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*Research Article*

# Pave-Ut—Hungarian environmental load application

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Abstract: Structural analysis of road pavement structures is necessary to reduce material waste in cross-sectional design and to accompany optimal feeling of use within the service life. As a result of many studies, it is known that the effect of environmental load on roads is significant. Since environmental loads have regional characteristics, this study focused on the application of environ-mental loads in structural analysis in the light of regional characteristics in Hungary. In this study, a structural analysis program called Pave-Ut, which is based on the finite element analysis method, was developed. Among the major environmental factors, stiffnesses of the temperature influence on asphalt layer and water content change influence on subgrade are featured. Pave-Ut was verified through BISAR and ALVA, which are codes for research. An error of about 10% occurred, which will be reinforced in future studies. Finally, a comparative analysis was carried out in a case in which the asphalt temperature profile for each layer was reflected and a case in which the stiffness of the subgrade was reflected in the monthly average rainfall, and these were com-pared to a case in which these characteristics were not taken into account.

*Keywords: asphalt material property programming; dynamic modulus at specific depth; dynamic modulus; Hungarian asphalt temperature prediction; pavement structural analysis*

## I. INTRODUCTION

Structural analysis in road pavement design is a dynamic prediction process for the horizontal or vertical strain in the surface layer, base layer, and subgrade [1]. The predicted horizontal or vertical strain becomes the main variable in serviceability analysis.

The aim of this study is to investigate the influence of the climatic indexes on pavement system, especially the temperature and water content. The numerical model for the temperature distribution inside of the asphalt layer is prepared and the application of water content change on the subgrade modulus variation is carried out. The result of this study shows that the temperature effect on asphalt layer's stiffness and structural responses with consideration of this change is distinguishably different from the simple design condition with fixed stiffness value which does not consider such change. Whereas the subgrade modulus variation does not show big difference in response.

### 1. Literature Review

A design input variable provides the basic data for estimating the optimal thickness of pavement. Design input variables are used to predict the mechanical behavior and utility of a preliminary pavement section during the service period [2, 3]. For design input variables, the environmental characteristics include the internal temperature of the asphalt concrete pavement, the water content of the sub-base and subgrade, and the freezing index. The internal temperature of an asphalt concrete pavement layer is determined in the form of the distribution with respect to depth by using the temperature prediction model of the road pavement structure design based on the atmospheric temperature [4, 5]. The asphalt concrete temperature is known to be influenced by some weather indexes. Chao et al. investigated the effects of those indexes on the pavement temperature. The study revealed that the air temperature and relative humidity had a great influence on the asphaltic temperature, whereas cloud cover, wind speed, and precipitation had weaker influences [2]. The sub-base and subgrade moisture contents are determined by using the water content prediction model of the road pavement structure design with the average monthly atmospheric temperature, the average monthly accumulated precipitation, and the grain size characteristics of the sub-structure material.

Asphalt is a petroleum compound that left over after crude oil refining which is sticky, black viscous liquid or semi-solid. Asphalt exhibits a very complex rheological behavior, which mainly depends on temperature, traffic load, and application rate. At low temperatures and low load application rates, asphalt acts as an elastic solid, while at high temperatures and longer load rates, it acts as a viscous liquid. At medium temperatures, it is characterized as a viscoelastic fluid [3]. To determine the importance of the effect of temperature on asphalt's durability, many studies were carried out to estimate the temperature [8, 9].

In the design stage of a road, the viscosity as a function of the temperature is important due to the pavement's aging and distresses caused by climate change. In NCHRP Project1-40D, a part of the Mechanistic–Empirical Pavement Design Guide, Bari and Witzcak proposed a set of predictive models for the viscosity and modulus of asphalt binders [4].

Environmental and climatic factors that affect the behavioral characteristics of asphalt concrete pavement structures are largely divided into changes in the physical properties of the asphalt concrete layer due to changes in atmospheric and internal temperature and changes in the properties of the subgrade, granular layer, and sub-base layer due to seasonal influences. It is important in terms of road engineering to predict these characteristics in advance and to reflect them in the structural capabilities.

Temperature sensitivity plays an important role in understanding asphalt pavement failure and indicates how quickly asphalt properties change over time in terms of indicators such as penetration index [5]. There are many ways to detect the road surface. In this study, direct temperature measurement was performed using a thermometer. Another study presented road background segmentation based on watersheds [6].

Efforts have been made to accurately predict the temperature in the structure of asphalt concrete pavement. The calculation of the pavement temperature with the thermal properties of pavements started with the work of Barber. A maximum temperature estimation was predicted with observed weather data. This work made a correlation of locally limited and time-limited observed data with a standard weather report [7]. External factors, such as insolation, atmospheric temperature, wind speed, precipitation, cloud coverage, and subgrade water content, all influence the temperature of the pavement. The internal conditions of the binders, as well as the types of binders, have an impact. Dickinson incorporated external meteorological conditions into the temperature estimation of asphaltic pavements [8].

Saas created a road condition model that was integrated into the Danish Meteorological Institute's autonomous road temperature prediction system. The findings of this investigation revealed that the temperature forecast sensitivity is highly dependent on atmospheric meteorological data [9]. At the request of the Canadian weather center, a system named METRo was built in Canada for scientific purposes. This system has the advantage of being able to use weather and road temperature observation values from the road meteorological information system, as well as weather data projected by the Canadian weather center's own model. It can also explain the state of the collection of water on the road surface and whether it is liquid or solid [10].

