World Academy of Science, Engineering and Technology
International Journal of Urban and Civil Engineering
Vol:15, No:2, 2021

Temperature Profile Modelling in Flexible Pavement Design

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***Abstract*—**The temperature effect on asphalt pavement structure is a crucial factor at the design stage. In this paper, by applying the German guidelines for temperature along the asphalt depth is estimated. The aim is to consider temperature profiles in different seasons in numerical modelling. The model is built with an elastic and isotropic solid element with 19 subdivisions of asphalt layers to reflect the temperature variation. Comparison with the simple three-layer pavement system (asphalt layers, base, and subgrade layers) will be followed to see the difference in result without temperature variation along with the depth. Finally, the fatigue life calculation was checked to prove the validity of the methodology of considering the temperature in the numerical modelling.

***Keywords*—**Temperature profile, flexible pavement modelling, finite element method, temperature modelling.

I. Introduction

THE pavement temperature matters for establishing rehabilitation plan for the structure due to its viscoelastic characteristics. Modulus of the pavement depends on the temperature that means closer estimation of the strength can be done when the temperature prediction could be possible which is important in terms of choosing proper grade and design. Many empirical methods were used to prepare prediction of the pavement temperature. Linear regression method with weather forecast is widely used to prepare such a prediction [1], [2].

The calculation of pavement temperature by the thermal properties of pavements is started from the work of Barber (1957) [3]. Study focuses on directly that observed temperature can be used to correlate the pavement temperature. Some weather factors are picked up for representing the thermal properties of the pavements, such as solar radiation, air temperature, wind and precipitation. In 1969, Rummey et al. set up a monogram for temperature estimation up to 50 mm. This model considered solar radiation per hour. The approximate temperature-depth relationships are prepared by adjusting Benkelman beam deflection by Southgate et al. [4]. With the developed model, it is possible to relate the deflections taken at any temperature [4]. The most elaborated study on temperature estimation came to be completed under the United States' long-term pavement performance project (LTPP) [1].

From the site measured pavement surface temperature, the temperature inside of the pavement system can be predicted. However, it is limited to a specific area. Accordingly, a temperature prediction method suitable for general purpose has been studied. Stream of studies were lead to how to apply and treat those thermal properties in prediction of temperature quantifiably. Thompson et al. quantified the temperature with computer model with those thermal properties [5]. Here, the German guide method is chosen for the temperature estimation [2]. From the surface temperature measurement, the temperature of the pavement along the depth could be predictable. Based on the prediction model of German guide, the modulus of the pavement is calculated with Witczack model which includes temperature as input of the modulus calculation [1].

Many studies are about how to model the pavement system with Finite Element method [6], [7]. In this study, the pavement system is relatively simple thus the boundary condition modelling is key factor for establishing the computational model. Bottom side locates over 18 radii of depth, and moving is allowed on radial direction on the sides, and is constrained on the direction of x axis over 12 radii from the centre [6]. Each layer is assumed to meet continuity condition that the layers are in contact with shear resistance fully active between them so that the layers can act together as an elastic medium with a fully continuous with stress and displacement across the interface [7].

II. Surface Temperature Distribution in a Full Depth Asphalt Pavement

The relative frequency of the temperature distribution was calculated from the temperature data collection obtained from a previously established weather station. The weather station was mounted in 2006, and the data set was used from 1/8/2006 to 31/7/2007. The weather station measured and logged the data every 10 minutes, which equates to 48 441 data sets. Each data set contains the ambient temperature, the surface temperature of the pavement structure, and in-depth temperatures at 2, 7, 14, 29, and 49 cm. These results are in a very high frequency of data collection and a high number of temperature data for a detailed analysis.

Fig. 1 shows the surface temperature variation throughout one year. For the Hungarian climatic conditions (Central-Europe), the data show relatively high pavement surface temperatures, which may be explained by the local climatic conditions around the weather station. The station is located in

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the asphalt manufacturing company yard and sits next to the company building which is located outskirt of Budapest. The weather station was shut down for a two weeks period. Therefore data were not collected for this short period, which is considered to have a neglectable effect on the yearly temperature distribution.

