

Effects of Thermal Properties on Pavement Fatigue Life

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Abstract

Asphalt pavement performance is highly temperature dependent due to the viscoelastic behavior of the binder. Although rheological characteristics of bitumen (e.g., softening point, elastic recovery) are widely analyzed, thermal properties as diffusivity (or its components conductivity and specific heat capacity) are rarely tested. The most up-to-date design processes use asphalt master-curves to calculate temperature-dependent stiffness for versatile weather conditions, yet the temperature susceptibility of the mixture is neglected. In this paper a full approach is presented in order to determine the sensitivity of the pavement to changing in thermal properties. Surface temperatures are based on real-life data, in-depth temperatures are calculated *via* 1-D Fourier's heat transfer equation with the primary governing variable of diffusivity. The stiffness of the mixture is predicted by the Witczak–Bari model for every centimeter of depth to get a full stiffness profile. Multi-layer elastic theory is used to calculate pavement response. To evaluate conditional numerical sensitivities within the selected parameter space, 200 different combinations of thermal conductivity and specific heat capacity were tested as theoretical inputs. The connection between fatigue life and these numerical parameters was found non-linear. It was discovered that an increase of 1 W/mK in thermal conductivity can cause an average fatigue life reduction of 7.2%, while a 100 J/kgK change in specific heat capacity increases fatigue life with 1.0%. The ultimate general sensitivity analysis to thermal diffusivity showed that in the typical range of this property relative fatigue life can vary between 88.5–104.0% of the base scenario.

Keywords

pavement design, thermal properties, sensitivity analysis, fatigue analysis

1 Introduction

Asphalt pavement design is a crucial part of road engineering. The viscoelastic behavior of bituminous mixture makes pavement response calculations challenging. The most up-to-date design procedures can use master-curves in order to take temperature-frequency domain into consideration [1–4]. Multi-layered elastic theory (MLET) serves as the engine for widespread design software e.g., BISAR, WESLEA or JULEA, which is applied by the AASHTOWare Pavement ME Design [5–8]. KENLAYER or ALVA can add non-linearity to MLET solutions [9, 10], while the most modern software as FlexPave™, Illi-Pave or MichPave use the finite element method (FEM) to model viscoelasticity realistically and accurately [11–13]. Some researchers build their own FEM model to calculate pavement distress [14]. The complexity of the software is increasing with the increasing number of required inputs. Long climate time series and reliable material characteristics are needed for accurate modeling. The Enhanced Integrated Climatic Model for AASHTOWare Pavement ME uses 30 years long

time series to determine hour-long temperatures for design lifespan [15]. To use FlexPave, a material testing database needs to be built first [11]. Based on the results of Asphalt Mixture Performance Tester, master-curves can be determined and used for designing thickness. One can observe that all the laboratory tests of asphalt mixtures are related to temperature (or frequency), but the thermal properties of mixtures fall out of scope despite various sensitivity analyses [16]. Some researchers investigated the correlation between fatigue life and thermal properties [17, 18]. Others found that fatigue life has higher sensitivity to thermal conductivity than specific heat capacity. They concluded that thermal conductivity can be an important factor to predict pavement fatigue life, although it is neglected in modern road design procedures [19]. The temperature susceptibility of asphalt binder has been investigated in recent years more than its effect on pavement behavior [20, 21].

The objective of this paper is to examine the dependency of fatigue life of the pavement on thermal diffusivity,

which serves as the primary governing variable in heat transfer modeling. To thoroughly map the sensitivity of the applied model, the conditional effects of its specific components (thermal conductivity and specific heat capacity) were also decoupled and analyzed. Through temperature dependency of stiffness modulus, cumulative fatigue damage was calculated based on linear-elastic theory.

1.1 Thermal properties of asphalt mixtures

Thermal diffusivity, thermal conductivity and specific heat capacity are considered thermal properties of mixtures, beside absorptivity, emissivity, heat convection coefficient, and albedo. The previous characteristics describe how the heat is transferred through the material, while the latter describes how the heat is captured from or emitted to outside the material. This paper focuses on the effects of heat transfer, because the pavement fatigue criteria is determined at the bottom of the asphalt layers.

Equation (1) presents the connection between material properties:

$$\alpha = \frac{\lambda}{\rho \times c_p}, \quad (1)$$

where:

- α is the thermal diffusivity (m^2/s);
- λ is the thermal conductivity (W/mK);
- ρ is the mass density (kg/m^3);
- c_p is the specific heat (J/kgK).

In the context of the one-dimensional temperature model utilized in this study, thermal diffusivity (α) inherently governs the rate of heat transfer. While thermal conductivity (λ) and specific heat capacity (C_p) define the material's ability to conduct and store heat respectively, their coupled physical effect in transient heat conduction is represented entirely by diffusivity.

