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PHD THESIS

ASSESSMENT, RESEARCH AND USE OF METHODS FOR DETERMINING THE STRENGTH OF BASE COURSES OF ROAD PAVEMENT STRUCTURE

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Abstract. This summary of the author's PhD thesis supervised by Prof Dr Alfredas Laurinavičius and defended on 21 December 2011 at the Vilnius Gediminas Technical University. The thesis is written in Lithuanian and is available from the author upon request. Chapter 1 covers the analysis of the literatute. There is the review of research works carried out in Europe and other countries of the world for determining structural strength of road pavements by calculation methods during their design and gives a wide description of the main methods used in Lithuania. Chapter 2 gives the analysis of the effect of different factors on the road pavement strength, studies a damaging impact of the axle loads of moving vehicles on road pavement, also the dependency of strength and condition of road pavement on the changes in the ambient temperature and seasonal precipitation. Chapter 3 analyses the stages of experimental research, selection of a test section for experimental research, methodology for investigating pavement structure parameters and the equipment used, gives the analysis of research data obtained by the author. Chapter 4 describes statistical analysis and assessment of research results obtained on the subgrade and the lower pavement layers. Reduction coefficients are suggested to be used betwen the static and dynamic measuring methods.

Keywords: strength of road pavements, road pavements, static and dynamic measuring methods, static beam, FWD.

Formulation of the problem

The road network of Lithuania has been developed well enough and in recent years no considerable changes have taken place (21 267 km of roads of national significance), however, the earlier constructed roads are not able to carry the increased loads and the growing traffic volume of heavy vehicles. Due to those factors much more funds are required for the road maintenance and for the assurance of traffic volume. On the main roads of Lithuania the number of equivalent axle loads has increased more than twice since the year 2000, and the total traffic volume – by about 55%. Though, at present due to the worldwide crisis the traffic volume has lowered, the increased heavy loads cause a rapid deterioration of road pavements.

Pavement structural strength is one of the main indices to determine pavement ability to carry traffic loads. The strength of separate layers of flexible pavement structures and of the whole pavement structure can be calculated during their design. When building and reconstructing roads it is necessary to control whether the strength of the newly built structural layers corresponds to their design strength. For this purpose, various methods for determining pavement structural strength are used. The static and dynamic non-destructive methods are worldwide used to determine the deformation modulus of pavement structures, however, in many countries when designing and building road pavement structures their strength is defined by a static deformation modulus.

The object of research is as follows: methods for determining structural strength of road pavements, their assessment and use, employment and assessment of measuring methods. **Experimental object** – road pavement structure built in the test section, analysis and assessment of comparable measurements taken by the static and dynamic measuring methods.

The aim of research – to theoretically justify suitability and compatibility of the static and dynamic measuring methods for measuring the strength of different structural pavement layers (except the upper layers of pavement structure) and to select the most reliable method under the conditions of Lithuania.

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The tasks of thesis

The following tasks were solved to achieve the aim of research:

1. Analysis of methods for measuring structural strength of road pavements.
2. Experimental research on the structural strength of Lithuania‘s road pavements using different measuring devices by the static and dynamic measuring methods.
3. Determination of a reliable relationship between the results of measuring methods obtained with the help of experimental measurements by the static and dynamic methods.
4. Justification of the most suitable measuring method for the separate pavement structural layers.

Methodology of research

Methodologies of research are based on the analysis of works in this field by the scientists of Lithuania and foreign countries. The following research methods were employed in this work: analytical, statistical, mathematical; experimental – laboratory; experimental field-test (on roads).

The dissertation is based on the scientific publications by the authors of Lithuania and foreign countries, scientific and information publications by academic institutions.

Scientific novelty

Scientific novelty and importance of the work are represented by the following results:

1. For the first time with the help of different static and dynamic measuring devices the research was carried out of different pavement structures laid on the subgrade of equal strength.
2. For the first time a comparable analysis of the static and dynamic measuring methods and measuring results was performed using different measuring devices.
3. Having assessed the currently used strength methods, based on deflection measurements, where suggested suitable measuring method for separate structural layers. According to the reduction equations obtained, the reduction coefficients were suggested to be used between the results of static and dynamic measuring methods.

Practical value

1. The research showed that methods and devices to determine strength shall be used based on the application of measuring results:

– static measuring methods – most suitable for the determination of deformation modulus at the surface of pavement layers laid from aggregate materials.

– dynamic measuring methods – most suitable for the detail investigation of the whole condition of pavement structure.

