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Visco-elastic analysis of typical Polish flexible pavements using VEROAD

Analiza polskiej typowej nawierzchni podatnej przy zastosowaniu modelu lepko-sprężystego i programu VEROAD

ABSTRACT

The traditionally used pavement design methods are commonly based on linear elastic layered theory. Unfortunately this theory can't describe the real pavement response due to a moving load without using „engineering type of” approximations. New developments of visco-elastic response models and the availability of powerful PC have made it possible to predict the pavement response in a more accurate and fast way. VEROAD, or Visco-Elastic Road Analysis Delft, is an analytical linear visco-elastic multilayer program developed at the Delft University of Technology in the Netherlands. VEROAD takes into account the visco-elastic properties of the asphalt mixtures as well the movement of the load. The program calculates three dimensionally displacements, stresses and strains as well as dissipated energy and permanent deformation. Comparison between measured strain curves from two full scale pavements tests and VEROAD calculated strain curves are showing good correlation.

The purpose of this paper is to show the field of application of VEROAD. The paper describes also the analysis of a flexible pavement chosen from the Polish Catalogue of Typical Flexible Pavement Constructions. Different axle loads, vehicle speed and maximum air temperature are taken into consideration.

STRESZCZENIE

Większość programów komputerowych wykorzystywanych do obliczeń naprężeń i odkształceń w nawierzchniach podatnych bazuje na zasadach liniowej teorii sprężystości, a obciążenie jest statyczne. Stwarza to problemy z modelowaniem pracy warstw bitumicznych, które w wyższych temperaturach eksploatacji pracują w strefie lepko-sprężystej. Stworzony na Politechnice w Delft (Holandia) program VEROAD modeluje warstwy nawierzchni przy pomocy lepko-sprężystego modelu Burgersa, a obciążenie jest ruchome.

W artykule przedstawiono teoretyczne zasady na których oparto działanie programu VEROAD oraz wyniki przeprowadzonych w Delft obliczeń jednej z polskich,

katalogowych nawierzchni podatnych. W obliczeniach brano pod uwagę różne obciążenia osi i prędkości pojazdów oraz maksymalne temperatury powietrza z lata 1988 i 1994 roku.

Introduction and problem

In many countries, the trend of pavement design system is towards the use of analytically or mechanistic-empirically models. The reason of this is the accelerated increase of deterioration and maintenance costs of the road network observed during the recent years. This deterioration cannot be explained or predicted by empirical methods due to the fact that these methods are valid within a framework of constant conditions, whereas prevailing conditions are not constant (i.e., increased magnitude and number of axleloads, increased use of supersingle tyres, new materials etc.). Whereas, an analytical design method is more flexible to new conditions as they may be taken into consideration. The essence of analytical design models is the calculation of the response (displacements, stresses and strains) of a pavement structure imposed by traffic loads. Several response models have been developed to predict and describe the "real" response in a pavement structure. A majority of them assume the wheel load as static (fixed in position and magnitude) and the mechanical properties of the material as linear elastic. Some of these models are used in elastic multi-layer pavement analysis programs, among which Bisar-PC [1] is most likely the best known. Unfortunately road building materials do not meet these assumptions, even if evidence has shown that it is allowed in cases where only the magnitude of the stresses and strains are considered as critical design parameters.

However, for a more realistic description of the pavement response due to the transient traffic loads and the time-dependencies of the material one need an model that takes account of the visco-elasticity of the material. Two response models do account for the visco-elasticity of the asphalt material, but model the moving wheel as static loads with in- and decreasing magnitude without changing its position, that is Pace [2] and Kenlayer [3]. Recently a fully analytical linear visco-elastic multi-layer program, VEROAD, has been developed at the Delft University of Technology , Hopman [4,5,6].

Description of VEROAD

VEROAD or Visco Elastic ROad Analysis Delft, is a linear visco-elastic multi-layer program which fully accounts of both the visco-elasticity of the material and the time dependencies of a true moving wheelload. VEROAD thus calculates the 3-dimensional response of a pavement structure subjected to a moving, sliding wheel load. Furthermore, VEROAD permits calculation of permanent deformation and dissipated energy in the pavement for one load cycle, from the theory of linear visco-elasticity , Hopman [7]. Consequently a better and more realistic prediction of the pavement response are obtained.

General approach

The general approach used in VEROAD, based on the correspondence principle, which states that a visco-elastic problem is an elastic problem in Fourier or frequency space. This is shown in figure 1.