The three main properties are highly related to the composition of the mixture. Typically, 3–4 aggregate fractions plus filler are used to create mixture skeleton, and usually, the aggregate comes from different quarries. Bitumen is an industrial material but characteristics can change based on the crude oil from which it was produced. Air voids also affect the heat transfer. Therefore, mixtures can exhibit these properties over a wide range. Table 1 represents previously published results [22–24].

Thermal conductivity is primarily governed by aggregate mineralogy, void content and $D_{\max}$. Finer mixtures with low air void content have higher thermal conductivity,

Table 1 Range of thermal properties

Property	Unit	Range
Thermal diffusivity (α)	m^2/s	$0.4\text{--}1.7 \times 10^{-6}$
Thermal conductivity (λ)	W/mK	0.8–2.8
Specific heat capacity (c_p)	J/kgK	800–1600

while coarse aggregate mixtures with more air voids transfer heat less effectively. Bitumen has typically lower thermal conductivity (between 0.65–0.75 W/mK) [25]. These factors also influence the specific heat capacity. This may explain why no reliable variation of these properties can be found in literature. Although the range of the thermal properties is wide, some authors suggest that specific heat can be found more likely in a narrower range between 1116–1364 J/kgK [22].

2 Methods and materials

2.1 Approach

Section 2.1 presents the basic process of the analysis and introduces the methods and materials used for the calculations. The following steps summarize the structure of the analysis:

1. Defining temperature profiles in pavement;
2. Determining stiffness along depth based on temperature profiles;
3. Calculating strains at the bottom of the asphalt layer using ALVA;
4. Determining cumulative fatigue damage applying the Miner-principle based on simulated traffic distribution;
5. Sensitivity analysis of thermal parameters on fatigue life.

All the calculations were carried out in Matlab [26].

2.2 Pavement structure

The pavement structure for the analysis is described as a six-layer ideal structure based on Hungarian specifications [27]:

- 4 cm wearing course;
- 7 cm binder course;
- 12 cm base course;
- 20 cm cement-treated base course, $E = 2000 \text{ MPa}$;
- 50 cm untreated subgrade; $E = 80 \text{ MPa}$;
- Embankment, $E = 40 \text{ MPa}$.

This pavement structure is prescribed for Class K traffic load between 10–30 million ESAL under 20 years of service. Asphalt layers are supposed to be fully bonded, while full slip was estimated between any other layers.

This pavement structure was incorporated into the design script; however, to accurately capture the continuous stiffness profiles, the asphalt layers were discretized with a 1 cm vertical resolution. All layers under asphalt layers remained unchanged during the entire process in order to examine the behavior of the bituminous layers only. Mixture content is shown in Table 2.

Mixture content was indicated by South-Korean specifications [28] and is also in alignment with Hungarian specifications [29]. The frequency is used only for the purpose of the Witzak-Bari stiffness-estimation and cannot be understood as a loading frequency. The real traffic load frequency can largely differ from 25 Hz, specifically for multiple wheel arrangements of heavy trucks.

2.3 Heat transfer in asphalt pavements

Asphalt surface temperature is related to weather conditions. The most influential factors are ambient temperature, solar radiation and wind-speed [30], while one additional factor also needs to be considered which is the constant heat flux to the center of the Earth. One can solve the heat balance equation on the surface of the pavement [31] or use regression models [32, 33]. Road operators are measuring surface temperatures in order to determine salting time accurately during winter maintenance, therefore huge databases are built in several countries, although the accessibility to these databases are unknown. In-depth temperature measurements are conducted less frequently, and one must consider the accuracy of the depth of sensors. If the surface temperature is known, Eq. (2), also known as Fourier's heat transfer equation, can be solved.

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}, \quad (2)$$

where:

- T is the temperature (°C);
- t is the time (s);
- z is the depth (m);
- α is the thermal diffusivity (m²/s).

Table 2 Mixture content

	Wearing course	Binder course	Base course
p_{34} (%)	0	2.5	13
p_{38} (%)	38.75	24	35
p_4 (%)	72.5	45	51
p_{200} (%)	10	6	4
V_{beff} (%)	12.2	10.5	9.3
V_a (%)	3.08	4.159	3.777
f (Hz)	25	25	25

One dimensional approach fulfills the required accuracy, as in the centerline of the pavement the main heat flux is vertical, and horizontal heat transfer is negligible.