2. Having made the analysis of measuring results a reliable correlation between the measuring methods was determined; the difference between the results obtained by the static and dynamic devices was identified; regression equations were suggested to reduce the E moduli values by dynamic measuring devices to the E_{v2} values measured by static measuring methods. Reduction coefficients were suggested for the comparison of the static and dynamic measuring methods.

Analytical review of methods for the determination of pavement structural strength

Pavement structural strength is one of the main indices to determine pavement ability to carry traffic loads. The strength of the separate layers of flexible pavement structures and of the whole pavement structure can be calculated during their design. When building and reconstructing roads it is necessary to periodically control whether the strength of the newly built structural layers corresponds to their design strength.

Most European countries use analytical methods for pavement design and determination of the need for pavement strengthening which conceptually are very similar. All the European and worldwide design methods are adjusted to the local climatic factors and materials used in that country. When using pavement strength determination models of other countries it is essential to adjust them to the particular country.

At present Lithuania uses different methodologies for the design of road pavements: the American AASHTO methodology as well as the pavement design methodology developed by DORNII on a basis of the *Russian Road Instruction VSN 46-83*.

The most important pavement indices are strength and roughness. If the road pavement is not strong enough the ruts and damages occur, the skid-resistance considerably increases, sometimes the road pavement becomes absolutely impassable. Driving on rough pavement causes not only vehicle and pavement damages, but also inconveniences for the passengers and transported goods. Therefore, the road pavement must be strong enough, free of any ruts or damages.

The scientists of foreign countries use to determine the performance of pavement structure under real conditions by building and testing pavement structures in special test polygons. One of the largest test polygons was established in 1989, in the French Central Laboratory of Roads and Bridges. Here the scientists of various European countries tested and evaluated the performance of three different pavement structures. The pavement structures were tested under the effect of different loads, the readings of the transducers of stresses, pressure, temperature and moisture were recorded and the tendencies for the development of defects in the upper pavement layers were determined.

In 2006–2007 the testing of road pavement structures by six different transducers was carried out in the University of Maine (Lauren, Swett 2007). Transducers were installed in different pavement structural layers to determine seasonal effect on the structural strength of road pavement.

The USA carried out investigations of experimental pavement structures in order to find out the change in the strength of separate layers during freeze – thaw periods. The Falling Weight Deflectometer (FWD) was used here to measure pavement structure in different periods of the year and to define the resistance of each pavement layer to frost effect.

Models of the performance of pavement structure under real conditions have been comprehensively analyzed by the Professor of the Technical University of Denmark P. Ullidtz (Ullidtz 1998). The scientist studies elasticity of pavement structure, distribution of stresses, models influencing the service life of road pavement, its condition and tendencies for the initiation and development of defects.

Šiaudinis (2006) stated that Falling Weight Deflectometer is suitable to determine the structural strength of investigated road pavements and FWD measured results are close to results from measurements with static testing device. After range of experimental research the seasonal factors for measurements with FWD for Lithuanian conditions were determined (Šiaudinis, Čygas 2007). Talvik and Aavik (2009) founded good relationship between equivalent *E* modulus measured with FWD and road pavement structure layers indicators. Relationship between measured *E* modulus and subgrade indicators was founded not very strong.

More research relative with evaluation of correlation of measuring methods for road pavement structure layers were done in last decade (Deblois *et al.* 2010; Jin Hak Yi *et al.* 2010; Kavussi *et al.* 2010; Mehta, Roque 2003; Motiejūnas *et al.* 2010; Tompai 2008; Vaitkus *et al.* 2005).

For the control purposes various methods are used to determine the structural strength of pavement layers. Deformation modulus is most frequently determined by the non-destructive static and dynamic methods. The strength of road pavement and its separate structural layers in Lithuania is regulated by the static deformation modulus.

In order to use a dynamic measuring method for all pavement structural layers the research was started the aim of which was to determine the correlation between the measured dynamic and static modulus. The new dynamic values would give an opportunity to carry out quality control and to identify the bearing capacity of the study layer not only by a static plate load test, which is time-consuming and requires much effort, but also by dynamic devices.

To find out and compare the accuracy of testing results obtained by the static and dynamic methods the first measurements in Lithuania were carried out in 2004 at the selected 20 points of the road A5 Kaunas – Marijampolė – Suvalkai, from 16.10 km to 16.40 km (grade-separated Garliava intersection). Measurements were carried out during road construction and this allowed to measure deflections of each structural layer and to estimate their deformation modulus. In 2007 the experimental test section of road pavement structures was built in Pagiriai where experimental research was carried out by the author of the dissertation. Further research results, their analysis and assessment will allow to select the most suitable measuring method for the separate pavement structural layers.

