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VIASTRUCTURA – A NEW WAY OF PAVEMENT STRUCTURE DESIGN

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Abstract. The catalogues of standard pavement structures are common way to design road pavements. In 2019, new regulation for the design of standard pavement structures KPT SDK 19 was issued in Lithuania. One of the new requirements require verification of layer thickness of high-class pavement structures. Such verification should be done by internationally approved mechanistic-empirical methods. In addition, it is recommended to use the same methods to adjust the layer thickness of the selected standard pavement structure for lower classes. These calculations are particularly applicable when the design load (ESAL) is at the lower or upper limit of the class range. Vilnius Tech Road Research Institute experts and outsource IT specialists spent two years for the design model ViaStructura development. Web software based on mechanistic-empiric approach include the boundary conditions, based on Austria, the United States and Germany experience and laboratory test results of construction materials. Materials can be selected from created database, which can be simply expanded with the new materials by the user. as Additional function allow comparison of separate designed pavement structures. The article present the concept of the ViaStructura model for the design of flexible pavement structures, reveals its main principles and advantages comparing to the pavement structure selection by the standard catalogue..

Keywords: ViaStructura, pavement structure, mechanistic-empirical method, design software, asphalt fatigue, permanent deformation, pavement design.

Introduction

Typically, the pavement structures for road are designed according to catalogues (or guidelines) of standard pavement structures. The standard pavement structure performs well at standard (empirically approved) conditions, however its is not adapted to special purpose pavements, do not take into account the impact of special loads that occurs when:

- heavy traffic travels on the same tracks;
- heavy vehicles travel exclusively one after the other;
- heavy traffic occurs in short radius turns;
- there is slow heavy traffic;
- heavy transport brakes and accelerates often;
- heavy traffic is in the intersection area;
- at heavy vehicle parking lot.

Therefore, standard pavement structures limit the application of new and non-standard materials to the construction of the pavement structure. The concept of a standard pavement structure catalog simplifies the design process, however the decision is not always optimal due to many approximations associated with design load, hydrothermal condition, climate condition (pavement temperature and frost heave), material properties. Vaitkus, Žalimienė, Židanavičiūtė and Žilionienė (2019) found that one of the most significant factors for pavement structure strength is the bearing capacity of subgrade and hydrothermal impact which are highly interconnected. Mshali and Steyn (2020) investigated the effect of truck speed on the response of flexible pavement structures. It was found that increased vehicle speed results in the decrease in elastic surface deflection response which results in lower stresses and strains and affects the further performance of the pavement structure. Tran and Hall (2007) found that the spectrum of axle loads on the studied roads differed and significantly influenced the performance of the pavement structure. The study showed that the predicted pavement service life differed by up to 25 percent compared to the values determined using the default load values.. This shows that underestimation of such factors can lead to unsatisfactory performance of the pavement structure, faster degradation or inefficient use of funds.

Also, other currently valid normative technical documents in Lithuania do not encourage the design and substantiation of the suitability of design solutions, as they are focused on the application of standard materials, indirectly assessing the impact of their mechanical properties on the wear rate of the pavement structure. There has been a lot of research in recent years on the use of new materials in road construction. Researchers have explored the potential of using materials such as waste (Choudhary, Chattopadhyay, Kumar and Julaganti, 2017, Vaitkus, Gražulytė, Vorobjovas, Šernas and Kleizienė, 2018), geogrid (Zofka, Maliszewski and Maliszewska, 2017, Šiukščius, Vorobjovas, Vaitkus, Mikaliūnas and Zarinš, 2019), noise-reducing pavement (Vaitkus, Vorobjovas, Jagniatinskis, Adriejauskas and Fiks, 2014, Vaitkus, Šernas, Vorobjovas and Gražulytė, 2019), and a design model based on a mechanistic-empirical method could be a useful tool to assess the performance of pavement structures using such materials and possibly accelerate the practical application. Therefore, it is necessary to evaluate the possibilities of adapting fast non-destructive bearing capacity determination methods to Lithuanian conditions. For these purposes, by order of the Lithuanian Road Administration under the Ministry of Transport and Communications, a design model for asphalt pavement structures with application software ViaStructura was developed, based on a mechanistic-empirical approach. This article reviews the concept of the ViaStructura model for the design of flexible pavement structures, reveals its main principles, highlights the possibilities and advantages of application compared to the application of standard pavement structures, and takes into account the challenges of the model application.