The temperature equivalency factor, which is a function of the type of distress, the structure, and the material characteristics, was suggested. This was applied to convert in-service traffic loading into its equivalent at the reference time [11].

To prepare the temperature profile, the heat transfer theory and heat balance at the surface were considered [12]. The internal temperature distribution could be predicted from the surface temperature of asphalt concrete [8]. The prediction of the surface temperature of asphalt concrete is the result of the heat exchange balance between the asphalt concrete and the atmospheric temperature based on the thermal equilibrium equation. From the net energy balance of the pavement structure, Solaimanian and Kennedy proposed a quadratic equation for the prediction of the maximum pavement surface temperature [13].

Based on the BELLS model, a temperature prediction equation at the midpoint of the asphalt was proposed in Tennessee. With this predicted temperature, the expression for inversely calculating the modulus of asphalt concrete was expressed as an exponential function [14].

Witczak set the temperature of the one-third depth point of an asphalt concrete layer that was calculated using the atmospheric temperature as the representative temperature and proposed an equation for calculating the elastic modulus of the asphalt concrete layer using this. In addition, Witczak proposed an equation for obtaining the modulus of elasticity at an arbitrary temperature based on the modulus of elasticity of the asphalt concrete layer at 25 °C [15]. Currently, the American Asphalt Association sets the temperature at one-third of the asphalt concrete layer's depth as the representative temperature and sets the standard temperature at 21 °C. The modulus of elasticity is corrected and used.

Dickinson predicted the internal temperatures of pavement structures by developing a finite difference temperature prediction program that used Australia's solar radiation, average monthly maximum temperature, and meteorological data, such as sunrise and sunset times, as input data [8]. As part of the NCHRP 1-37A project, an empirical–mechanical design method for asphalt properties was established to predict the viscoelasticity and complex shear modulus of asphalt binders based on an extensive binder characterization database [4].

When the wheel load is applied, the element within the lower part of the pavement system is confined not only by the pavement system above it, but also by the wheel load's repeated deviator stress. As the number of repetitions of loads rises, one piece of the package's bottom will repeat elastic deformation and recovery, accumulating plastic deformation. The recovery strain rate becomes more prominent than the plastic deformation as the number of repetitive loads rises, and the slope of the stress–strain curve is characterized as the recovery elasticity factor (**Fig. 1**). Under repeated stress, the subgrade exhibits nonlinearity, which is a deformation that is recoverable from some fraction of the plastic deformation [16].

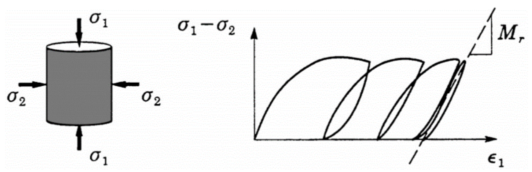



***Figure 1.*** *Triaxial test and resilient behavior of granular materials.*

The stiffness of a material with respect to a resilient response can be found with equation (1):

$$M_r = \frac{\sigma_d}{\varepsilon_r} \qquad (1)$$

This implies that a resilient modulus ($M_r$) is expressed as the deviatoric stress ($\sigma_d$) divided by the recoverable strain ($\varepsilon_r$).

In an effort to describe the resilient behavior of the subgrade, the earliest model of $\mathrm{K}-\theta$ (equation 2) arose from Hicks and Monismith [17].

$$M_r = k\theta^n \qquad (2)$$

The mean pressure acting on the specimen ($\theta$, bulk stress) is raised to a power, n, in this simple model. Many modifications have been devised by specialists from this simple design. Uzan discovered that deviator stress had a non-negligible effect on the resilient modulus and included a deviator term in his model [18]. Later, Witczak built the Witczak–Uzan model by substituting the deviator component from the Uzan model into octahedral stress [19]. This model is extensively utilized in three-dimensional FE modeling, since the octahedral stress in the model is a three-axis term (equation 3).

$$M_r = \mathrm{k_1 P}_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}\right)^{k_3} \qquad (3)$$

where $k_1$, $k_2$, and $k_3$ are regression coefficients from triaxial test, $\tau_{oct}$ is the octahedral shear stress ($= \frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2}$), and $\mathrm{P}_a$ is the atmospheric pressure.

The material properties of the pavement substructure are the modulus of elasticity and Poisson's ratio. For the empirical model for determining the design input variables, the volumetric stress model is applied.

$$E = k_1 + k_2 \cdot \theta \qquad (4)$$

where $E$ is the elastic modulus, $\theta$ is the bulk stress ($= \sigma_1 + \sigma_2 + \sigma_3$) [kPa], and $k_1$ and $k_2$ are model coefficients (**Table 1**).

***Table 1.*** *Range of the properties of a crushed stone base material [38].*

| *Index* | *Range* |
|---|---|
| Elastic modulus | $100 \le E \le 600$ |
| $k_1$ | $80 \le k_1 \le 270$ |
| $k_2$ | $0.1 \le k_2 \le 0.6$ |

Whether the road structure satisfies the safety conditions of the specification for various load conditions should be reviewed. In general, satisfaction is checked through experiments or numerical analyses. The method of design verification through numerical analysis is generally applied to the design formula presented in the design regulations or to the method of numerical analysis using finite element analysis. Depending on the physical characteristics of the applied load, various stability evaluation methods, such as structural analysis, flow analysis, vibration analysis, and fatigue life evaluation, are applied.