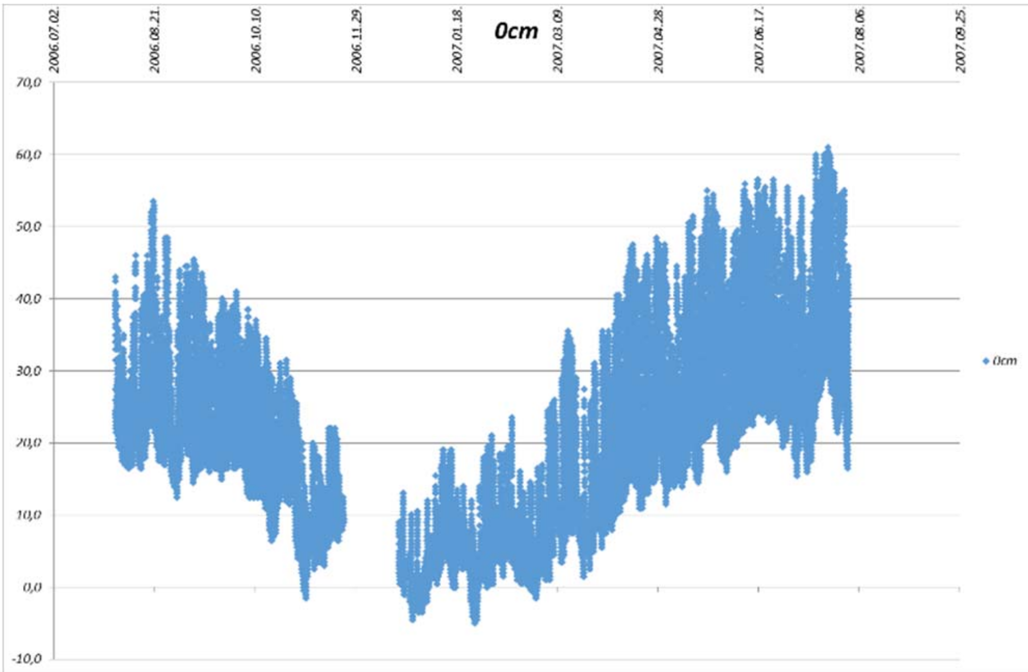

Fig. 1 Surface temperature variation throughout a one-year period

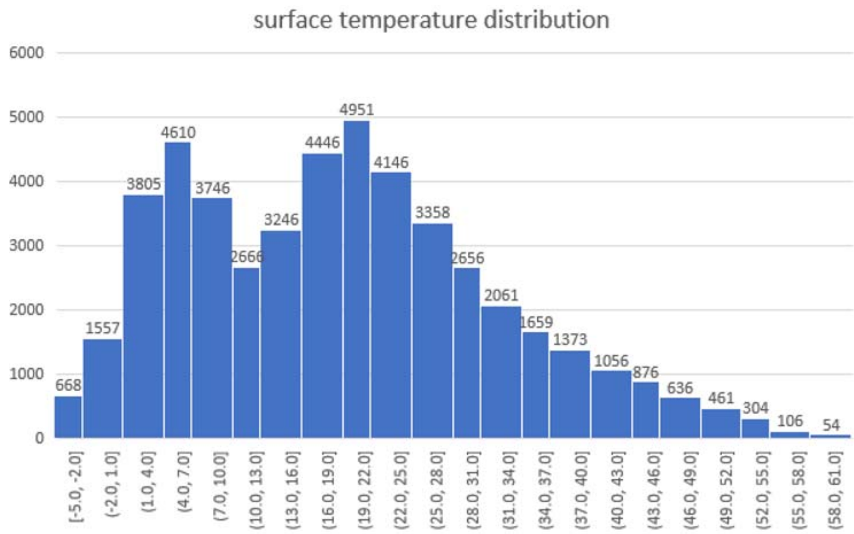

Fig. 2 Temperature distributions

The histogram shows the distribution of the collected data set in Fig. 2. The temperature domain was split into by 3 °C for this analysis, and it makes 22 temperature bins.

From the temperature distributions (Fig. 2) it can be concluded that bin 19-22 °C shows the highest frequency. The pavement surface temperature experiences the value within this range at 10.22% throughout the year. This was calculated as:

$$\frac{4951}{48441} = 0.1022$$

III. Estimating the Temperature of an Asphalt Pavement In-Depth

The model pavement for this analysis, which is typical for medium volume roads in Hungary, was considered as:

- 4 cm wearing course
- 6 cm intermediate (binding) layer
- 9 cm asphalt base layer; total asphalt pavement thickness

of 19 cm.