1. ViaStructura pavement structure design model

ViaStructura is the design model of flexible pavement structures based on the mechanistic-empirical approach. The design result, in this case, is not the thickness of the layers of the pavement structure, but the effect on the trial pavement structure and its resistance to defined type of distress. Figure 1 presents the procedure of pavement structure design according to ViaStructura.

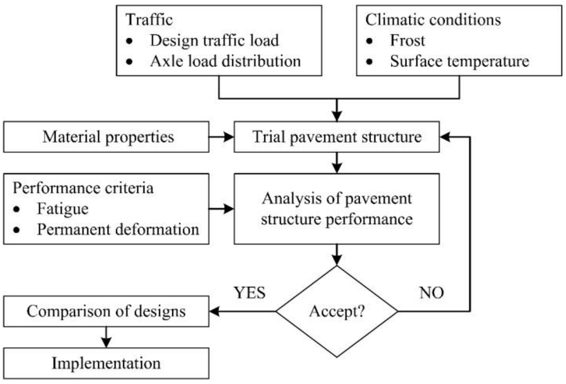


Figure 1. ViaStructura design procedure of pavement structure

The model first evaluates traffic loads, climatic conditions, subgrade soils, then proceeds to the selection of layer thicknesses and materials for the trial pavement structure. The trial pavement structure is then analyzed through performance criteria taking into account user input parameters. ViaStructura model is subject to the performance criteria for resistance to fatigue in bound layers and permanent deformations in unbound layers and subgrade. If the design does not meet the desired performance criteria, it has to be revised and the evaluation process repeated. The user can comprehensively analyze the interaction of input parameters and results, compare different designs and thus make optimal decisions. Each stage of the design process is discussed in more detail in the subsections below.

1.1. Design traffic load

The first requirement for a designed pavement structure is that it must withstand the cumulative traffic loading in the design lane over the selected design period. Estimation of this loading requires the calculation of the cumulative number of heavy vehicle axles over the design period. Design model ViaStructura gives two different methods to calculate the design load, which are based on Lithuanian Design rules for standard road pavement structures KPT SDK 19. These methods are:

- According to the average daily traffic of heavy vehicles;
- According to the axle loads of particular classes of heavy vehicles.

The calculation method, based on average daily traffic when data of vehicle axle loads is absent, evaluates the average quantity of axles and their effect on pavement structure expressed in equivalent standard axles through empirical coefficients related to the category of the road. In contrast, the calculation method, based on data of axle loads of heavy vehicles, evaluates the effect on pavement structure of each axle expressed in equivalent standard axles through fourthorder exponential function. To bring the design conditions as close as possible to the real operating conditions of the structure, the load distribution has been applied in the model. The distribution consists of 11 load ranges from 0 to 22 tons, for each of which the stresses and strains of the pavement structure are calculated later. The percentage distribution of axle loads intervals by road category in Lithuania is presented in Figure 2.

