Abstract. Pavement is one of the most important structural elements of road. It is continuously affected by static and dynamic traffic loads and climate change. Due to the impact of traffic and climate the physical and mechanical properties of subgrade soils and materials of the structural pavement layers change. A rapidly increasing heavy traffic volume, a growth of normative axle load from 10 to 11.5 t on the main roads of Lithuania force the scientists to look for new durable road building materials and their mixtures. A continuously increasing need for the strengthening of road pavement structures in Lithuania induces to implement new road reconstruction technologies, to look for new alternatives in laying structural pavement layers, to make research of pavement structures in real conditions of their operation. The article studies methods for the determination of road pavement structural strength, gives the evaluation of equipment used for static and dynamic determination of pavement structural strength. In order to determine and compare the accuracy of testing results carried out by static and dynamic methods the comparative measurements were carried out on the experimental road section using four measuring devices on subgrade. Further results of the research of experimental road section, their analysis and assessment will allow to select the most suitable measuring method for each structural pavement layer.

Keywords: traffic loads, road pavement, pavement strength, static and dynamic methods, subgrade.

1. Introduction

The sector of Lithuanuan transport accounts for more than 10 % of the gross domestic product (GDP), and most of which is falling on road transport. This may be explained by the density of road network as well as the state and technical parameters of road (Sivilevičius and Šukevičius 2009).

Road pavement is one of the most important structural elements of road. It is continuously affected by static and dynamic traffic loads, as well as climate change. Due to the impact of traffic and climate the physical and mechanical properties of subgrade soils and materials of structural pavement layers are changing. Critical conditions are created in winter and spring when, under the influence of cold, pavement materials become fragile and with a thawing ground they get to plastic due to excessive moisture. Unfavourable situation is caused in spring when separate structural pavement layers still contain excessive moisture, and asphalt pavement warms up under high temperatures (Vorobjovas et al. 2007). Therefore, the subgrade soils and structural pavement layers undergo deformation and their strength decreases.

The quality of road pavement, designed according to the highest technical standards and laid using advanced technologies, has been gradually changing: its service properties worsens, various defects appear and develop, pavement strength becomes insufficient (Brauers et al. 2008) (Adamek et al. 2007). Due to the impact of traffic and climate it is necessary to determine structural condition of the road pavement and to select a strategy for pavement strengthening.

Until restoration of independence of Lithuania asphalt concrete and other “black” pavements were designed according to the “Instruction for the Design of Flexible Pavements VSN 46-83”. In 1995 – 1996 the new normative documents for motor roads came into force and the mentioned instruction was not further used. Asphalt concrete and other “black” pavements were started to be designed according to the “Standards and Rules for the Design of Flexible Pavements PNT – K95”.

At present, in Lithuania the main normative document regulating the design of asphalt concrete and other “black” pavements on motor roads is the Construction Technical Regulation KTR 1.01:2008 “Motor Roads” which came into force in 2008. Technical measures and methods for implementing the requirements of this Regulation are defined by the “Regulations for the Design of Standardized Pavement Structures of Motor Roads KPT SDK 07”.

RESEARCH OF STRENGTH MEASUREMENT METHODS ON SUBGRADE OF EXPERIMENTAL ROAD PAVEMENT

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All the above mentioned Lithuanian normative documents were prepared on the basis of German normative documents and standards.

The main problem is that any methodology must have a legal background for its application, i.e. it must be approved (approbated) in the established order by the respective institutions. The use of methodologies having no legal background under certain conditions, for example if pavement structure fails during a warranty period, may cause criminal liability. Non-approbated methodologies could be applied only as additional technical measures.

At present, Lithuania has no single methodology approved in the established order and defining the principles of strengthening design of asphalt concrete pavements on the existing roads.

Detail designs of pavement strengthening and repair of roads of all forms of ownership outside the limits of residential areas are currently prepared according to the requirements and provisions of KTR 1.01:2008.

The strength of separate layers of flexible pavement structures and of the total structure of road pavement can be calculated during their design (Dawson et al. 2009)(Markevičienė and Atkočiūnas 2006). When constructing and reconstructing roads it is necessary to control if the strength of structural pavement layers correspond to their design strength. For this purpose various methods are used to determine the strength of structural pavement layers.

