Mechanics Transport Communications
Academic journal
ISSN 1312-3823
issue 3, 2009
article № 0405
http://www.mtc-aj.com

ON THE BACKCALCULATION OF FLEXIBLE ROAD PAVEMENT MATERIAL PROPERTIES AND NEW METHODS

Mehmet Saltan, Mustafa Karaşahin, Serdal Terzi
msaltan@mmf.sdu.edu.tr sterzi@tef.sdu.edu.tr

Faculty of Engineering-Architecture, Suleyman Demirel University, Isparta 32260,
Faculty of Technical Education, Suleyman Demirel University, Isparta 32260
TURKEY

Abstract. *The determination of pavement layer structural efficiency is an important issue in determining the performance of existing road pavements and in performing pavement design and rehabilitation processes. In order to apply the most appropriate rehabilitation and management decisions, the most efficient method for determining the structural capacity of pavements should be utilized. As the theoretical approaches such as linear elastic analysis and finite element method used to determine the stress–strain relationships in pavement layers calculate the deflections for given mechanical properties, it is necessary to consider an inversion algorithm as a backcalculation tool. Over the years, several methodologies involving static, dynamic, and adaptive processes have been used for obtaining in situ pavement layer mechanical properties thorough Nondestructive Testing (NDT) measurements. This paper summarizes the basic backcalculation methods and new trends.*
Keywords: *Flexible pavement; Backcalculation; Nondestructive Testing.*

1. INTRODUCTION

In recent years, highway and transportation agencies have an increased responsibility for the maintenance and rehabilitation planning of flexible pavements. Knowledge of the structural condition of the pavement is essential in order to assess the need for rehabilitation and the nature of the required treatment which may be a strengthening overlay, partial and/or complete reconstruction. Efficient and economical methods are required for determining the structural capacity of existing flexible pavements. Since highway infrastructure deteriorates, reconstruction and rehabilitation of the vast road networks have become increasingly important. Nowadays, a large proportion of highway funds are being used for maintenance, rehabilitation and reconstruction of pavements. The structural capacity of the existing pavement system needs to be evaluated as part of the rehabilitation design process. Considerable savings in rehabilitation cost can be made by predicting accurately the strength of the existing pavement system. Nondestructive Testing (NDT) and backcalculating pavement layer moduli are well-accepted procedures for the evaluation of the structural capacity of pavements (Chou, 1993). "Backcalculation" is the accepted term used to identify a process whereby the material properties such as elastic moduli, Poisson's ratio, and layer thickness of individual pavement layers are estimated based on measured surface deflections (Gopalakrishnan, 2009). NDT enables the use of a mechanistic approach for pavement design and rehabilitation because *in-situ* material properties can be backcalculated from the measured field data through appropriate analysis techniques (Uzan *et al.*, 1989). In order to backcalculate reliable moduli, it is essential to accomplish several deflection tests at different locations along the highway sections having the same layer thicknesses (Chou, 1993). Until now, many highway agency throughout the world used simple methods such as linear elastic theory and equivalent layer thickness. Uzan developed the MODULUS program using linear elastic theory (Chou, 1993). Huang developed KENLAYER program with using the same method (Huang, 1993). The same method was used in developing many programs such as PADAL, ELSYM5, BISTRO, CHEVRON, MODCOMP, EFROMD. Ullidtz used the Equivalent Layer Thickness (ELT) Method and developed the ELMOD program (Tam, 1987). Zhou developed the BOUSDEF program in 1990 using the ELT method (Zhou et al., 1992). Then, the finite element method is extensively used paralleling with new technologies. Barksdale developed the GAPS series and Wilson and Duncan developed the ILLI-PAVE program using the finite element method (Thompson, 1992). This method was used in developing programs such as FENLAP, FEAD, and SAPIV. An axially symmetric finite element method was used for another backcalculation program, SDUFEM by Saltan (1999). On the other hand, in recent years, Neural Networks (NNs), neuro-fuzzy systems, Genetic Algorithms (GAs), and Fuzzy Logic approach were used for backcalculation of pavement layer properties (Gopalakrishnan, 1999).