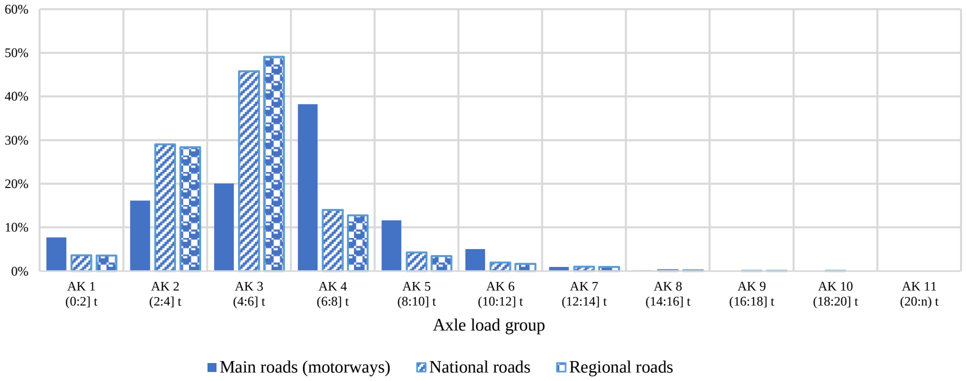


Figure 2. Percentage distribution of axle loads by road category in Lithuania (Kleizienė, Vaitkus and Čygas, 2015)

The flow of heavy vehicles, as well as the loads, are unique to each region and even the road, so it is recommended to perform periodic weighing of heavy vehicles on the roads. It is also recommended to perform heavy axle load analysis on priority, strategic roads or road structures before adopting pavement structure design solutions and to assess additional threats and impact on pavement structure deterioration.

1.2. Climatic conditions

The performance of the road structure depends not only on the traffic loads but also on the effects of climate. Climate (hydrothermal conditions and pavement temperature) significantly influences the effects of transport loads by reducing or increasing them. It is important to ensure that precipitation has no or little effect on the load-bearing capacity of the pavement structure, i. properly designed transverse and longitudinal profiles of the road, and ensure good drainage. It is also very important to reduce the negative impact of temperature on the pavement structure. Estimation of climatic conditions in the ViaStructura model includes assurance of sufficient resistance to frost damage through the minimum total thickness of pavement structure, and determination of hydrothermal condition seasonality effect as well as pavement surface temperature distribution.

Simonsen and Isacsson (1999), Thomson et al. (1987) and Huang (1993) found that the load-bearing capacity of the pavement structure increases to 15% in winter, returns to its original state in summer, and the load-bearing capacity of the subgrade decreases from 15% to 70% in autumn and spring. Sufficient frost resistance of the pavement structure and protection against possible damage due to repeated exposure to freezing and thawing cycles are ensured by the thickness of the pavement structure. If no special tests have been carried out or there is no experience in determining the thickness of the frost-resistant pavement structure, then this thickness shall be calculated taking into account:

- maximum frost depth;
- the frost sensitivity of subgrade soils;
- design traffic load;
- the provisions for adjusting the thickness of the pavement structure.

The thickness of the frost-resistant pavement structure shall include the stabilized top layer of frost-sensitive subgrade soil, but shall not include the improved top layer of frost-sensitive subgrade soil, even if tests have shown that it has become non-frost susceptible.

During the design of the new pavement structure, it is assumed that the hydrogeological conditions are neutral in all cases, due to the requirements for construction to ensure good drainage. However, during the design of the pavement rehabilitation, there may be a need to assess unfavorable hydrothermal conditions due to seasonal climate change. The seasonal decrease in soil bearing capacity is estimated when the pavement temperature changes from -10 to + 10 ° C. The level of decrease of bearing capacity is based on RDO Asphalt 09 (FGSV 498, 2009) assuming a 0% reduction in F1 class (non-frost susceptible) soil bearing capacity, a 45–55% reduction in F2 class soil (low to moderately frost susceptible) and an 65–80% reduction in F3 class soil (highly frost susceptible) bearing capacity. It is assumed that in the case of qualified improvement or stabilization of subgrade soils, seasonal fluctuations of hydrogeological conditions do not affect the bearing capacity of the pavement structure.