2.4 Surface temperature analysis

Data from a functional weather station was collected. The weather station is located on M5 motorway 147 + 688 km in Hungary. The time series include 19 years of air temperature, surface temperature, 8 cm deep temperature and 30 cm deep temperature. Temperatures were logged each 10 min. Only surface temperature was used in this paper. Based on statistical analysis, a representative year was established, exhibiting the same temperature frequency distribution as the entire 19-year long time series. As the goal was to use surface temperature as an input in the heat transfer equation, the 10-minutes resolution was interpolated according to Fourier number stability criterion.

$$Fo = \frac{\alpha \Delta t}{(\Delta z)^2} \leq 0.5 \quad (3)$$

Maximum timestep can be calculated as following:

$$\Delta t \leq \frac{0.5(\Delta z)^2}{\alpha}. \quad (4)$$

Applying 1 cm spatial resolution for depths and the maximum diffusivity of 1.5625×10^{-6} m²/s:

$$\Delta t \leq \frac{0.5(\Delta z)^2}{\alpha} = \frac{0.5 \times (10^{-2})^2}{1.5625 \times 10^{-6}} = 32 \text{ s}. \quad (5)$$

For the representative year 30 s was chosen as final resolution. The space domain was 3.00 m. The boundary condition at the bottom was constant 11.0 °C. The base layer was 20 cm cement-bond layer, characterized with $\alpha = 1.24 \times 10^{-6}$ m²/s [34], 50 cm subgrade was characterized with $\alpha = 0.7 \times 10^{-6}$ m²/s (as a low-water content sand) and the rest of the space domain was characterized with $\alpha = 0.35 \times 10^{-6}$ m²/s (as a clay type soil) [35]. Although thermal properties of the non-asphaltic materials depends on water-content and grain-size, these characteristic values were constant for all calculations to focus only on the effect of thermal properties asphalt layers. Thermal continuity condition was used on layer boundaries, since layers are compacted. Initial condition was a linear temperature distribution along the space domain.

2.5 Determining temperature profiles

Equation (2) was solved with 200 different thermal diffusivity parameters ($0.17\text{--}1.5625 \times 10^{-6}$ m²/s), which was built up from different combinations of thermal

conductivity and specific heat capacity. Thermal conductivity varies from 0.6 to 3.0 by 0.1 W/mK step, resulting in 25 different cases, while specific heat capacity changes from 800 to 1500 by 100 J/kgK step, resulting in 8 different cases. Mass density was uniformly set to 2400 kg/m³. Equation (2) was solved for every cm of a 23 cm deep asphalt pavement. To spare computational capacity, 30 s resolution was averaged to hours, which is in alignment with EICM approach. Finally 8760 different temperature profiles were determined for the year with 200 different diffusivity setting. Fig. 1 shows a calculated diurnal temperature profile along depth (3rd April).

As the measured dataset contained temperatures for 8 cm depth, it was suitable for backtesting the temperature-model. With $\lambda = 1.60$ W/mK and $C_p = 920$ J/kgK RMSE = 0.81 °C was found for 8 cm depth. While this comparison supports the model's performance at the measured depth under the selected conditions, it does not by itself validate the full continuous temperature profile along the entire pavement depth, but indicates a reasonable accuracy for the sensitivity analysis. For representative purposes Fig. 2 shows the comparison between the measured and modelled temperatures between 07.05. and 07.08.

Because of the initial condition, bias was expected but reduced below 2 °C only at 19:40 on 1st of January. Computed temperatures were below measured ones in this initial phase, which ultimately led to higher modeled stiffness on the first day. Considering that the measured temperature was also low (therefore the stiffness high), and

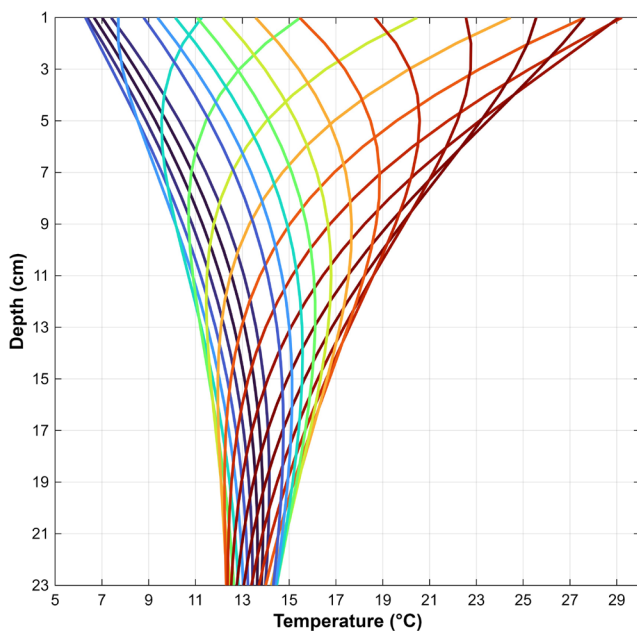


Fig. 1 Diurnal temperature profile along depth

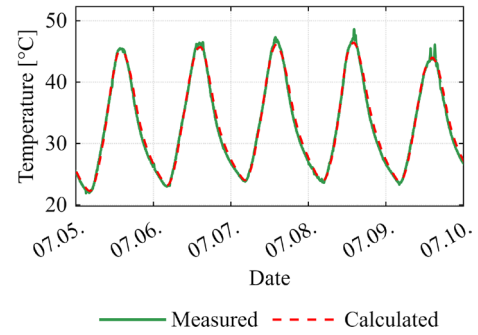


Fig. 2 Validation of the FDM calculation

that this discrepancy lasted only for the first day, the effect on the final results was found negligible.