2 BACKCALCULATION OF PAVEMENT LAYER PROPERTIES

"Backcalculation" is a mechanistic evaluation of pavement surface deflection basins generated by various pavement deflection devices. Backcalculation takes a measured surface deflection and attempts to match it (to within some tolerable error) with a calculated surface deflection generated from an identical pavement structure using assumed layer stiffnesses (moduli). The assumed layer moduli in the calculated model are adjusted until they produce a surface deflection that closely matches the measured one. The combination of assumed layer stiffnesses that results in this match is then assumed to be near the actual *in situ* moduli for the various pavement layers. The backcalculation process generally refers to an iterative procedure and normally done with computer software. NDT and backcalculation processes are well-accepted procedures for the evaluation of structural capacity of the flexible pavements.

The backcalculation of pavement moduli from surface deflection measurements using nondestructive tests has been used for more than four decades to assess and manage existing pavements and to design overlays. Unfortunately, the backcalculated pavement moduli lack the accuracy in spite of the existence of many backcalculation programs employing different backcalculation procedures and algorithms (Alkasawneh, 2007).

A basic flowchart (patterned after Lytton, 1989) that represents the fundamental elements in all known backcalculation programs is shown as Figure 1. Briefly, these elements include (http://training.ce.washington. edu/wsdot/):

- *Measured deflections*. Includes the measured pavement surface deflections and associated distances from the load.
- *Layer thicknesses and loads*. Includes all layer thicknesses and load levels for a specific test location.
- *Seed moduli*. The seed moduli are the initial moduli used in the computer program to calculate surface deflections. These moduli are usually estimated from user experience or various equations.
- *Deflection calculation*. Layered elastic computer programs are generally used to calculate a deflection basin.
- *Error check*. This element simply compares the measured and calculated basins. There are various error measures which can be used to make such comparisons (more on this in a subsequent paragraph in this section).
- *Search for new moduli*. Various methods have been employed within the various backcalculation programs to converge on a set of

layer moduli which produces an acceptable error between the measured and calculated deflection basins.

- *Controls on the range of moduli.* In some backcalculation programs, a range (minimum and maximum) of moduli are selected or calculated to prevent program convergence to unreasonable moduli levels (either high or low).

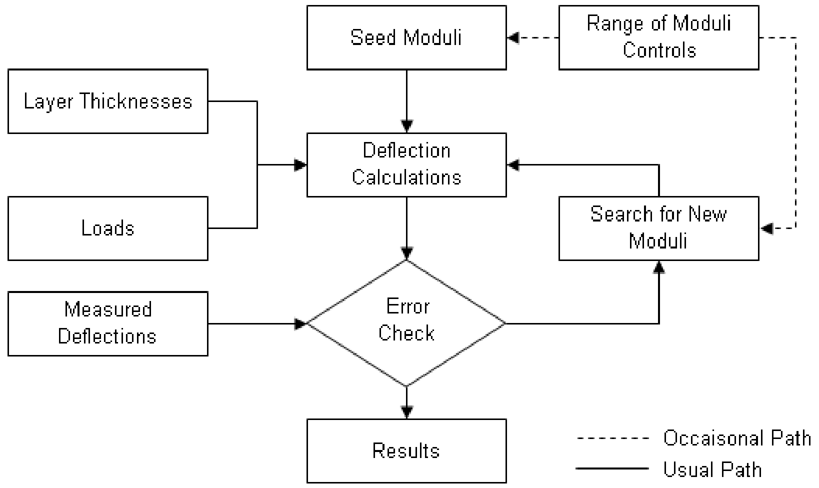

Figure 1. Backcalculation Flowchart (http://training.ce.washington.edu/wsdot/)