- First; Remove all time-dependencies of the problem, by transforming all time dependent "parameters and equations" to the Fourier-domain.
- Second; Express the visco-elastic material properties in terms of frequency, thereafter solve per frequency the obtained linear elastic problem.
- Third; Transform the obtained frequency dependent dsas back to the time domain.

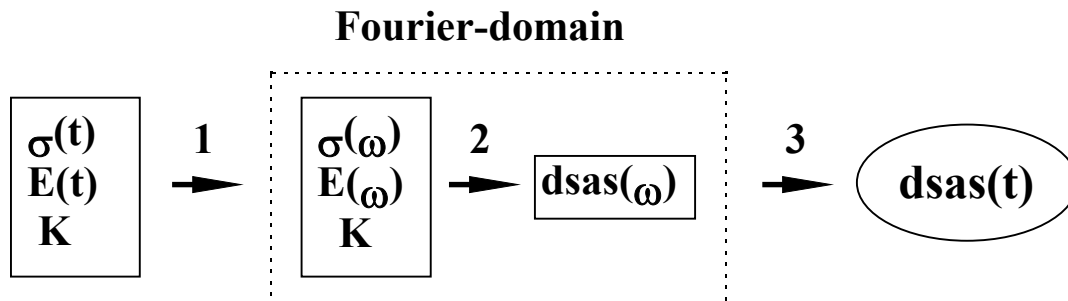


FIGURE 1. General approach in VEROAD.

Load model

In VEROAD the wheelload is modelled by vertical and shear stresses, uniformly distributed over a circular area, sliding over the pavement surface at constant velocity. The wheelload is characterised by the contact stresses, radius of the contact area and the velocity. Modelling of more detailed load distribution and contact conditions is possible by superposition of different loads. Also different wheel and axle configuration can easily be modelled.

It is essential to understand the difference between a moving load and a fixed load especially regarding to the principal stresses. By a wheel, moving upon the pavement surface, vertical, horizontal and shear stresses are induced on each material element in the pavement. During the loading cycle, the magnitudes of these stresses are changing continuously. Hence, the principal stresses acting on a given element are also continuously changing in direction (rotation) over time. Figure 2 shows this rotation. VEROAD takes this rotation of the principal stresses into consideration. This effect can not be obtained by modelling the load, as fixed in place.

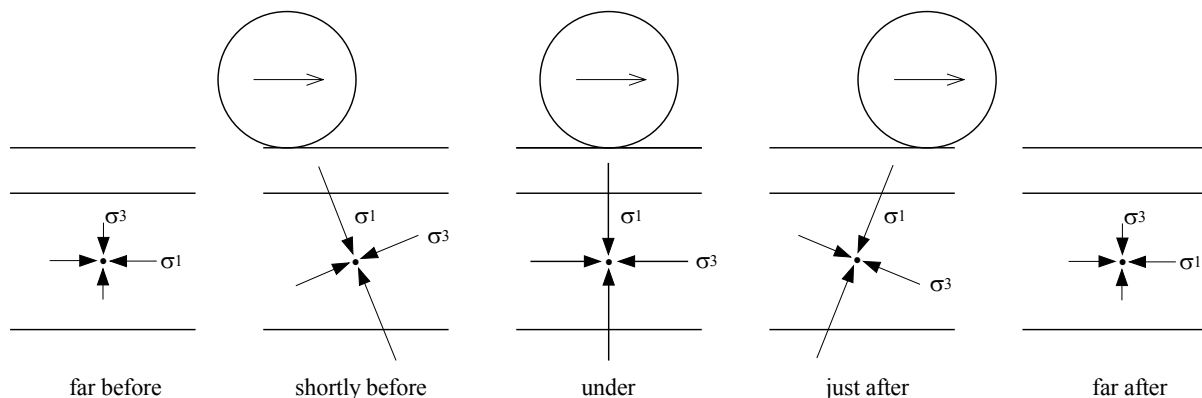


FIGURE 2. Rotation of principal stresses due to a passing wheel [8].

