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Analysis of temperature gradient in concrete pavement

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Abstract. The paper presents the results of experimental research that is the continuation of the research conducted as a part of a Ph.D. dissertation. The experimental research consisted in measuring the temperature at various depths inside a concrete slab, including its surface, and measuring the air temperature. The temperature distribution was measured on a concrete slab with dimensions similar to real road slab dimensions. The aim of the research was to determine the temperature gradient in the concrete slab in Polish climatic conditions and to verify the available analytical methods.
Keywords: temperature gradient, concrete pavement, thermal stress in concrete pavement
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1. Introduction

The paper presents the results of experimental research aimed at determining the temperature gradient in a concrete pavement slab in Polish climatic conditions. The research has been carried out continuously since December 2013 at the measuring stand at the Military University of Technology.

This paper is the continuation of experimental research conducted as a part of a Ph.D. dissertation [4]. The research conducted will enable the correct determination of the temperature gradient in the concrete slab. The temperature gradient affects the maximum tensile stress and thus determines the fatigue strength of the pavement.

A temperature change in the concrete slab results in a change of the concrete slab volume. If the temperature affects the entire slab thickness evenly, only axial deformations occur in the slab. However, in reality, the temperature change in the pavement is a function of the distance from the top pavement surface and it results in the slab bending (Fig. 1) and thermal stress (Fig. 2).

