Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 57 (2013) 270 – 277

Procedia Engineering

www.elsevier.com/locate/procedia

11th International Conference on Modern Building Materials, Structures and Techniques, MBMST 2013

Stiff-Plate Bearing Test Simulation Based on FWD Results

Jakub Fengier[a] *, Andrzej Pożarycki[b], Tomasz Garbowski[c]

[a, b]Institute of Civil Engineering, Poznan University of Technology,
Piotrowo St. 5, 60-965 Poznan, Poland
[c]Institute of Structural Engineering, Poznan University of Technology,
Piotrowo St. 5, 60-965 Poznan, Poland

Abstract

The control of compaction's degree of the lower pavement layers in Poland usually is done by making use of stiff-plate bearing tests. After the subgrade and/or subbase are constructed, there is no further possibility to check if the proper (designed) Ev2 values were achieved during the construction works. Some possible remedy of this problem can come with a nonstandard use of falling weight deflectometer results analysis. This paper presents potential applications of numerical simulations of plate bearing test based on dynamic deflection data and theoretical model of flexible pavement with high modulus asphalt concrete. Considering the combination of dynamic test results with static numerical or theoretical models used as components of inverse procedure the promising estimates of Ev2 can be achieved within non-destructive test frame. The conducted studies show how much the theoretically evaluated Ev2 secant modulus can be reliably characterized from nonstandard testing data with acceptable engineering accuracy.

Selection and peer-review under responsibility of the Vilnius Gediminas Technical University

Keywords: plate bearing test simulation, deformation modulus, inverse analysis, extended FWD analysis,

---

1. Introduction

The stiff-plate bearing (SPB) test is one of the most commonly used test carried out on construction sites. Particularly an important factor is the compaction ratio I_o, which is widely used in Polish standards and technical specifications as a way to evaluate compaction of unbound and/or hydraulically stabilized bound materials. Polish standard "*PN-S-02205: 1998 Car Roads, Earthworks Test and requirements"* specifies required values of secondary deformation modulus (Ev2) for bearing capacity control as well. Furthermore the legal regulations in other countries such as Germany by "*DIN 18134 Determining the deformation and strength characteristics of soil by the plate loading test*" also accepts secondary deformation modulus as a parameter used to characterize the base, subbase and subgrade pavement layers. Moreover, this parameter is often used by engineers as an approximation of the elastic modulus for unbound layers.

In the literature one can find a great number of publications on the identification of the elastic modulus based on the falling weight deflectometer (FWD) test results [1–11] and just few sources that treat the correlation of Ev2 end elastic/resilient modulus [12], [13]. The proposed by researchers correlation formula is, however limited to a specific pavement test conditions. The work [14] describes the relationship between the identified modulus Ev2 based on dynamic and static methods, emphasizing the meaning of FWD tests. The road managers in need of reducing the number of invasive (destructive) tests, attempt to put more attention on enhanced analysis of non-destructive FWD testing results.

The issue of repeatability and reproducibility of FWDtest results was discussed in the work of Rocha [15]. An effect of temperature and humidity in the soil on the identification procedure ofpavement layer moduli using the inverse calculation and FWD tests is presented in [16]. Another work which deals with the inverse calculation [17] focused an attention on the

---

* Corresponding author.
E-mail address:[a]jakub.d.fengier@doctorate.put.poznan.pl; [b]andrzej.pozarycki@put.poznan.pl; [c]tomasz.garbowski@put.poznan.pl

1877-7058 © 2013 The Authors. Published by Elsevier Ltd.
Selection and peer-review under responsibility of the Vilnius Gediminas Technical University
doi:10.1016/j.proeng.2013.04.037

determination of elastic modulus of the subgrade and on correlation of the results with Automated Dynamic Cone Penetrometer.

2. Scope of work

In this study the calculation of Ev2 was carried out on a certain homogeneous section of road located in the western part of Poland. The authors analyzed the results of: (a) the SPB tests performed on the surface of the mechanically stabilized aggregate base layer and (b) the dynamic deflectometer FWD test. The series of FWD test were conducted on each layer surface of pavement, namely on: (1) the aggregates base layer (Agg); (2)the base course (HMAC); (3)the binder course (HMAC) and (4)the wearing course (SMA).

