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Structure and Environment 2024, vol. 16, (3), pp. 141-147, Article number: el 013
https://doi.org/10.30540/sae-2024-013

Structure and Environment
ISSN 2081-1500
e-ISSN 2657-6902
https://content.sciendo.com/sae
https://sae.tu.kielce.pl

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DOI: 10.30540/sae-2024-013

ANALYSIS OF THE DEFORMATION OF ROAD SURFACE CONSTRUCTION BASED ON MONITORING CLIMATIC FACTORS

ANALIZA ODKSZTAŁCEŃ KONSTRUKCJI NAWIERZCHNI DROGI NA PODSTAWIE MONITORINGU CZYNNIKÓW KLIMATYCZNYCH

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Abstract

The article presents the results of simulation of the deformation state of a road surface structure intended for traffic categories KR 3-4. Climatic factors such as temperature and humidity were obtained from a database collected based on the installed monitoring. The performed validation of the deformation state indicated a very good fitness of the model to the experimental results, provided that the viscoelastic model. The results indicated that the difference in pavement load time between 1 s and 1200 s in summer may result in an increase in horizontal deformation under the asphalt layer by 949%, and in winter by 74%. The calculated vertical displacement in winter after 1200 seconds of loading is equivalent to the displacement calculated after 1 second of loading the road surface in summer.

Keywords: pavement diagnostic, visco-elastic model, climatic factors monitoring

Streszczenie

W artykule przedstawiono wyniki symulacji stanu odkształcenia konstrukcji nawierzchni drogowej przeznaczonej dla kategorii ruchu KR 3-4. Informacje na temat czynników klimatycznych takich jak temperatura oraz wilgotność pozyskano z prowadzonego monitoringu. Wykonana walidacja stanu odkształcenia wskazała na bardzo dobre dopasowanie modelu do wyników eksperymentu pod warunkiem zastosowania modelu lepkosprężystego. Wyniki symulacji wskazują, że różnica czasu obciążenia nawierzchni pomiędzy 1 s a 1200 s w okresie lata może spowodować wzrost odkształcenia poziomego pod warstwą asfaltową względnie o 94%, natomiast w okresie zimy o 74%. Obliczone przemieszczenie pionowe w okresie zimy po 1200 s trwania obciążenia jest równoważne z przemieszczeniem obliczonym po 1 s obciążenia nawierzchni drogowej w okresie lata.

Słowa kluczowe: diagnostyka nawierzchni, model lepkosprężysty, monitoring czynników klimatycznych

1. INTRODUCTION

In Poland, the bespoke design of the surface structure system is based on the assumption that a single load from a design axis of 100 kN causes exceedingly small deformations. For this reason, an adequate model for the analysis of the stress and deformation state of the flexible surface, is the elastic model defined for a load time of 0.02 s (vehicle speed of approximately 60 km/h) and an equivalent temperature of +13°C. Catalogue of typical flexible and semi-rigid pavements was developed for such reference conditions[1].

The issue related to measuring the deformation condition escalates in the case of using innovative materials. Their impact on the deformability in some cases differs from the information contained in the Catalogue. In spite of the fact, Polish legal system

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allows for the potential use of viscoelastic models, which permit the incorporation of load time in the design process [2]. There are numerous locations along the route of a road where the vehicles move at a low speed, and consequently, this results in load durations which are considerably longer than the design value provided for in the aforementioned Catalogue. In such case, the significant phenomenon of the relaxation of the rigidity modulus of the construction layers is of key importance for consideration, in particular at the design stage of a road repair or reconstruction project. An examination of the deformation state of the surface structure may be carried out on a case-by-case basis [1]. In order to achieve this purpose, it is absolutely crucial to possess knowledge of the mechanical characteristics of the materials that constitute the road surface structure [3, 4]. In result, the use of the viscoelastic model allows for a more precise design of structures where the load duration is relatively large during the summer period, such as, for instance: bus bays, road intersections. Afterwards, there is a possibility to run a series of simulations with various materials in order to achieve the optimal configuration. This article presents the results of a simulation of the deformation state taking into account the temperature and loading time using a viscoelastic physical design of the structural layers. Furthermore, the results were subject to validation of the condition of deformation of the terrain, based on the data obtained from the monitoring system installed on section of the road under surveillance.