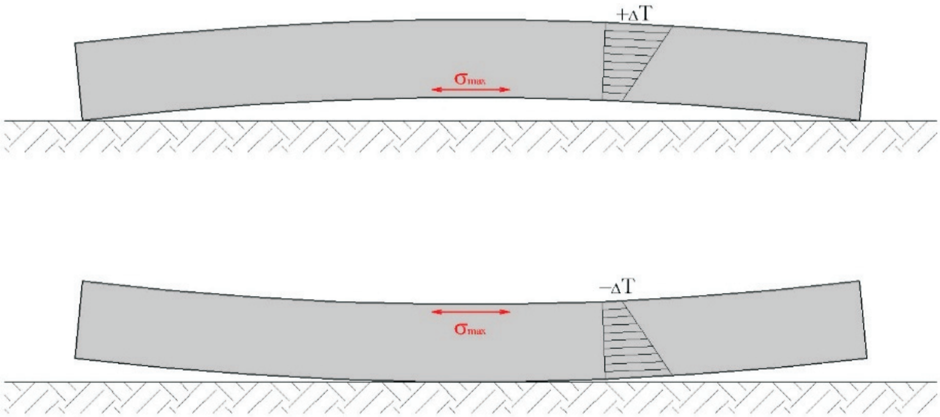

Fig. 1. Slab deformations caused by temperature gradient

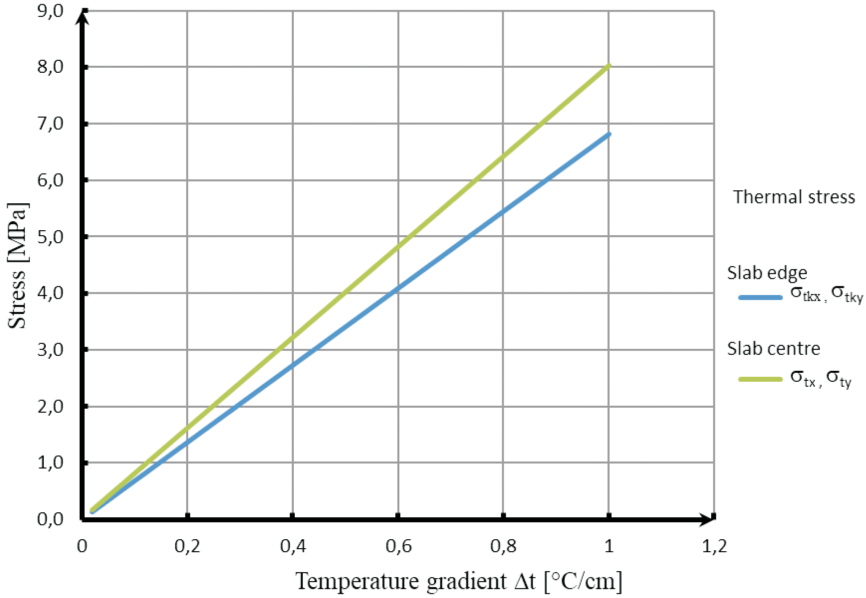

Fig. 2. The influence of the temperature gradient on the maximum stress in the concrete slab (E = 34200 MPa, h = 35 cm, k = 150 MPa/m)

The temperature gradient value determined in the experimental research conducted in the United States in the 1930s is currently used in Poland. However, this value of 0.66°C/cm does not correspond to Polish climatic conditions, which is also pointed out in the paper [5, 6]

Numerous models of the temperature distribution in the cement concrete pavement [2, 3] are described in the relevant literature. Short-term experimental research was also conducted [1], which unfortunately did not contribute to the verification of the currently used temperature gradient values.

The purpose of the study was to examine the actual temperature gradient inside the concrete slab in Polish climatic conditions based on observations carried out for several years and to determine the best suitable analytical model for the experimental research results.

2. Measuring stand

The tests were carried out at the measuring stand (shown in Figure 3) at the Military University of Technology. As a part of the measuring stand, a concrete slab was made of C30/37 strength class concrete to simulate the actual road slabs with the dimensions of 3.5 × 3.5 m and a thickness of 35 cm. Seven PT-100 temperature sensors with a temperature measuring range from -40°C to +80°C were placed in the concrete slab and the subbase. The arrangement of the temperature sensors is shown in Figure 4.

Fig. 3. View of the measuring stand

The temperature sensors were connected to an eight-channel thermometer, powered from an external source, equipped with a digital current interface with time histories the same as in RS232C standard. Successive results recorded by the device were sent every few seconds. The results were sent in real time by the device via the RS232C interface to a computer and saved automatically in a text file every minute. The research results were analysed using a spreadsheet with proprietary macros introduced to enable the presentation of measurement data.

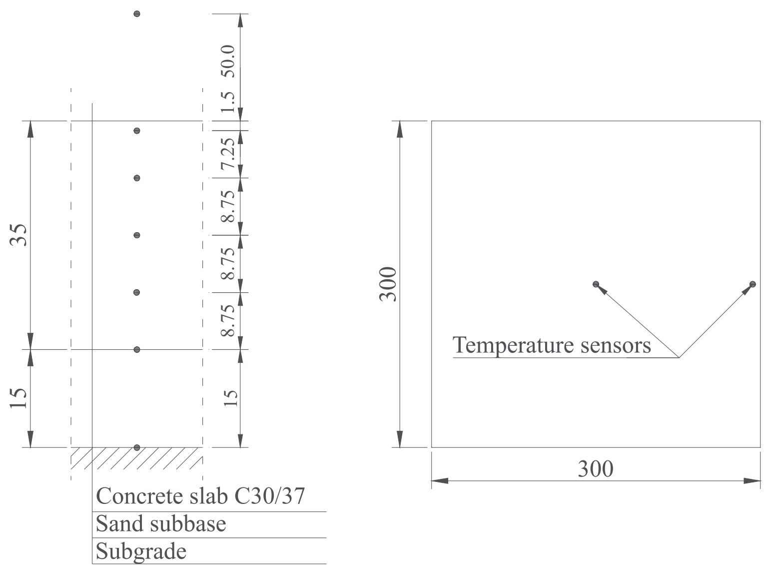

Fig. 4. The arrangement of the measuring sensors in the concrete slab

The temperature distribution measurements were carried out in a single concrete slab with each of its sides adjacent to the ground. In reality, concrete slabs are adjacent to each other. Only the outermost slabs are adjacent to the ground. Due to the measuring stand design and the small size of the slab, there was a risk that the adjacent ground could affect the temperature distribution inside the concrete slab. In order to determine the effect of the ground on the slab temperature, an additional temperature sensor was placed at the slab edge, at the centre of the slab height.