Based on the collected SPB and FWD experimental data, the modulus Ev2 of the aggregate base layer is determined in two independent stages. First an identification procedure is performed and corresponding resilient/elastic moduli are assigned to each layer of the pavement. This can be done by making use ofa backcalculation concept, where through numerical or analytical model (with embedded sought parameters, i.e. E_i) deflection bowl is computed and compared to experimentally measured one. Through an iterative update of pavement's moduli one can minimize a discrepancy between numerically computed deflection and those measured by FWD. In the second stage a forward modeling of SPB test is performed with all model parameters fixed to the values obtained from previous stage.

3. Motivation and objectives

The main objective of this work is to characterize and control the base and/or subgrade layers of the pavement structure through nondestructive deflectometertest.

The main task is to calculate the value of Ev2 from the FWD test. This objective is obtained in 2 steps: (a) the identification of resilient moduli in each layer is performed on the basis of FWD tests and inverse analysis; (b) the model for SPB test simulation is constructed (here all parameters are known from previous step) and the Ev2 is computed by making use of formula (2). Afterwards calculated values were compared with in situ measured Ev2.

FWD test combined to inverse analysis serves here as a tool for the pavement layer moduli characterization, which are in the later stage inserted to a rigid-plate bearing testsimulated in order to determine the Ev2 modulus, which in Polish law is interpreted as a bearing capacity criterion. The ability to control the quality of the lower road layers (which are covered after the construction of pavement is finished) without a need for multiple drilling tests will fulfill needs of managers of public roads.

4. Experiment methodology

The results used for the analysis are obtained during a construction of certain road in Western Poland. The test section for measurements is located in the urban area on one of the main streets of Poznan. The uniform road section is considered here with a length of 245 m (section from 0+150 to 0+395 km). On this section 20 measuring points is located. The pavement was arranged in the following design: (1) improved subgrade (stabilized soil) (Fig. 1b), thickness of 25 cm; (2) mechanically stabilized crushed-stone aggregate, thickness of 62 cm; (3) a sub-base and road-base layers of HMAC (Fig. 1a), thickness (hAC) of 9 cm and 8 cm respectively; (4) base course layer 8 cm thick and (5) SMA wearing course, thickness of 4 cm. The bonding between asphalt layers was obtained by spraying asphalt emulsion D70/100 in an amount of 0.3÷0.5 kg/m^2.

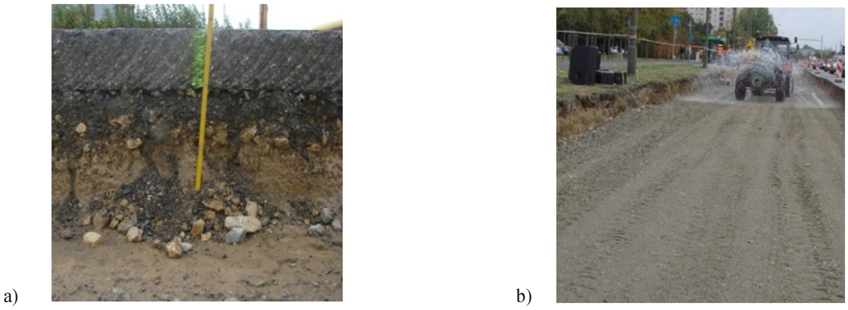


Fig. 1. Construction site a) earth works, b) improved subgrade compaction

In the next stage the series of FWD test on each layer were conducted (Fig. 2a). On the sub-base aggregate layer, the dynamic force equals to 30 kN was applied. On the subsequent asphalt layers the dynamic force was increased to 50 kN.