For mechanical analysis, tools for structural analysis are essential. In the case of road pavement using only elastic materials, structural analysis can even be performed well with the multi-layer elasticity theory, but as the complexity of materials and interlayer boundary conditions increases, the use of numerical methods, such as finite element analysis, is essential.

Duncan and his colleagues prepared the axisymmetric structural modeling of asphalt concrete and suggested the boundary condition location at a depth of 18 radii for the bottom and vertical boundaries at 12 radii from the center. The Gonzales bypass process was used to reflect the granular layer's resilient modulus. An emphasis was made on the fact that the variation of the resilient modulus in the vertical direction had to be adapted in the model. In addition, the different temperatures were set at each node of the asphalt concrete to show the nonlinearity [16]. It appeared that the applied load in the prediction of deflection could be treated as static loading according to the results of laboratory tests. This is thanks to the small influence of an inertial effect [20].

Computer programs that are used to solve the boundary value problem of a multilayered pavement system fall into two groups: finite element theory and elastic layer theory [21]. ALVA calculates the structural responses of pavement based on Burmister's layered elastic theory [22].

Nowadays, finite-element-based programs are used widely thanks to their versatility, whereas layered elastic analysis based on closed-form solutions is not sufficient to characterize the materials used [23]. Currently, various codes for finite element analysis have been developed, and there are commercial products such as ANSYS and ABAQUS that are manufactured for general use, as well as research codes, such as ILLIPAVE and EAPAVE, which are manufactured exclusively for road pavement. ILLIPAVE addresses the axisymmetric problem and applies the K-θ method for granular materials [24].

Commercial code has the advantage of having a variety of material models, but has the problem of being expensive to use. Research code also has a disadvantage in that it is almost impossible to add elements or materials because access to the source-code level is limited. Therefore, to solve these problems, we developed a finite element code. To apply the nonlinear properties of an asphalt concrete layer to the structural analysis, the method of subdividing the layer and applying the elastic modulus was adopted.

The finite element analysis code developed for road pavement was named Pave-Ut. Partially using both C# and MATLAB, the code is for an axisymmetric problem. In this study, an introduction of the axial symmetry analysis method implemented in Pave-Ut, the formulation of the calculation of the input material properties for the analysis, and the process of the numerical verification of the developed code are additionally described.

The biggest reason to predict the temperature of the road pavement and apply it to the structural analysis is to predict the bearing capacity more accurately. This is the basis of life cycle cost in construction [25]. Also, according to a numerical study conducted previously, it was found that using only one stiffness for composite structures was insufficient [26]. Therefore, in this study, various stiffnesses considering the temperature distribution were applied to the asphalt mixed layer modeling.

## II. Research Method

In this study, research was conducted on the prediction of the temperature of existing asphalt pavement according to time and depth by using the temperature measurement data at the actual site. A temperature sensor for each depth was buried in the center of Budapest, and the surface and internal temperatures of the pavement were periodically measured every 15 minutes. Structural analysis based on the finite element analysis method was performed by analyzing these field data and applying the internal asphalt temperatures estimated using the temperature prediction formula used in Hungary to the prediction of the stiffness of the asphalt concrete layer. Based on the results of this study, a method for applying environmental loads suitable for the climate and environmental conditions of Hungary is suggested.

### 2. Material Properties

Based on the predictive Witzcak model, a program that can calculate the dynamic modulus at a specific depth was prepared. In addition, a predictive model for the temperature at a specified depth of asphalt was introduced for the Hungarian climate, which would be an input for the program. This calculator program was built with C#, an object-oriented computer language with the aim of free usability for anybody while also saving computational capacity.

*A. Asphalt Concrete Layer*

**Internal Temperature**

The internal temperature distribution can be predicted from the surface temperature of asphalt concrete [8]. The prediction of the surface temperature of asphalt concrete is the result of the heat exchange balance between the asphalt concrete and the atmospheric temperature based on the thermal equilibrium equation [13].

The solar energy from the sun on the surface of the pavement at any time is [27]:

$$I(t) = \frac{2S}{t_1}\sin^2\frac{\pi t}{t_1} \tag{5}$$

$S$: total insolation for a day ($Wh/m^2$); $t_1$: time ($h$, set as 0 at 1 hour before sunrise); $t$: time.

At any time on the surface of the pavement, the convective energy between the surface of the pavement and the atmosphere is:

$$E(t) = h_c[T_a(t) - T_S(t)] = h\Delta T(t) \tag{6}$$

$h_c$: coefficient of surface thermal transfer ($W/m^2{}^\circ K$); $T_a$: air temperature (K); $T_S$: surface temperature (K).

Thus, the energy flux can be stated as:

$$\gamma I(t) - E(t) \tag{7}$$

$\gamma$: absorptivity of the surface for solar radiation.

A quadratic equation for the maximum and minimum pavement temperatures that considers the latitude was suggested by [13] based on the energy balance.

$$q_{net} = q_s + q_a - q_c - q_k - q_r = 0 \tag{8}$$

$q_s$ : direct solar radiation; $q_a$ : atmospheric radiation; $q_c$ : convection energy; $q_k$ : conduction energy; $q_r$ : radiation energy emitted from the surface.