2.6 Determining stiffness profile

After accurate modeling of temperatures through the representative year, stiffness profiles need to be determined. Witczak-Bari [36] stiffness predictor equation was used for this purpose:

$$\log|E^*| = 6.940166 - 0.00176(p_{200}) + 0.003889(p_4) - 0.08776 \times V_a - 1.33426 \frac{V_{beff}}{V_{beff} + V_a} + \frac{(-3.63992 - 0.3114(p_4) + 0.015546(p_{38}) + 0.010469(p_{34}))}{1 + \exp\left(\frac{-0.09942 + 0.162727 \log f}{+0.180695 \log \eta}\right)} \quad (6)$$

where:

- E^* is the stiffness modulus (MPa);
- p_{34} is the percentage of aggregate retained on 3/4-inch sieve;
- p_{38} is the percentage of aggregate retained on 3/8-inch sieve;
- p_4 is the percentage of aggregate retained #4 sieve;
- p_{200} is the percentage of aggregate passing #200 sieve;
- V_{beff} is the effective asphalt content as percentage of total mix volume;
- V_a is the air voids as percentage of the total volume;
- f is the loading frequency (Hz);
- η is the binder viscosity (cP).

Temperature is taken into consideration *via* binder viscosity:

$$\log \log \eta = A + VTS \log T_R \quad \text{for } T_R > T_{critical}, \quad (7)$$

$$\log \log \eta = 1.095 \quad \text{for } T_R \leq T_{critical}, \quad (8)$$

where:

- η is the binder viscosity (cP);
- T_R is the temperature (°R);
- A and VTS are the constant coefficients for a given binder.

PG 64-22 grade bitumen was selected for this analysis, applying $A = 10.980$ and $VTS = -3.680$ [37]. Equations (6) to (8) was applied to the annual temperature profiles of the 200 cases for every cm of the asphalt layer. The result was $200 \times 8760 = 1\,752\,000$ stiffness profile and pavement structure to input in computational algorithm.

2.7 Calculation of strains

The most up to date design software uses viscoelastic theory and master-curves for more accurate modeling of pavement behavior. Required computational capacity for this analysis is high (1 752 000 cases), therefore only software with "packaging functions" could be applied. The final solution was a Matlab-based code, Adaptive Layered Viscoelastic Analysis (ALVA), which is an open-access tool for civil engineers with high adaptive skills [10].

One only needs to define loading conditions, pavement structure geometry, material properties, numerical parameters, analysis type and evaluation points. The model is based on layered elastic half-space shown in Fig. 3. All layers are modeled as linear elastic, isotropic and homogenous. The material properties are Young's modulus, Poisson's ratio while layer thickness and friction can also be applied as structure set up.

Several load configurations can be implemented, in this analysis, a static 50 kN load was introduced on circular rigid plane with a 15 cm radius on the surface which equals with a 700 kPa uniform stress. This assumption may differ

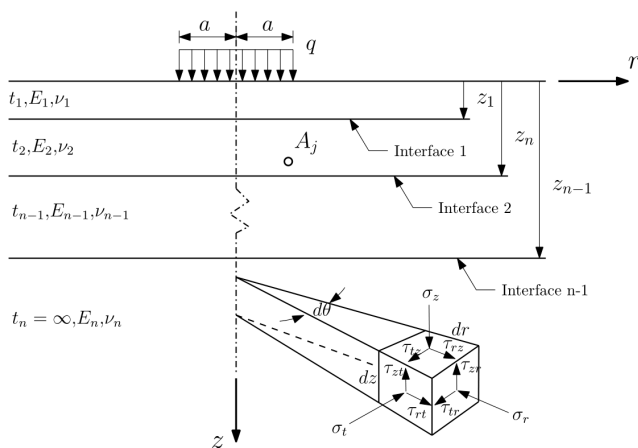


Fig. 3 N-layered elastic half-space [10]

from realistic traffic load, but is the current used practice in pavement engineering. Although, script also contains viscoelastic analysis, only the linear elastic theory was used as it fulfills the accuracy requirements, saves computational capacity and most importantly, through the versatile temperature and stiffness profile of asphalt layers were taken into account with the inputs. This solution does not make the analysis fully-viscoelastic, but a more accurate linear-elastic modeling. The response of the structure was calculated at the bottom of the asphalt layer, 23 cm deep in horizontal direction (ϵ_x) under the central of the load. This calculation was carried out with each stiffness profile.

2.8 Traffic

A full year of traffic data was collected from an existing traffic counting device implemented on M1 motorway 17 + 630 km. Using statistical analysis, hourly distribution of the heavy trucks were determined based only on weekdays. Fig. 4 shows the measured traffic, the averaged diurnal profile and the hourly averaged relative frequencies.