The load-bearing capacity of a flexible pavement structure depends on the temperature due to the composition and physical properties of the asphalt mix. Therefore, when designing a flexible pavement structure, possible temperature and load scenarios during operation must be considered. Studies by Nunn and Smith (1997) have shown that the stiffness modulus of an asphalt mix usually decreases from 0.12 GPa to 0.06 GPa with increasing temperature by 1 ºC. It has also been found that the sensitivity of the stiffness modulus of an asphalt mix due to a change in temperature decreases as an asphalt mix has higher stiffness modulus (Nunn and Smith, 1997).

Typical pavement structures designed and constructed for the average daily temperature decay faster than the expected service life due to the prolongation and heating of the summer season, which results in a change in the top asphalt layer volume, binder rise to the pavement surface, and faster plastic deformation (rutting) (Qiang, Mills and Mcneil, 2011; Mundt, Marano, Nunes, and Adams, 2009). Due to extreme climatic factors (extremely negative or positive temperatures, heavy rainfall and excess humidity, deeper than average freezing depth and a higher number of freezing/thawing cycles), the service life of the pavement structure is significantly reduced in terms of degradation and wear factors (Meyer, Amekudzi and O'Har, 2010; Meyer and Wiegel, 2011). Therefore, the methodology of modern pavement construction and material selection must be flexible and allow to estimate temperature and its variation.

The influence of temperature on the performance of the pavement structure depends on the thickness of the pavement structure. When modeling the temperature change of a pavement structure, it is assumed that the temperature in changes (increases or decreases) only in the vertical direction (it is assumed that the temperature does not change in the horizontal direction) (Herb, Marasteanu, and Stefan, 2006).

The temperature change in the pavement structure is modeled by dividing each layer of the pavement structure into sublayers of smaller thickness. In the ViaStructura model, the upper and lower layers of asphalt are divided into 1 cm thick sublayers, and the asphalt base layer is divided into 4 parts as the temperature change gradient is higher in the upper part of the pavement.

The ViaStructura model is based on a simplified method for determining the temperature change in the pavement used in the calculations of the pavement structure in Germany (FGSV 498, 2009). In Germany, the surface temperature of the pavement surface varies from -15 to +50 ° C. This pavement temperature range is divided into 13 ranges every 5 ° C. Based on the statistical distribution of the surface temperature in the intervals, the territory of Germany is divided into 4 zones. When developing the ViaStructura model, it was taken into account that the surface temperature in Lithuania drops below -15 ° C, therefore the temperature distribution has been expanded. According to the statistical temperature distribution, Lithuania was divided into 3 zones.

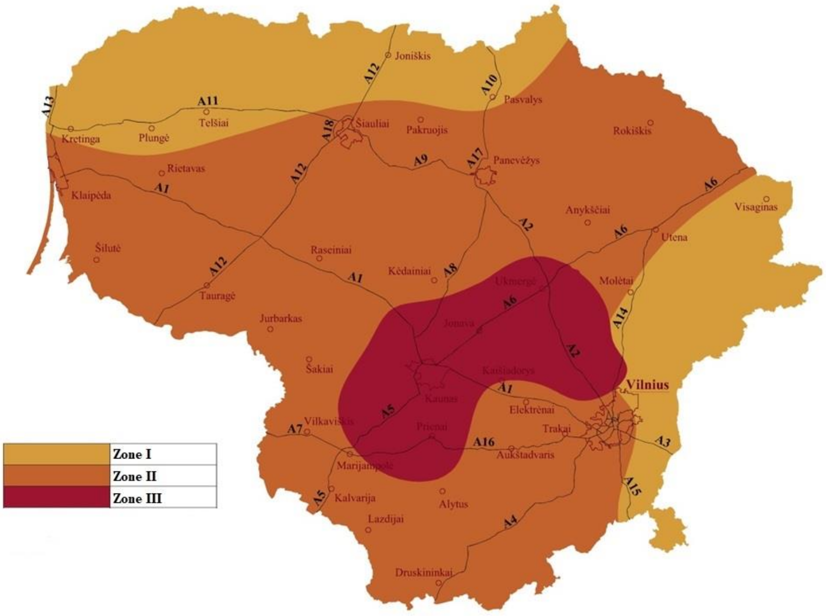


Figure 3. Zones according to the percentage distribution of pavement surface temperature intervals in Lithuania (Kleizienė, Vaitkus, Židanavičiūtė and Marcinkevičius, 2017)

