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Influence of temperature on fatigue life or reinforced pavement by whitetopping

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Abstract. The article presents the influence of temperature on the fatigue strength of concrete slabs used for reinforcing susceptible flexible pavement. In Poland, so far, there is no research on thermal interactions on concrete pavement. The article presents an analysis of various climatic conditions occurring in Poland and temperature distribution in concrete pavement. The dependence of daily temperature fluctuations on the temperatures appearing in the concrete slab was demonstrated. An analysis of thermal stresses in concrete slabs depending on their parameters was shown, and then fatigue life was determined. The applied 3DFEM model includes elements of contact, friction, and gravity in order to better approximate the behaviour of the board from temperature change. On this basis, the significant influence of cyclical daily temperature changes on the durability of the concrete pavement was indicated. The presented analyses can be applied to reinforcements of existing flexible pavements.

1. Introduction

Whitetopping is a technology based on the reconstruction of damaged pavement using a layer of cement concrete. This method was used for the first time in 1918 in the United States making reinforcements of exploited pavement of motorways, runways, and roads with smaller street loads and parking lots [1]. Until the 90s of the last century, few projects using whitetopping technology were implemented. It was not until 1992 that this technology was used on a larger scale, covering around 500 projects in the United States ([2], [3], [4]). Then this technology has come into focus, among others, in Canada, Brazil, Taiwan, and in Europe. At the time of implementation of this method, the different thickness of the concrete cover was taken into account for the renovation of existing pavement. Three methods were defined in this way: Conventional Whitetopping (slabs above 20 cm), Thin White-Topping (slabs from 10 to 20 cm) and Ultra-Thin Whitetopping (slabs from 5 to 10 cm).

According to American experiments [5], non-reinforced, reinforced, doweled, or undoweled or continuous reinforced concrete slabs can be used for whitetopping. It was found that cracks in the asphalt pavement do not transfer to the concrete cover (no reflective cracks). French experiences [6] show that whitetopping can be used with ruts smaller than 30 mm. However, according to Belgian experience [7] with ruts smaller than 40 mm. The levelling of larger uneven surfaces (e.g. ruts larger than 50 mm) can be done by milling. Another method of levelling the surface before laying the concrete overlay is to arrange the asphalt mixture as a levelling layer.

An important problem of performing whitetopping appears in summer periods. During long-lasting exposure to sunlight, the asphalt pavement heats up and the surface temperature can reach several dozen degrees Celsius. High temperature of the surface together with the temperature created during

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hydration of the cement may cause high stresses in the concrete during the night cooling of the cover. The result of this phenomenon may be cracking. To reduce the temperature in the US, for example, two methods are used: water spraying (water Jogging) and applying a white coating (whitewashing).

In the article, we present results of thermal analyses in the concrete layers depending on their thickness, strength and various capacities of existing pavement. Attention was focused on conventional whitetopping (from 20 to 30 cm), but the additional analysis was also carried out for thin plates with a thickness of 10 cm. The numerical calculations allowed to determine the fatigue life resulting from the cyclic impact of temperature on the concrete pavement. The work uses 3DFEM with elements of contact, friction, and gravity in order to better approximate the behaviour of the slab from temperature change.

2. The impact of temperature on concrete pavement

The first detailed stress tests on the temperature in rigid concrete pavement date back to 1900. Westergaard published two papers related to the estimation of stresses on a concrete surface. The first one concerned stresses and deformations in the pavement caused by a load of vehicles [8], the second one took into account linear changes from the temperature on the slab thickness [9]. In contrast to Westergaard, it was shown that the temperature profiles on the thickness of the concrete slab are non-linear ([10], [11]). In the next stage, modelling was carried out using the finite element method and simulations of temperature impact on rigid pavement. Initially, these were 2D models ([12], [13], [14], [15]). Along with the development of computer technology, FEM 3D models have been developed. Using the 3D FE Shoukry et al. [16] investigated the effect of linear and non-linear temperature gradients in concrete slabs. Also, many interesting computer programs have been developed. Some programs, such as the integrated climate impact model of the pavement [17] and the extended integrated climate model [18] capable of generating rainfall patterns, solar radiation, cloud cover, wind speed and air temperature. Part of the work concerns the analysis of the concentration of stresses around dowels. Riad [19] and Luoke [20] carried out analysis of the influence of load and temperature on these stresses. The same thermal analysis and the associated stress distribution in the concrete around the dowels were handled by Shoukry [21] and Mackiewicz [22].