Material model

The fundamental material properties, shear modulus G , and the bulk modulus K , are used in the model to describe the material behaviour. The Burgers' model is used for the description of the linear visco-elastic behaviour of the shear modulus, which describes the shape changes of a body under shear stress. In this model the material is determined by the parameters η_1 , η_2 , G_1 , G_2 where: G_1 represents the instantaneous elastic behaviour, η_1 represents the flow or permanent deformation and G_2 and η_2 represents the delayed elasticity. The bulk modulus K , describing the volume changes of a body under hydrostatic stress, is taken as linear elastic. The Burgers' model and its parameters are shown in figure 3. Determination of the Burgers' parameters can easily be obtained from any frequency sweep test (i.e., two, three or four point bending test or direct tensile test etc.). The bulk modulus can be determined from triaxial tests. The G and K modulus can of course be expressed by the stiffness modulus E and/or the Poisson's ratio ν . That is, E described by Burgers' model and ν taken linear elastic. All according to the relations between the elastic constants in the theory of elasticity.

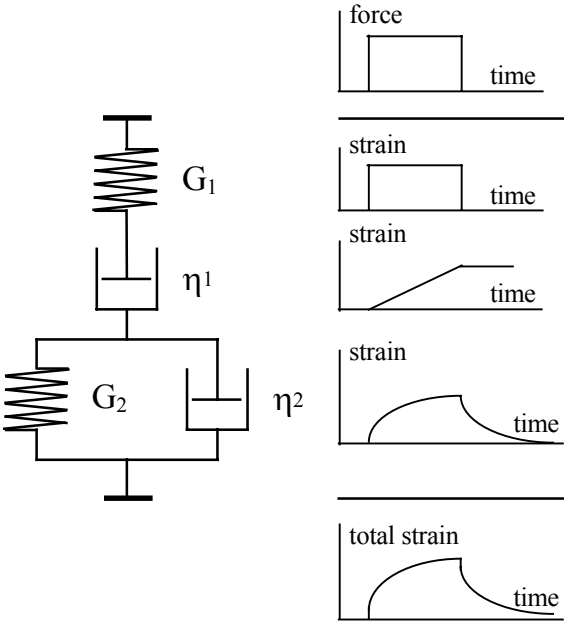


FIGURE 3. The Burgers model for the shear modulus and responses [7].

Pavement model

The pavement is described by a multi-layer system containing at most 15 horizontal layers resting on a half space. Each layer is assumed to have a uniform thickness and to extend infinitely in the horizontal plane. The characteristics of each layer are determined by a maximum of 5 material parameters: a linear visco-elastic stress-strain relationship requires 5 parameters, a linear elastic behaviour is modelled by 2 parameters (e.g. by setting η_1 , η_2 and G_2 to infinity). Furthermore, the material in each layer is assumed to be homogeneous and continuous. Furthermore each pavement layer is assumed to extend to infinity in the horizontal plane. Full or "partial" friction between the layers can be modelled. It is also possible to model different friction in the longitudinal and transversal direction. The lowest layer, the half space, can from a physical principles not have a finite value for η_1 .

Distinction between VEROAD and a linear elastic response model

A calculation of strains at the bottom of the asphalt layer in a pavement structure was made by VEROAD and a linear elastic multi-layer program to show the differences between the

two calculations. The input parameters were the same in both calculations except for the velocity and the visco-elastic modelling of the asphalt material used by VEROAD. The Young's modulus for the linear elastic calculation was taken equal to the stiffness modulus at 8 Hz using the visco-elastic description. The input parameters are in table 1.

These calculations show a distinctive difference of the longitudinal and transversal strain curves, as can be seen in figure 4. The strain is on the vertical axis in [mm/m], tension is positive, wheel position in [mm] is on the horizontal axis. The load is moving from the left to the right, the strain gauge is at $x = 0$. The figures should be read as follows: when the wheel is at position $x = x_1$, the strain given at the coordinate is the strain measured by the "strain gauge".

TABLE 1 INPUT PARAMETERS

Wheel load	: 75N	Velocity	: 5.5 m/s				
Contact pressure	: 0.95 MPa	Temperature	: 20°C				
Radius of contact area	: 158.5 mm	Type of wheel	: 425/65 R22.5				
layer thickness	η_1 [MPa.s]	η_2 [MPa.s]	G_1 [MPa]	G_2 [MPa]	K [MPa]	E^* [MPa]	ν^*
150 mm	250	120	4200	5000	9000	6700	0.38 ¹
∞	∞	∞	60	∞	180	162	0.35

* Corresponding values, ¹ Determined at 8Hz.