Methods for the determination of structural strength parameters of road pavement

Road pavement strength is the resistance of pavement to stresses and strains caused by traffic loads and climatic conditions. Road pavement strength is an invisible quantity, however, it is of special importance for the determination of pavement condition. It is very expensive to construct asphalt overlays, therefore, information about road pavement strength helps to plan pavement repair works taking into consideration the traffic volume and its composition.

From the recently worldwide used methods for determining road pavement strength the most effective method is based on deflection measurements (Fig. 1). The scientific research works of different countries have explained the relationships between load, elastic deflection of road pavement and modulus of elasticity of the thicknesses of pavement layers. Those relationships, determined by the same-size load, can be used to identify the strength of road pavement structure. The testing method enables to determine the force amplitude and its duration which is approximately equal to the duration of the wheel load impact on the road pavement, to evaluate indirect and plasto-elastic deformation value, to measure deflections in points situated at a distance from the loading centre.

In order to determine the strength of separate pavement structural layers it was necessary to find out the relationship between deformation moduli calculated from pavement structure deflections obtained by the static and dynamic devices.

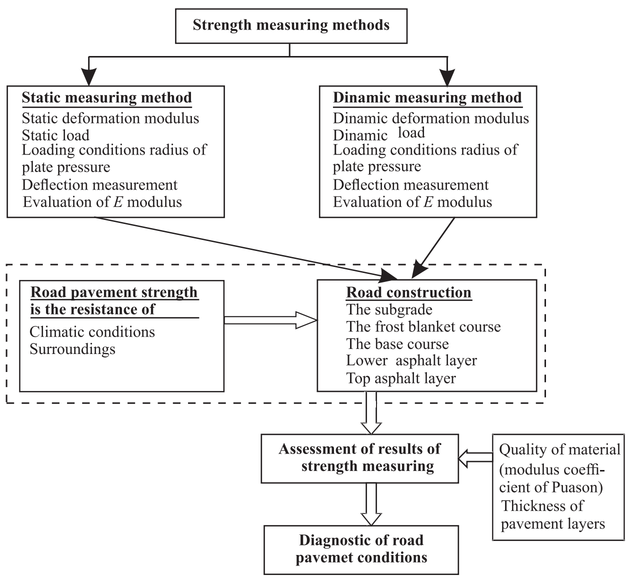

Fig. 1. Strength measuring methods based on deflection measurements

For practical purposes the most simple is a static strength measuring method. When taking measurements by static measuring devices a certain area of the pavement structure is being gradually loaded and unloaded. The certain indices could be distinguished characterizing the static strength of road pavement, i.e. ability of the structure to resist vertical stresses and horizontal stresses.

The essence of the static methods for determining pavement structural strength – to initiate a relative pressure to the pavement surface which, according to its value, corresponds to the load impact produced under the plate by vehicle wheel or dual wheels. In the first case the impact to the pavement surface is transferred through a rigid plate in an area which is equal to the calculated wheel track. Depending on the elastic deflection the total modulus of elasticity is calculated by the formula according *Otsenka prochnosti nezhostkikh dorozhnykh odezhd 218.1.052-2002*:

$$E = \frac{PD}{l}(1 - \nu^2), \quad (1)$$

where P – vehicle wheel pressure to the pavement, Pa; D – diameter of the plate, m; l – forced pavement deflection, m; ν – Poisson's ratio.

The above mentioned tests basically describe the average statistical modulus of elasticity of road pavement structure during a period of pavement service life. Based on the test data it is only possible to determine the ability of road pavement structure to resist main vertical stresses. However, the tests do not allow to fully describe the condition of road pavement structure and to predict its further worsening.

A common disadvantage of all static methods is that when using such methods it is impossible to assess the ability of pavement structure to essentially realize a dynamic impact caused by real traffic movement (Iliopolov *et al.* 2002; Iliopolov, Selezniov 1997).

Generally, all the static calculation schemes and assessment methods should be used for determining pavement structural strength, the ability of road pavement structure to carry the considerably increasing traffic loads and, thus, to avoid a rapid failure of road structure. Based on the static strength measuring results obtained with the help of dynamic coefficients and taking into consideration the rapidly growing traffic flows and increasing loads – this is an empirical transition from static decisions of the theory of elasticity to the failure of insufficiently investigated road structures due to the impact of dynamic stresses. With the worsening pavement surface a dynamic impact of traffic is increasing. This is first of all evidenced by the increase in energy accepted by the road structure. Then, the tendency of changing relations between different micro structural elements of road structure becomes obvious as well as of their failure.