This article gives the initial results of structural investigations of experimental road section, consisting of 27 different pavement structures, constructed for the first time in the Lithuanian history of roads (Čygas et al. 2008). Further results of investigating this experimental road section, their analysis and evaluation will allow to select road pavement structures the best corresponding to the climatic and traffic conditions in Lithuania. A separate chapter describes methods for measuring structural pavement strength on the selected experimental road section with the use of four measuring devices.

2. Static and dynamic methods for measuring strength

Structural pavement strength is one of the main indices describing pavement ability to carry traffic loads. The strength of separate layers of flexible pavement structures and of the total structure of road pavement can be calculated during their design. When constructing and reconstructing roads it is necessary to control if the strength of structural pavement layers correspond to their design strength. For this purpose various methods are used to determine the strength of structural pavement layers. 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 constructing road pavement structures their strength is defined by a static deformation modulus.

2.1. Static method for measuring strength

In practice, the less complicated is a static strength measuring method. When using static measuring methods a certain area of road pavement structure is gradually loaded and unloaded. Generally, the following indices could be distinguished characterizing the static strength of road pavement, i.e. ability of the structure to resist: vertical stresses (σz); horizontal stresses (σx, σy);

Ability to resist vertical stresses is expressed by the required modulus of elasticity; to resist horizontal stresses – by the quantity of permissible resistance to displacement. Comprehensive information about the static measuring method of strength could be given by a methodology aimed at a complex evaluation of all its components.

The essence of static methods for the evaluation of structural pavement strength is to create at road pavement surface a relative pressure which, according to its value, corresponds to the impact of load 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. Taking into consideration elastic deflection the total modulus of elasticity is calculated by the formula:

\[
E_i = \frac{P \cdot D}{l} \left(1-\mu^2\right),
\]

where \(P\) – vehicle wheel pressure to the pavement, Pa; \(D\) – diameter of the plate, m; \(l\) – forced inverse pavement deflection, m; \(\mu\) – Poisson’s ratio.

In course of measurements and processing of test results one should take into consideration the effect of natural – climatic factors. In this case a “typical condition of pavement structure” should be assumed described by the modulus of elasticity (Ogėnka...2003):

\[
E = A - B \left(\lg \sum_{i=1}^{m} \frac{t_{E_i}}{10} - 0.4\right),
\]

where \(A\) and \(B\) – empirical coefficients depending on the type of road pavement structure, calculated load and climatic factors; \(m\) – number of measurements per year; \(E_i\) – modulus of elasticity of road pavement structure in a reference point at a certain moment of time, Mpa; \(t_{E_i}\) – duration with \(E_i\).

The above tests basically describe the average statistical modulus of elasticity of road pavement structure in a period of pavement service time. Based on investigation data it is only possible to evaluate pavement ability to resist main vertical stresses. This test does not allow to fully describe a condition of road pavement structure and to predict its further worsening.
A common disadvantage of all static methods is that when using these methods it is impossible to evaluate the ability of road structure to essentially realize a dynamic impact caused by a real traffic movement (Илиополов и Селезнев 1997). Static methods for calculating and evaluating road pavement strength are based on the maximum normal and tangent stresses. According to these criteria pavement failure takes place in a way of tear (according to maximum normal stresses) and shear (according to maximum tangent stress).

Generally, all the static calculation schemes and evaluation methods should be used to determine the structural pavement strength, ability of road structure to carry the significantly increasing traffic loads and, thus, to prevent the rapid failure of road structure. Based on the static strength results obtained with the help of dynamic coefficients and taking into consideration the rapidly increasing traffic flows and traffic 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 showed by the increase in energy accepted by the road structure. Then, the tendency of changing relations between the different micro structural elements of road structure becomes obvious as well as of their failure.

2.2. Dynamic method for measuring strength

In order to objectively evaluate road pavement condition it is suggested to use impact analogical to a real transport movement. Unlike the static measuring methods, dynamic methods make it possible to evaluate loads from moving transport.