Despite the significant number of research works accumulated in recent years in the field of concrete pavement, the assessment of the behaviour of environmental conditions on pavement still needs to be analysed, especially if it concerns different climatic conditions that occur in Central Europe, including Poland. So far, the influence of temperature on the total durability of both new concrete pavement and those used in whitetopping technology in the period of operation has not been analysed.

3. Analysis of climatic conditions in Poland

There is a temperate climate in Poland between the maritime and land climate. As a result, the climate in Poland is characterized by quite significant fluctuations in temperature and pressure. Every month it is possible to extract characteristic values of air temperature, which have a significant impact on the behaviour of concrete pavement.

Due to the considerably extended atmospheric circulation in Poland, significant climate differences are observed throughout the country depending on different periods of the year. Representative thermal conditions prevailing in a given place can be determined primarily on the basis of average values and extreme air temperatures and in the case of the need to design concrete pavement using temperature amplitude (diurnal, annual). Impacts on a concrete slab are most often analysed in a day-night cycle. In Poland, there are many days when the daily temperature goes through 0°C and a large number of days with a high thermal diurnal gradient.

Based on meteorological data, a distribution of daily temperature changes for Poland has been developed. Fig. 1 shows the distribution of the average daily temperature amplitude in the whole year from the last thirty years [23]. There is a marked reduction in the daily fluctuations of air temperature near the Baltic Sea of 6-7°C. In the prevailing area of Poland, daily fluctuations range from 7°C to

9°C. Diurnal temperature variations increase from north-west to south-east and reach the highest values (over 9°C) in the southeast of the country.

Figure 1. Diurnal air temp. amplitude in Poland during the whole year [°C], [23].

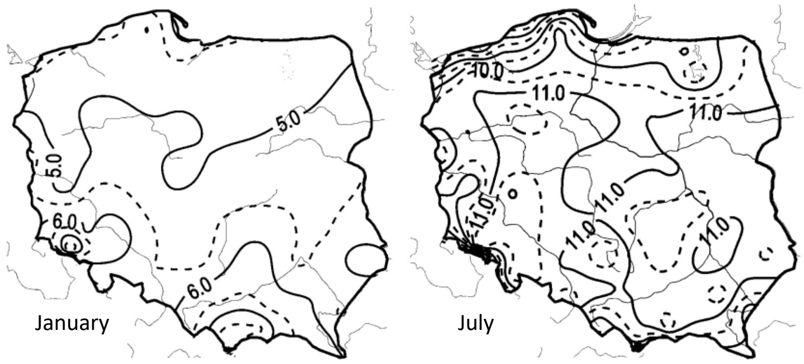

Figure 2. Daily amplitude of air temperature in Poland for January and July [°C], [23].

Analysing different regions of the country, it can be concluded that the greatest variation in temperature circuits occur on the coast (north) and in mountain areas (south). The major part of Poland with a relatively unchanged distribution (2-3°C) is the central area. Therefore, the area of the country as a whole has been treated for the practical design of the pavement without dividing the areas.

However, detailed attention was paid to temperature changes in the different seasons of the year. Fig. 2 shows the distribution of the daily temperature amplitude in Poland for selected months. The listings also come from data from thirty years. January, characterized by small fluctuations and July, in which the largest daily temperature fluctuations occur were presented [23]. Typical daily variations in air temperature for different seasons in Poland have values: spring 10°C, summer 12°C, autumn 8°C, winter 6°C. It should be noted that in Poland, characteristic atmospheric circulations (D2C-south-west and south and E1-north-east and east. Circulations are variable and although they persist in a few days, they will significantly affect the increase in average daily temperature fluctuations (for example in July daily fluctuations reach 24°C). Such even short, incidental, multi-day periods, in which the air temperature will change, will affect the behaviour of the concrete pavement.

4. Results of the temperature distribution tests in concrete pavement

On the basis of long-term own measurements of temperature on the concrete pavement, temperature changes during the day in different places on the thickness of the concrete slab were analysed. Due to the occurrence of the largest daily fluctuations in the summer months, attention was focused on measurements in these months. Fig. 3 shows a typical temperature change in the analysed concrete pavement during the day in the summer. Measurements were recorded continuously on pavement in central Poland (Łódź airport) and in the west on the A4 motorway.