The VEROAD calculated strain curves are clearly showing time retardation and asymmetry, this asymmetry is not found in the output of the elastic calculation. Furthermore, the magnitude of the calculated transversal strain, in this case, is larger than the longitudinal strain. Whereas, the strain peaks of the elastic calculations are equivalent.

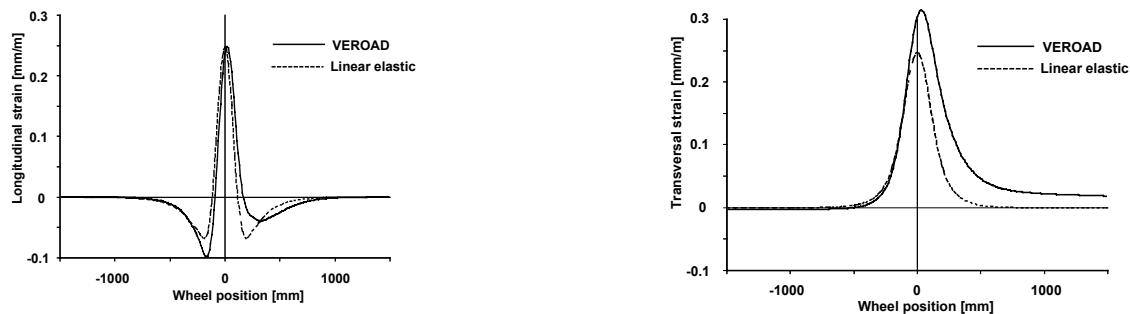


FIGURE 4. Strain curves calculated by VEROAD and a linear elastic multi layer program [9].

The VEROAD calculated strain curves contain much information about the pavement behaviour and the load characteristics.

- First; it is obvious that the width of both curves has to do with the velocity of the load and the radius of the contact area.
- Second; the fact that the maximum transversal strain peak is higher than the maximal longitudinal strain peak indicates that the material is visco-elastic. The strains in the transversal direction take a longer period of time than those in the longitudinal direction and therefore the material acts "softer" in transversal direction. Thus resulting in larger strain.

- Third; The maximum of the peaks is not developed at $x = 0$ but somewhat after. This is the time retardation that also follows from the visco-elastic properties of the pavement material. The time delay is larger at higher pavement temperatures and/or slower moving loads.
- Fourth; The remaining offset in the transversal strain indicates that the material model has inherently a component causing permanent deformation.
- Fifth; Concerning the longitudinal strain, the asymmetry in the shape depends on the visco-elastic nature of bituminous materials.

VEROAD calculated strain curves shows good correlation compared to strain curves measured at full scale-tests as shown by Nilsson et. al. [9].

Analysis of typical flexible pavements in Poland using VEROAD

In Poland, as in other countries (also in the Netherlands), an increase of traffic loads is observed. Increasing number of axles and axle loads leads to greater stresses and strains in pavements. Additionally, maximum summer air temperatures in Poland have changed from +28°C in 1988 to +36°C in 1994 (calculated by SUPERPAVE method). Increased pavement temperature accelerated deterioration of road network, severe rutting is observed.

In November 1995, calculations of stresses, strains and permanent deformations for one type of Polish typical pavement construction were made at TU Delft (The Netherlands). For analysing the VEROAD software was used. The aim of calculation was to compare the influence of axle loads and load speed on flexible pavement in two different temperature conditions. Due to lack of the real parameters of the Burgers' models for Polish road materials, estimation of them was done based on engineering knowledge. Therefore, obtained results should be treated more general, as a checking of the VEROAD possibilities.

Description of the calculation data

Pavement construction

Pavement construction was chosen from Polish Catalogue of Typical Flexible & Semi-rigid Pavements (pav. F7). Structure of pavement, thickness of layers and materials are presented on FIG. 5

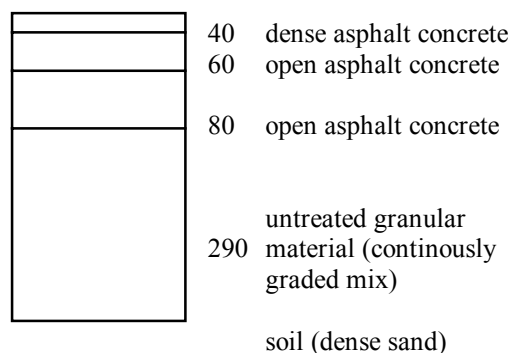


FIGURE 5. Typical flexible pavement structure in Poland

Temperature characteristics

Calculation was carried out for two temperature periods: summers 1988 and 1994. For these years, the maximum daily temperatures (day by day) of summer period (June-August) were obtained from the weather station in Łódź (Central Poland). According to SUPERPAVE method, from these sets of data the periods with the maximum average 7-days temperature were found in 1988 and 1994 respectively.