The temperatures of the individual asphalt layers (and sub-layers) at any depth were estimated by using the German method, which is published as Guidelines for mathematical dimensioning of foundations of traffic surfaces with a course asphalt surface RDO - Asphalt 09. The calculation was performed according to (1) [2]:

$$y = a \cdot ln(0.01 \cdot x + 1) + T \qquad (1)$$

where, y is asphalt temperature at depth x [°C], x is the depth below the surface of the pavement structure [mm], T is the surface temperature [°C], a is the parameter as a function of T (Table I).

The pavement temperature at 2, 7 and 14 cm depth was estimated using the German method as explained above. The estimated data were correlated with the measured data, collected from the weather station. It was found that there was a strong correlation as R^2 values were calculated as:

- 2 cm depth: 0.98
- 7 cm depth: 0.89
- 14 cm depth: 0.79

Fig. 3 shows the estimated temperature versus the measured temperature at various depths.

TABLE I
PARAMETER 'A' AS A FUNCTION OF SURFACE TEMPERATURE

Temperature	*a*
<-10	6.5
<-5	4.5
< 0	2.5
< 5	0.7
< 10	0.1
< 15	0.3
< 20	0.4
< 25	-1.6
< 30	-4.0
< 35	-6.2
< 40	-8.5
< 45	-10.5
> 45	-12.0

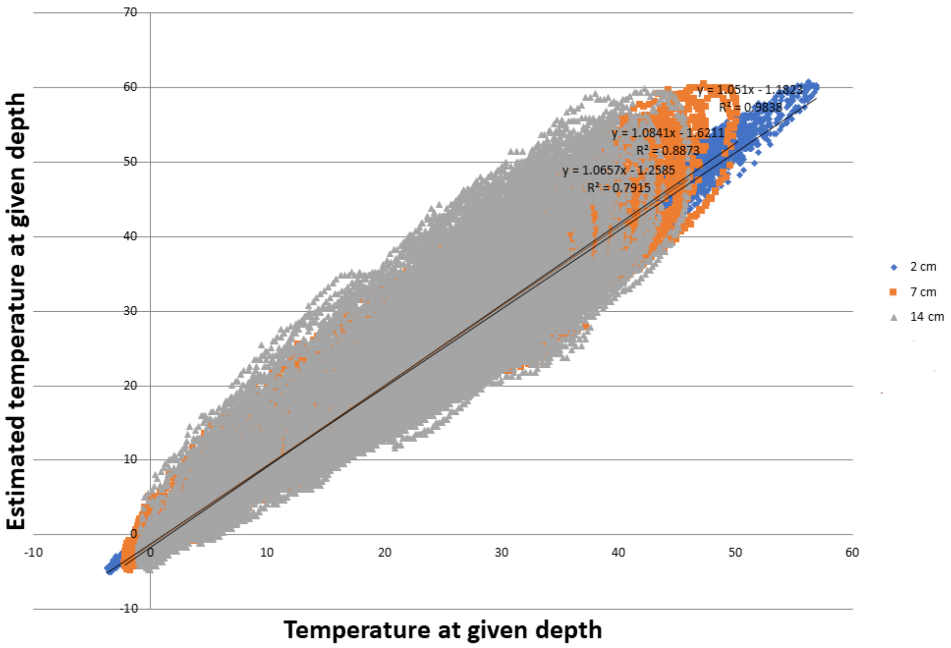

Fig. 3 Estimated temperature versus the measured temperature

The total asphalt depth is 19 cm and it is divided by 1 cm and makes 19 individual sub-layers. The objective of this step was to provide a more accurate in-depth temperature for a detailed analysis. As it was shown above, the German prediction model provides an accurate methodology therefore it was used for predicting the in-depth temperature of each 1 cm thick sub-layer. Considering that the surface temperature was split into 22 temperature bins as explained above, the in-depth pavement temperatures were predicted as summarized in Table II. For this prediction the mid-value of each bin was used as input parameter.

IV. BINDER AND ASPHALT PARAMETERS AS A FUNCTION OF IN-DEPTH TEMPERATURES

For the calculations the binder properties were considered to comply with PG 64-22 grade. The viscosity-temperature relationship was established in (2a) and (2b) [8].

$$loglog(\eta) = A + VTSlog(T_R) \qquad when\ T_R > T_{critical} \qquad (2a)$$

$$loglog(\eta) = 1{,}095 \qquad when\ T_R <= T_{critical} \qquad (2b)$$

where, η Viscosity [cP], T_R Temperature [Rankine].