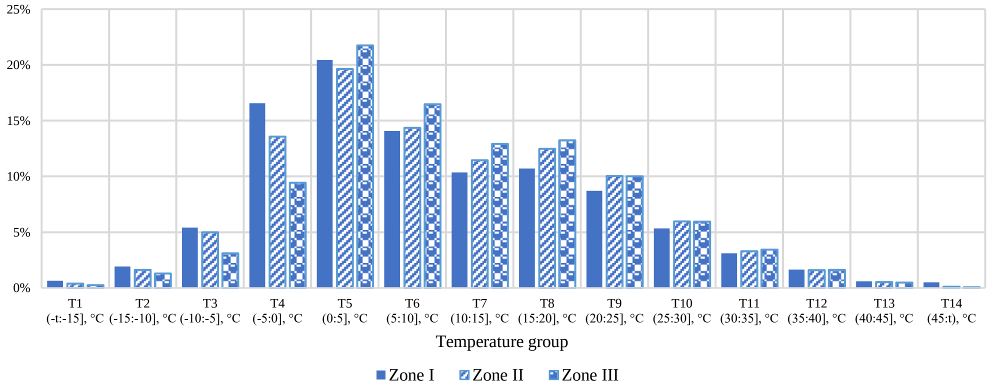


Figure 4. Percentage distribution of pavement surface temperature intervals by zones in Lithuania (Kleizienė, Vaitkus, Židanavičiūtė and Marcinkevičius, 2017)

Knowing the pavement surface temperature, the asphalt pavement temperature at any depth can be calculated. The temperature gradient (change) function in asphalt layers under different conditions can be estimated according to the equation given by Speth (1985) or Hess (1996):

$$y = b \cdot ln(0{,}01 \cdot x + 1{,}00) + T, \tag{1}$$

where: y – temperature at the depth x of the asphalt layer ° C; x – depth at which the temperature is to be determined, mm; T – temperature of the pavement surface, °C; b – parameter depending on the temperature of the pavement surface.

The calculated temperatures are used to calculate the stiffness modulus of each asphalt sublayer, which is used as input to the MnLayer (Khazanovich & Wang, 2007) algorithm to determine the reactions of the pavement structure.

1.3. Trial pavement structure and materials

When designing the pavement structure by the ViaStructura, first of all, the computational model of the structure is created, the loads and configuration of the vehicle wheels are defined, and the stresses and strains at critical layers of structure are calculated. The input data used to calculate the response of the pavement structure to loads are:

- tire-pavement contact area (fixed) and magnitude (dependent on road significance) of the wheel load;
- thickness of each layer.
- stiffness modulus and Poisson's coefficients of each layer;
- bonding (friction) between the separate layers.

The ViaStructura model offers three methods for entering the properties of asphalt mixtures:

- stiffness modulus at different temperatures;
- Hirsch method;
- Francken/Verstraeten method.

In the first method, the stiffness modulus of the asphalt mixture is entered at 15 different temperatures. Based on the entered stiffness modules, the software recalculates the stiffness modulus of the asphalt layers according to the pavement temperature ranges and the temperature at a specific depth. The stiffness modules can be determined according to standard LST EN 12697-26, as well as the data from the back-calculation using the falling weight deflectometer measurement data if the rehabilitation of the pavement structure is planned. The Hirsch and Francken / Verstraeten methods use input data determined in the laboratory. The stiffness modulus is calculated from the shear stiffness of bitumen using a complex shear modulus and the volumetric properties of the aggregate mixture or an asphalt complex modulus.