The measurement equipment (FWD-8002) used here is capable to apply loading force ranges from 7 to 120 kN. On AC courses surfaces, the measurements are usually done by using force equals to 50 kN, which simulates equivalent single axle load (ESAL 100 kN). Performing the preliminary measurements with the load of 50 kN on aggregate course surface made the readings from sensors installed in FWD-8002 exceed its admissible measuring range from 0 to 2000 µm. Therefore the loading force on subgrade was reduced to 30 kN [19].

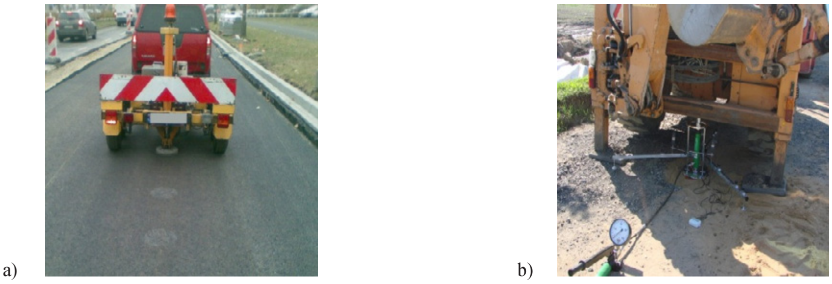


Fig. 2. In situ measurements a) FWD, b) SPB

The SPB tests were carried out on the surface of mechanically stabilized crushed-stoneaggregate layer. The study was conducted with pressure range of 0.0÷0.5 MPa, wherein the calculation of the secondary deformation modulus Ev2 the standard pressure levels of 0.35 MPa and 0.25 MPa were used. The statistical data of Ev2 values obtained from in situ measurements are shown in Fig. 3.

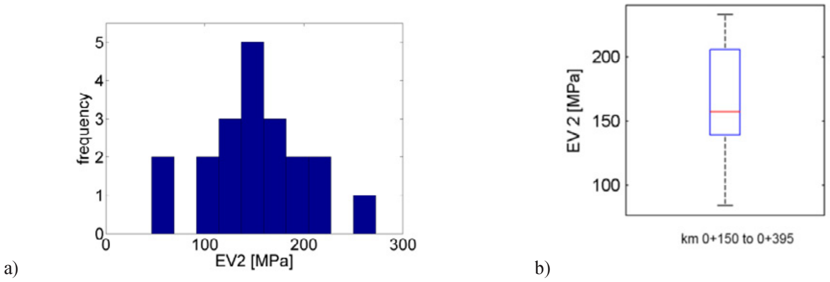


Fig. 3.Statistics of Ev2 values from in situ measurements a) Histogram, b) Boxplot

The average measured value of Ev2 for SPB tests was 167 MPa, whereas the required value of 150 MPa was expected. In each point 3 FWD drop tests were made but only the last test was considered. The typical FWD results (both loading force vs. time and defections vs. time) are shown in Fig. 4.

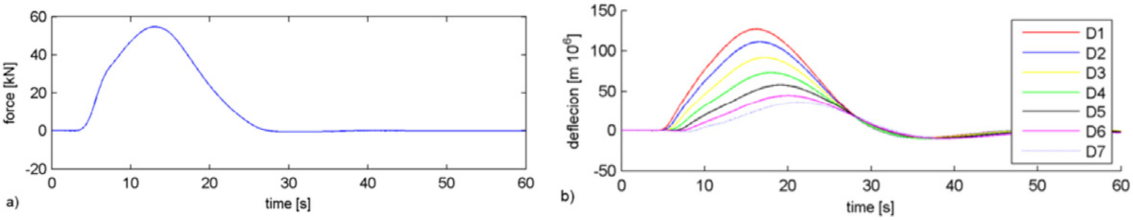


Fig. 4.Example of results achived on binder course by FWD test a) load, b) deflections from particular geophones

All FWD test were performed exactly at the same locations as SPB (Fig. 2b) tests in order to be able to compare results (Fig. 5).

5. Calculations by a Layered Elastic Theory

The preliminary calculations were performed with the use of a program which belongs to the Everseries software. Evercalk and Everstress software uses an elastic layer theory and is widely used both for forward calculations and backward calculations of pavement structures [18].