2. METHODS AND MATERIALS

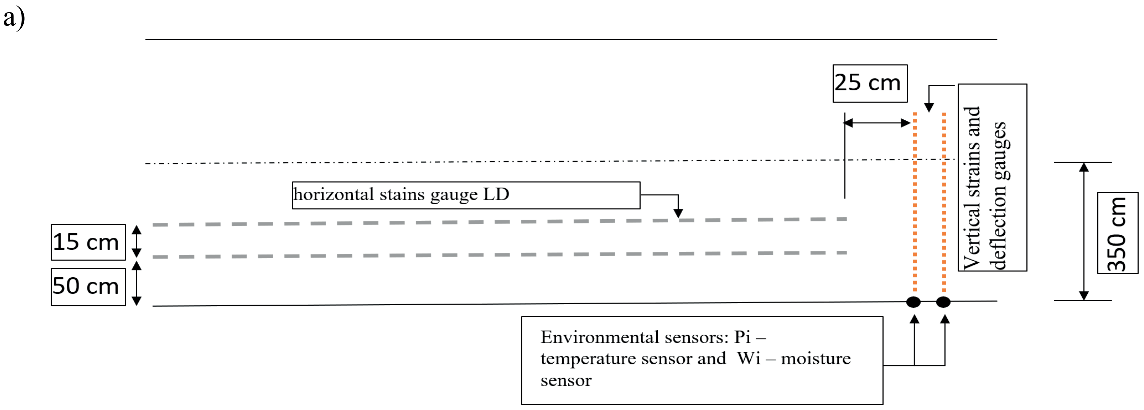
The analysis focuses on the deformation state of the road surface, the construction was carried out during the Techmatstrateg I project [5]. Under the project, the construction with the following arrangement was constructed:

- wearing/binding layer made using SMA-JENA, grammage 8 cm;
- the substructure layer constructed using deep cold recycling technology (FRCM) with foamed asphalt and a dedicated mixed adhesive grammage 20 cm;
- ground substrate at bearing capacity group G1.

The substructure layer was a mixture of deep recycled (FRCM) with foamed asphalt [5]. It was manufactured with the use of an innovative mixed binder as part of the TECHMATSTRATEG I project. Detailed information on the application of this specific binder and the optimisation process is presented in the works [5, 6]. The layer subject to wear and serving as a binder was made using the innovative SMA-JENA mineral-asphalt mix instead of the traditional two-layer system. The SMA-JENA layer was prepared in line with the recommendations specified in the work [7].

2.1. Monitoring system sensor diagram and the layout of structural layers

Data on environmental factors were gathered by monitoring the experimental section situated within the premises of the organic fertiliser production and sand extraction facility Z.W.P. „MOSTY" sp. z o.o., where the main objective focused primarily on observing changes in the deformation state at significant points in the surface structure. An assembly of fibre optic sensors was embedded in two sections where the effects of the mixed binder was tested [6, 8]. The monitoring data was complemented by the recordings of environmental parameters, precisely meaning temperature and humidity. Monitoring set manufactured by SHM System®. A diagram of the layout of sensors (installation) is presented in Figure 1 [5].



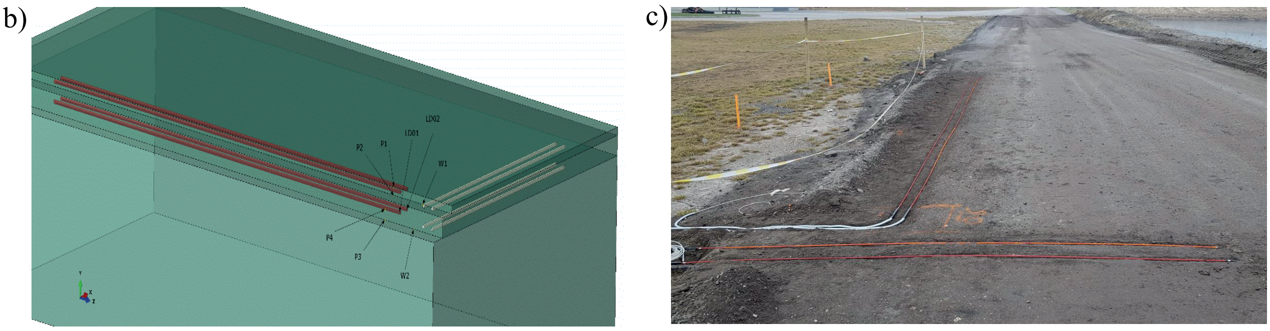


Fig. 1. Surface monitoring system: a) sensor installation diagram (top view); b) isometric view; c) optical fibre installation

