION

Forest roads with asphalt pavement represent the basis of the forest road networks in Hungary. Properly maintained asphalt pavements offer a high level of service. While traffic load of forest road networks have grown, expenses for their maintenance remained lower than required in the last three decades. As a result, these roads are in poor condition, generally. Renovation projects demand the knowledge of the roads' bearing capacity. The term "bearing capacity", although widely used at pavement management projects, is hard to define. In fact, direct measurement of bearing capacity is impossible. Instead, one can measure the deflection caused by a known load, and calculate the bearing capacity afterwards.

The traffic transfers its loads to road pavements through the tyres of the vehicles. Due to this, shearing stresses originate from vertical loads (pressing, beating, shaking, bending etc.) and horizontal stresses (braking, accelerating, wearing) (Kosztka 1978, 1986). These stresses affect each pavement layer differently, such as the elastic and plastic (permanent) deformation, the break and the structural realignment (Boromisza 1976). All these structural changes appear on the surface of the pavement as deformations, and the so-called deflection bowl or deformation surface forms.

To measure the evolving deformations several methods have been elaborated.

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Currently the measuring procedures based on absorbed oscillation are widely used. These are called Falling Weight

Deflectometers, FWD. These deflectometers, operating with impulses, often drop a given weight from a given height onto a disc with anti-shock – using the potential energy – then they record the evolving displacements (Kosztka et. al. 2008). Researchers of the Institute of Geomatics and Civil Engineering at the University of West Hungary developed a new instrument to measure the full deflection bowl with the Benkelman beam (Markó et. al. 2013). The development was based on the Benkelman beam, extending its properties with automated data logging and the ability measure multiple points of the deflection bowl. The Improved Benkelman Beam Apparatus (IBBA) continuously measures the vertical displacement of one point on the surface of the pavement, together with the horizontal position of the truck (*Figure 1*).

Figure 1. Falling Weight Deflectometer (left) and Improved Benkelman Beam Apparatus (right) in action.

The deflection bowl recorded during the test provides much more information about the current state of the pavement structure than the central deflection in itself. Therefore we can define its bearing capacity, remaining lifetime, and the thickness of the needed strengthening layer more precisely. Choosing the applicable rehabilitation procedure in the case of a given pavement structure has a really great economic significance. Without appropriately knowing the condition of the pavement, decisions could become very expensive. This is why it is so important to gain additional information by analysing the deflections, which makes it easier for the practising engineers to make decisions. We started our work with this approach, and summarized our results in this paper.

1 MATERIAL AND METHOD

1.1 Estimating the deflection bowl with functions

When deflection is measured to define the bearing capacity, displacements are measured and recorded only in certain distances from the load. This makes it necessary to fit functions onto the discrete measurement points to get the complete plot of all the evolved deflections. It is practical to apply functions describing the deflection bowl, because this way the geometrical attributes that are important regarding the stressed pavement can be defined with comparatively easy calculations.

Because of the surface sinking caused by mining (e.g. tunnel building), functions were already elaborated long time ago. Most authors (Aversin, Martos, Beyer, Bals etc.) suggested functions similar to the Gaussian bell curve (Fazekas 1978).

Hossain (1991) used exponential function to estimate the deformation caused by external load:

$$D(x) = ae^{bx}$$

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Using the altered function higher correlation can be achieved, though the layer parameters cannot be concluded from the equation's factors as the coefficients depend on all the layers differently (*Figure 2*. Grätz (2)). To describe the deformation curve in practice, it is suggested to apply functions with which one bowl parameter can be deduced, which describes a special layer of the pavement (e.g. radius of curvature).