Relative occurrence of traffic was used for cumulative fatigue damage. The same distribution profile was applied for everyday in the entire year. A 1 000 000 axle load was distributed equally throughout the year. Only daily fluctuations were considered and used for fatigue calculations. The traffic volume fits the boundaries of the Class K pavement structure (10–30 M ESAL) considering 20 M axle loads under 20 years.

2.9 Cumulative fatigue damage

The allowed number of axle load was calculated based on Asphalt Institute fatigue equation used by WESLEA software [38]:

$$N_f = 2.83 \times 10^{-6} \times \left(\frac{10^6}{\epsilon_x} \right)^{3.148}, \quad (9)$$

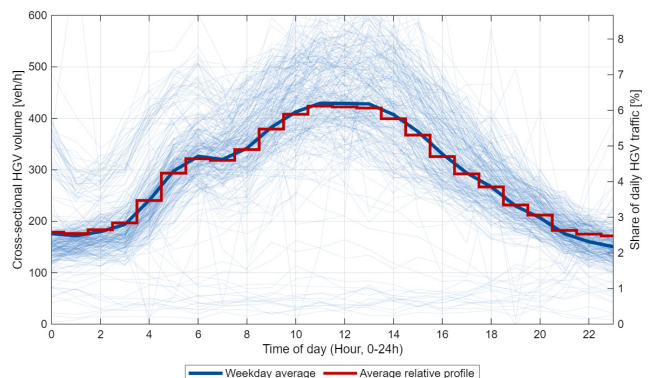


Fig. 4 Traffic distribution for 24 h

where:

- N_f is the number of allowed axles;
- ε_x is the tensile strain at the bottom of the asphalt layer.

Equation (9) was calculated for every 1 752 000 cases. After that cumulative damage factor (CDF) was determined for every hour of the year based on Miner's principle in Eq. (10) [39, 40]:

$$CDF = \sum_{i=1}^{8760} \frac{N_{1,fact}}{N_{1,allowed}} + \frac{N_{2,fact}}{N_{2,allowed}} + \dots + \frac{N_{8760,fact}}{N_{8760,allowed}}. \quad (10)$$

Results of the cumulative damage are gathered in a Damage matrix with 200 elements. Fatigue life of the thermal properties combinations is calculated with Eq. (11):

$$FL_{ij} = \frac{1}{CDF_{ij}}. \quad (11)$$

2.10 Sensitivity analysis

Sensitivity analysis was carried out for thermal diffusivity (α) and thermal conductivity (λ) and specific heat capacity (C_p) for the decomposed effect. In order to do that, fatigue life was normalized, taking $\lambda = 1.36$ W/mK, $C_p = 920$ J/kgK, $\alpha = 0.616$ m²/s as the baseline reference parameters, yielding the reference service life (FL_{ref}). The relative service life ($FL_{\%}$) for any discrete parametric combination was thus defined with Eq. (12):

$$FL_{\%}(\lambda, C_p) = \frac{FL(\lambda, C_p)}{FL_{ref}} \times 100 [\%]. \quad (12)$$

To isolate the individual structural impact of each thermal property and to evaluate the partial gradients of degradation within the multi-variable domain, a dimension reduction technique was implemented. This approach projects the multi-dimensional fatigue response into two-dimensional parametric curve families by systematically holding one variable constant while perturbing the other. Mechanistically, these discrete sections represent the quasi-partial derivatives of the fatigue life as Eq. (13):

$$\frac{\partial FL_{\%}}{\partial \lambda} \Big|_{C_p=\text{const.}_j} \text{ and } \frac{\partial FL_{\%}}{\partial C_p} \Big|_{\lambda=\text{const.}_i}. \quad (13)$$

The slope, local curvature, and vertical shifting of these extracted 2D functions directly quantify the pavement's structural sensitivity and susceptibility to thermal variations. The result gives us the sensitivity in one point, but it is reasonable to think that non-linearity will be discovered. To overcome the limitations of local partial derivatives in

characterizing non-linear response of the system, a global relative sensitivity approach was introduced. A multivariate power-law regression model was fitted to the complete simulation matrix to establish a continuous surrogate model of the objective function. The mathematical formulation of the response surface is defined in Eq. (14):

$$FL_{\%} = k_1 \times \lambda^{k_2} \times C_p^{k_3}, \quad (14)$$

where:

- k_1 is the scaling constant;
- k_2 is the relative sensitivity index of λ ;
- k_3 is the relative sensitivity index of C_p .

The unknown parameters were determined using the linear least squares method applied to the logarithmically transformed dataset. The primary advantage of this power-law formulation is that the exponents directly represent constant elasticities across the entire domain. Consequently, k_2 mathematically quantifies the exact percentage change in the relative fatigue life induced by a 1% variation in thermal conductivity, regardless of the absolute position within the investigated parameter space.