In ideal case, condition assessment methodology shall explain reasons for the decrease of strength and to clearly distinguish the condition of separate elements: pavement, base courses and subgrade layers, and this in each case will allow to decide on the most efficient complex of repair measures. The standard solution to increase strength by laying a strengthening layer can appear ineffective in case when the sugrade soil is weak or the base courses are damaged. In that case the static condition assessment methods are uninformative.

Thus, static methods used for the design of road pavement structures and their strength assessment have the following disadvantages:

- static methods allow to determine the ability of road pavement structures to carry loads considerably exceeding the loads caused by road traffic and are uninformative for assessing the level of fatigue development processes in the structural layers of road pavement;
- static testing methods do not allow to find out the reason for the decrease in the strength of road pavement structure and restrict the effective decision-making when predicting road repair and maintenance.

In order to objectively assess road pavement condition it is advisable to apply impact analogical to a real traffic movement. Unlike the static measuring methods, dynamic methods make it possible to assess loads from moving vehicles.

When using dynamic measuring methods the load is produced by the drop of a falling massive cylinder in a very short period of time which causes deformations of structural pavement layers.

Dynamic deformation modulus E_{vd} describes deformation of soil under the load of predetermined size. Having measured the soil deformation s under the loading plate the value of modulus is found by the formula:

$$E_{vd} = 1.5r\frac{\delta}{s}, \quad (2)$$

where: r – radius of the loading plate, cm; δ – dynamic load equal to 0.1 MN/m^2; s – soil deformation under the loading plate, mm.

Dynamic deformation modulus E_{vd} MN/m^2 is found from the Eq (2). Knowing the determined value of dynamic load under the plate δ, the plate diameter and the average value of measured deformations s mm, dynamic deformation modulus is calculated from the Eq (3):

$$E_{vd} = \frac{22.5}{s}. \quad (3)$$

In Lithuania the recommended values for reducing dynamic deformation modulus E_{vd} to static deformation modulus E_{v2} are given in *LST 1360.5:1995 Road Soils. Testing Methods*.

Having taken measurements with the use of dynamic measuring method the obtained elastic deflection is reduced to a comparable shape (static deflection) using coefficients of regression relationship:

$$l_f = X_1 l_d + X_2, \quad (4)$$

where l_f – real deflection, mm; l_d – deflection measured by a dynamic device, mm; $X_{1,2}$ – empirical coefficients of regression relationship.

Calculation of data obtained by dynamic methods requires much time even when using modern electronic calculation techniques. Therefore, all the mathematical models of modern high-efficiency falling weight equipment are oriented to the calculation of the general modulus of elasticity of the road structure.

Dynamic measuring methods exceed the static ones both in the accuracy of results obtained and in the mobility of the execution of experiments. But the most important advantage of dynamic methods is, without doubt, their adequacy to real loads and traffic impacts. A wide experience of the use of dynamic analysis when testing road pavement proves a perspective development of those methods in the field of strength assessment. The most informative is the analysis of the structural strength of dynamically loaded road pavement.

When determining the strength of different pavement structural layers by the static and dynamic measuring methods it was necessary to find out correlation between deformation modulus calculated from pavement structure deflections obtained by the static and dynamic devices.

For the meantime, the dynamic method is not widely used in Lithuania and in some foreign countries since dynamic modulus has not been acknowledged for the assessment and control of the quality of pavement structural layers. Therefore, dynamic measuring devices are used rather seldom, mostly in small-scale projects where testing by a static plate load would be too complicated.

In order to use those dynamic devices for the measurements on the lower layers of road pavement structures the research was started aimed to determine correlation between the measured dynamic modulus and static modulus.

The main objective of research – to determine correlation between the dynamic and static moduli. Since the formulas for calculating direct correlation are seldom used in practice the aim was to estimate reduction coefficients for dynamic values.

In other words, in the near future the quality assessment, based on dynamic moduli, could replace the widely used slow and complicated static plate load test. The results would help to create and employ new design methods.

Most of Lithuania‘s normative documents have been prepared according to the German normative documents and standards. At present based on *LST 1360.5:1955 Road Soils. Testing Methods. Load Test.* 1995 Lithuania uses the recommended approximate values for reducing dynamic deformation modulus E_{vd} to static deformation modulus E_2. Therefore, it is very important to justify the most suitable measuring method for the separate pavement structural layers and based on measuring results to suggest reduction coefficient values for each structural layer.