2.2. An analysis of alterations in climatic factors in relation to surface construction

The scope of the monitored climatic factors included measurements of temperature and humidity. The temperature measurement covered the period ranging from the beginning of 2020 to February 2024. The temperature was recorded at 3 locations of the recycled substructure (bottom and middle of the FRCM, the SMA-JENA junction with the FRCM, and at a height of 1 m above the ground surface). Figure 2 presents a diagram of the temperature fluctuation situated at the contact point between the SMA-JENA layer and the FRCM (P2 sensors in accordance with Fig. 1b), depending on the month.

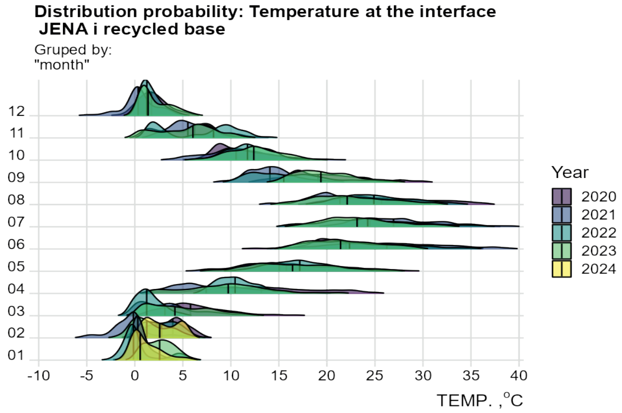


Fig. 2. The distribution of temperature at the contact area of the SMA-JENA surface and the recycled substructure (P2 sensors as shown in Fig. 1b)

Due consideration shall be given to the fact that during the 4 years of continuous surface monitoring, a slight displacement of the median result (horizontal line) towards higher temperatures (green and yellow) can be detected. Such result brings a dual implication. The initial implication is that the progressive warming of the climate is reflected by the value of the surface temperature. The second meaning, significantly more acute, the increase in temperature will cause a decrease in the stiffness modulus of structure layers which will manifest itself as an increased accumulation of plastic deformation on the surface.

For the purpose of determining the distribution of deformation of the road surface structure, it was necessary to define the conventional temperature levels at the surface of the SMA-JENA layer and in the centre of the FRCM substructure layer. Their graphical visualisation is presented in Figure 3.