When using dynamic measuring methods the load is produced by the drop of a falling massif cylinder in a very short period of time which causes deformations of structural pavement layers. Dynamic impact \( Q_d \) and loading time \( T_f \) are calculated by the approximation formulas (Оценка...2003):

\[
Q_d = M g \sqrt{\frac{2H}{\delta}} k_d , \quad (3)
\]

\[
k_d = 0.5 (l + l') , \quad (4)
\]

\[
T_f = \pi \sqrt{\frac{g}{\delta}} \approx 0.1 \sqrt{\delta} , \quad (5)
\]

where \( M \) – mass of the falling weight, kg; 
\( g \) – free acceleration of the falling weight, m/c²; 
\( H \) – height of the falling weight, cm; 
\( \delta \) – indicator defining a rigidity of suspension; m; 
\( k_d \) – energy-loss coefficient of the falling weight; 
\( l, l' \) – vertical deformations from the drop of the first and the second falling weight, cm.

Having made measurements with the use of dynamic measuring method the obtained elastic deflection is reduced to a comparative shape (static deflection) using coefficients of regression relationship (Илиополов и Селезнев 1997):

\[
l_f = X_1 l_d + X_2 , \quad (6)
\]

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

The studded foreign methods and devices were based on the solutions of dynamic tasks and in the course of measurements and calculations the characteristics of road pavement deflections were taken into consideration. It should be noted that progressive equipment use a dynamic impact, whereas, the most expensive and most effective equipment are based on the impact data of a moving vehicle. The main disadvantages – a high price of equipment and serious technical difficulties related to the calibration of the measuring equipment.

A similar approach to the determination of structural pavement strength is the most common. However, it is followed by the difficulties related to the necessity to correct calculation model for each part of one-type road (road pavement structure must be known beforehand). The solution is not the only, i.e. a more than one set of the moduli of elasticity can meet the experimentally determined displacement areas, and the calculation itself requires plenty of time even when using modern electronic calculation techniques. Therefore, all the mathematical models of modern high-efficiency falling weight equipment are oriented to the estimation of the general modulus of elasticity of the road structure.

The main advantage of dynamic methods is, by no means, 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 these methods in the field of strength evaluation. The most informative is the analysis of the structural strength of dynamically loaded road pavement.

3. Construction of experimental road section

In order to determine the strength of subgrade and structural base layers of experimental road section four different devices were used different in their measuring methodology and their operational principles. This article describes investigations carried out solely on the subgrade.

To determine the strength of subgrade (on the left side of the road) of the experimental road section (Fig 1) four different devices were used: dynamic – FWD Dynatest 8000, LWD Prima 100 and ZORN ZSG 02; static – static beam (press) Strassentest. On the right side of the road – FWD and static press Strassentest.

Measurements on each of the structural pavement layers were taken by the same selected scheme (location of a measuring point differs ± 0.5 m) under the same weather conditions. Pavement deflections were measured by FWD Dynatest 8000 with 50 kN load.
When laying subgrade for the experimental road section it was necessary to achieve the sufficiently equal subgrade strength, at least 100 MPa. The previously laid subgrade consisted of various building waste, the soil was heterogeneous. It was decided that the subgrade strength of more than 100 MPa will have no large influence on the strength of all pavement structures as well as their operational indicators. The subgrade strength of more than 100 MPa was achieved (Bertulienė and Laurinavičius 2008).

Investigations of the subgrade strength were carried out and the results were obtained using the static and dynamic measuring methods with four different measuring devices: dynamic – LWD Prima 100 (mini FWD), FWD Dynatest 8000 and ZORN ZSG 02; static – static beam (press) Strassentest.

4. Statistical analysis of investigation results on the subgrade

Investigations showed a clear interrelation between the data obtained by static and dynamic devices. Analysis of measuring methods showed that there is a regular dependence between the static and dynamic methods.

The results in Figs 2 and 3 show that the measuring data obtained by different measuring devices in different measuring points has a regular variation though their values differ. Taking into consideration small distances between measuring points it could be stated that the layer has not been evenly compacted, heterogeneous materials have been used for this layer or the measurement was taken not accurately.

The left side of the road section is affected by several times larger loads than the right side as this road leads to Pagiriai query.

Analysis of measuring results on the subgrade shows that there is a regular dependence between all the measuring devices but the numerical values of deformation modulus (MPa), compared to static beam, vary and are lower: mini FWD and ZORN – 14 –17% from the average, the values of FWD – 1.7 -2 times higher. This is explained by the difference in measuring and calculating methodologies (Čygas et al. 2008). For example, in the calculation methodology of FWD the applied load distribution coefficient f influences the quantity of deformation modulus. In the measurements f = 8/3 was used where the values calculated at the coefficient f = π/2 are very close to the values measured by other 3 devices.