The values obtained by dynamic method would give an opportunity to carry out quality control and to assess the bearing capacity of the study layer not only by a static plate load test, which requires much time and efforts, but also by dynamic devices. A more wide use of the above mentioned dynamic devices would make it easier for the contractors, laboratories and engineers of road and railway construction enterprises to carry out a rapid and continuous quality control of embankments, roadbeds, soil layers and back-fillings.

Experimental research on measuring methods of pavement structural strength

The chapter describes experimental research on the determination of pavement structural strength, selection of the test section for experimental research and its construction, methodology for investigating pavement structure parameters and the equipment used. The analysis was carried out of the measurements taken on the subgrade and the lower layers of pavement structure.

In order to determine and compare the accuracy of the results obtained by the static and dynamic measuring methods, first of all, it is necessary to analyse methods for determining pavement structural strength and to make a review of similar scientific works. Also, to carry out the impact analysis of factors influencing road pavement structure, such as traffic loads, climatic and environmental factors. The need for strengthening road pavement structures necessitates to introduce new road reconstruction technologies, to look for new alternatives in building pavement structural layers, to investigate pavement structures in their real conditions of operation. Namely for this reason the comparable measurements were carried out on the road and on the test section. The first measurements were taken in 2004 on the selected road A5 Kaunas – Marijampolė – Suvalkai, in the section from 16.10 km to 16.40 km (grade-separated Garliava intersection), and in 2007 the experimental test section was constructed in Pagiriai for further research.

The following experimental research had to be carried out in order to theoretically justify the suitability of static and dynamic measuring methods and the compatibility of measuring devices for measuring the strength of the separate pavement layers and to select the most reliable:

- to carry out measurements of the structural strength of road pavement on the road and on the test section;
- to experimentally investigate the structural strength of road pavement by different measuring devices using the static and dynamic measuring methods;
- to make the assessment of measuring results obtained by different measuring devices;
- to justify the most suitable measuring method for the separate layers of road structure.

When constructing the experimental test section in Pagiriai the deformation modulus of the separate pavement structural layers and the whole pavement structure was determined, like on the road section Kaunas – Marijampolė – Suvalkai (16.10–16.40 km), by the static and dynamic methods using the following devices:

– static method – static beam (press) "Strassentest";
– dynamic method – light dynamic device "ZORN ZSG 02"; Falling Weight Deflectometer LWD "Prima 100"; Falling Weight Deflectometer FWD "Dynatest 8000".

Based on the executed comparable strength measurements on the road and on the test section the author of this dissertation made the analysis and assessment of comparable measurement data.

Analysis of the measuring results by dynamic devices on the subgrade shows that there is a regular correlation between all measuring devices. On the road section Kaunas – Marijampolė – Suvalkai (16.10–16.40 km) the numerical values of deformation modulus (MPa), compared to a static beam, vary and are higher: LWD and ZORN – 8–80% from the mean, and the values of FWD are 8% lower from the mean compared to a static beam. The results of measurements on the test section in Pagiriai showed that the numerical values of deformation modulus, compared to a static beam, vary more and are lower: the values of LWD "Prima 100" and "ZORN ZSG 02" are 14–17%, and the values of FWD "Dynatest 8000" are 70% higher than the numerical values of deformation modulus measured by a static beam.

Analysis of the measuring results by dynamic devices on the frost-blanket course shows that there is a regular correlation between all measuring devices, though, the numerical values of deformation modulus, compared to a static beam, vary. The values of Falling Weight Deflectometer LWD "Prima 100" and dynamic device "ZORN ZSG 02" are 33–43% lower that the mean numerical value of deformation modulus measured by a static beam, and the values of Falling Weight Deflectometer FWD "Dynatest 8000" are 40% higher.

Analysis of the measuring results by dynamic devices on pavement base shows that there is a regular correlation between all measuring devices, though, the numerical values of deformation modulus, compared to a static beam, vary more. On the road section Kaunas – Marijampolė – Suvalkai (16.10–16.40 km) analysis on a gravel base showed that the values of dynamic device "ZORN ZSG 02" are 9%, the mean values of Falling Weight Deflectometer LWD "Prima 100" are 32%, and the values of Falling Weight Deflectometer FWD „Dynatest 8000" are 4% lower that the mean numerical value of deformation modulus measured by a static beam. Analysis on a crushed dolomite base showed that the values of Falling Weight Deflectometer FWD „Dynatest 8000" are 3%, the mean values of LWD "Prima 100" are 34% lower than the mean numerical value of deformation modulus measured by a static beam. Analysis of measuring results on the test section in Pagiriai showed that the values of LWD "Prima 100" and dynamic device "ZORN ZSG 02" are 31–35% lower than the numerical values of deformation modulus measured by a static beam, and the values of Falling Weight Deflectometer FWD "Dynatest 8000" are 30% higher.