From the net energy balance of the pavement structure, Solaimanian and Kennedy proposed the quadratic equation for the prediction of the maximum pavement surface temperature [13].

$$R_0 \cdot \alpha_1 \tau_a^{\frac{1}{\cos z}} \cos z + \varepsilon_a \sigma T_a^4 + h_c(T_s - T_a) - \frac{k}{x}(T_s - T_x) - \varepsilon \sigma T_s^4 = 0 \tag{9}$$

$R_0$ : solar constant ( $1367\, W/m^2$ ); $\alpha_1$ : solar absorptivity (asphalt concrete: 0.85–0.93); $\tau_a$ : transmission coefficient (clear day =0.81, cloudy day = 0.62); $z$ : Zenith angle; $\varepsilon_a$ : coefficient of atmospheric radiation; $\sigma$: Stefan–Boltzman constant ($5.67 \times 10^{-8}\ W/m^{2\circ}K^4$); $k$: thermal conductivity ($1.36\ W/m$°C); $T_x$: temperature at depth $x$.

The solution of this equation using the finite difference method is developed as the following equation. In this study, the finite difference method is used to solve the problem, and the space of the asphalt concrete layer is divided into the finite spatial element $\Delta x$ and time $\Delta t$. $i$ is the location of the time node, and $m$ is the location of the spatial node.

The change in temperature with time on the surface (difference equation) is:

$$\gamma I(t) + h(T_a - T_o^i) + \kappa \frac{T_1^i - T_o^i}{\Delta x} = \rho C_v \frac{\Delta x}{2} \frac{T_o^{i+1} - T_o^i}{\Delta t} \tag{10}$$

$\rho$: density ($2.24\ t/m^3$); $\kappa$: thermal conductivity ($W/m°K$); $h$: specific heat ($840\ Ws/kg°K$).

The estimation of the temperature at the bottom of the asphalt layer, which is calculated with energy conservation, is:

$$\kappa \frac{T_1^i - T_o^i}{\Delta x} = \rho C_v \frac{\Delta x}{2} \frac{T_o^{i+1} - T_o^i}{\Delta t} \tag{11}$$

With the boundary conditions described in equations 10 and 11, the temperature inside the pavement can be estimated.

The finite difference method is a method of solving a differential equation as an algebraic differential equation under general boundary conditions, and the temperature of the center can be known [28]. The discretization of the space and time is performed with the mesh size of $\Delta x = 0.2$ and $\Delta t = 0.2$ . In this study, the solution of the temperature distribution is calculated with the Crank–Nicolson implicit method (equation 12).

$$-\left(\frac{\alpha \Delta t}{\Delta x^2}\right) u_{i-1,j+1} + 2\left(\frac{\alpha \Delta t}{\Delta x^2}\right) u_{i,j+1} - \left(\frac{\alpha \Delta t}{\Delta x^2}\right) u_{i+1,j+1} = \left(\frac{\alpha \Delta t}{\Delta x^2}\right) u_{i-1,j} + 2\left(\frac{\alpha \Delta t}{\Delta x^2}\right) u_{i,j} + \left(\frac{\alpha \Delta t}{\Delta x^2}\right) u_{i+1,j} \tag{12}$$

Based on the finite difference equation described above (equation 12), a Pave-Ut module was built with Matlab. The internal temperature prediction results will be applied to the further structural analysis of the pavement system as an input.

**Witzcak modulus prediction model**

A dynamic modulus prediction model that was prepared by Witzcak for the National Cooperative Highway Research Program (NCHRP) 1-37A is implemented in Pave-Ut [29].

$$\log_{10}|E^*| = -1.249937 + 0.02923 p_{200} - 0.001767 (p_{200})^2 - 0.002841 p_4 - 0.05809 V_a - 0.082208 \frac{V_{eff}}{V_{eff} + V_a} + \frac{3.971877 - 0.0021 p_4 + 0.003958 p_{3/8} - 0.000017 (p_{3/8})^2 + 0.00547 p_{3/4}}{1 + \exp(-0.603313 - 0.313351 \log f - 0.393532 \log \eta)} \tag{13}$$

where $p_{200}$ is the percentage of aggregate passing a #200 sieve, $p_4$ is the percentage of aggregate retained in a #4 sieve, $p_{3/8}$ is the percentage of aggregate retained in a 3/8 inch sieve, $p_{3/4}$ is the percentage of aggregate retained in a 3/4 inch sieve, $V_a$ is the percentage of air voids, $V_{beff}$ is the percentage of effective asphalt content, $f$ is the loading frequency (Hz), and $\eta$ is the binder viscosity at the temperature of interest.

In this study, as an input of the dynamic modulus prediction model (equation 13), the viscosity ($\eta$) at a temperature is used according to the value predicted by Bari and Witzcak [4].

$$\log \log \eta_{f_s,T} = A' + VTS' T_R \tag{14}$$

$$A' = 0.9699 f_s^{-0.0527} \times A \tag{15}$$

$$VTS' = 0.9668 f_s^{-0.0575} \times VTS \tag{16}$$

where $\eta_{f_s,T}$ is the viscosity of the asphalt binder as a function of both the loading frequency ($f_s$) and the temperature ( $T_R, Rankine\ scale$ ; cP), A is a regression intercept from the conventional ASTM $A_i$ - $VTS_i$ , VTS is the slope from the conventional ASTM$A_i$-$VTS_i$, and $A'$ and $VTS'$ are adjusted values of A and VTS.

### B. Subgrade

In all design stages, the elastic modulus of the subgrade should consider long-term and short-term changes in the water content [30].