While the multivariate regression provides insight into partial mathematical sensitivities of the individual parameters, the 1D transient model with constant density is governed by the thermal diffusivity (α) which incorporates the effect of the thermal conductivity and specific heat capacity. For a better understanding of the combined effect of these properties, relative fatigue life is further evaluated as a function of thermal diffusivity. A single-variable power-law regression model was fitted to the dataset in Eq. (15):

$$FL_{\%} = k_4 \times \alpha^{k_5}, \quad (15)$$

where:

- k_4 is the scaling constant;
- k_5 is the relative sensitivity index of α .

This function evaluates the overall susceptibility of the pavement to the actual rate of the heat transfer and thereby reflecting the mechanistic response based on the changing thermal properties.

3 Results and discussion

In the 1-D Fourier's equation, thermal diffusivity (α) was the primary governing physical variable. The separate analysis of λ and C_p in Section 3 represents their conditional numerical sensitivity within the simulated parameter matrix, rather than acting as independent causal material effects.

Fig. 5 presents the 3D response surface illustrating the variation of the investigated parameter, $FL_{\%}$ as a function of thermal conductivity (λ) and specific heat capacity C_p . The purpose of this spatial representation is to represent the combined effect of two thermal properties on the fatigue behavior of the pavement structure. The topography of the surface reveals that the sensitivity of the model is not constant across the entire investigated parameter range. To provide an exact mathematical and physical description of this, the previously defined partial differential operators were applied. The gradient taken along a given j -th constant specific heat capacity value represents the slope of the corresponding cross-section of the surface, quantifying the magnitude of the system's response to a unit change in thermal conductivity. In parallel, the partial derivative with the given i -th constant thermal conductivity characterizes the behavior of the surface along the other axis. This value demonstrates how a change in the heat capacity of the asphalt mixture affects the investigated $FL_{\%}$ output at a fixed thermal conductivity. Based on the analysis of the 3D surface, the regions where the model is particularly sensitive to the accuracy of thermal input data can be clearly identified, which is a critical aspect during the numerical simulation of real temperature profiles and thermal stresses.

The relative fatigue life varies from 88.5% to 113.4% on the thermal conductivity – specific heat capacity domain. For better understanding, separating the two variables visualizes the unit change under different conditions.

Fig. 6 shows the change in relative fatigue life based on specific heat with different constant thermal conductivity curves. One can observe that fatigue life is increasing with higher specific heat, which is reasonable, since higher specific heat capacity requires more heat for the same 1 °C change in temperature, making the material insulation properties more significant, and reducing the effect of

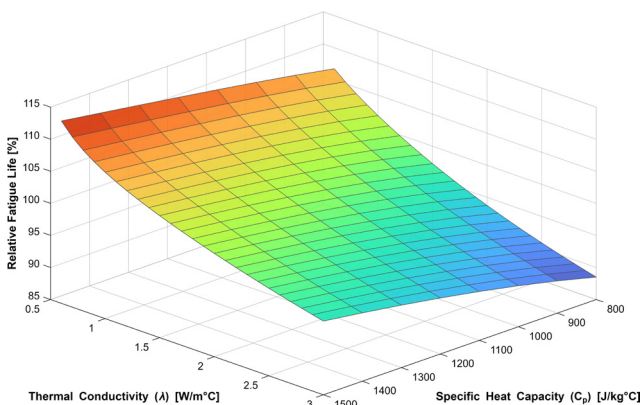


Fig. 5 3D response surface of the combined effect of thermal conductivity and specific heat capacity

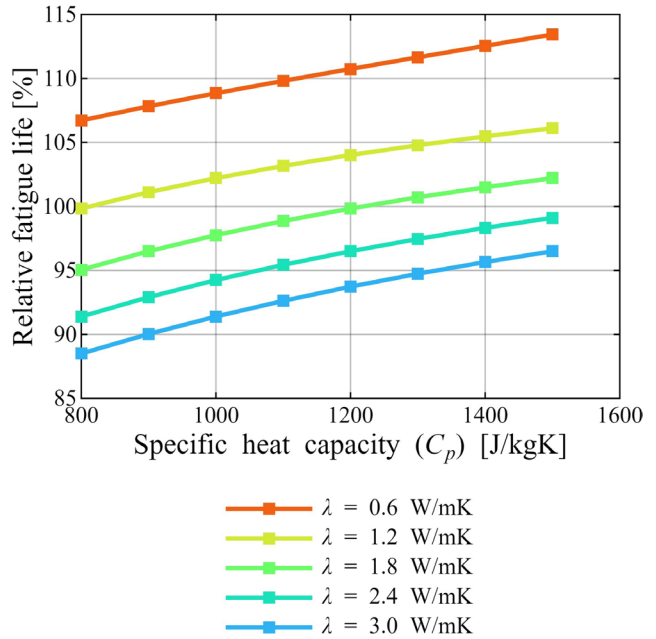


Fig. 6 Change in fatigue life based on specific heat capacity, with different constant thermal conductivity values

extreme high temperatures. The density of the conductivity curves are changing, meaning that very low thermal conductivity has more significant effect on fatigue life, while closing to $\lambda = 3.0$ value, differences become smaller. The average sensitivity of the fatigue life to 100 J/kgK increase in specific heat capacity with a constant λ is 1.0%.