3 NONDESTRUCTIVE TEST DEVICES FOR PAVEMENT STRUCTURAL EVALUATION

Structural evaluation of pavement deflection response using Non Destructive Test (NDT) data has been growing since the introduction of the Benkelman Beam at the Western Association of State Highway Organizations (WASHO) Road Test in 1952 is a simple device that operates on the lever arm principle. The Benkelman Beam is used with a loaded truck - typically 80 kN (18,000 lb) on a single axle with dual tires inflated to 480 to 550 kPa (70 to 80 psi). Measurement is made by placing the tip of the beam between the dual tires and measuring the pavement surface rebound as the truck is moved away. The Benkelman Beam is low cost but is also slow, labor intensive and does not provide a deflection basin (Figure 2) (http://training.ce.washington.edu/wsdot). Developments in analytical techniques, coupled with improved deflection measurement capabilities, have resulted in the current so-called backcalculation techniques widely employed in pavement evaluation.

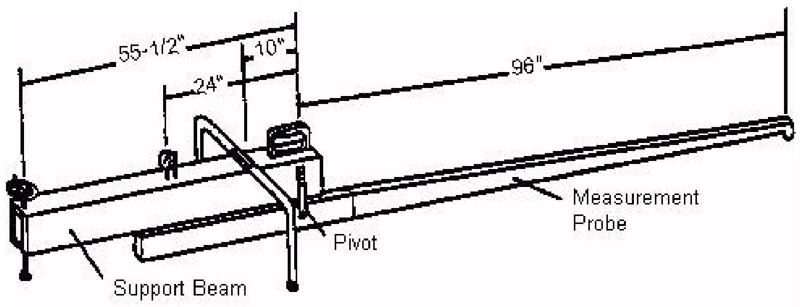

Figure 2. Benkelman Beam Schematic (http://training.ce.washington.edu/wsdot/)

Calculation of load-related pavement surface deflections of specific points, using material properties of pavement layers (modulus, Poisson's ratio, and thickness), is well established (Noureldin, 1993). Of the different load responses (stress, strain, and deflection), only surface deflections are measured easily. Pavement deflection is the basic response of the structural system (surface-base-subgrade) to the applied load. It is used frequently as an indicator of pavement structural capability and performance potential. Surface deflection measurements are rapid, relatively cheap, and nondestructive (Garg and Thompson, 1999). Pavement deflection is measured through a series of velocity transducers at various distances from the baseplate, and the data can be used to backcalculate *in situ* pavement layer properties. This information can in turn be used in pavement structural analysis to determine the bearing capacity, estimate the remaining life, and calculate an overlay requirement over a desired design life (Wang and Lytton, 1993). The Falling Weight Deflectometer (FWD) was first introduced in France in 1970s to test the flexible road networks. It has since gained increasing acceptance as one of the most effective methods for evaluating flexible roads (Karadelis, 2000). In order to simulate the truck loading on the pavement, a circular mass is dropped from a certain height on the pavement. The height is adjusted according to the desired load level. Underneath the circular plate a rubber pad is mounted to prevent shock loading. Seven geophones are generally mounted on the trailer (the number of geophones can change). When the vertical load is applied on the pavement, the geophones collect the deflection data. The duration and magnitude of the force applied is representative of the load pulse induced by a truck moving at moderate speeds (Garg and Thompson, 1999).

Benkelman beam and Dynaflect (Figure 4) which are most commonly used devices in the developing countries, give the information about underneath the centre of circular mass (i.e. these devices give one deflection data in each measurement) whereas the FWD (Figure 5) gives the information about other six points (or more points) which are away from the circular plate. Therefore, the effect of the wheel loading can also be seen in other points.

Figure 3. Dynaflect in use (http://training.ce.washington.edu/wsdot/)

Figure 4. FWD Application (http://training.ce.washington.edu/wsdot/)

There are many types of FWDs which can apply similar loading. The time of loading varies between 0.025 and 0.030 sec; the applied loads vary between 6.7-156 kN. The loading time of 0.030 sec represents duration of a load pulse produced by a wheel moving at a speed of 30 km/h $\pm$ 0.023 mm deviations can be seen from the FWD measurements (Moreland, 1983). Typically, 200-300 FWD measurements can be made in a day.