Pavement temperature on depth 20 mm was calculated from:

$$T_{20} = (T_{\text{air}} - 0.00618 \text{ Lat}^2 + 0.2289 \text{ Lat} + 42.2) * (0.9545) - 17.78$$

where:

- T_{20} - temperature 20 mm below surface,
- T_{air} - air temperature according to SUPERPAVE (maximum average of 7-days extremely hot temperature),
- Lat - latitude.

Air temperature and temperature in pavement (20 mm below surface) are presented in TABLE 2.

TABLE 2. PAVEMENT AND AIR TEMPERATURES

	7-days maximum average temperature	pavement temperature on depth 20 mm
summer 1988	28°C	44°C
summer 1994	36°C	52°C

Description of the moving load

In VEROAD the load is modelled as a circle with a uniform vertical stress. The calculations were done for 80 kN/axle and 100 kN/axle, tire pressure 0.56 MPa and 0.707 MPa respectively. The speed of the wheelload was either 30 km/h or 60 km/h.

Material parameters

In calculations, the asphaltic layers are modelled visco-elastically. The bituminous (180 mm) layers were divided into 3 „sublayers”. For each sublayer temperature and resilient modulus were determined according to results from Nottingham Asphalt Tester. Problems occurred during determination of stiffness moduli in temperature above +30°C. At high temperatures bitumen stiffness falls down below 5 MPa and one can't use BANDS program for calculation of mixture stiffness. Therefore stiffnesses were estimated by extrapolation of results from NAT.

For given sublayer data the Burgers' model parameters G_1 , G_2 , η_1 , η_2 , K were estimated with VEPROAD program. All parameters are showed in TABLES 3 and 4.

TABLE 3. INPUT PARAMETERS OF MATERIALS IN SUMMER 1988 CONDITIONS

Summer 1988 Sublayer	thickness [mm]	η_1 [MPas]	η_2 [MPas]	K [MPa]	G_1 [MPa]	G_2 [MPa]
1. dense asphalt concrete	40	55	39	9000	1750	1450
2. open asphalt concrete	70	230	110	9000	4800	4000
3. open asphalt concrete	70	500	300	9000	8000	7000
4. granular subbase	290	∞	∞	335	300	∞

5. subgrade - dense sand	∞	∞	∞	112	100	∞
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TABLE 4. INPUT PARAMETERS OF MATERIALS IN SUMMER 1994 CONDITIONS

Summer 1994 Sublayer	thickness [mm]	η_1 [MPas]	η_2 [MPas]	K [MPa]	G_1 [MPa]	G_2 [MPa]
1. dense asphalt concrete	40	25	18	9000	1100	980
2. open asphalt concrete	70	130	60	9000	3400	2900
3. open asphalt concrete	70	350	180	9000	6000	5800
4. granular subbase	290	∞	∞	335	300	∞
5. subgrade - dense sand	∞	∞	∞	112	100	∞

Calculations

Calculations for 3-dimensional „network” of points is timeconsuming. For this project, two computers with Pentium 90 processors were utilized.

Results

For every point calculated one obtained the results of displacements, stresses and strains (dsas). These results are not discussed in this paper. Examples of result of the dsas are presented on FIGURES 6-8.