TABLE II
IN-DEPTH PAVEMENT TEMPERATURE PREDICTION

	Pavement model number	1	2	3	…	20	21	22
	Lower limit of the temperature bin (°C)	-5	-2	1	…	52	55	58
	Upper limit of the temperature bin (°C)	-2	1	4	…	55	58	61
	Mid-value of the temperature bin (°C)	-3.5	-0.5	2.5	…	53.5	56.5	59.5
Pavement depth (mm)	10	-3.3	-0.3	2.6	…	52.4	55.4	58.4
	20	-3.0	0.0	2.6	…	51.3	54.3	57.3
	30	-2.8	0.2	2.7	…	50.4	53.4	56.4
	40	-2.7	0.3	2.7	…	49.5	52.5	55.5
	50	-2.5	0.5	2.8	…	48.6	51.6	54.6
	60	-2.3	0.7	2.8	…	47.9	50.9	53.9
	70	-2.2	0.8	2.9	…	47.1	50.1	53.1
	80	-2.0	1.0	2.9	…	46.4	49.4	52.4
	90	-1.9	1.1	2.9	…	45.8	48.8	51.8
	100	-1.8	1.2	3.0	…	45.2	48.2	51.2
	110	-1.6	1.4	3.0	…	44.6	47.6	50.6
	120	-1.5	1.5	3.1	…	44.0	47.0	50.0
	130	-1.4	1.6	3.1	…	43.5	46.5	49.5
	140	-1.3	1.7	3.1	…	43.0	46.0	49.0
	150	-1.2	1.8	3.1	…	42.5	45.5	48.5
	160	-1.1	1.9	3.2	…	42.0	45.0	48.0
	170	-1.0	2.0	3.2	…	41.6	44.6	47.6
	180	-0.9	2.1	3.2	…	41.1	44.1	47.1
	190	-0.8	2.2	3.2	…	40.7	43.7	46.7

For a PG 64-22 grade binder the following applies;

A = -3,680 and VTS = 10,980.

Considering the first column of Table II, which is temperature bin -2 to -5 °C (mid-value of -3.5 °C), the in-depth pavement temperatures can be calculated according to (1). The temperature is estimated according to the detailed model at every 1 cm of the asphalt layer, a total of 19 cm. The estimated temperature values provide now input parameters for prediction of the dynamic viscosity of the binder, which is calculated according to (2a) and (2b). In the next step, (3) is used. This equation is the so-called Witczak equation, which can predict the modulus of the asphalt layer as a function of dynamic viscosity of the binder and the asphalt mix properties [1].

$$\log|E^*| = 6.940166 - 0.00176(P_{200}) + 0.003889(P_4) - 0.08776(V_a) - 1.33426\frac{V_{eff}}{V_{eff}+V_a} + \frac{(-3.63992-0.03114(P_4)+0.015546(P_{38})+0.010469(P_{34}))}{1+\exp(-0.09942+0.162727\times\log f+0.180695\times\log\eta)} \quad (3)$$

For a detailed modelling, various asphalt layers were considered with different parameters. This is in line with real life applications; the parameters are summarized in Table III [9].

For the -2 to -5 °C temperature bin, referenced as bin of -3,5 °C moving forward, the asphalt layer modulus is estimated as summarized in Table IV. This table provides an example for the temperature bin of -3,5 °C as this calculation was performed for each temperature bin as outlined in Table II.

Based on Fig. 1, a one-year period can be modelled with 22 distinctive pavement structures, where each of these pavement structures is considered with the mid-range temperature of the relevant temperature bin.

TABLE III
ASPHALT MIX PARAMETERS FOR VARIOUS PAVEMENT LAYERS

Pavement layer	p_{34}	p_{38}	p_4	p_{200}	v_a	v_{beff}	f (Hz)
Wearing course	0	38,75	72,5	10	3,08	12,2	25
Intermediate layer	2,5	24	45	6	4,159	10,5	25
Asphalt base layer	13	35	51	4	3,777	9,3	25

p_{34} = percentage retained on 3/4-inch sieve, p_{38} = percentage retained on 3/8-inch sieve, p_4= percentage retained on #4 sieve, p_{200} = percentage retained on #200 sieve, v_{beff} = effective asphalt content as percentage of total mix volume, v_a = air voids as percent total volume, f = loading frequency.