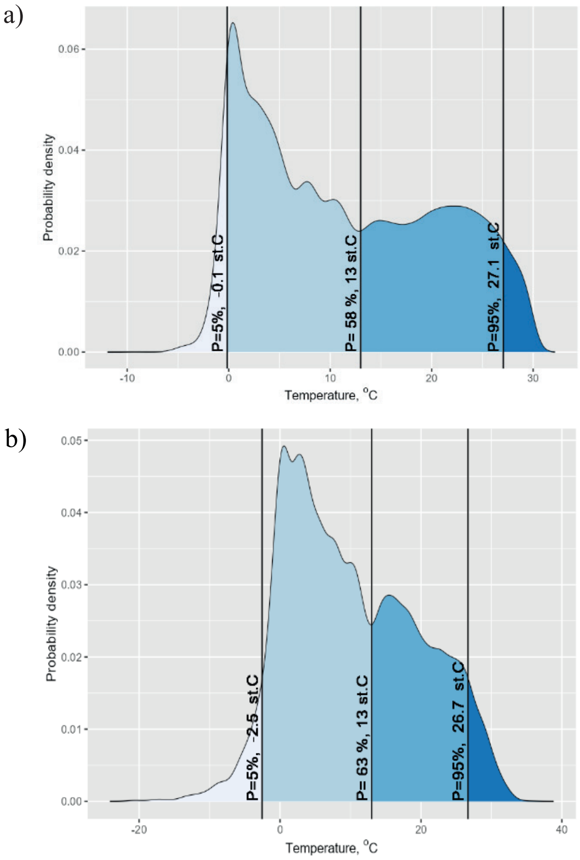


Fig. 3. Temperature distribution across the surface layer: a) FRCM; b) JENA

It was determined that for further analyses the “low” temperature will be represented by the temperature corresponding to the 5% quantile of the probability distribution. However, the “high” temperature will be represented by the temperature taken from the 95% quantile of the probability distribution. In the case of the FRCM layer (Fig. 3a), the “low” temperature value was represented by -0.1°C, whereas the “high temperature” was 27.1°C. In the case of the SMA-JENA layer (Fig. 3b), the temperature value labelled as “low” equalled –2,5°C. Conversely, the “high” temperature equalled 26.7°C. In the case of the FRCM layer, the determination of the probability distribution function was based on the results of temperature measurements at the top surface of the JENA layer (h = 0 cm), in the middle (h = 10 cm) and at the bottom (h = 20 cm). In addition, Figure 3 indicates the probability of the reference temperature occurring in Poland for asphalt surfaces of +13°C. The divergence from the mean value may imply a potential requirement for its validation in view of the constant rise in temperature gradient observed, among others, within the segment subject to experiments.

3. ANALYSIS OF THE SURFACE STRUCTURE DEFORMATION CONDITION

The assessment of the deformation condition took into account a range of linear viscoelasticity, omitting the non-linear effects dependent on the stress level [9, 10]. A generalised Maxwell model (labelled as GM) for linear viscoelasticity (LVE) was taken into account as an adequate model for describing the material stress relaxation phenomenon [11]. The process of identifying the GM model parameters entailed a concurrent effort to minimise the discrepancy between the experimental outcomes of the dynamic module and the phase shift angle, in comparison with the modelled results. A comprehensive compilation of the results of identifying parameters in the GM model, presented as a leading curve pertinent to the behaviour of the FRCM substructure and SMA-JENA layer is presented in Table 1.

The model parameters obtained in Table 1 were subject to validation and presented in works [5, 8, 12]. It must be clearly noted that the validation of the numerical model is not the focus of this paper (the results of the deformation measurements from the field tests are not presented here), however it was presented in the work [8]. The simulation of surface deformation was conducted for a load duration of 1s (brief period) and 1200 s (prolonged load period) utilising the parameters of the GM model as presented in Table 1. The statistical analysis results depicted in Figure 3 were utilised for temperature. The state of “low” temperature consisted in designating –2.5°C to the SMA-JENA layer and –0.1°C to the FRCM layer. Conversely, the state of “high” temperature consisted in assigning a temperature of +26.7°C to the SMA-JENA layer, whereas the FRCM layer: +27.1°C. It must be noted that the temperature of asphalt surfaces in Poland can achieve levels as high as +60°C [13]. Such variant was not taken into analysis as the monitoring did not record a >40°C temperature reading on the surface of SMA-JENA. Furthermore, there was approximately a 5% chance of temperatures exceeding +25°C. In the case of the specified numerical model, the fundamental

Table 1. The leading curve parameters based on the relaxation function of the generalized Maxwell model for the SMA-JENA layer and FRCM at the reference temperature of 13°C

Technology type	Generalised Maxwell model parameters		a_T coefficient (WLF formula)	
G_i [-]		τ_i [s]	C_1	C_2
FRCM recycled substructure	$G_1 = 0.229$ $G_2 = 0.193$ $G_3 = 0.193$ $G_4 = 0.193$ $G_5 = 0.193$	$\tau_1 = 0.00097$ $\tau_2 = 0.08296$ $\tau_3 = 5.06899$ $\tau_4 = 213.756$ $\tau_5 = 12007.6$	7.1	67.1
	$G_0 = 11421$ MPa			
	$R^2 = 0.97$; RMSE = 5.3%			
SMA-JENA wearing/binding layer	$G_1 = 0.252$ $G_2 = 0.252$ $G_3 = 0.222$ $G_4 = 0.177$ $G_5 = 0.096$	$\tau_1 = 0.00085$ $\tau_2 = 0.06414$ $\tau_3 = 2.79957$ $\tau_4 = 110.362$ $\tau_5 = 6066.03$	32.4	229.8
	$G_0 = 18060$ MPa			
	$R^2 = 0.99$; RMSE = 7.8%			