Tests to determine the mechanical properties of asphalt mixes are time-consuming, so the models for calculating these properties are relevant to this day. The application of these models allows calculating with sufficient accuracy the dynamic modulus of the asphalt mixture according to the granulometric composition of the asphalt mixture, the volume of air voids, the amount of bitumen and the mechanical properties of bitumen. Pellinen, Zofka, Marasteanu and Funk (2007) conducted a comparison study of three prediction models for the modulus of elasticity of an asphalt mix by Olard-DiBenedet, Andrei-Witczak, and Hirsch. The researchers found that all three models correlated with each other and with laboratory-determined values, but the Hirsch model is closest to the behavior of the asphalt mix because it was developed using an elastic viscous liquid model. Pellinen et al. (2007) emphasize that these models must be applied with great caution when assessing the characteristics of asphalt mix at high temperatures, where the mean error of prediction can be up to 40%, while the error of experimental test results is 20%.

The stiffness modulus of unbound materials is considered to be temperature independent. The design of the pavement structure may take into consideration that the modulus is influenced strongly by the stress level. For unbound granular materials, modulus increases significantly with increasing mean normal stress and decreases with increasing shear stress (Jameson, 2012).

1.4. Analysis of pavement structure performance

Multilayer elasticity theory is used to model flexible pavement structure and to calculate the reaction parameters (stresses and strains). Multilayer elastic theory is applied both in the design and analysis of the performance of the asphalt pavement structure. The multi-layer elastic theory is based on the following assumptions:

- all layers are linearly elastic;
- all layers are unlimited in the horizontal direction;
- all layers except the last one are of constant thickness;
- the layers have the same adhesion/friction conditions over the entire surface area;
- the calculations do not take into account the own weight of the structure and the initial stresses/deformations;
- the load on the surface is distributed over the circled.

The high-performance analysis program MnLayer, developed by professor Lev Khazanovich and Qiang Wang at the University of Minnesota in 2008, is used to calculate the stresses, strains and displacements of the pavement structure. A computational algorithm developed exclusively for the ViaStructura software that generates input data files, submits it to the MnLayer and returns the output files to the software with the calculated load response parameters of the pavement structure. The MnLayer computational algorithm is designed specifically for ViaStructura software and is covered by the patent protection of the ViaStructura brand and the design model of the ViaStructura.

The degradation (fatigue) effect of the pavement structure is assessed according to the ratio of the total design load and limit load for the intended design period. This method is called the Miner hypothesis and its basic principle is that the total number of passes of the design load cannot exceed the limit total number of passes. The Miner's rule is checked for each layer of the pavement structure separately, using boundary state equations for critical points. Miner’s rule is expressed as:

$$Impact = \sum \frac{N_{design,i-j}}{N_{lim.,i-j}}, \qquad (2)$$

where: $N_{design,i-j}$ – design load for the load range i and temperature range j; $N_{lim.,i-j}$ – limit load for the load range i and temperature range j.

To estimate the fatigue resistance of asphalt layers, the boundary state model based on Austrian pavement structure design methodology RVS 03.08.68 (FSV, 2016) is used. The limit load is calculated as follows:

$$N_{lim.,i-j} = \frac{k_1(T)}{F_{(\varepsilon 6)}} \cdot \left(\frac{S_{mix}(T)}{\sigma_{v,i-j} \cdot \gamma_{AC}}\right)^{k_2(T)}, \qquad (3)$$

where: $S_{mix}(T)$ – temperature-dependent stiffness modulus of asphalt mix, MN/m2; $\sigma_{v,i-j}$ – vertical stress under load level i and temperature range j, MN/m2; γ_{AC} – safety factor; $F_{(\varepsilon 6)}$ – fatigue factor depending on type of binder and strain of the asphalt layer at 106 load cycles determined by a four-point bending test according to EN 12697-24; $k_1(T)$, $k_2(T)$ – temperature factors.