The largest temperature change in the concrete slab occurs in the afternoon and at night. Then the so-called the highest positive and negative temperature difference between the upper and lower surfaces of the concrete slab is observed.

In the morning hours 5.00-8.00 and in the afternoon 16.00-19.00 you can observe a change in the temperature difference in value, the slab does not deform, but there may still be small axial stresses due to the remaining temperature in the centre of the slab.

Due to the fact that higher values have a positive temperature difference (appearing in the midday hours) and cause higher stress in the slab, it was included in further analyses. Using the results of the measurements from July in Figure 4, an example of the dependence of diurnal change in air temperature on the positive temperature difference in the slab is shown.

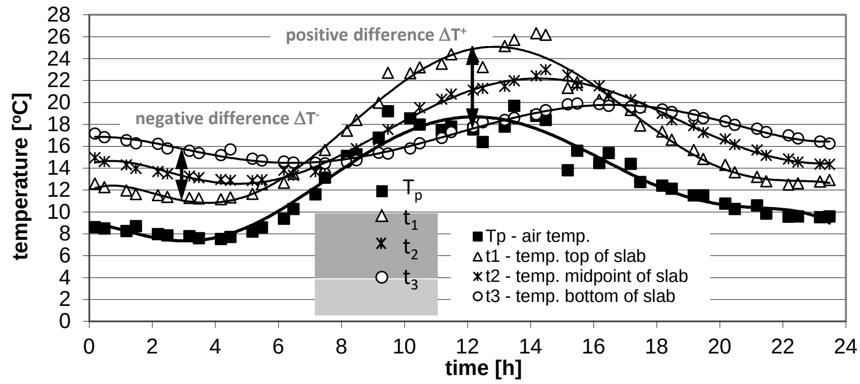

Figure 3. Daily amplitude of air temperature in Poland.

In the further analysis, taking into account the dependence presented in Fig. 5 and the temperature distribution on the slab thickness (Fig. 4), the equation allowing to determine the maximum daily slab temperature differences depending on its thickness and the daily temperature change of the air were determined:

$$\Delta T_h^{+} = (0.01412 \cdot \Delta T_p + 0.16037) \cdot h \quad (1)$$

where:
ΔT_h^{+} - positive temperature difference for variable slab thickness [°C],
ΔT_p - daily change of air temperature [°C],
h – thickness of a concrete slab [cm].

As a result of the analyses, it was found that the average gradient in our climatic conditions equals 0.4°C /cm.

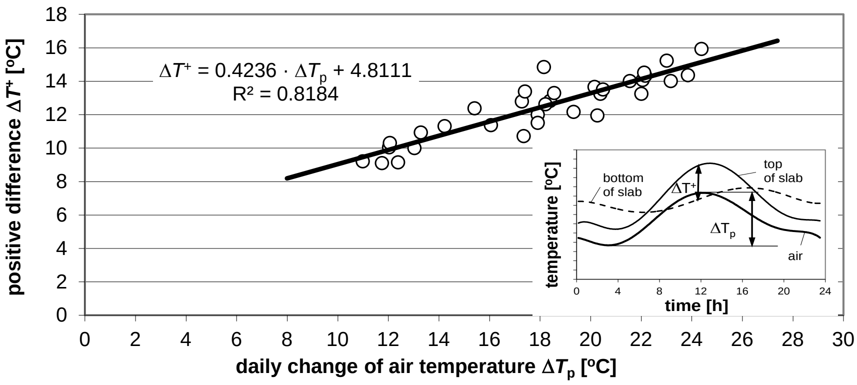

Figure 4. Diurnal change in air temp. depending on the positive temp. difference in the slab.

5. Numerical analysis of stresses in a concrete slab under the influence of temperature

The concrete pavement model was developed in the Cartesian three-dimensional system xyz using the finite element method. In the cross-section, a slab width equal to 4.0 m was adopted. In the longitudinal section, boards with a length of 4.0 m and 5.0 m were analysed. A model scheme of the pavement is shown in Fig. 5.