dimensions of the FEM grid component were 0.2 × 0.2 × 0.2 m. In respect of the contact area (where the wheels of a vehicle remain in contact with the surface of the road), the dimensions of the component were reduced to 0.04 × 0.04 × 0.04 m. Furthermore, the segmentation was determined in such a way that for the following layers: SMA_JENA and FB-RCM, their thickness dimension was divided into at least four parts (solid elements) in accordance with the conclusions drawn in work [4]. The eight-node linear shape function C3D8R was used as the shape function. The computational vehicle was weighted in such a manner as to produce a load of 850 kPa on the rear wheel for each axle. Conversely, the front axle wheel generated a surface pressure of 475 kPa. An exemplary horizontal simulation for "high" temperatures in the form of E22 deformation maps are presented in Figure 4.

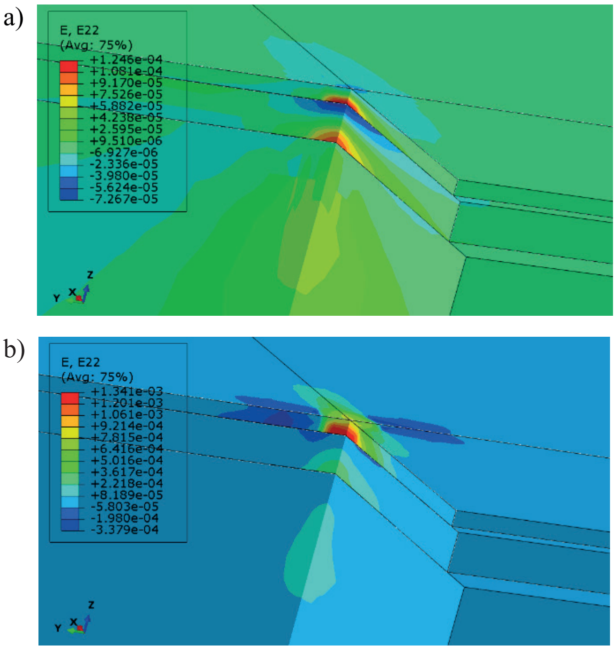


Fig. 4. E22 deformations (in parallel with the axis of the road – Y-Y axis) for "high" temperatures: a) applicable for a duration of a load of 1 s; b) applicable for a load duration of 1200 s

For the purpose of carrying out an accurate diagnosis of the surface, the duration of the load and the temperature of the surface must be taken into account. Due to that fact, the elastic model, while it is commonly implemented, is characterised by a limited use when addressing intricate surface loading scenarios in favour of the viscoelastic model. The viscoelastic Maxwell model is used to determine the detailed horizontal strain values at different depths of the road surface at the load application point, as summarised in Figure 5.

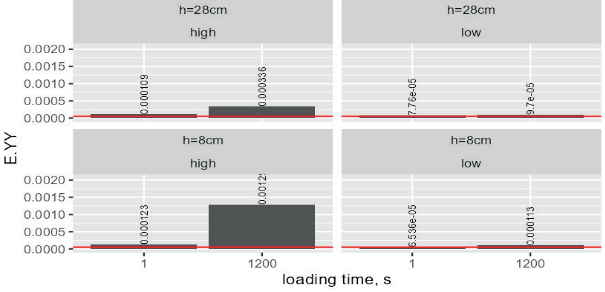


Fig. 5. Detailed readings of simulated E_{YY} deformation at the point of application of a vehicle wheel load of 850 kPa

Upon examination of the results presented in Figure 5, attention must be paid to the fact that the SMA-JENA layer displays significantly greater stiffness in comparison to the FRCM substructure layer in a low-temperature environment. In connection, the value of the deformation in the substructure has been reduced. At high temperatures, the stiffness modulus of SMA-JENA, which contains a large amount of asphalt, was significantly reduced. Its increased susceptibility causes significant deformations in the substructure, which may potentially initiate multiple cracks at its base. At the same time, the forming concentration of deformations at the bottom of the asphalt layer will likely initiate a sequence of net-like cracks on the asphalt's surface in the spring and autumn seasons. In Figure 5, the red horizontal line represents the secure LVE range (100 με) for asphalt layers. Comparing its value to the displacement values during summer temperatures, it must be concluded that in case of recurring loads on the surface for a duration of 1200 s, there exists a significant probability of accumulation of plastic deformations.