Analysis of the measuring results by dynamic devices on the subgrade, frost-blanket course and base courses shows that there is a regular correlation between all measuring devices, though, the numerical values of deformation modulus, compared to a static beam, vary and are lower. This explains the differences in measuring methods and calculation methodologies. Analysis of the results indicated that there is no possibility to unambiguously decide which method is the best and most acceptable.

Analysis and assessment of research results on measuring methods of pavement

The chapter describes statistical analysis and assessment of research results obtained on the subgrade and the lower pavement layers. Mathematical statistics is one of the methods allowing to properly generalize research data. The differences obtained and the conclusions made can be essential only when they are proved as mathematically reliable.

For the strength determination analysis of the road section Kaunas – Marijampolė – Suvalkai (16.10–16.40 km) the static and dynamic methods were applied for all structural road pavement layers. To continue scientific research and to find the most suitable and cost-effective road pavement structures the functioning of which would be studied under natural conditions and under a concrete heavy traffic volume the scientific research work was implemented in Pagiriai test section on the subgrade, frost-blanket course and base courses using the same measuring methods like in the previously investigated Kaunas section by showing functional correlation $E_{v2} = f(E_{v(FWD)})$, $E_{v2} = f(E_{v(LWD)})$, $E_{v2} = f(E_{v(ZORN)})$ between measuring devices.

To determine the reliability of results using the above methods the methods of mathematical statistics were applied. Having implemented the analysis and assessment of measurement data the reduction coefficient was suggested for the comparison of measuring results obtained on the pavement structural layers by the static and dynamic measuring methods.

When implementing research of experimental road sections for the analysis and assessment of the strength indices that were obtained the methods of mathematical statistics were used: descriptive statistics, analysis and interpretation methods.

A width of data set is defined as the difference between max and min values of statistical data.

Width is informative only in case where there are no exceptional values. A quartile width is most frequently used. It describes 50% dispersion of data values. A quartile width in statistics is represented by rectangular plots (Fig. 2). A rectangular plot shows a graphical min Q_1, Md, Q_3 image.

Dispersion plots of results on the subgrade, frost-blanket course and pavement base showed a dispersion of results between each device. A large difference could be observed between min and max value. The lowest dispersion of results was indicated by the dynamic device "ZORN ZSG 02" and a static beam "Strassentest" and this shows more reliable measuring results. The highest dispersion of results was indicated by FWD "Dynatest 8000".

Correlation analysis. Correlation was obtained between the min and max different values of deformation modulus (Fig. 3).

The highest correlation was obtained when measuring deformation modulus on the subgrade on the left side by FWD “Dynatest 8000“ and a static beam “Strassentest“ (r^2 = 0.5853, r = 0.7651), however, on the right side the correlation coefficient is not considerably lower (r^2 = 0.2513, r = 0.5013). Though the relationship between the static beam and other dynamic devices is not very strong this is explained by different methodologies.

The highest correlation was obtained when measuring deformation modulus on the frost-blanket course on the left side by “ZORN ZSG 02“ and a static beam “Strassentest“ (r^2 = 0.5198, r = 0.7210). Though the relationship between the static beam and other dynamic devices is not very strong this is explained by different methodologies.

Correlation results of measurements on pavement base by all devices were poor. The highest correlation coefficient on pavement base on the left side was determined between a static beam “Strassentest“ and Falling Weight Deflectometer FWD “Dynatest 8000“, correlation coefficient r = 0.4541.

Mathematical expression of the suggested reduction coefficient k^* developed for the comparison of results obtained by the static and dynamic methods is as follows:

$$k^* = \frac{E_{v2}}{E_{vd}} \pm \Delta k. \quad (5)$$

When analysing measurements on the separate structural layers it was assumed that Poisson‘s ratio is constant (ν = *const*), the effect of temperature was not considered (the effect of temperature must be considered when assessing strength measurements on asphalt layers).