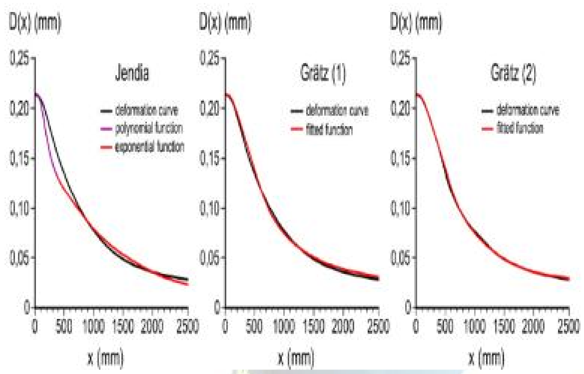

Figure2. Comparing different deflection bowl functions

1.2 Estimating the deformation curve on the basis of mechanics functions

Starting with the Boussinesq stress formulas, the value of deflection under the centre of the diameter flexible circle plate can be deduced (Papagiannakis and Masad 2008.

$$D_0 = 2pr(1-\mu^2)$$

where

D0 : vertical deflection measured in the load axis [mm],

Ee : the modulus of the flexible halfspace [MPa],

p : surface distributed load [MPa],

r : radius of the loading plate [mm],

m : the Poisson factor [–].

1.3 Estimation of the strain rising at the bottom of the bound layer

Knowing the radius of curvature derivate from the fitted function on the measured deformation points, and the thickness of the overlay, the strains rising at the bottom of the bound layers can be estimated with the following formula:

□ : strain in the load axis,

h : thickness of the bound layer,

R0 : radius of curvature in the load axis.

The conditions defined on the bound layer are satisfied if Hooke's law is present and the elastic modulus is equal for compression and for tension (Primusz – Tóth 2009).

1.4 Computer simulation with the BISAR software

The simulation is basically an examination where the expected and real behaviour of the system is being studied through the physical or computer model of a process**.**

1.4.1 Setting the simulation model

Nowadays, the most popular and most accepted method of defining the stresses evolving in pavements is the application of computer software. One of the oldest and most referred software is the BISAR (Bitumen Stress Analysis in Roads), developed by the SHELL Research Center. The software can calculate stress, strain, and deflection in an elastic multilayer system loaded with vertical load.

1.4.2 Pavement models used in simulation

The layers of the pavements can basically be divided into three groups: subgrade (together with frost protecting and/or improving layers), base layer, and overlay. Each group can be divided into further layers, so an average real pavement can be built of 3–5 layers (*Figure 3*).

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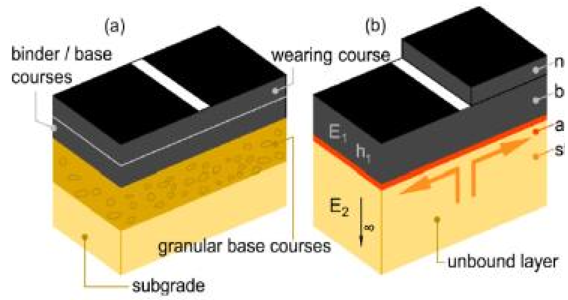

Figure4. The structure of the pavement models in the simulations

1.4.3 Calculating stresses

The BISAR software is able to handle several loads and calculate their superposition. The loads and the examined points are placed in one frame of reference and can be arbitrarily defined by the *x, y, z* coordinate triplet. During the simulation we took size kN single wheel load, which affects the top layer vertically, and scatters evenly a radius m elastic circle plate (*p* = 0.707 MPa). The distance of the examined points – measured.

2 RESULTS AND DISCUSSION

During the first part of the evaluation we examined how much effect each layer had on the evolving deformations in the case of a given pavement. This question is described in detail in Van Gurp's study (1995).
Figure 5 shows how much the layers of a three-layer structure effect the surface deflections (Van Gurp 1995). Naturally, the distribution changes with the modifying of the layer thickness or stiffness. According to the study, the thicker and stiffer the upper layers are, the more important the darkened areas of *Figure 5* become. The figure demonstrates well that the bearing capacity of subgrade has the greatest influence on the peak value of the surface deflections, and 900 mm from the load axis, the measured deflection represents the deflection of the subgrade in 100%. It can also be observed that if we consider the subgrade and base layer as one, then the effect of the top bound (asphalt) layer expands only 300 mm from the load axis, so it mostly affects the central deflections. This theory can be examined with the BISAR simulation.