During investigations of the subgrade of experimental road section for the analysis and evaluation of the strength indices obtained the mathematical statistical methods were used. In the analysis of the determination of subgrade strength the static and dynamic methods were used. To determine the reliability of results the methods of probability theory and mathematical statistics were applied. For the reliability interval the upper limit of 95 % (significance level) reliability was set.

The best results of correlation were obtained between the FWD Dynatest 8000 and the static beam (Fig 4).
Correlation between the FWD Dynatest 8000 and the static beam Strassentest on the left side is strong (R = 0.8332). That shows the dependence of measurement results of deformation modulus between the FWD Dynatest 8000 (EV(FWD)) and static beam Strassentest (EV(SB)). The analysis of the linear regression equation shows that one variable depends on another variable. In this case, an estimate of the variable EV(FWD) – dependence of EV(SB) is described by the equation:

\[ EV_{(FWD)} = -15.8385 + EV_{(SB)} \cdot 1.8111, \quad (7) \]

Though methodologies of these devices are different the data reliability is accurate.

Correlation between the FWD Dynatest 8000 and the static beam Strassentest on the right side is weak (R = 0.5013) (Fig 5). That shows the poor relationship of measurement results of deformation modulus between the FWD Dynatest 8000 (EV(FWD)) and static beam Strassentest (EV(SB)). In this case, an estimate of the variable EV(FWD) – dependence of EV(SB) is described by the equation:

\[ EV_{(FWD)} = 85.9621 + EV_{(SB)} \cdot 1.0484, \quad (8) \]

Data dispersion diagrams show a rather large difference between the maximum and minimum value. The higher correlation is represented by two different devices, i.e. the FWD and the static beam on the left side, though on the right side the correlation is significantly lower. However, interrelation between the static beam and other dynamic devices is not very strong, and this is explained by different methodologies.

Dispersion diagrams of measuring results in Fig 6 show a dispersion of results between each device. A large difference could be observed between the minimum and maximum value. The lowest dispersion of results on the subgrade was indicated by the dynamic device ZORN ZSG 02, the highest – by the FWD Dynatest 8000.

**Fig 5.** The chart of interdependence between the measuring results of the FWD Dynatest 8000 and the static beam Strassentest on the subgrade (right side)

**Fig 6.** Static evaluation of measuring results on the subgrade layer by all the devices

**Conclusions**

Investigations were carried out and results were processed on the experimental road section of the Scientific Laboratory of Roads of the Vilnius Gediminas Technical University which was constructed in Pagiriai settlement. Measurements of the experimental road section were implemented using the static and dynamic measuring methods with the following measuring devices: static beam Strassentest, dynamic Falling Weight Deflectometer FWD Dynatest 8000, Light Weight Deflectometer LWD Prima 100 and dynamic device ZORN ZSG 02. It could be stated after the measurements that all the above devices are suitable for determining deformation moduli on the subgrade.

1. According to the results of previous investigations it could be noticed that measuring devices and methods to determine pavement strength shall be applied based on the use of measuring results:
   - Static beam – most suitable for determining deformation moduli on the surface of pavement layers consisting of loose materials.
   - Deflectometer – for detail investigations of the condition of the whole road pavement structure.

2. The highest correlation coefficient of measuring results on the subgrade was determined between the static beam Strassentest and the Falling Weight Deflectometer FWD Dynatest 8000. Correlation coefficient on the left side R = 0.8332.

3. Analysis of results of the measurements taken by dynamic devices on the subgrade showed that there is a regular dependence between all the devices but the numerical values of deformation modulus, compared to static beam, vary and are lower, therefore it could not be uniquely decided which method is the best and the most acceptable.

4. Having made the analysis of measuring results an assumption could be made that interrelation between the
devices could be as follows: if data of the measuring results of the static beam Strassentest are equated to \(= 1\), the following coefficients could be used (suggested) for other devices: FWD Dynatest 8000 = 1.7 – 2.0; LWD Prima 100 = 0.75 – 0.85; ZORN ZSG 02 = 0.7 – 0.8.

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