Fig. 7 represents the change in relative fatigue life based on thermal conductivity with different constant specific heat capacity. It is clearly shown that as λ increases,

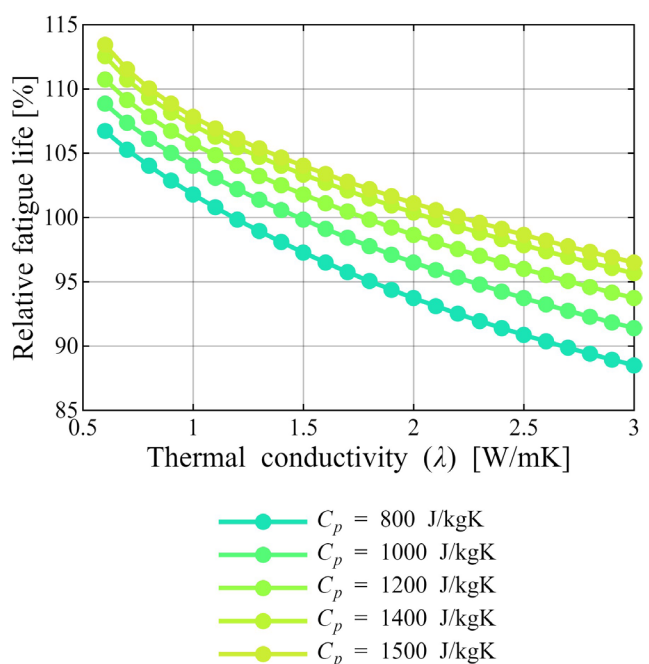


Fig. 7 Change in fatigue life based on thermal conductivity, with different constant specific heat capacity values

relative fatigue life is decreasing significantly. This phenomenon is found reasonable, since if the heat transfer in the asphalt layer is faster, warmer conditions and lower stiffness can be applied in deeper layers, increasing the strains and dropping fatigue life. The average sensitivity of the fatigue life to a 1.0 W/mK increase in thermal conductivity along a constant C_p value is -7.2% . The dependency with low specific heat is greater.

As these average values cannot represent the sensitivity of the total modeled surface, Eq. (14) was applied. The fitted response surface is defined by Eq. (16):

$$FL_{\%} = 47.2329 \times \lambda^{-0.1066} \times C_p^{0.1137}. \quad (16)$$

The statistical evaluation of the regression model demonstrated an excellent agreement with the mechanical simulation results, confirmed by a coefficient of determination $R^2 = 0.99$ and RMSE limited to 0.50%. This negligible average error conclusively validates the use of this continuous analytical formulation as a reliable substitute for computationally demanding numerical simulations within the investigated parameter space. The extracted exponents quantify the global relative sensitivities of the system. The dimensionless sensitivity index for thermal conductivity is $k_2 = -0.107$ indicating that a 1% increase in λ systematically results in a 0.11 % reduction in the relative fatigue life. Conversely, the specific heat capacity exhibits a positive sensitivity index of $k_3 = 0.114$.

While the absolute values of these elasticities (approximately 0.11%) suggest that the mathematical model is equally sensitive to a 1% relative change in either parameter, interpreting their practical engineering impact requires caution. The actual influence of these properties on pavement design is governed not only by their theoretical sensitivities but also by their natural variability in real asphalt mixtures. Since the thermal conductivity (λ) typically exhibits a proportionally wider range of variation in physical practice compared to specific heat capacity (C_p) its cumulative effect on the uncertainty of the fatigue life prediction is expected to be more pronounced. Therefore, despite the equivalent mathematical elasticities, average sensitivity describes the difference more indicative.

The general susceptibility of the pavement was calculated according to Eq. (15):

$$FL_{\%} = 21.31 \times \alpha^{-0.1078}. \quad (17)$$

It means that a 1% increase in thermal diffusivity results in an approximately 0.11% reduction in fatigue life. The negative sign of k_5 term confirms the inverse effect of the thermal diffusivity. Asphalt can transfer heat more

rapidly with higher diffusivity, causing lower stiffness along the depth and ultimately leading to reduced fatigue life. Fig. 8 shows the calculated points and the fitted curve of the thermal diffusivity function. As the typical values of thermal diffusivity vary between $0.4\text{--}1.7 \times 10^{-6} \text{ m}^2/\text{s}$ results indicate that relative fatigue life of a 23 cm asphalt pavement can change between 88.5% and 104.0%, which is a significant range.