The resilient modulus prediction model for the pavement considering the water content is as follows [31] [32].

$$\log\left(\frac{M_R}{M_{Ropt}}\right) = a + \frac{b-a}{1+\exp\left(\ln(-\frac{b}{a}) + k_m \cdot (S - S_{opt})\right)} \quad (17)$$

where $M_R/M_{Ropt}$ is the resilient modulus ratio, $a$ is the minimum of $\log(M_R/M_{Ropt})$, $b$ is the maximum of $\log(M_R/M_{Ropt})$, $k_m$ is the regression parameter, and $(S - S_{opt})$ is the variation in the degree of saturation expressed in decimals.

This model was updated later and applied into Korean road design specifications [33].

The subgrade water content is determined by a model that includes the monthly average temperature, monthly accumulated precipitation, and soil distribution characteristics (**Table 2**). The model in this specification suggests using the following water content inputs.

$$\mathrm{E} = k_1 \theta^{k_2} \sigma_d^{k_3} 10^{k_w(\boldsymbol{\omega} - \boldsymbol{\omega_{opt}})} \quad (18)$$

$k_1$, $k_2$, and $k_3$ are model coefficients, $\omega_{opt}$ is the optimal water content, ω is the water content, and $k_w$ is a model coefficient that reflects the water content, which is –0.1417 (for coarse-grain material) or –0.0574 (for fine-grain material). $\mathrm{E}_{opt}$ is the estimated subgrade modulus in an optimal water content condition. prec is the monthly precipitation (mm), and P200 is the #200 sieve passing ratio.

AASHTO guides the resilient modulus of the subgrade, which takes into account the deviation of the water content due to seasonal fluctuation [34]. Equation (19) is a generalized estimation of the resilient modulus based on AASHTO MEPDG, and the $M_r$ determination test method is based on AASHTO T 307 or NCHRP 1-28A [30].

$$M_r = k_1 p_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3} \quad (19)$$

where $P_a$ is the normalizing stress and $k_1$, $k_2$, and $k_3$ are model coefficients.

## 3. Numerical Method

The key concept of a program using the finite element method is to build finite elements. There is a huge number of libraries of finite elements in commercial and scientific finite element programs. Thus, the study of the existing codes and their employment with modifications are important [35].

The purpose of this study is to prepare a calculator for the asphalt modulus at a specific depth (**Fig. 2**). To fulfill this purpose, we take the temperature as a function of the asphalt mix depth, which is the input of the binder viscosity (equations 14-16).

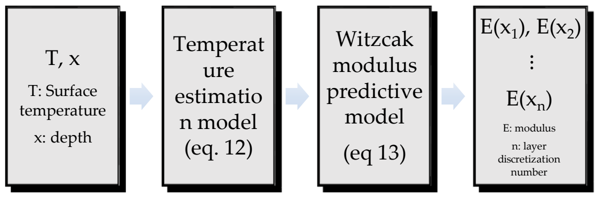
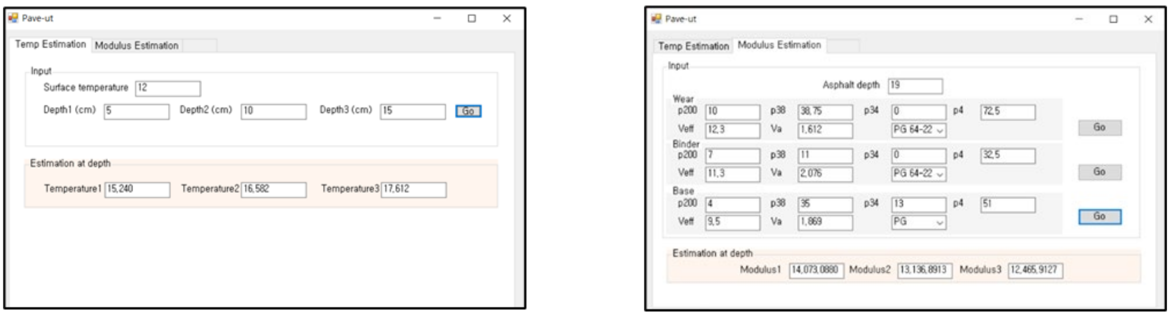



***Figure 2.*** *Scheme of modulus calculator.*




(**a**) (**b**)

***Figure 3.*** *Graphical user interface of Pave-Ut: (a) Temperature estimation part; (b) Modulus estimation part.*

***Table 2.*** *Subgrade water content estimation model [3].*

| ***Region*** | ***Subgrade water content estimation model (ω)*** |
|---|---|
| Northern part | $\boldsymbol{\omega} = 23.54759 + 0.15216 \times \text{temp} + 0.00070721 \times \text{prec} + 0.17990 \times P_{200}$ |
| Southern part | $\boldsymbol{\omega} = 21.84699 + 0.09598 \times \text{temp} + 0.00064287 \times \text{prec} + 0.9130 \times P_{200}$ |

The program first gets the surface temperature of the pavement and then estimates the temperature at the desired depth. Later, the user inputs the asphalt data; the program starts to match the input data and built-in material data, and then calculates the corresponding modulus.

**Fig. 3** depicts the graphical user interface of the calculator. The program was made with two tabs; the first tab displays the temperature estimation and the second displays the dynamic modulus estimation.

The calculation time required for analysis increases in the order of frame element, plate element, and solid element [36]. A study indicated that the 3D analysis did not display major differences from the 2D axisymmetric analysis for predictions of the structural responses of pavement [37].

Displacements occur as a result of loading in the r and z directions, and they are denoted by $u$ and $z$ (**Fig. 4**).