TABLE IV
MATERIAL PARAMETERS CALCULATED FOR TEMPERATURE BIN -3.5°C

Pavement layer	Depth (mm)	Dynamic viscosity of the binder (106 Poise)	Asphalt modulus (MPa)
Wearing course	10	25 820	23,211
	20	23 725	22,832
	30	21 955	22,489
	40	20 438	22,176
Intermediate layer	50	19 125	27,784
	60	17 976	27,489
	70	16 963	27,215
	80	16 062	26,959
	90	15 255	26,719
	100	14 529	26,494
Asphalt base layer	110	13 872	32,697
	120	13 275	32,452
	130	12 729	32,220
	140	12 228	31,999
	150	11 768	31,789
	160	11 342	31,589
	170	10 947	31,398
	180	10 581	31,214
	190	10 239	31,039

V. Analysis of the Pavement Models Using FEM

The total asphalt pavement, considered as 19 cm, 1 cm thick asphalt sub-layers, was modelled with 20 cm thick, 350 MPa unbound granular base layer and 50 MPa subgrade as support. A 9 m x 9 m x 9 m, cubic domain of the previously mentioned materials was loaded on the top surface of the 1st asphalt sub-layer. 50 kN load was distributed uniformly over a circular area with 15 cm radius about the centre of the top surface. In the finite element model one fourth of the domain was considered and symmetric boundary conditions were applied on the surfaces of symmetry, while the bottom points of the subgrade were constrained against vertical displacements, and the whole domain against rigid body motions.

In the finite element model eight-node 3D structural solid elements (element type SOLID185 in ANSYS software) were applied, with three degrees of freedom at each node. The 19th asphalt sub-layer to the granular base, as well as the granular base to the subgrade was connected using frictionless contact elements.

The horizontal strain at the bottom of the asphalt layers and the vertical displacement on the top of the subgrade were calculated (Fig. 4). The strains were calculated for all 22 pavement models using FEM; the results are summarized in Table VIII.

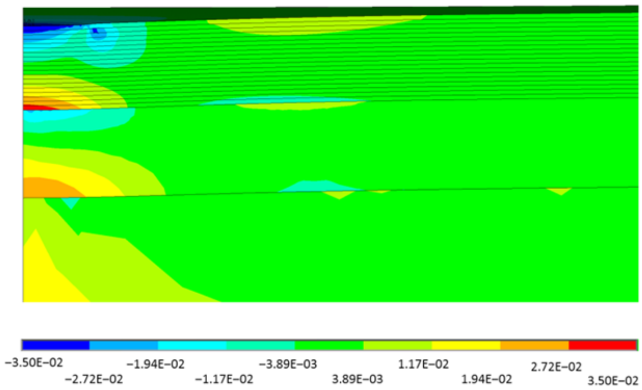

Fig. 4 Horizontal strain [-] distribution in pavement model 22

VI. Simplistic Pavement Model Calculated Using the Equivalent Pavement Temperature

The original pavement structure, 19 cm of asphalt in total, was modelled with using the equivalent pavement temperature method. As mentioned earlier, a 19 cm pavement structure is considered for medium volume traffic conditions in Hungary.

In this calculation a single pavement model was established in line with using the equivalent pavement temperature method. Consequently, the asphalt parameters are representative at the equivalent pavement temperature; this calculation is widely used due to its simplistic approach as it requires limited input data and low level of computing power. The equivalent temperature is an aggregated value and its calculation is not covered in this paper. The equivalent pavement temperature for Hungary was established at 20 °C and the modulus values were considered for this temperature value as outlined in Table V.

TABLE V
Pavement Model for the Simplistic Method

Pavement layers	Modulus values (MPa)
4 cm wearing course	4,000
6 cm intermediate layer	5,800
9 cm asphalt base layer	4,500
20 cm unbound granular base layer	350
Subgrade	50

The calculated horizontal strain at the bottom of the asphalt layers for the above pavement model was 143 microstrain. The allowable loading was calculated as 4,250,836 ESA (rounded to 4.25 million ESA) at this strain level for 95% reliability level.

VII. Cumulative Fatigue of the Pavement Structure

For this analysis it was considered that the traffic loading is 1 million ESA, which is evenly distributed throughout the year. As a result, the strains calculated for each of the 22 pavement models occur in line with the relative frequency of the surface temperature bin as shown in Table VI.