The largest differences were obtained taking measurements by the FWD device, therefore, those measuring results will be discussed more widely. Reduction coefficient measured by FWD on the subgrade is 50% higher than the normative, on the frost-blanket course is 2 times lower than the normative, and the errors of small devices are similar in all cases and vary from 40 to 60% from the normative values. The charts in Figs 4–6 show the variation of reduction coefficient not only at the mean values but also at the min and max values measured on the structural layers of the road.

The values of reduction coefficient k^*(FWD) on the subgrade vary from the mean value approx from 0.4 to 0.7, and could be represented by the following mathematical expression:

$$k^* = k_{ave} \pm (0.4 \ldots 0.7) k_{ave}. \quad (6)$$

The values of reduction coefficient k^*(FWD) on the frost-blanket course vary from the mean value approx by 0.8 time, and could be represented by the following mathematical expression:

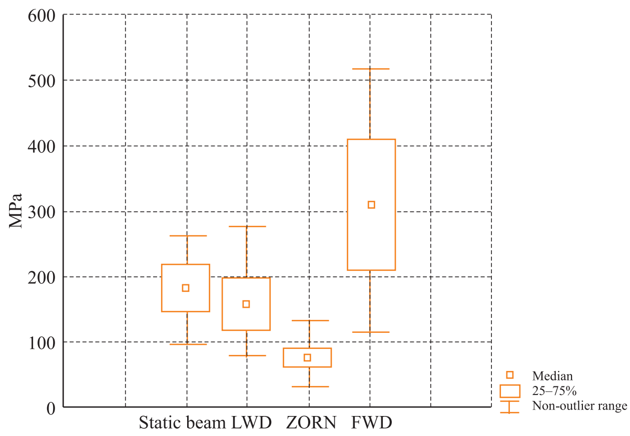

Fig. 2. Dispersion plot of measuring results on the subgrade (left side)

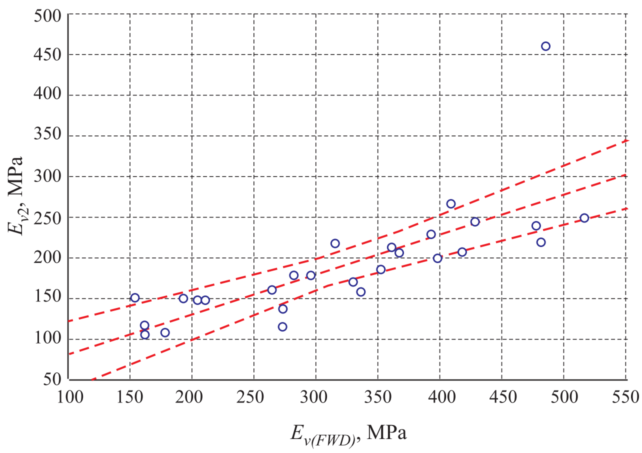

Fig. 3. Correlation between measuring results of the FWD “Dynatest 8000“ and a static beam “Strassentest” on the subgrade of experimental road section in Pagiriai (left side)

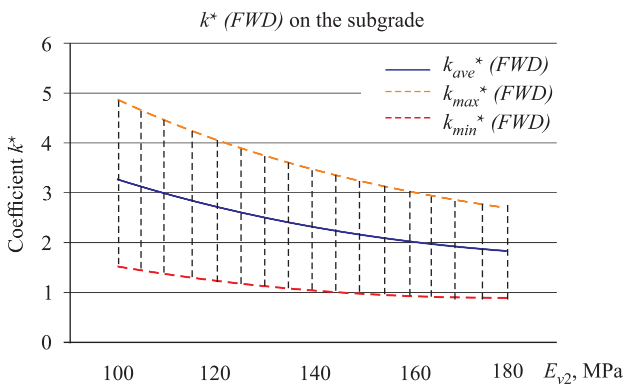

Fig. 4. Variation limits of reduction coefficient k^* (FWD) measured on the subgrade

$$k^* = k_{ave} \pm 0.8k_{ave}. \quad (7)$$

The values of reduction coefficient k^*(FWD) on the base course vary from the mean value approximately from 0.7 to 0.8, and could be represented by the following mathematical expression:

$$k^* = k_{ave} \pm (0.7...0.8)k_{ave}. \quad (8)$$

Based on the analysis and assessment of research results the following supplement to the mathematic expression (5) could be suggested for the reduction coefficient k^* developed for the comparison of results obtained by the static and dynamic measuring methods:

$$k^* = \frac{E_{v2}}{E_{vd}} \pm (0.4...0.8)k_{ave}. \quad (9)$$

General conclusions

1. The research was carried out and the results were processed based on the investigations carried out by the Laboratory of Road Research of Road Department of Vilnius Gediminas Technical University on Kaunas road section and Pagiriai experimental test section. Measurements were taken by the static and dynamic methods using the following devices: the static beam "Strassentest", the dynamic Falling Weight Deflectometer FWD "Dynatest 8000", the LWD "Prima 100" and the dynamic device "ZORN ZSG 02". Having taken measurements it could be stated that all the study devices are suitable for the determination of deformation modulus on the subgrade and frost-blanket course.