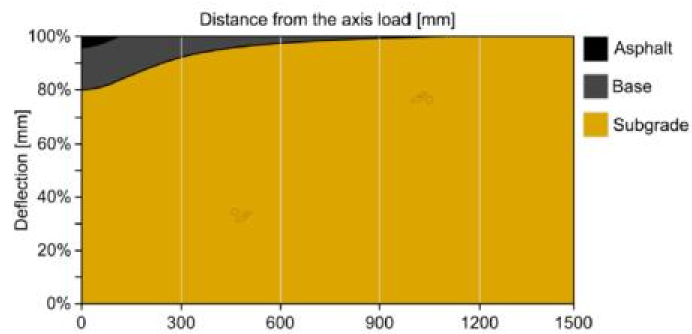

Figure5. The effect of each layer on the surface deflection (Van Gurp 1995)

Using the results of the BISAR software we looked for relationship between the parameters deduced from the shape of the deflection bowl (Primusz and Tóth 2009), and the layer parameters of the two-layer system.
The examination revealed that the "c" shape factor, the quotients of the layer moduli (*K*) and the thickness of the bound layer (*h*) have very close correspondence. The graphical evaluation of the results is shown in *Figure 6*.

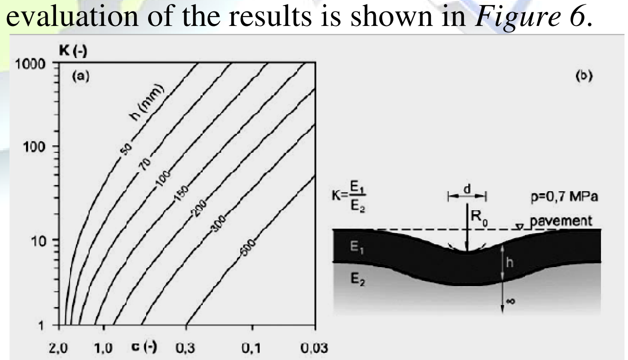

Figure6. Function between the shape factor

2.3 Estimating the modulus of the bound layers

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The definition of the modulus of the bound layers is done using the following simple formula:

$$E_1 = K.E_2$$

where
*E*1 : modulus of the bound layer [MPa],
*E*2 : modulus of the unbound granular layer [MPa],
K : rate of the layers compared to each other .
In the function (26), *K* is the rate of the bound and unbound layers compared to each other, which is calculated with the formula (20). To estimate the modulus we use the formula (24). Therefore we proved that in the case of two-layer pavement models, the moduli of the layers can unequivocally be calculated back from the deformation curve, so it is not necessary to use the iterative back calculation methods.

3 SUMMARY

The function suggested by us can be fitted not only onto deflection curves calculated with the FWD or IBBA, but also the ones calculated with the BISAR software. We showed that by knowing the deflection curve and the thickness of the bound layer, without using further iteration procedures (backcalculation), we could define the modulus of the examined pavement's layers. The modulus calculated this way can certainly not be matched with the result of any laboratory tests. The practical benefit of the procedure is thatwith the defined moduli, we can create a pavement model whose behaviour – shape alterations under wheel load – well approximates the real pavement.
Knowing the radius of curvature we can calculate the strain of the bottom of the bound layer; knowing the strain, we can calculate the existing pavement's lifetime. The analysis of the three-layer models made it possible to estimate the strains evolving at the bottom of the existing asphalt layer after building the reinforcement layer, and so we can establish the theoretical possibility of a harmonic and economic reinforcement design method. The elaborated modelling procedure on the network level has the capability to be the base of a pavement management system.

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Available online at www.ijartet.com
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External Report AMSR. 0006.73. Amsterdam: Koninklijke Shell Laboratorium