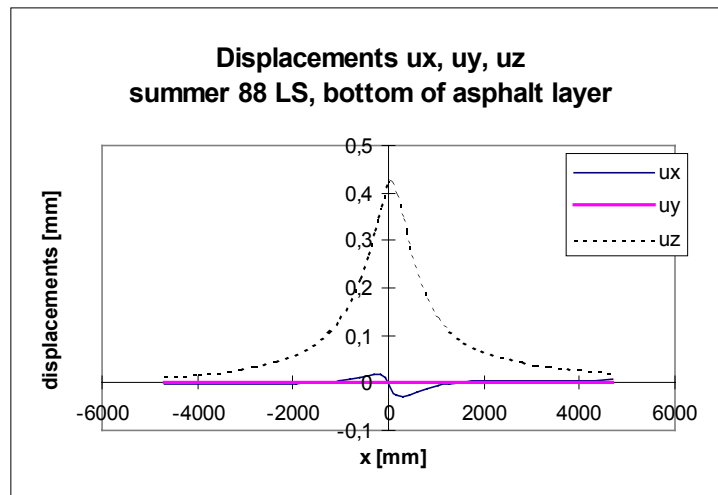


FIGURE 6. Displacements calculated for summer 1988, 30 km/h, 100 kN/axle

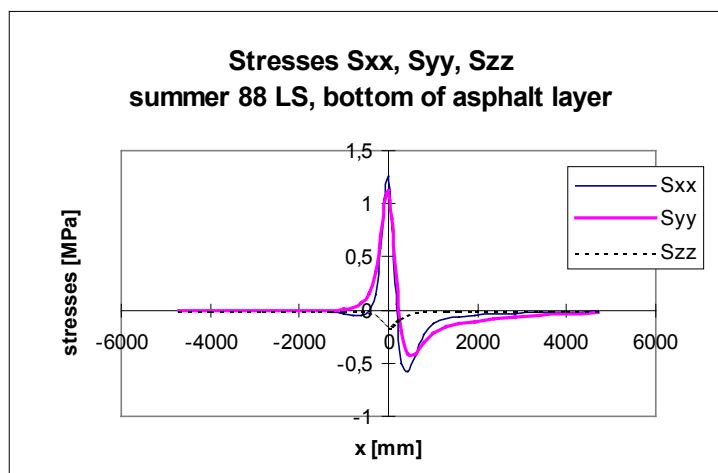


FIGURE 7. Stresses calculated for summer 1988, 30 km/h, 100 kN/axle

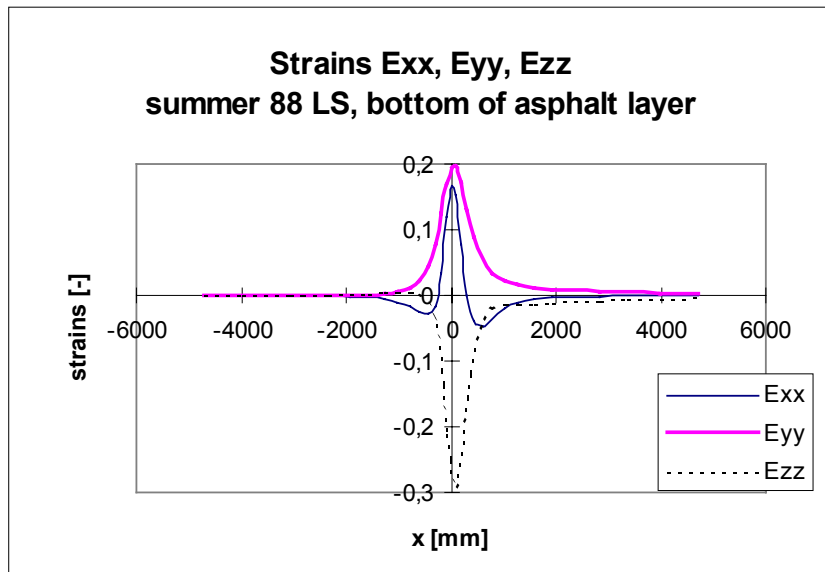


FIGURE 8. Strains calculated for summer 1988, 30 km/h, 100 kN/axle

Moreover, the results of the permanent deformations were obtained. Influence of different factors (speed, load) on rut depth creating is presented on FIGURES 9-12.