The adopted model corresponded to the concrete pavement made in whitetopping technology. The concrete slab was located on a layered system, characterized by equivalent elastic modulus, which can be determined using FWD and inverse calculations [24]. For a wider analysis, the variable range of the equivalent module (E_z) of layers from 90 to 1200 MPa was taken into account. The model assumes the modulus of elasticity of the slab from the temperature changes E_t = 26,000 MPa. Numerical

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calculations were made for slabs with a thickness of 10, 20, 25 and 30 cm, as well as a length of 4.0 m and 5.0 m. The case was also considered with dowels and without dowels.

In dowelled slab dowels with a diameter of 25 cm, length 50 cm, and spacing every 25 cm were included. In the analyses, linear-elastic materials were described with the modulus of elasticity and the Poisson coefficient. In order to perform the relevant calculations with regard to temperature, additional parameters for the concrete slab were adopted: thermal conductivity: 2.5 W/m°C, specific heat: 700 J/kg°C, thermal expansion coefficient: 0.00001 m/(m°C), density: 2400kg/m^3. The slab was loaded with a positive difference of 0.4°C /cm. Loads of gravity were also considered.

In addition, the model includes the appropriate boundary conditions and the cooperation of the concrete slab with the foundation in the form of a slip layer characterized by cohesion 0.2 MPa which corresponds to a coefficient of friction around 0.7. Here, the appropriate GAP-contact elements have been used. Two-node GAP elements are often used in 2D and 3D contact problems, in which the elements are in contact with each other due to the influence of external forces.

In order to determine the share of temperature-induced durability in relation to the total durability of the pavement, which also includes the vehicle's load, the load from the vehicle's wheel located in the centre of the slab was additionally taken into account. A load radius of 0.15 m and a force of 57.5 kN were assumed.

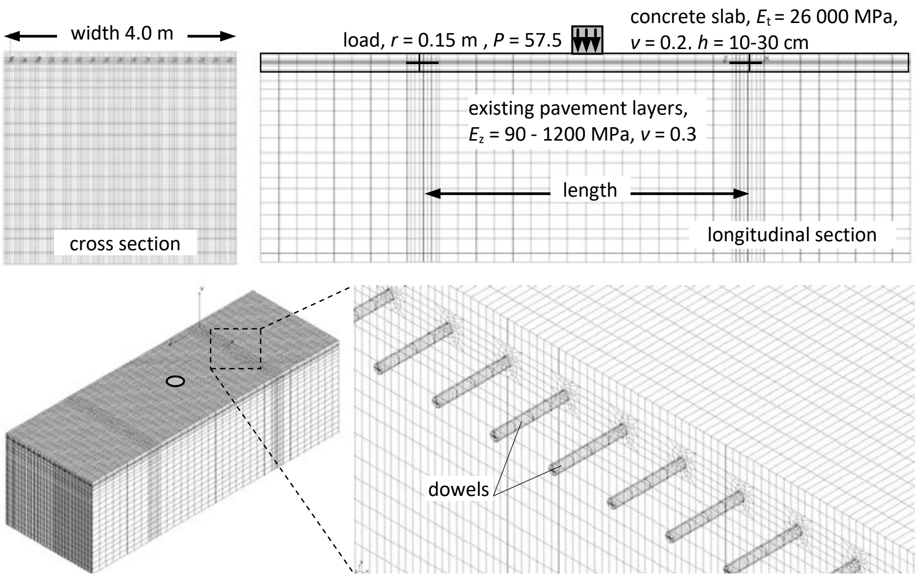

Figure 5. 3DFEM concrete pavement model.

The thermal effect was taken into account by applying appropriate temperature gradients in selected nodes of the slab. COSMOS/M [25] was used in the calculations, which makes it possible to analyse structures in terms of statics as well as linear and non-linear dynamics. Eight-cubic volume SOLID elements were used in the model. The appropriate discretization was also used. The division into 30,000 elements ensured sufficient convergence of results. The iterative procedure in the calculation was based on the modified Newton - Raphson method.

6. The results of FEM calculations

In the first stage of the calculation, the maximum tensile stresses from the temperature occurring on the surface of the concrete slab were assessed. In Fig. 6 for the smallest equivalent module 90 MPa of the existing pavement layers an exemplary distribution of stresses σ_x and deformation for a dowelled slab 20 cm thick and 5.0 m long are shown.