To estimate the permanent deformation resistance of unbound base/subbase layers and subgrade, the boundary state model based on German pavement structure design methodology RDO Asphalt 09 is used. The limit load is calculated as follows:

$$N_{lim.,i-j} = 10^{\frac{1}{5}\left(84 - \frac{100 \cdot \gamma \cdot \sigma_{zz,i-j}}{\beta_{Bz}}\right)}, \qquad (4)$$

where: $\sigma_{zz,i-j}$ – vertical stress under load level i and temperature range j, MN/m2; γ – safety factor; β_{Bz} – the flexural strength of the hydraulically bound layer (MPa).

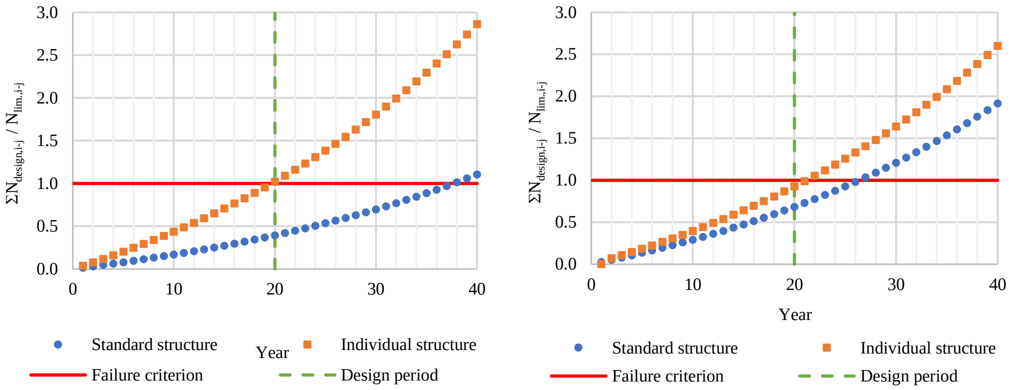
$$N_{lim.,i-j} = 10^{\frac{1}{0.7}\left(\frac{0.00875 \cdot E_{v2}}{\sigma_{zz,i-j} \cdot \gamma}\right)}, \qquad (5)$$

where: E_{v2} – the deformation modulus of unbound layer/subgrade, MPa; $\sigma_{zz,i-j}$ – vertical stress under load level i and temperature range j, MN/m2; γ – safety factor.

It should be noted that the boundary condition models are calibrated for Lithuanian conditions, but each user has access to the system parameters associated with a specific user account. This provides a wide range of model applications and versatile analysis capabilities.

2. Comparison of ViaStructura-designed and standard pavement structures

One of the advantages of applying the developed model is the testing and optimization of standard pavement structures by assessing the climatic and traffic load characteristics of the specific area. Figure 5 shows a graph of the performance of a standard and individually designed pavement structure using the ViaStructura model, showing the change in the effect on the pavement structure according to Miner's rule. A common case where the design load is in the beginning of the range for which standard pavement designs are selected from the catalog is represented in Figure 5 a. According to the catalog, the designer must choose a pavement design that is adapted to a load of 2 million to 3 million ESAs. It can be seen that the standard design is not optimal for the selected design period, as the service life of the structure is almost 38 years in terms of fatigue resistance. By choosing a special design and reducing the thickness of the asphalt base layer by 2 cm, it can be seen that the bearing capacity of the structure ideally corresponds to the selected design period of 20 years Figure 5 b shows the case where the calculated design load is at the end of the range. In this case, the standard and ViaStructura-designed pavement structures are identical. The difference in performance is determined by the load distribution used, as only a single axle load of 10 t is used to calculate the standard design. It can be seen that in some cases the real impact on the pavement structure may be greater and may even lead to pavement failure several years earlier than expected.



a) b)

Figure 5. Performance comparison of standard and ViaStructura-designed pavement structures at design load of a – 2.05 mill. ESA's, b – 2.95 mill. ESA's

As the load-bearing capacity of a flexible pavement structure depends on the temperature due to the composition and physical properties of the asphalt mix, it is crucial to assess the climatic condition under which the designed pavement structure will operate. Figure 6 represent how the performance of the same pavement structure can differ at different pavement surface temperature distribution.