4. Backcalculation Methods

Pavement structural evaluation analysis has long been a problem for pavement engineers. Previous approaches concentrated on statistical formulae mostly based on regression analysis to predict the performance. These equations illustrate the effects of various factors on the performance of pavements. These equations are valid only under certain conditions and should not be used if the actual conditions are different. Besides, this approach is very cumbersome and time consuming in terms of the calculation and in terms of the acquisition of the data required for doing the calculations (Kaur and Chou, 1999).

Elastic layered programs used in asphalt pavement analysis assume linear elasticity. Pavement geo-materials do not, however, follow linear type stress-strain behaviour under repeated traffic loading. In effect, nonlinear stress sensitive response of unbound aggregate materials and fine-grained subgrade soils has been well established. Unbound aggregates exhibit *stress hardening* and fine-grained soils show *stress softening* type behaviour. When these geo-materials are used as pavement layers, the layer stiffnesses, i.e., moduli are no longer constant but functions of the applied stress state. Pavement structural analysis programs that take into account nonlinear geo-material characterization need to be employed to more realistically predict pavement responses needed for mechanistic based pavement design (Ceylan et al., 2004).

Current basin-matching programs fall into two broad groups. Most programs employ gradient search techniques to adjust the pavement layer moduli iteratively until the theoretical and experimental deflection basins agree within a specified tolerance. Required inputs include experimental deflection measurements and pavement layer thicknesses. The iterative solution technique also requires an initial estimate of the solution (seed moduli) and a range of moduli to constrain the solution. A second approach is to interpolate within a database of theoretical basins. A database of theoretical basins is generated for prescribed pavement layer thicknesses by parametrically varying the pavement layer moduli within expected ranges (Meier and Rix, 1994; Meier and Rix, 1995).

As can be seen from Figure 2, pavement response analysis (calculation of deflections) can be considered as either static or dynamic. Initial studies of this problem were based on static analysis, and attempts were made to establish the inverse correlation with functional, statistical, and empirical approaches. However, due to the inherent, sophisticated, and nonlinear nature of the problem, these attempts were not successful. In all static approaches, conventional methods are based on iterative optimization procedures, and forward pavement response is calculated using either layered elastic theory or finite element method (FEM) for linear or nonlinear elastic material behaviors. Since the nonlinearity is closer to the nature of pavement materials, it is obvious that the nonlinear analysis increases the precision of the forward model. In addition, optimization processes can be performed by using a parameter identification algorithm (PIA), such as nonlinear least squares, database search algorithm (DSA), and genetic algorithm (GA). It should be noted that GA is an AI (artificial intelligence)-based model-free optimization technique, which mimics the theory of evolution (Göktepe et al, 2006).