The assumptions made for the purpose of identifying modules of elasticity are as follow:

- asphalt layers are treated as a package,
- there is full bounding between layers,
- Gauss-Newton algorithm used for optimization,
- layers are infinitely long in the horizontal directions,
- layers have uniform thickness,
- bottom layer is semi-infinite in the vertical direction,
- all layers are homogeneous, isotropic, linear elastic materials, characterized by elastic modulus and Poisson's ratio.

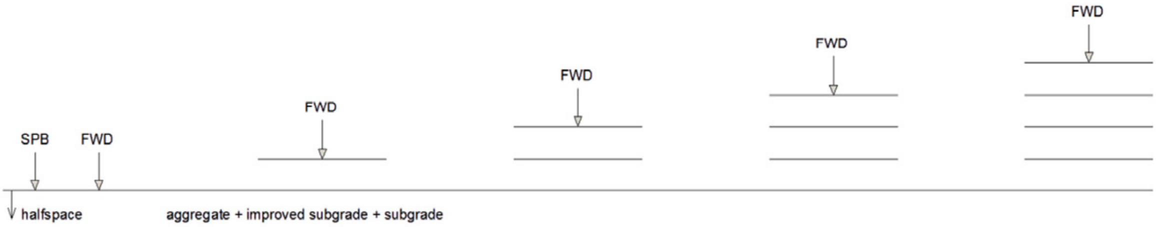


Fig. 5. Scheme of measurements

Identification of the parameters necessary for the calculation of the secondary deformation moduli made use of three models (Fig. 6) based on pavement design:

- 2-layer model
- 3-layer model
- 4-layer model

The backcalculation method was used here for identification of all values of elastic moduli in each layer to match the deformation bowl computed by the analytical modelto the one resulting from the FWD test.

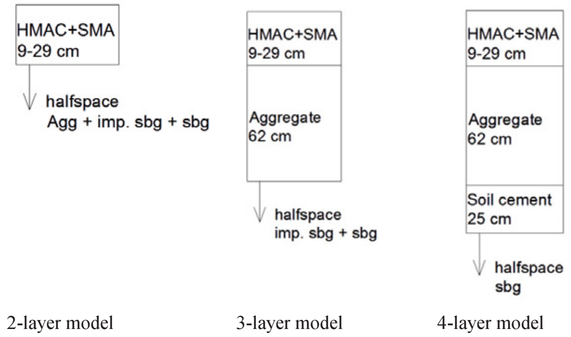


Fig. 6.Models used in backcalculation

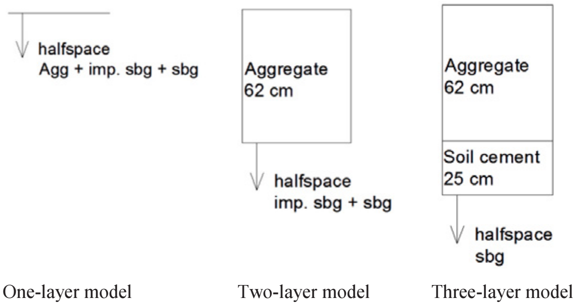


Fig. 7.Models used in calculation of Ev2

The average RMSerror obtained from the backcalculation was around 1%.Identified from the inverse process elastic moduli were later used to feed forward models to determine Ev2 (Fig. 7). The RMS error was calculated by the formula.

$$RMS = \sqrt{\frac{1}{n_d}\sum_{n=1}\left(\frac{d_{ci}-d_{mi}}{d_{mi}}\right)^2} \cdot 100[\%] \tag{1}$$

where: RMS– root mean square error in percent, d_{ci} – calculated pavement surface deflection at sensor i, d_{mi} – measured pavement surface deflection at sensor i, n_d – number of deflection sensors used in the backcalculation process.

According to polish standards, the values of secondary deformation modulus were computed from the formula:

$$Ev2 = 0.75 \cdot D\frac{\Delta p}{\Delta s} \tag{2}$$

where: Ev2 – secondary deformation modulus, D – loading plate diameter, Δp – pressure difference, Δs – deflection difference (*PN-S-02205: 1998 Car Roads, Earthworks Test and requirements)*.