***Table 3.*** *Pavement parameters used in the analysis*

| Index | Material properties | |
|---|---|---|
| | **Stiffness [MPa]** | **Poisson's ratio** |
| Asphalt | 260 | 0.35 |
| Base | 500 | 0.4 |
| Subgrade | Inf. | 0.45 |

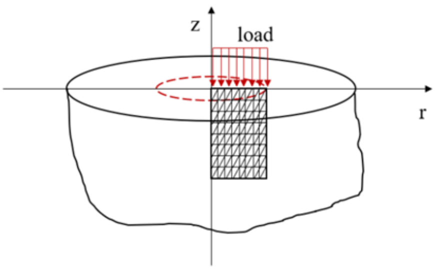


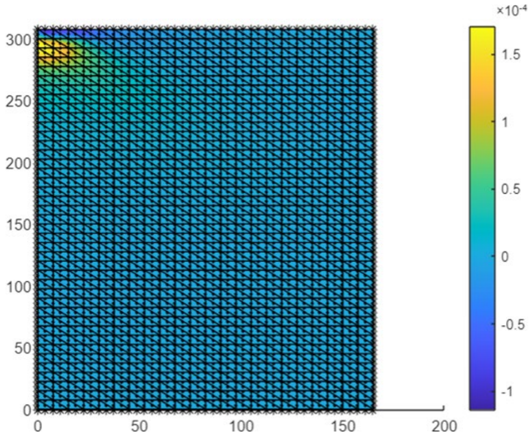

***Figure 4.*** *Axisymmetric finite element formulation.*

$$\begin{Bmatrix}\sigma_{rr}\\ \sigma_{zz}\\ \sigma_{\theta}\\ \tau_{rz}\end{Bmatrix} = \frac{E}{(1+\nu)(1-2\nu)}\begin{bmatrix}1-\nu & \nu & \nu & 0\\ \nu & 1-\nu & \nu & 0\\ \nu & \nu & 1-\nu & 0\\ 0 & 0 & 0 & \frac{1-2\nu}{2}\end{bmatrix}\begin{Bmatrix}\varepsilon_{rr}\\ \varepsilon_{zz}\\ \varepsilon_{\theta}\\ \gamma_{rz}\end{Bmatrix} \quad (20)$$

where $\sigma_{rr}$, $\sigma_{zz}$, $\sigma_{\theta}$, and $\tau_{rz}$ are stresses in each direction, $E$ is the stiffness, $\nu$ is Poisson's ratio, and $\varepsilon_{rr}$, $\varepsilon_{zz}$, $\varepsilon_{\theta}$, and $\gamma_{rz}$ are strains in each direction.

Equation 20 describes the structural responses in constitutive equation form that designers are interested in. The pavement structure has symmetricity in its geometry, applied loadings, and the material properties. Thus, solving the axisymmetric problem with cylindrical coordinates is possible. Here, the tangential strain ($\varepsilon_{\theta}$) depends only on the $r$ direction.

Pave-Ut employs a six-node triangular element with full-bond interlayers and three Gaussian points for the calculations. The mesh size and boundary condition settings are standardized to avoid program crashes. Meshes are restrained in the horizontal direction, and the meshes in the bottom part are fixed




```
nnd = 0;
k = 0;
for i = 1:NXE
    for j=1:NYE
        shapefunction;
         %
         geom(n1,:) = [(i-1)*dhx - X         (j-1)*dhy - Y];
         geom(n2,:) = [((2*i-1)/2)*dhx - X   (j-1)*dhy - Y];
         geom(n3,:) = [i*dhx - X             (j-1)*dhy - Y];
         geom(n4,:) = [(i-1)*dhx - X       ((2*j-1)/2)*dhy - Y];
         geom(n5,:) = [((2*i-1)/2)*dhx - X  ((2*j-1)/2)*dhy - Y];
         geom(n6,:) = [i*dhx - X           ((2*j-1)/2)*dhy - Y];
         geom(n7,:) = [(i-1)*dhx - X          j*dhy - Y];
         geom(n8,:) = [((2*i-1)/2)*dhx - X    j*dhy - Y];
         geom(n9,:) = [i*dhx - X              j*dhy - Y];
         %
         nel = 2*k;
         m = nel -1;
         connection(m,:) = [n1  n2  n3   n5   n7   n4];
         connection(nel,:) = [n3   n6   n9   n8   n7   n5];
         max_n = max([n1  n2  n3  n4  n5  n6  n7  n8  n9]);
         if(nnd <= max_n); nnd = max_n;
end;
         %
         XIG(2*i-1) = geom(n1,1); XIG(2*i) = geom(n2,1); XIG(2*i+1) = geom(n3,1);
         YIG(2*j-1) = geom(n1,2); YIG(2*j) = geom(n4,2); YIG(2*j+1) = geom(n7,2);
    end
end
```

***Figure 5.*** *Mesh generation of Pave-Ut and code with horizontal strain distribution.*

in all directions. Assumptions are made for each layer to have linear elastic and cross-anisotropic material models. The analysis is based on axisymmetric geometry and formulation. Full bonding on all layers is assumed (**Fig. 5**).

**Verification of Pave-Ut**

For the verification of Pave-Ut, among the popular pavement analysis programs, BISAR and ALVA were chosen. The pavement parameters used in the analysis are described in **Table 3**. A load of 0.7 MPa was considered in a circular area with a radius of 150.8 mm.