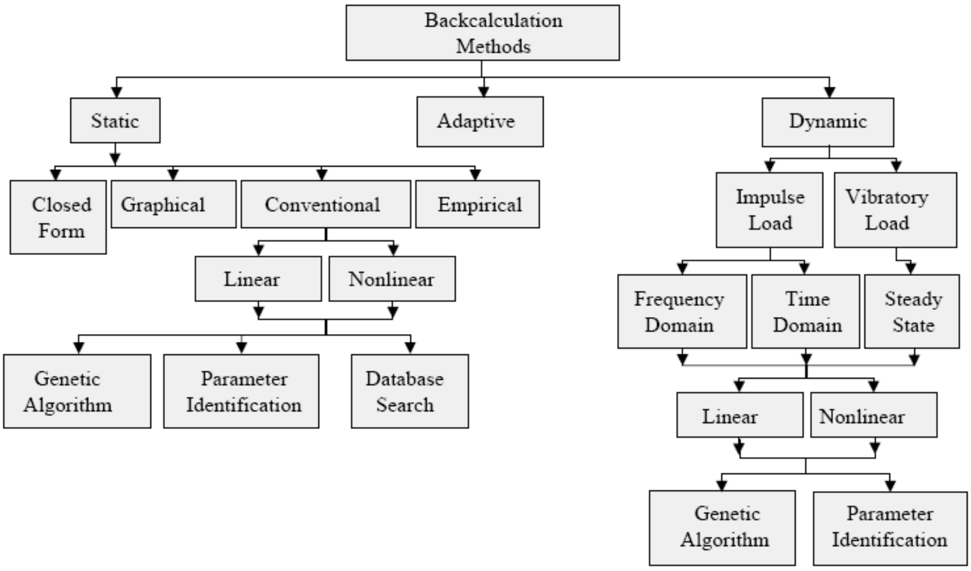

Figure 5. Overview of backcalculation methods

4.1. New Backcalculation Techniques

In recent years, one of the most important and promising research field has been "Heuristics from Nature", an area utilizing some analogies with natural or social systems and using them to derive non-deterministic heuristic methods and to obtain very good results. Artificial Neural Network (ANN) and Fuzzy Logic Approach (FLA) methods are among the heuristic methods.

Artificial neural networks (ANN) are valuable computational tools that are increasingly being used to solve resource-intensive complex problems as an alternative to using more traditional techniques (Ceylan et al., 2004). Ceylan employed ANN in the analysis of concrete pavement systems and developed ANN-based design tools that incorporated the state-of-the-art finite element solutions into routine practical design at several orders of magnitude faster than those sophisticated finite element programs (Ceylan, 2002). Meier and Rix (1994 and 1995) and Meier *et al.* (1999) firstly attempted to backcalculate the pavement layer properties using ANN. Also, the first author (Saltan et al., 2002) and the authors of the paper (Saltan and Terzi, 2004; Saltan and Terzi, 2005) used the ANN approach in backcalculating pavement layer properties. From these studies, it can be said that there are several advantages to using ANN for NDT evaluation of highway flexible pavements. The mathematical simplicity of ANN makes them computationally efficient (Meier and Rix, 1994).

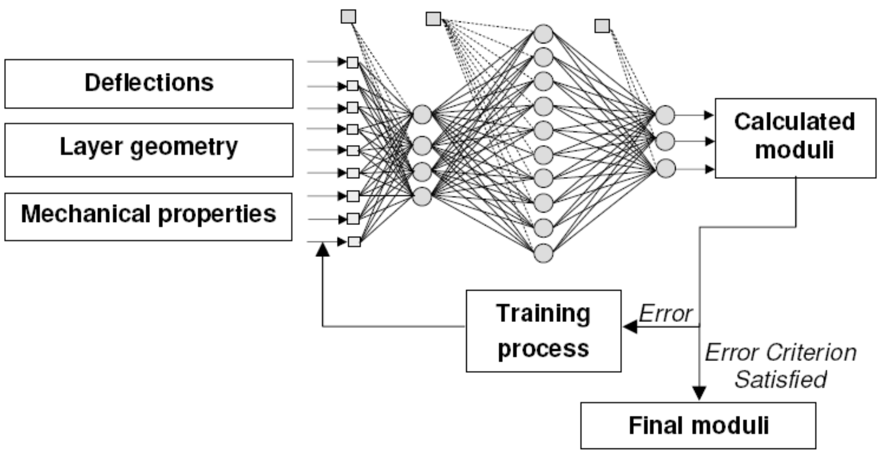

Figure 6. Illustration of ANN-based Backcalculation Procedure (Göktepe and Altun, 2006)

The application of fuzzy methodology is performed for the FWD non-destructive testing by Saltan et al., (2007). In this study, a model is established which estimates the surface deflection values of a flexible pavement from different loading conditions using fuzzy logic. Seven different load applications as input and three surface deflections positioned at different radial locations as output variables were used.

Jang (1993) first proposed the adaptive neural based fuzzy inference system (ANFIS) method and applied its principles successfully to many problems. It identifies a set of parameters through a hybrid learning rule combining the back-propagation gradient descent error digestion and a least squares method. It can be used as a basis for constructing a set of fuzzy IF-THEN rules with appropriate membership functions in order to generate the preliminary stipulated input-output pairs.