Here the pressure difference for which the deflection difference was measured was constant and equaled to 0.1 MPa.

6. Calculation by Finite Element Method

The main calculations were performed on the 2D axisymmetric Finite Element (FE) model which consists of fully-integrated linear quadrilateral elements. The kinematic boundary conditions are applied on the bottom and free-end of the model. In order to reduce an effect of boundary conditions model was extended to 120 × radius of loading plate in vertical direction and to 50 × radius in horizontal direction.

Here all asphalt layers were modeled as a “package” meaning no distinction between sub-layers was introduced. The interaction definitions between asphalt layer and the subgrade as well as between subgrade and base are modeled through the frictionless contact. The uniform thickness of layers is assumed and constitutive relations are chosen to be linear elastic as in previous example. In the Finite Element simulation the FWD test loading pulse is taken from the experimental data.

For the elastic moduli identification the full implicit dynamic model which mimics the FWD test were used together with inverse analysis based on Trust Region Algorithm (TRA). The TRA is an iterative gradient based algorithm implemented in the frame of least square technique, where the Hessian is approximated by the Jacobian of residuals (the differences between computed and measured quantities).

The simulations of SPB test, whichis a static test, were done by a FE static implicit model with similar properties as the previously discussed model. Here all constitutive parameters were fixed to the values identified by the previous analysis and the deflections under the loading plate were computed for the two levels of pressure (namely, 250 kPa and 350 kPa). By making use of the computed deflections the secondary deformation modulus Ev2 can be easily estimated.

7. Results

Based on the above described models and calculations the set of results for different pavement structures (see Fig. 6) were obtained. Theset of the results for a specific model consists of: (1) elastic moduli of each pavement structurelayer; (2) vertical displacementsof central pointon crushed-stone aggregate base layer for different pressure levels and (3) computed

Ev2 of the aggregate layer.The selected results of elastic moduli identification obtained from the 4-layer FE model are shown in the Fig. 8.

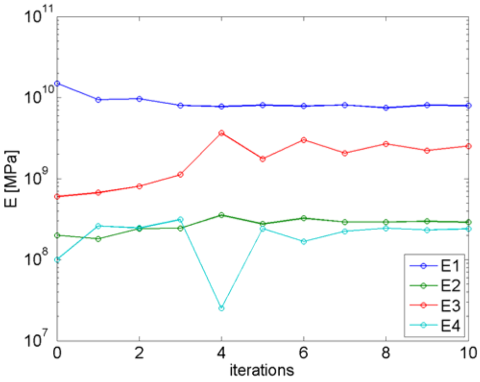
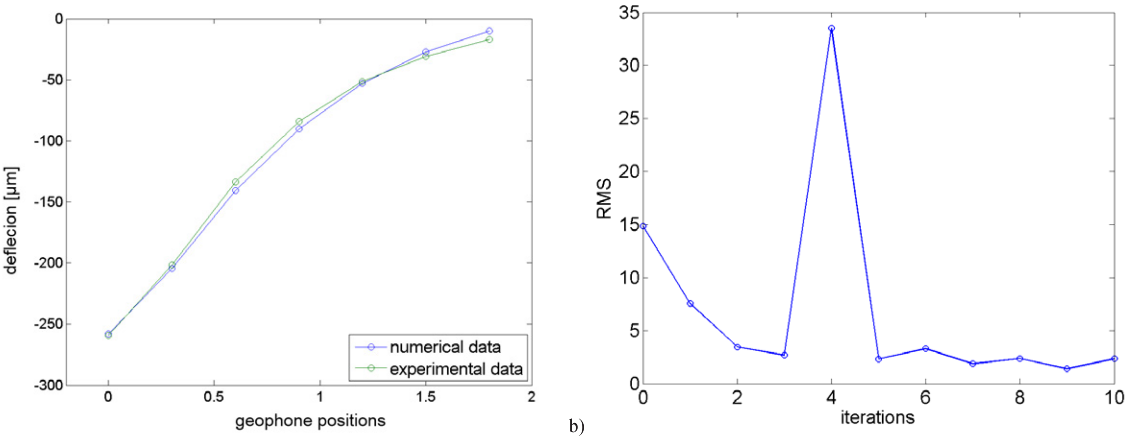


Fig. 8.Convergence of the calculated by FEM parameters

The convergence can be observed after just seven iterations, giving an RMS value less than 2% (see Figs 9 and 10).