Pave-Ut shows reliable results when compared with the other programs. However, there is a tendency to overestimate the horizontal strain and slightly underestimate the vertical strain. The

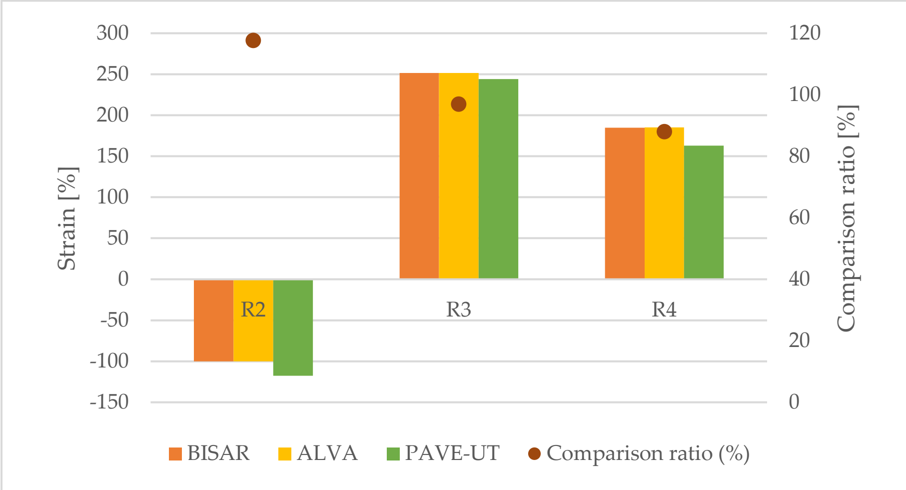



***Figure 6.*** *Comparison of structural responses; R2: horizontal strain at the bottom of the asphalt layer; R3: vertical strain at the top of the base layer; R4: vertical strain at the subgrade (με) and comparison ratio between Pave-Ut and BISAR.*

comparison ratio is marked in **Fig. 6**, which shows the ratio of the responses calculated with Pave-Ut to those calculated with BISAR.

## III. Results

With material properties that reflect the climatic conditions from Section 2.1, Pave-Ut carried out a structural analysis. Once the dynamic moduli of asphalt layers with specific depths were calculated, these material properties were applied to the structural analysis stage.

The basic section and physical properties for 'K' (heavy traffic) and 'N' (normal usage) roads specified in the Hungarian specifications are as follows (**Table 4**).

For the parametric study to check the influence of environmental factors on the structural responses, two cross sections are chosen: 1) simple model with simple material properties guided in Hungarian specification (**Table 4**), and 2) material properties calculated upon temperature profile on asphalt mix layer and water content change on subgrade.

***Table 4.*** *Basic pavement parameters suggested in Hungarian specification e-UT 06.03.13 [38].*

| Index | Stiffness [MPa] | Poisson's ratio | Thickness [mm] |
|---|---|---|---|
| Asphalt | 5000 | 0.35 | 160 |
| Base | 500 | 0.35 | 200 |
| Subgrade | 40 | 0.35 | - |

***Table 5.*** *Weather data from July.*

| Index | Average temp [°C] | Acc. Precipitation [mm] |
|---|---|---|
| July | 23.56 | 124.7 |

The cross-sections that were compared with the simple cross-section from the Hungarian design code were **(Fig. 8)**: 1) the material properties reflecting the temperature distribution of the asphalt layer and 2) those reflecting the properties of the subgrade considering the monthly average accumulated precipitation. Structural analysis was carried out based on the weather information in July. The weather data can be found below.

**Table 5** refers to Hungary's average temperatures in July and the monthly-accumulated precipitation data. These are the input data for the estimation of the subgrade modulus. **Fig. 7** shows the temperature distribution at points at 2, 5, and 10 cm from the surface according to the prediction model in Equation 12. With this distribution, the variation in the dynamic modulus inside the asphalt layer can be traced. These climatic conditions were applied in the calculation of the structural response.

The influence of environmental factors was evaluated and confirmed for two layers: the asphalt layer and the subgrade. As a result of confirming the results, the influence of environmental factors on road structural analysis was significant.

**Table 6** shows the results of the application of load and climatic conditions in July to the pavement structure. According to the results shown in **Table 6**, the influence of the asphalt stiffness on the performance of the flexible pavement when considering temperature change is greater than that of the change in the subgrade modulus when considering water content. Critical points may occur at the interface of the asphalt layer and base layer, and a bottom-up crack is expected.

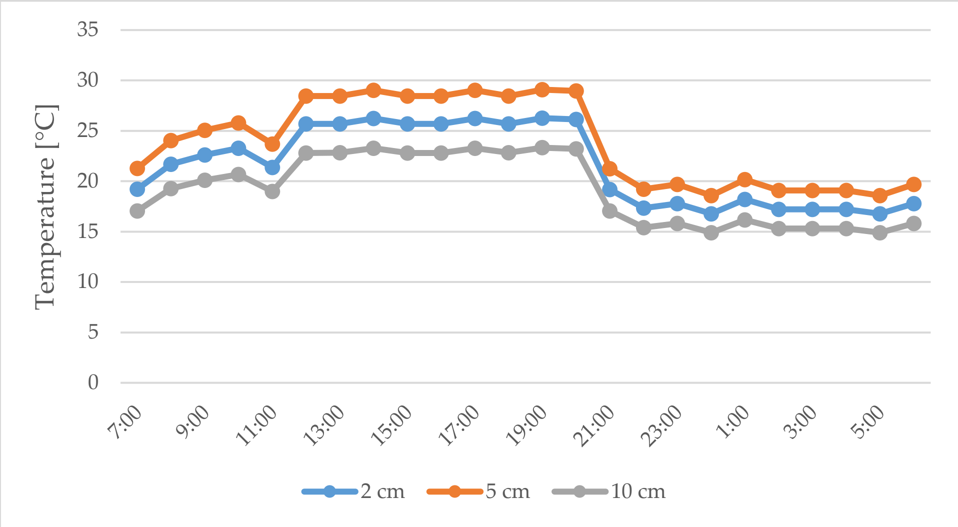



***Figure 7.*** *Estimated temperature inside of the asphalt mixture layer on July 1st according to the Hungarian estimation model (Equation 12).*