Kaur and Chou (1999) applied the Neuro-Fuzzy techniques for modeling the highway pavement performance prediction. Also, Göktepe *et al* (2005) used the ANFIS methodology for backcalculating the mechanical properties of flexible pavements.
Gene Expression Programming (GEP) is also used in modeling the deflection basins measured on the surface of the flexible pavements (Terzi, 2005). GEP is a genotype/phenotype system that evolves computer programs of different sizes and shapes (expression trees) encoded in linear chromosomes of fixed length.

Conclusions

The evaluation of pavement layer mechanical properties is essential for pavement management purposes. Nondestructive Testing techniques are generally used for determining the layer characteristic properties. Falling Weight Deflectometer (FWD) test deflection data has especially been used for inverse analyzing the *in situ* pavement layer properties. Firstly, some approximate methods were used for the backcalculation purposes such as Linear Elastic Theory, Elastic Layer Thickness and Nomograms. Then, Finite Element Method (FEM) was widely used for the backcalculation. Nowadays, new methods are utilizing for backcalculation such as Fuzzy Logic, Artificial Neural Networks, Genetic Algorithms, and other Hybrid Systems.

References

1 Chou, Y.J., *Knowledge-based system for flexible pavement structural evaluation*, Journal of Transportation Engineering, ASCE, Vol.119, no.3, USA, pp. 450-466, 1993.

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

3 Uzan J, Lytton, R L & Germann, F P, *General procedure for backcalculating layer moduli, Nondestructive testing of pavements and backcalculation of moduli* (ASTM STP 1026), (1989) 217-228.

4 Huang Y H, *Pavement analysis and design* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, USA), 1993.

5 Tam W S, *Pavement evaluation and overlay design*, Ph D Thesis, Department of Civil Engineering, University of Nottingham, U.K, 1987.

6 Zhou H, Hicks R G & Bell C A, *Development of a backcalculation program and its verification*, 7th Int Conf Asphalt Pavements, 1, (1992) 391-400.

7 Thompson MR, *Illi-pave based conventional flexible pavement design procedure*, 7th Int Conf Asphalt Pavements, 1, (1992) 222-230.

8 Saltan, M., *Analytical Evaluation Of Flexible Pavements*, PhD Thesis, Suleyman Demirel University, 1999.

9 Alkasawneh, W., 2007. *Backcalculation of Pavement Moduli Using Genetic Algorithms*, PhD Thesis, The Graduate Faculty of The University of Akron, USA.

10 *Backcalculation*, http:// training.ce. Washington .du/ wsdot/, Last Access in 13 June, 2009.