The average RMS error was smaller in LET method, but in general, the value of Ev2 calculated for aggregate course based on backcalculation from FEM was closer to in-situ measured values. The 4-layer FE model is the most accurate model among all other considered models (see Fig. 9).



a) b)

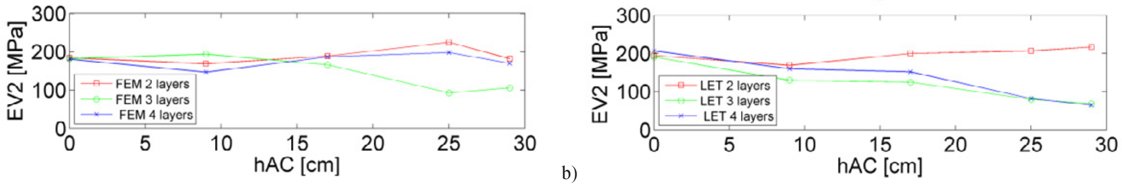
Fig. 9. a) Experimental and numerical deflection bowls calculated by using FEM, b) An example of FEM convergence process observed

It is shown in Table 1 that the obtained Ev2 estimates are sufficiently accurate from the engineering point of view. The Ev2 values computed by LET with 3 and 4 layers models are underestimated. The calculated secondary deformation modulus with all analyzed here FE models are slightly higher than the measured in-situ values.

It is evidenced that the employed backcalculation technique based on any of tested LET and/or FE models estimates the Ev2 in the accepted range of pavement engineering judgment. The differences between estimated and measured values increase while thickening of asphalt concrete course (Fig. 11).

Table 1.Mean values of Ev2 on surface of aggregate subbase course, calculated from LET and FEM

FWD tested layer	Model used for identification of elastic moduli	Mean value of Agg. EV2 from LET [MPa]	Mean value of Agg. EV2 from FEM [MPa]
Crushed-stone aggregate 62 cm	2-layer model	195	184
	3-layer model	191	182
	4-layer model	207	181
HMAC 9 cm	2-layer model	169	169
	3-layer model	130	194
	4- layer model	160	147
HMAC 17 cm	2-layer model	200	189
	3-layer model	125	166
	4-layer model	152	187
HMAC 25 cm	2-layer model	207	225
	3-layer model	80	93
	4-layer model	82	198
HMAC 29 cm	2-layer model	217	182
	3-layer model	69	106
	4-layer model	65	170



a) b)

Fig. 11. Ev2 modulus of aggregate base course calculated by a) FEM, b) LET, in function of asphalt package layer thickness

8. Conclusions

The calculation of the secondary Ev2 modulus of the lower layers of pavement structures is an important issue in terms of a roadway diagnosis.The results obtained in fully controlled conditions using a standard calculation and test procedures are not always correct and sometimes even impossible to be utilized, therefore the additional a-posteriori check seems as an important alternative. The methodology presented here is a novel procedure based on standard FWD test results but used in a nonstandard way. Dynamic deflectometer test combined with analytical (or numerical) modeling and inverse analysis serves as a preliminary step for moduli identification. Knowing elastic moduli of each pavement layer (within certain accuracy) one can easily perform a forward FE simulation of SPB with fixed (previously identified) model parameters. From this point it is just a small step to compute an estimate of Ev2.

Presented here the novel approach based on analytical, numerical and experimental methods can serve as a tool for a-posteriori diagnosis of the pavement subbase and subgrade layers (i.e. as a control of the bearing capacity of the lower pavement layers, after asphalt concrete courses are constructed). It is seen from the obtained results that the calculation of Ev2 from FWD test is possible, especially when the FEM model is employed with precise boundary conditions.