In the case of 5.0 m long dowelled slabs, it was found that as their thickness increases, they increase and then decrease the tensile stress caused by the temperature (Fig. 7). The optimum (maximum) stress has been observed for a thickness of approx. 25 cm. It can also be noticed that for thin slabs (10-20 cm) the stress values, despite the large scope of the equivalent module, do not differ significantly. For a 30 cm slab, the difference is bigger and amounts to about 0.4 MPa. The thicker slab, due to the greater uneven heating of its entire volume, has higher values of the temperature difference between the upper and lower surface and at longer lengths, it is more sensitive to thermal effects. It is also heavier which is of great importance in affecting the various support conditions for the subgrade.

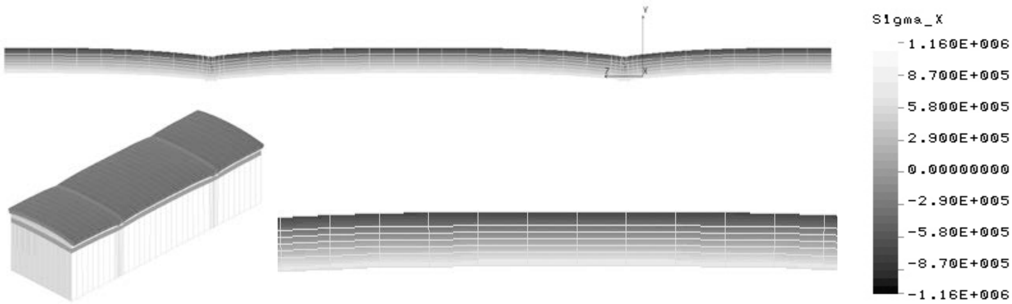

Figure 6. Deformation and stress distribution σ_x for a 20 cm dowelled plate loaded with a temperature gradient (scale factor x 200).

For a slab with a thickness of 25 cm, there is also a large influence of the value of the equivalent module of the subgrade on the values of stresses. It should also be noted that for the 25 cm thick slab, the highest tensile stresses were obtained, about 1.40 MPa, and the smallest for a thin slab 10 cm thick, which is affected by the smallest temperature difference (due to its small thickness).

In the case of a shorter slab with a length of 4.0 m (Fig. 8), smaller stress values were obtained by approximately 80%, however only for thicker slabs (above 20 cm). For a slab with a thickness of 10 cm, the sensitivity to temperature and replacement of the replacement module is smaller. It should be noted that in this case, the highest stress values occur for slabs with a thickness between 20 - 25 cm, depending on the value of the module of the subgrade (visible extreme in the figure). The optimum was obtained similarly to that for slabs with a length of 5.0 m.

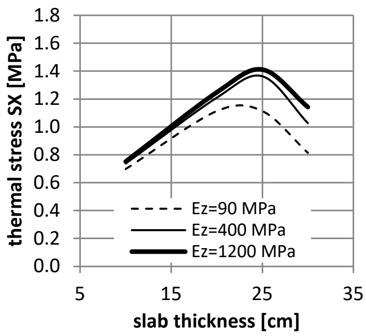

Figure 7. Change in the value of thermal stresses for slab thicknesses, for dowelled slabs with a length of 5.0 m.

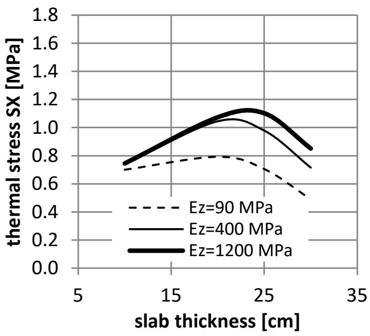

Figure 8. Change in the value of thermal stresses for slab thicknesses, for dowelled slabs with a length of 4.0 m.

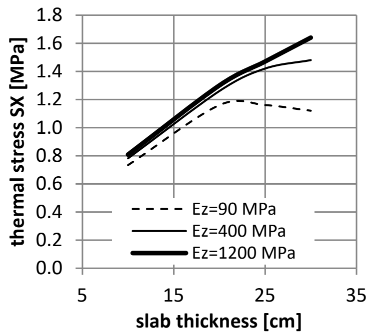

Figure 9. Change in the value of thermal stresses for slab thicknesses, for undoweled slabs with a length of 5.0 m.