4 Conclusions

This paper presented an analysis where sensitivity of pavement fatigue was investigated to thermal properties. 19 year long track record of Hungarian weather conditions was used in order to simulate a representative year of pavement surface temperatures ($-16.7\text{--}63.4 \text{ }^\circ\text{C}$). In the applied one-dimensional heat transfer framework, thermal diffusivity (α) inherently governs the internal temperature distribution. For a better understanding of how this property influences the mechanical response, thermal diffusivity was decomposed into its components to evaluate their conditional numerical sensitivities. Consequently, a comprehensive parameter matrix was established within specific boundaries: 25 distinct levels of thermal conductivity ($0.6\text{--}3.0 \text{ W/mK}$) and 8 levels of specific heat capacity ($800\text{--}1500 \text{ J/kgK}$) were tested, resulting in 200 theoretical combinations. The heat transfer equation was solved for each setting, followed by stiffness estimation using the Witczak-Bari model. Pavement responses were calculated according to linear elastic theory with temperature-dependent stiffness. The loading conditions were in alignment with current practice of pavement design (700 kPa uniform stress, horizontal strain calculation at the bottom). Service life was determined for Hungarian Class K traffic load (1 000 000 ESAL/year). Ultimately, while the partial sensitivities of the decomposed variables were mapped, the

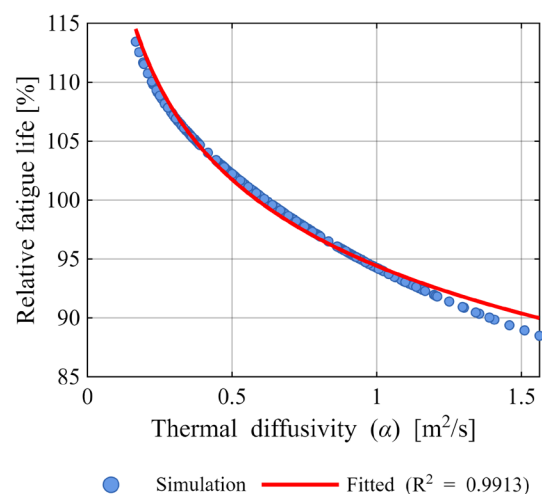


Fig. 8 Susceptibility to thermal diffusivity

final results demonstrate the comprehensive effect of thermal diffusivity on the service life of the investigated pavement structure. Considering the aforementioned conditions, the main findings of the paper are the following:

- Thermal properties can influence pavement fatigue life significantly. Heat conduction is a risk that needs to be addressed during pavement design.
- Non-linear correlation was found between thermal properties and fatigue life.
- Fatigue life is higher with low thermal diffusivity as asphalt works as an "insulation" rather than heat conductor.
- The average sensitivity was calculated for the components of the thermal diffusivity. 1.0 W/mK change in thermal conductivity can cause 7.2% change in fatigue life of a 23 cm thick asphalt pavement under the modeled climate and traffic conditions, but the sensitivity is reversed. A 100 J/kgK increase in specific heat capacity can cause 1.0% increase in fatigue life. The bigger impact of thermal conductivity is in alignment with literature findings.
- A general sensitivity function was also determined. The general finding was that both components have the same effect of a 1.0% change in either factor results in a 0.11% change in fatigue life of a 23 cm thick asphalt pavement under the modeled climate and traffic condition. Although it seems negligible, caution must be taken. Fluctuations in thermal conductivity are higher than in specific heat capacity, therefore the significance of this factor is higher.
- The sensitivity of the pavement to thermal diffusivity expresses the susceptibility of mechanical response to the change of thermal properties as the ultimate

result of this paper. 1% increase in diffusivity can cause 0.11% reduction in fatigue life. It is considered significant, since the general range of diffusivity lies between $0.4\text{--}1.7 \times 10^{-6} \text{ m}^2/\text{s}$, resulting in range of 88.5–104.0% of relative fatigue life variability.

Temperature-dependent linear elastic calculation uses stiffness more accurately, but it has some limitations. The dynamic wheel load is not taken into consideration. The tyre-contact pressure is rarely uniform, and the wheel-path can shift transversally, as trucks cannot keep the same wheel path perfectly. Change in moisture-content of the embankment was also neglected.

Heat distribution modeling in pavement is a crucial step in thickness design. Obtaining in-depth temperatures with heat transfer equation requires material characteristics. These thermal properties influence the temperature and stiffness of the deeper layers and thereby the service life of the pavement structure. Based on the simulation presented, thermal conductivity has significant impact on pavement fatigue. Although chemical engineering has scientific results in binder thermomechanical properties, civil engineering lacks these results regarding the mixtures. The analysis showed that thermal properties should be incorporated in pavement design procedures as primary inputs rather than negligible ones and highlighted the necessity of deeper research of this field. While direct mixture-development guidance requires broader investigation beyond the current linear-elastic framework, these numerical findings suggest that thermal properties could be carefully considered in future pavement design procedures. Better understanding of the thermal influence on the pavement life can help design more resilient infrastructure.

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