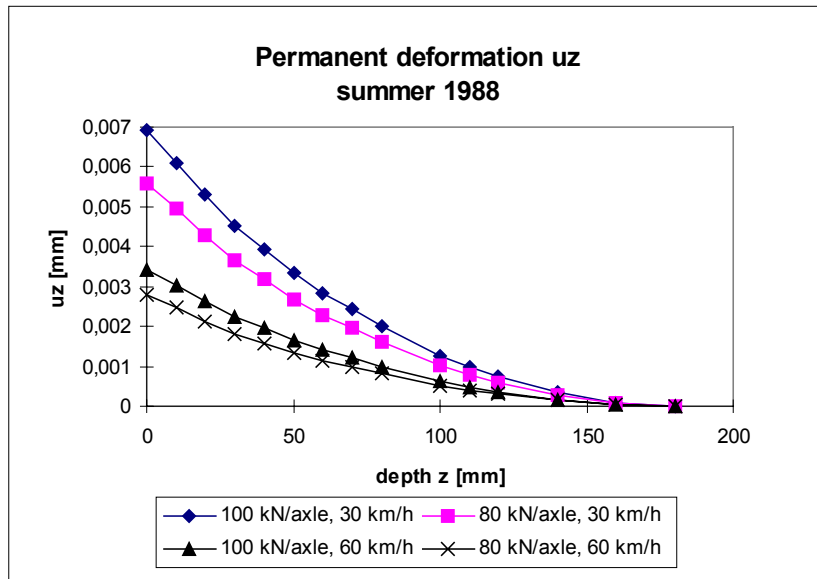


FIGURE 9. Comparison of permanent deformations calculated for summer 1988, all variables

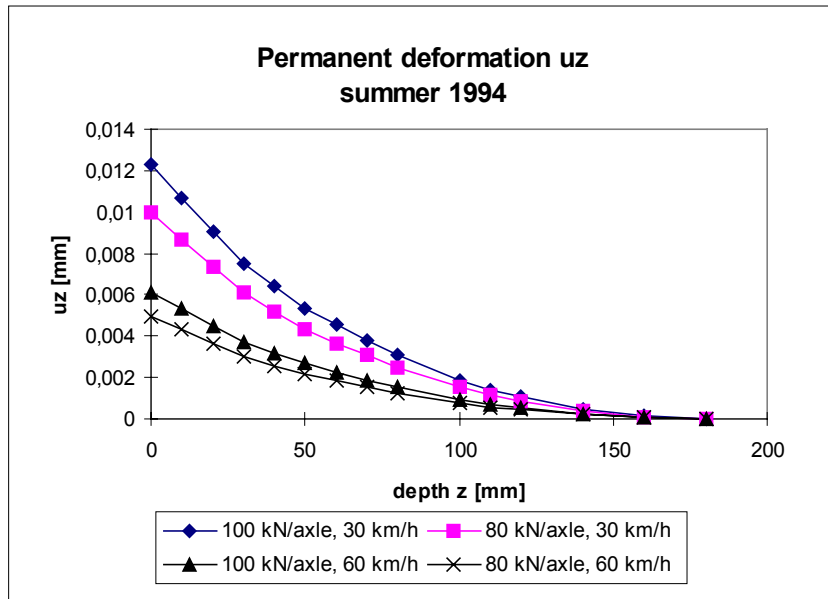


FIGURE 10. Comparison of permanent deformations calculated for summer 1994, all variables

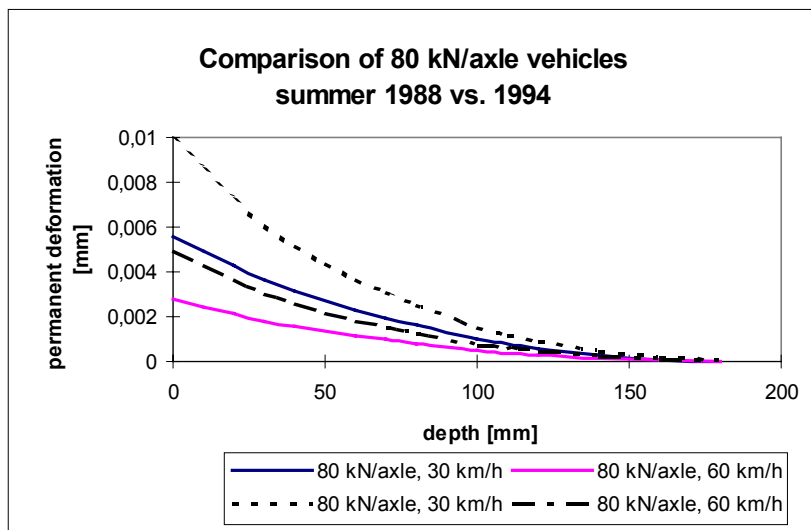


FIGURE 11. Comparison of permanent deformations calculated for 80 kN/axle load, all variables