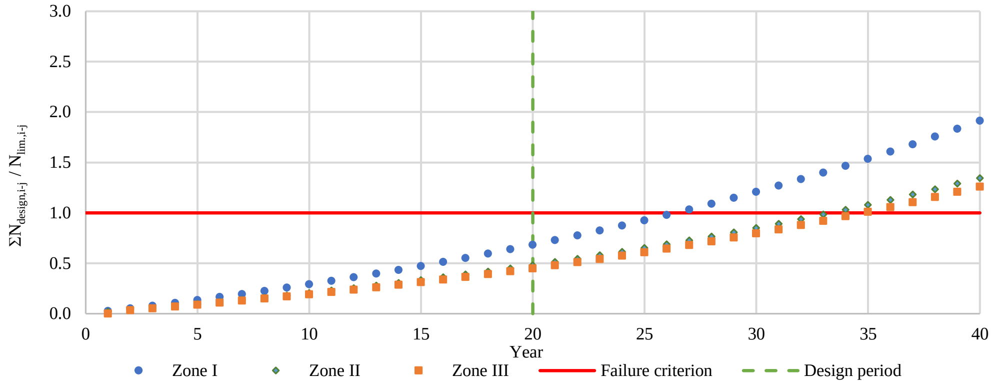


Figure 6. Performance comparison of pavement structure at different pavement surface temperature zones in Lithuania

Compared to other zones, zone 1 is more likely to have lower temperatures, but also extremely high temperatures are approximately 2 times more likely to occur. As asphalt mixtures are very sensitive to extremely high temperatures, in this case, it becomes an essential factor for differences in the fatigue resistance of the pavement structure. This shows how important is to have reliable data on the actual operating conditions of the pavement structure and it is necessary to properly assess the composition and materials for the designed pavement structure. The calculation results also show that the application of the same standard pavement structure regardless of location is not always effective and the possibility of individual design should be considered.

Conclusions

ViaStructura model represents a significantly different design concept for pavement structures than selection of standard pavement structures. ViaStructura provides a direct tie between structural design, degradation prediction, materials performance based characteristics, climate and traffic factors. This leads cost savings and pavement thickness design for particular design load instead of load range.

The major principles of the ViaStructura model include:

- Design traffic load evaluation through the axle load spectra in range between 2 t ant 22 t;
- Frost depth data and asphalt surface temperature intervals dependant on climate zone;
- Calculation of stress and strain in critical points of structure using multilayer linear elastic theory;
- Degradation analysis including asphalt and hydraulically bound base layer fatigue and permanent deformation (rutting) of unbound base layers and subgrade.

Compared to the pavement structure selection by standard catalogues, the following advantages of the model can be distinguished:

- Allows to design structure using asphalt layers stiffness characteristic based on particular pavement temperature range and load spectra instead of ESA ;
- Allows to evaluate pavement structure performance with newly composed construction materials by adding them to model database;.
- Allows a better understanding of the principles and factors affecting pavement structures performance and thus making more efficient decisions;
- Allows to combine the selection of pavement rehabilitation solutions with non-destructive bearing capacity measurements and thus obtain reasonable and expectation-meeting results.

On the other hand, the application of the model also poses some challenges related to the need for data. A larger amount of input data is required, covering not only usual traffic intensity data but also such as pavement surface temperatures, frost depth and axle load distribution, which require long-term monitoring data, which makes the design process more reliable. The applicability of the model is greatly facilitated by the development of a network of road traffic and climate monitoring systems.

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Author Contributions

MK conceived the study and were responsible for the data collection, analysis and preparation of the first draft of the article. RK was responsible for data analysis and interpretation and review of first draft of article. AV was responsible for planning of the data collection, finalization of article and conclusions.

Disclosure Statement

The authors declare no conflict of interest.

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