In order to improve an estimate of Ev2 modulus in further studies, the numerical model can be refine by taking into account the degree of asphalt interlayer bonding, stress sensitivity of granular subbase courses, subgrade ground water conditions, etc.

References

[1] Mooney, M., Miller, G., *et al.*, 2000. Importance of invasive measures in assessment of existing pavement, Journal of Performance of Constructed Facilities 14(4).

[2] Von Quintus, H. L., Simpson, A. L., 2002. Back-Calculation of Layer Parameters for LTPP Test Sections.Federal Highway Administration. McLean.

[3] Xu, B., Ranjithan, R., Kim, R., 2002. Case studies: using APLCAP for asphalt pavement layer condition assessment, Journal of the Transportation Research Board.

[4] Ceylan, H., Guclu, A., Tutumluer, E., Thompson, M., 2005. Backcalculation of full-depth asphalt pavement layer moduli considering nonlinear stress-dependent subgrade behavior, The International Journal of Pavement Engineering 6(3), pp. 171–182.

[5] Goktepe, B., Emine, Agar E.; Lav, H., 2006. Advances in backcalculating the mechanical properties of flexible pavements, Advances in Engineering Software 37, pp. 421–431.

[6] Grenier, S., Konrad, J., 2009.Dynamic interpretation of falling weight deflectometer tests on flexible pavements using the spectral element method: backcalculation, Canadian Journal of Civil Engineering 36, pp. 957-968.

[7] Gopalakrishnan, K., 2009. Backcalculation of Non-Linear Pavement Moduli Using Finite-Element Based Neuro-Genetic Hybrid Optimization, The Open Civil Engineering Journal 3, pp. 83-92.

[8] Lav, H., Goktepe, B., Lav, A., 2009. Backcalculation of Flexible Pavements Using Soft Computing, Intelligent and Soft Computing in Infrastructure Systems Engineering 259, pp. 67-106.

[9] Lee, H. S., Kim, J., 2011. Backcalculation of dynamic modulus from resilient modulus test data, Canadian Journal of Civil Engineering 38, pp. 582-592.

[10] Kutay, E., Chatti, K., Lei, L., 2011. Backcalculation of Dynamic Modulus Mastercurve from Falling Weight Deflectometer Surface Deflections, Transportation Research Record: Journal of the Transportation Research Board 2227, pp. 87-96.

[11] Saltan, M., Terzi, S., Küçüksille, E., 2011. Backcalculation of pavement layer moduli and Poisson's ratio using data mining, Expert Systems with Applications 38, pp. 2600–2608.

[12] Pantelidis, L., 2008. Determining of the soil strength characteristics through the plate bearing test, Foundationsof Civil and Environmental Engineering.

[13] Bertulienė, L., 2012. Assesment, research of strength measurement methods on subgrade of experimental road pavement, The Baltic Journal of Road and Bridge Engineering 7(3), pp. 228-236.

[14] Bertulienė, L., Laurinavičius, A., Vaitkus, A., 2010. Research and evaluation of methods for determining deformation modulus of a base course of road pavement, The Baltic Journal of Road and Bridge Engineering 5(2), pp. 110–115.

[15] Rocha, S., Tandon, V., Nazarian, S., 2004. Falling Weight Deflectometer Fleet. Repeatability and Reproducibility, Road Materials and Pavement Design 5(2), pp. 215-238.

[16] Salour, F., Erlingsson, S., 2013. Investigation of a pavement structuralbehaviour during spring thaw usingfalling weight deflectometer, Road Materials and Pavement Design.

[17] George, K., 2003. Falling weight deflectometer for estimating subgrade resilient moduli, The University of Mississippi.

[18] Everseries© user's guide Pavement Analysis Computer Software and Case Studies. 2005. Washington State Department of Transportation.

[19] Dynatest FWD/HWD Test Systems, Owner's Manual Version 2.3.6, 2007.