Analysis of calculations for undoweled slabs with a length of 5.0 m (Figure 9) allows concluding that dowelling has a significant effect on decreasing stresses from temperature only for thicker slabs (above 25 cm), whose global stiffness is higher and there is more effective cooperation with dowels when the temperature is affected. Smaller thick panels are more flaccid. For such slabs, the dropping of the slab in the central part was observed under the influence of its own weight. Therefore, for thin slabs with only very small lengths, the dowelling effect will have a significant effect on thermal stresses. For undoweled slabs, there is no visible extreme of stresses as in doweled slabs.

7. Analysis of fatigue life

The authors used the fatigue criterion used in the catalogue of rigid pavement [26] to assess the durability of the analysed concrete pavement. This is a stress criterion for determining the durability of a concrete pavement based on its strength.

$$f_f \cdot m_1 \cdot \frac{1}{\gamma_m} \geq (\gamma_p \cdot n_1 \cdot \sigma_p) + (\gamma_t \cdot n_1 \cdot \sigma_t) \quad (2)$$

where:
f_f – a characteristic tension of concrete for bending [MPa],
m_1 – factor taking into account the repeatability of loads = 1-0,078log$N$,
N – number of loads that concrete pavement at a given level of stress from load and temperature,
σ_p – maximum tensile stresses in the slab from the wheel load [MPa],
σ_t – maximum tensile stresses in the slab from temperature changes [MPa],
γ_m – material factor =1.06, γ_p – safety factor from load =1.1, γ_t – safety factor from thermal =1.1,
n_1 – a coefficient of slabs cooperation (0.9 – undoweled, 0.7 - doweled).

Using the dependence (2), the durability derived from the temperature N_t was determined on the basis of the share of stresses against temperature in relation to total stresses:

$$N_t = N - \left(N \cdot \frac{\sigma_t}{\sigma_p + \sigma_t} \right) \quad (3)$$

Such dependence allowed to sensitize the sensitivity of different slab thicknesses and subgrade stiffness on the pavement durability associated only with temperature. Fig. 10 shows the results of calculations of durability from the temperature for the undoweled concrete slab, while in Fig. 11 for the doweled plate.

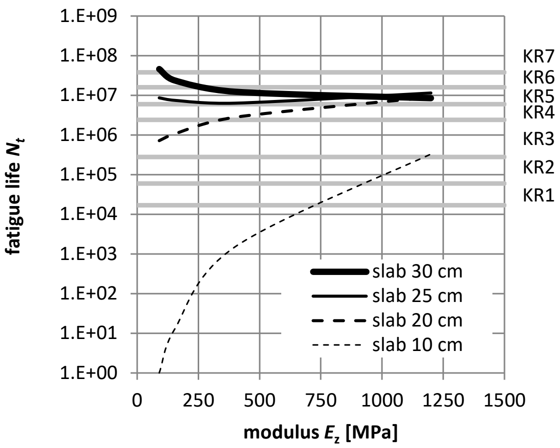

Figure 10. Changing the fatigue life N_t for a undoweled slab depending on the module E_z (slab length 5.0 m, strength 5.5 MPa).

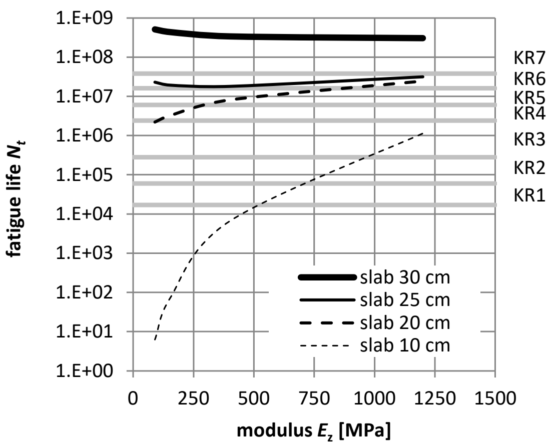

Figure 11. Changing the fatigue life N_t for a doweled slab depending on the module E_z (slab length 5.0 m, strength 5.5 MPa).