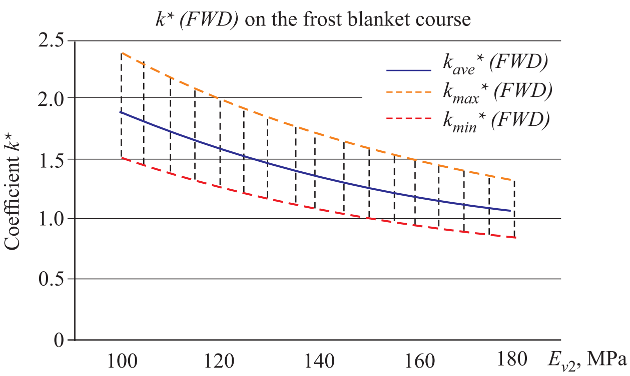

Fig. 5. Variation limits of reduction coefficient k^* *(FWD)* measured on the frost-blanket course

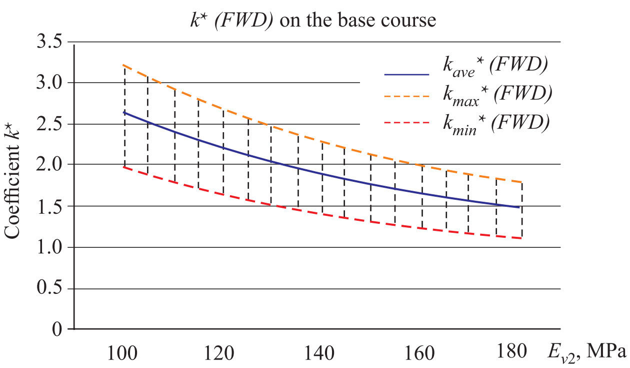

Fig. 6. Variation limits of reduction coefficient k^* *(FWD)* measured on the base course

2. Based on research results obtained from the measurements on Kaunas road section it was noticed that the methods and devices used to determine road pavement strength shall be used based on the application of measuring results:

- Static beam – most suitable to determine deformation modulus at the surface of aggregate layers;
- Deflectometer – for detail research of the whole condition of pavement structure.

3. Analysis of measuring results of the subgrade and frost-blanket course obtained by dynamic devices shows that there is a regular correlation between all the devices, though, the numerical values of deformation modulus, compared to a static beam, vary: FWD "Dynatest 8000" are by 70% higher, LWD "Prima 100" and the dynamic device "ZORN ZSG 02" are by 8–80% lower. Therefore, there is no possibility to unambiguously decide which method is the best and most acceptable.

Correlation results of the pavement base measurements between all devices are poor. The highest correlation coefficient (r = 0.4541) on pavement base on the left side was determined between the static beam "Strassentest" and the Falling Weight Deflectometer FWD "Dynatest 8000".

The results of research of deformations of the structural layers of experimental pavement structures by the static and dynamic measuring devices showed that the structural strength of pavement layers determined by the Falling Weight Deflectometer is close to the strength determined by a static testing device. There is a linear relationship between the E modulus determined by the static and dynamic methods. Correlation of deformation moduli determined by different methods shows that the Falling Weigth Deflectometer can be used for determining the strength of investigated pavement structures using reduction coefficients developed by experimental research.

Having made the analysis and assessment of subgrade research results it could be stated that all measuring devices represent reliable results. The most suitable devices for measuring strength of the frost-blanket course are a static beam and the dynamic device "ZORN ZSG 02". Based on the analysis and assessment of research results for the reduction coefficient k^* developed for the comparison of results obtained by the static and dynamic methods to use mathematical formula suggested by the author of the dissertation.

Based on research results it is suggested to carry out further scientific investigations on the subgrade and on road pavement layers taking into consideration thickness of the layer, material composition, temperature, to carry out measurements under similar conditions and to take into consideration the Poisson‘s ratio of each material used for the road structure. What concerns the base course it would be necessary to correct the load distribution coefficient, used in calculation methodology, as this coefficient influences the size of deformation modulus.

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