TABLE VI
method Temperature Relative Frequency and Traffic Distribution

Pavement model number	Temperature occurrence (-)	Temperature relative frequency (%)	Design traffic (Ni, actual)
1	668	1,38	13 790
2	1557	3,21	32 142
3	3805	7,85	78 549
4	4610	9,52	95 167
5	3746	7,73	77 331
6	2666	5,50	55 036
7	3246	6,70	67 009
8	4446	9,18	91 782
9	4951	10,22	102 207
10	4146	8,56	85 589
11	3358	6,93	69 321
12	2656	5,48	54 830
13	2061	4,25	42 547
14	1659	3,42	34 248
15	1373	2,83	28 344
16	1056	2,18	21 800
17	876	1,81	18 084
18	636	1,31	13 129
19	461	0,95	9 517
20	304	0,63	6 276
21	106	0,22	2 188
22	54	0,11	1 115
Total	48441	100,00	1 000 000 ESA

The number of allowable ESAs was calculated according to the Guide to Pavement Technology Part 2: Pavement Structural Design, Sydney 2017 as outlined in (4) [10]:

$$N = \frac{SF}{RF}\left[\frac{6918(0.856V_b+1.08)}{E^{0.36}\mu\epsilon}\right]^5 \tag{4}$$

where, N is the allowable number of repetitions of the load-induced tensile strain, $\mu\epsilon$ load-induced tensile strain at the base of the asphalt (microstrain), V_b percentage by volume of bitumen in the asphalt [%], E asphalt modulus [MPa], SF shift factor between laboratory and in-service fatigue lives (presumptive value = 6), RF reliability factor for asphalt fatigue (Table VII).

TABLE VII
RELIABILITY FACTORS (RF) FOR ASPHALT FATIGUE

Desired project reliability					
50%	80%	85%	90%	95%	97.5%
1.0	2.4	3.0	3.9	6.0	9.0

TABLE VIII
HORIZONTAL STRAIN AT THE BOTTOM OF THE ASPHALT LAYER, CALCULATED USING FEM

Pavement model number	Calculated horizontal strain, asphalt (ANSYS)	Allowable traffic (Ni, allow) according to (4)
1	48	30,039,423
2	56	20,120,211
3	60	15,579,040
4	68	10,986,355
5	79	7,431,197
6	91	4,999,914
7	105	3,460,413
8	120	2,412,376
9	127	1,974,324
10	143	1,422,479
11	149	1,216,528
12	167	899,067
13	174	771,340
14	181	670,285
15	201	512,766
16	210	444,640
17	231	348,753
18	244	299,301
19	267	240,659
20	290	196,196
21	314	162,043
22	339	135,481

The cumulative damage factor (CDF) was calculated by using the Miner hypothesis (8):

$$\sum_{MINER} = \frac{N_{1,actual}}{N_{1,allow}} + \frac{N_{2,actual}}{N_{2,allow}} + \frac{N_{3,actual}}{N_{3,allow}} + \ldots \frac{N_{22,actual}}{N_{22,allow}} \leq 1 \quad (8)$$

where, $N_{(a,b,\ c...),actual}$ the actual number of ESAs for a given pavement model (1 to 22), $N(a,\ b,\ c...)_{,allow}$ the allowable number of ESAs for a given pavement model (1 to 22, see Table VIII).

At 1 million ESA and 95% reliability level, the CDF value returned 0.72; consequently the pavement structure shows more than enough structural capacity. In case the traffic loading is increased to 1.34 million, the CDF value is calculated as 0.99, i.e. the pavement structure cannot carry more than this traffic loading. The value is in contrast with the 4.25 million ESA calculated using the equivalent temperature method (Section V). This is due to the simplistic method is not able to consider the detailed temperature impact on the asphalt pavement structure.

VIII. SUMMARY

The temperature effect on asphalt pavement structure is a crucial factor for the pavement structural design. In this paper, the in-depth temperature was estimated using the German guidelines. The prediction was correlated with real data collected from a previously established weather station and good correlation was found. Following this step, the relative frequency of the temperature distribution was established.

The pavement model was built with an elastic and isotropic solid element with 19 sublayers of asphalt to reflect the temperature variation, where the temperature data was used as input into binder viscosity and asphalt modulus prediction.

Comparison with the simplistic calculation using the equivalent temperature method showed that the detailed model outlined in this paper can provide a better prediction of the overall pavement structural capacity. This is due to the simplistic method is not able to consider the detailed temperature impact on the asphalt pavement structure.

The method highlights that the calculation using the detailed temperature profile provides realistic input into the pavement designs and the performance of various asphalt materials, such as crumb rubber asphalt or high modulus asphalt, can be realistically considered.

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