The results presented concern slabs with a length of 5.0 m and a concrete strength of 5.5 MPa. In addition, the durability intervals corresponding to the categories of movement contained in the catalogue of rigid pavement for the axes 115 kN are marked on the figures. It was found that the doweled slabs have much higher durability compared to the undoweled slabs. For a 30 cm doweled slab, there was a change of the traffic category from KR5 to KR7. The thinner slabs (20 and 25 cm) "moved" with KR3 / 5 to KR4 / 6. The smallest offset occurred for a thinner 10 cm slab from KR2 to

KR3 and only for a high modulus replacement subgrade. The 10 cm thin slab shows the greatest sensitivity to changing the equivalent module and above the value of 500 MPa it achieves KR1 (undoweled slab). Sensitivity to the change of the subgrade module is also exhibited by a slab with a thickness of 20 cm and in the module compartment from 90 to 1200 MPa changes the durability by 3 categories of movement. The smallest sensitivity is shown by the thickest 30 cm slab. It is worth noting that with low stiffness of the subgrade, its durability decreases slightly.

It should be noted that the calculations performed are simulations and, in engineering practice, not all slab thicknesses are suitable for dowelling. The calculations were made for average daily temperature fluctuations in the year. It should also be noted that the presented calculations refer to thermal interactions also associated with the additional impact of vehicles. The durability cannot be determined separately for each impact, as it depends "very non-linearly" on various factors (e.g. changes in the stiffness of the subgrade, stress values). Further analyses should also consider the total accumulation of stresses as a result of simultaneous temperature impact and unfavourable vehicle position on the concrete slab.

In tables 1 the relation between durability and temperature impact to total durability is presented, expressed in [%]. It should be noted that for thin slabs, the share of durability from the temperature in relation to the total durability, which is additionally durable from the load, is significant and amounts to about 70-80%. This means that the stresses are small, and the stresses from the load determine the loss of total durability. In the case of thick slabs (30 cm), the durability of the load transfer from the wheel rather than the sensitivity to temperature changes is more decisive. In this case, durability from temperature is only 30 - 40% of total durability. The effect of dowelling or reducing the length of the slab causes that for thicker slabs the stresses from temperature decrease with respect to stresses from load, which increases their share in the global durability of the concrete slab, to 50 – 60%.

The authors also conducted an evaluation of the impact of dowelling on the change in durability (Figures 12 and 13).

Table 1. Ratios of durability for temperature to total durability [%].

	undoweled slab – 5.0 m				doweled slab – 5.0 m				doweled slab – 4.0 m			
E_z [MPa]	90	153	400	1200	90	153	400	1200	90	153	400	1200
slab 10 cm	**85.9**	**84.1**	**80.0**	**72.4**	**86.5**	**84.8**	**80.9**	**73.8**	**82.9**	**81.3**	**77.1**	**71.0**
slab 20 cm	**57.8**	**54.7**	**49.2**	**42.1**	**58.8**	**55.7**	**50.2**	**43.1**	**67.8**	**63.3**	**55.2**	**49.0**
slab 25 cm	**49.1**	**45.0**	**38.0**	**31.7**	**50.1**	**45.8**	**38.9**	**32.6**	**62.2**	**56.2**	**48.1**	**39.7**
slab 30 cm	**42.8**	**37.7**	**30.6**	**23.9**	**50.8**	**46.4**	**38.9**	**31.1**	**63.6**	**58.4**	**48.5**	**38.8**

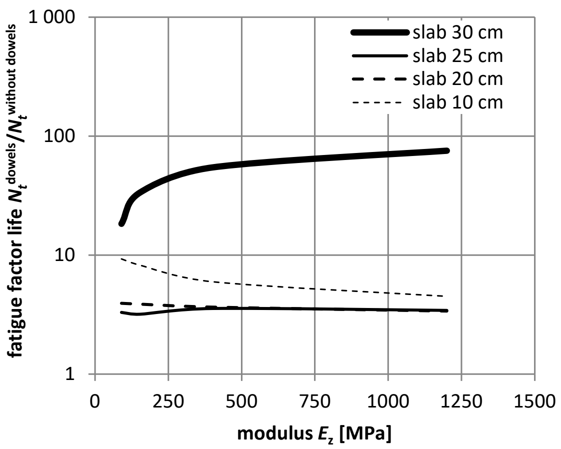

Figure 12. Change in the dowelling factor depending on the equivalent module (slab length 5.0 m, strength 4.5 MPa).