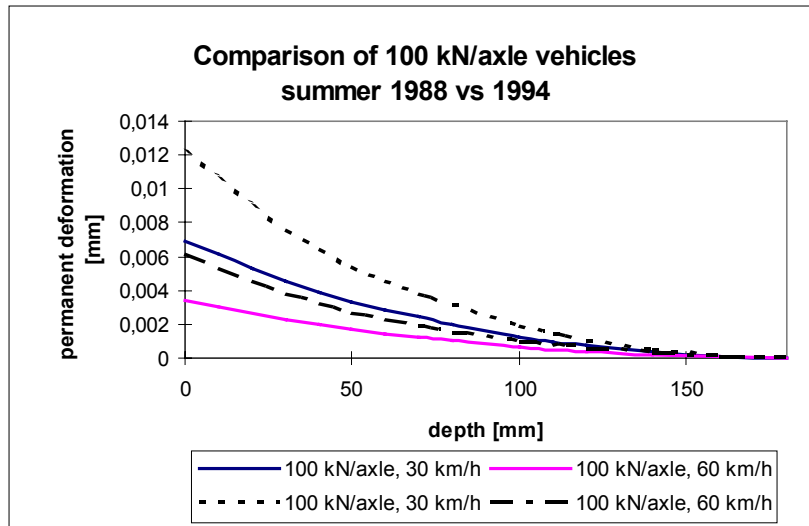


FIGURE 12. Comparison of permanent deformations calculated for 100 kN/axle load, all variables

Conclusions

Analysis of calculation results for both summers (1988&1994) allows to draw following conclusions:

- Graphs of relationships obtained for summers 1988 and 1994 show similar shape.
- Time-dependent stresses, strains and displacements mainly depend (for both summers) on the load magnitude. Time of loading (speed) is in this case less important. It is clear that load magnitude causes higher strains at the bottom of asphaltic layer. As a result a greater possibility of cracking occurs.
- The inverse dependency is observed for permanent deformations. Magnitudes of permanent part of the E_{yy} , E_{zz} and permanent deformation u_z mainly depend on loading time. For the same conditions in pavement and the same type of loading (e.g. equal load per axle) more dangerous are heavier vehicle at lower speed.
- Transversal strain is larger than longitudinal strains. It is due to loading frequency, which is different for different depths and directories. As a result also material response should be different. VEROAD takes this frequency dependent behaviour into account. This is due to the fact that transversal stress signal contains lower frequency components than longitudinal stress signals, meaning that material responds with a lower stiffness. It is quite different result from linear-elastic theory calculations where values of both strains are equal.

And more general conclusions:

- Program VEROAD seems to be very useful tool for research analysis of different types of pavement structures.
- There is necessity to determine the real visco-elastic parameters of Polish asphalt mixtures.

- Since the calculations are very time consuming, the applications of VEROAD will increase with development of computer processor's speed.

References

1. De Jong, D.L., Peutz, M.G.F., Korswagen, A.R., „Computer program BISAR, Layered Systems Under Normal and Tangential Surface Loads”, Koninklijke/Shell-Laboratorium, Amsterdam, AMSR. 00006.73 Shell Research B.V.,1979.
2. Rowe, G.M., Brown, S.F., Sharrock, M.J., Bouldin, M.G., „Visco-elastic analysis of hot asphalt pavement structures”, Offered for publication at the 1995 Transportation Research Board, Washington D.C., January 1995.
3. Huang, Y.H., „Pavement Analysis and Design”, University of Kentucky, Prentice Hall, Inc., New Jersey, 1993.
4. Hopman, P.C., „VEROAD: A linear visco-elastic multilayer program for the calculation of stresses, strains and displacements in asphaltic road constructions. Part I: A visco-elastic halfspace”, Delft University of Technology, ISSN-0169-9288-7-93-500-6, December 1993.
5. Hopman, P.C., „VEROAD: A linear visco-elastic multilayer program for the calculation of stresses, strains and displacements in asphaltic road constructions. Part II: A visco-elastic multilayer program”, Delft University of Technology, ISSN-0169-9288-7-94-500-6, November 1994.
6. Hopman, P.C., „VEROAD: A visco-elastic multilayer program”, Transportation Research Board, Washington D.C., 1996.
7. Hopman, P.C., „Calculation of energies dissipated, using a visco-elastic multilayer program”, International Seminar on Durable and Safe Road Pavements. Kielce, Polen, May 1995.
8. Mork, H., „Analyse av Lastresponsar for Vegkonstruktioner”, PhD Thesis, Doktor ingenjørsavhandling, 1990:6, Institutt for Veg-og Jernbanebygging, Norges Tekniske Högskole, Trondheim, 1990.
9. Nilsson, R.N., Oost, I., Hopman, P.C., „Visco-elatsic analysis of full scale pavements: Validation of VEROAD”, Transport Research Board 1996.