Another characteristic associated with the deformability of the surface was the vertical shift at the location where the load was applied. It allows for a rapid evaluation of the degradation level of all surface layers. A statement of the Uzz vertical displacement results is presented in Figure 6.

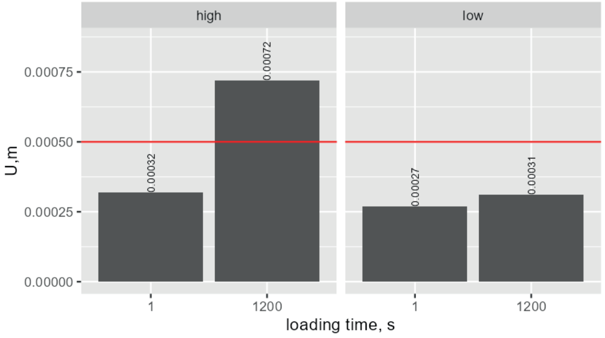


Fig. 6. Comprehensive readings of the simulated deformation of E_{YY} at the location where the vehicle wheel's load of 850 kPa was applied

The analysis of the results presented in Figure 6 leads to the conclusion that the duration of the load application significantly influences the surface deflection during periods of high temperatures. Under low temperature conditions, the duration of 1200 s led to a relative increase of deformation by 15%, whereas during the summer, it increased by 125%. Without a doubt, this was caused, as previously mentioned, by a drastic decrease in the stiffness module of the SMA-JENA layer, of a greater significance than in the case of FRCM layer. Taking into account the requirements of the Polish Catalogue of Reconstructions and Renovations of Flexible and Semi-Rigid Surfaces [14] the maximum deflection value should be < 0.5 mm for KR4 category roads. Hence, during the summer season, vehicles which put pressure on the surface for brief durations (<1 s) meet the criteria. Conversely, in the winter season, the duration of safe application of pressure can be significantly prolonged. Pursuant to the simulation, the surface deflection during winter season after 1200 s is comparable to the surface stress applied in the summer season for the duration of 1 s.

In summary, the duration for which the load is applied significantly impacts the deformability of the surface and it is influenced by the surface temperature. Considering the aforementioned two factors, the deformation state of the surface can be precisely mirrored, and its deformability can be tailored to real-world conditions based on lab material tests. Unfortunately, the traditional elastic model for materials containing asphalt binder is inadequate for such tasks and it displays the behaviour of the surface layers for a precisely outlined operational scheme of a road surface construction.

4. CONCLUSIONS

Based on the conducted studies and examinations, the subsequent detailed conclusions were drawn:

- Utilising data from the strain and displacement state monitoring affirmed the high effectiveness of the implemented modelling with the generalized Maxwell model to elucidate the relaxation phenomenon in recycled mixtures.
- Temperature monitoring has shown an increase in the mean temperature in the period from 2020 to 2024, which is due to climate warming. Thus, the conventional equivalent temperature used for surface design of +13°C might possibly require a review in specific regions of Poland in the future. With the probability of 95% that the temperature in the analysed layers of road surface construction did not exceed +27.1°C in the summer season and was lower than-2.5°C in the winter season. The peak summer temperature observed at the SMA-JENA layer's surface was lower than +40°C.
- During the summer season, the horizontal deformation at the bottom layer of SMA-JENA increased by 73% between the pressure application duration of 1s and 1200 s, whereas in the summer it increased by 94%. This fact must be taken into account when designing surface structures subject to heavy vehicle traffic in junctions characterised by low freedom of movement.
- For the examined road structure solution meant for KR3-4 traffic, the deflection in winter for the application of a load for a duration of 1200 s was comparable to the deflection of the same surface in the summer season for the duration of 1 s.

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