11 Noureldin, A.S., 1993. *New Scenario for Backcalculation of Layer Moduli of Flexible Pavements*, TRR 1384, 23-28.

12 Garg, N. and Thompson, M.R., 1998. *Structural Response of LVR Flexible Pavements at Mn/Road Project*, Journal of

Transportation Engineering, ASCE, 125 (3), 238-244.
13 Wang, F. and Lytton, R.L., 1993. *System Identification Method for Backcalculating Pavement Layer Properties*,TRR 1384,1-7.
14 Karadelis, J.N., 2000. *A Numerical Model for the Computation of Concrete Pavement Moduli: A Nondestructive and Assessment Method*, NDT&E International, 33, 77-84.
15 Moreland, P.B., 1983. *Calibration Services for Pavement Survey Equipment*, FHWA-RD-82-135 Final Report.
16 Kaur, D, Chou E, 1999. *Applying Neuro-Fuzzy Techniques for Intelligent Highway Pavement Performance Prediction Model*, Circuits and Systems, 42th Midwest Symposium, Vol 2, 922-924, Las Cruces, NM, USA.
17 Ceylan, H., Guclu, A., Tutumluer, E., Thompson, M.R., 2004. *Use of Artificial Neural Networks for Backcalculation of Pavement Layer Moduli*, 2004 FWD Users Group Meeting, University Inn, West Lafayette, Indiana.
18 Meier, R.W. and Rix, G.J., 1994. *Backcalculation of Flexible Pavement Moduli Using Artificial Neural Networks*, TRR 1448, 75-82.
19 Meier, R.W., Rix, G.J., 1995. *Backcalculation of Flexible Pavement Moduli from Dynamic Deflection Basins Using Artificial Neural Networks*, TRR 1473, 72-81.
20 Göktepe, A.B., Ağar, E., Lav, A.H., *Advances in backcalculating the mechanical properties of flexible pavements*, Advances in Engineering Software 37 (2006) 421–431.
21 Ceylan, H., 2002. *Analysis and design of concrete pavement systems using artificial neural networks*, Ph.D. Dissertation, University of Illinois at Urbana-Champaign.
22 Meier, R.W., Alexander, D.R. and Freeman, R.B., 1999. *Using Artificial Neural Networks as a Forward Approach to Backcalculation*, TRR 1570, 126-133.
23 Saltan, M., Tığdemir, M. and Karaşahin, M., 2002. *Artificial Neural Network Application for Flexible Pavement Thickness Modeling*, Turkish J. Eng. Env. Sci., 26, 243-248.
24 Saltan, M. and Terzi, S., 2004. *Backcalculation of pavement layer parameters using Artificial Neural Networks*, Ind J Eng & Mat Sci 11 (1), 38-42.
25 Saltan, M. and Terzi, S., 2005. *Comparative analysis of using artificial neural networks (ANN) and gene expression programming (GEP) in backcalculation of pavement layer thickness*, Ind J Eng & Mat Sci 12 (1), 42-50.
26 Jang, J., 1993. *ANFIS: adaptive-network-based fuzzy inference system*, IEEE Transactions on Systems Management and Cybernetics, 23(3), 665–685.
27 Göktepe, A.B., Ağar, E. and Lav, A.H., 2005. *Comparison of Multilayer Perceptron and Adaptive Neuro-Fuzzy System on Backcalculating the Mechanical Properties of Flexible Pavements*, ARI The Bulletin of the Istanbul Technical University, 54 (3), 65-77.
28 Göktepe, A.B. and Altun, S., 2006. *Artificial Intelligence Applications in the Backcalculation of the Mechanical Properties of Flexible Pavements*, Conference for Computer Aided Engineering and System Modeling with Exhibiton Taksim International Hotel, - Abant-Bolu, September 13-15, 2006 Turkey.
29 Saltan, M., Saltan S., Şahiner, A., 2007. *Fuzzy logic modeling of deflection behavior against dynamic loading in flexible pavements*, Construction and Building Materials 21 (2007) 1406-1414.
30 Terzi, S., 2005. Modeling the Deflection Basin of Flexible Highway Pavements by Gene Expression Programming, Journal of Applied Sciences, Vol 5 (2): pp 309-314.

ЗА ОЦЕНКАТА НА МЕХАНИЧНИТЕ СВОЙСТВА НА ГЪВКАВИ МАТЕРИАЛИ И НОВИТЕ МЕТОДИ

Мехмет Салтан, Мустафа Карашахин,Сердал Терзи
msaltan@mmf.sdu.edu.tr, sterzi@tef.sdu.edu.tr

Университет „Сюлейман Демирел”, Испарта 32260
ТУРЦИЯ

Ключови думи: *гъвкави настилки; оценка на механичните свойства; безразрушителни изпитания.*
Резюме. *Определянето на ефективността на структурата на слоя на настилката е важен въпрос при определяне на състоянието на съществуващите пътни настилки и при проектирането на настилките и възстановителните процеси. За да се приложат най-подходящите решения за възстановяване и управление, трябва да се възползваме от най-ефикасният метод за определяне на структурния капацитет на настилките. Тъй като с теоретичните подходи като линейния еластичен анализ и метода на крайните елементи, използвани за определяне на съотношението натоварване-напрежение в слоевете на настилката, се изчислява деформацията за дадени механичните свойства, е необходимо да се отчете алгоритъм за инверсия като инструмент за оценка на механичните свойства. През годините няколко методологии, включващи статични, динамични и адаптивни процеси са били използвани за получаване на механичните свойства на слоя настилка на място чрез измервания по метода на безразрушителните изпитания (БРИ). Този доклад обобщава основните методи за оценка на механичните свойства и новите тенденции.*