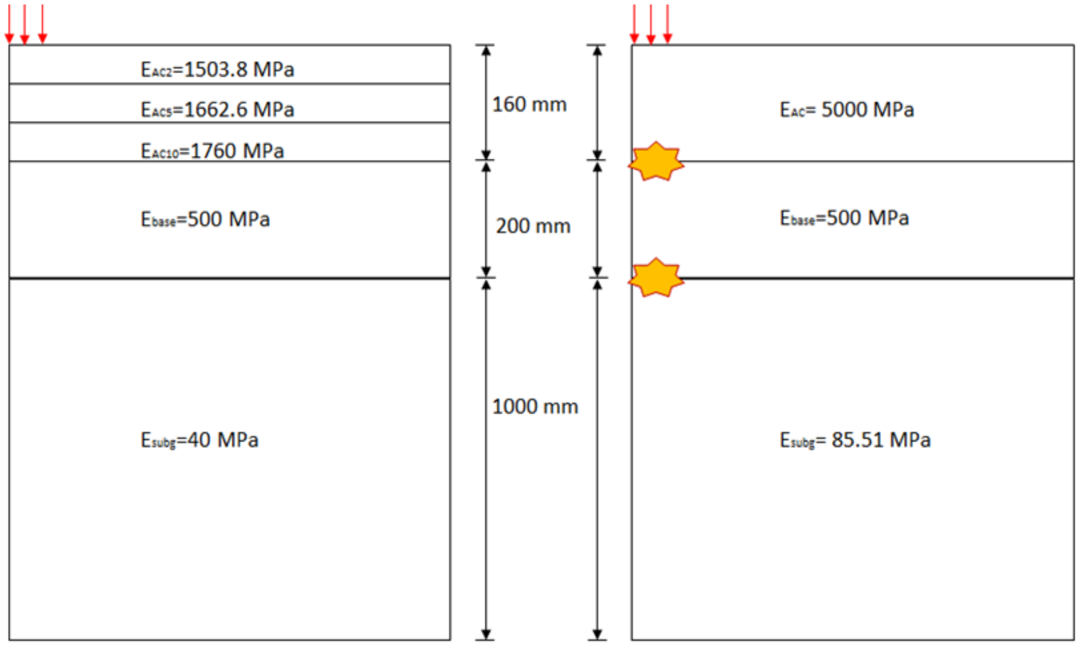



***Figure 8.*** *Material properties and cross section: (a) Variations in the predicted modulus: asphalt temperature profile considering stiffness; (b) subgrade modulus with consideration of precipitation in July. The critical points are indicated with star shapes.*

***Table 6.*** *Structural responses of three cases of Figure 9.*

| Index | Hungarian spec | Varying Asphalt stiffness | Subgrade |
|---|---|---|---|
| Horizontal strain bottom of asphalt layer | 150.7 | 124.4 | 149.5 |
| Vertical strain at the top of base | –337.5 | –131.1 | –334.7 |
| Vertical strain at the top of subgrade | –493 | –213.2 | –489 |

## IV. Conclusion

In this study, a dynamic modulus estimation program was prepared. The Hungarian asphalt temperature estimation model and Witzcak and Bari's viscosity and dynamic modulus prediction models were used. The results of this simple calculator can be used for the analysis of the aging of pavement. Here in this study research focuses on temperature and water content influence among the environmental factors that influencing pavement structure.

This study was conducted on the quantification of environmental loads for road design in Hungary. Since regional characteristics are important in the application of environmental loads to structural analysis, Hungarian weather information was actively used. The validation of the results was confirmed by comparing them with those of BISAR and ALVA, which are research codes. There was a tendency to overestimate the horizontal strain at the bottom of the asphalt layer and to slightly underestimate the vertical strain at the top of the base layer. We intend to improve this through future research.

This program has the advantage that it can be used for structural analysis by predicting physical properties by reflecting the temperature distribution inside an asphalt mixture layer.

The influences of considering the temperature profile of the asphalt layer and the variation of the water content on the subgrade noticeably exist. The strains differ from those suggested in the suggestion of a simple cross-section in the design specifications when taking the climatic conditions into account in the analysis. As a result of the confirmation of the findings, it is clear that environmental elements have a substantial impact on road structural analysis.

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## Data Availability Statement

The program prepared in this study can be downloaded at:
https://tomok4737.tistory.com/category/Archive/Dynamic%20modulus%20calculator.

Anybody who is interested in this program can access PaveUt.exe. The password is: 45NDQxNT.

## AUTHOR CONTRIBUTIONS

**S. Cho**: Software, Validation, Data curation, Writing, Methodology, Investigation, Visualization.

**C. Tóth**: Supervision, Conceptualization, Formal analysis, Investigation, Resources, Review.

## Disclosure Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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