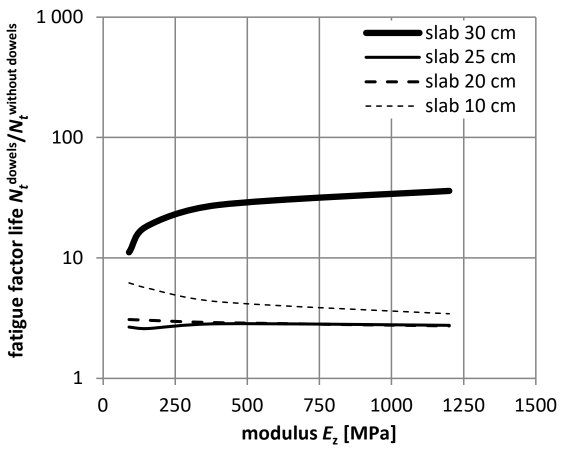

Figure 13. Change in the dowelling factor depending on the equivalent module (slab length 5.0 m, strength 5.5 MPa).

The dowelling factor was determined as the ratio of temperature stability for dowel panels to the durability of panels without dowels. It was found that the dowelling factor reaches higher values for thicker slabs (30 cm) from about 10 to 80. The effect of dowelling is more visible for lower strength concrete. For thinner slabs (20 and 10 cm), the stiffness of the subgrade for the dowelling is not significantly affected. The dowel index varies from just 3 to 8. For the thinnest slabs, 10 cm, a larger index (from 6 to 9) was obtained than for a 20 and 25 cm slabs. It should be noted, however, that in practice, for technological reasons, there is no point in making such thin slabs.

8. Summary

The experience gained so far in the world of road engineering shows that the whitetopping method allows for the pavement characterized by a long service life, low maintenance costs and a high degree of safety for car traffic. This technology allows also repairing typical damage of asphalt pavement, such as: ruts, surface flakes, temperature and fatigue cracks. However, it should be remembered that when reinforcing old pavement by whitetopping method, it is important to correctly identify pavement parameters, because depending on the value of the equivalent module, such values will be stresses from vehicle movement and temperature, and consequently durability.

The biggest impact on the change in durability due to the value of the equivalent module of the subgrade is noticeable for slabs with a thickness of 20 cm (and below). For such slabs, for the module from 90 to 1200 MPa, durability changes by about a dozen million. This means a change of 2 - 3 traffic categories. The smallest influence on the change of the traffic category in relation to the equivalent module value is shown by thicker 25 and 30 cm slabs. Such slabs practically do not change the movement category for both small and large values of the replacement module. For example the 25 cm dowelled slabs is for the movement category KR6 and 30 cm for KR7. Although it should be noted that for high traffic categories, i.e. KR6, the durability range is up to 20 million axles.

Dowelled slabs have significantly higher durability compared to the boards being drilled. For boards with a thickness of 30 cm, the use of dowels increases the durability of more than several tens of millions of axes. Dowelling a thinner slab with a thickness of 20 and 25 cm increases the durability by about several million axes. The smallest effect is obtained for thinner slabs, e.g. 10 cm (several hundred thousand). It was found that the repeatability of thermal stresses significantly reduces the durability of the concrete pavement in the long-term period of impact. Even small temperature fluctuations along with the load from the vehicle can be sufficient to initiate local damage in concrete. Especially high tensile stresses were found for 25 cm thick slabs, for which there is still a relatively large temperature difference. It is therefore recommended to use dowels for slabs above 25 cm, while for the design of thinner slabs (less than 25 cm) for low traffic categories (below KR4) pay attention to the values of the substitute module of the reinforced pavement.

The conducted analyses can be helpful in the design of new concrete pavement, and above all in the assessment of the load-bearing capacity of existing pavement in whitetopping technology. The optimal choice of thickness, slab length or dowelling needs should be taken into account together with the impact of the load and the need to transfer the required traffic at the design stage.

The subject of further work will be an analysis of the impact of the interconnection variable between the slab and the ground and the analysis of stress caused by the load on vehicles and their unfavourable location.

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