3. Analysis of the experimental research results

The effect of temperature on a concrete pavement is complex. Based on observations, it has been found that the temperature on the concrete slab surface does not, as it does on the available theoretical models, depend on the air temperature.

Very often, the slab surface temperature is much higher than the air temperature (Fig. 5), but sometimes, especially in winter, the slab surface temperature is the lowest (Fig. 6). The temperature distribution in the concrete slab is also considerably affected by cloud cover, which limits heat radiation from the concrete slab.

Temperature parameters shown in the diagrams: T1 — air temperature; T2 — slab surface temperature; T3 — temperature at the depth of 8.25 cm under the slab surface; T4 — temperature in the centre of the slab height; T5 — temperature at the depth of 22.75 cm; T6 — temperature at the bottom of the concrete slab; T7 — temperature at the bottom of the sand subbase; T8 — temperature at the concrete slab edge, in the centre of its height.

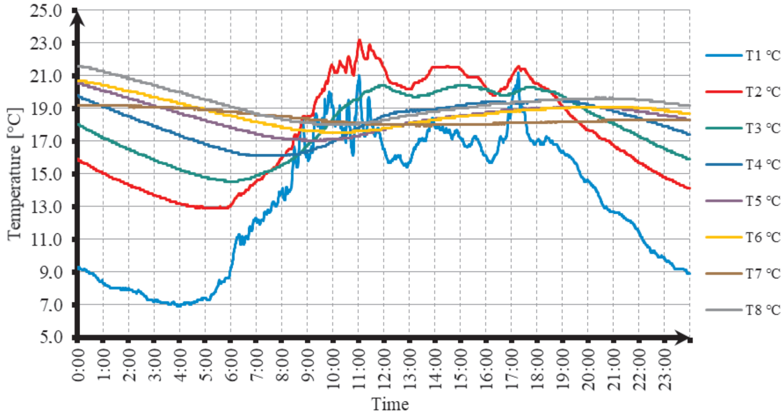

Fig. 5. Temperature gradient on 24/06/2016

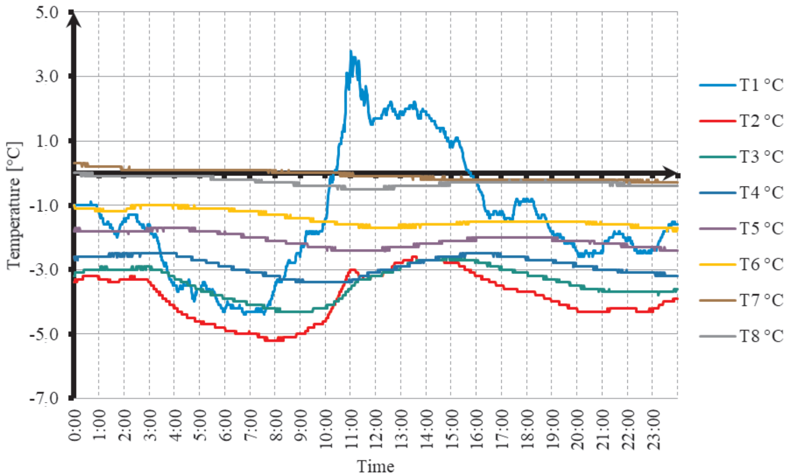

Fig. 6. Temperature gradient on 02/02/2015

Analysing the diagrams shown, one can notice that the temperature reaches the minimum value on the concrete slab surface, although it is heated from above by warmer air and from the bottom by a warmer part of the slab. The presented phenomenon was observed mainly on cloudless days before sunrise and after sunset, which suggests that skyward radiation occurs.

On cloudy days, the concrete slab surface temperature was usually lower than the air temperature. This was due to the limited effect of solar radiation on the concrete slab surface (Fig. 7). This situation recurred in winter-autumn periods during the analysed measurement period.

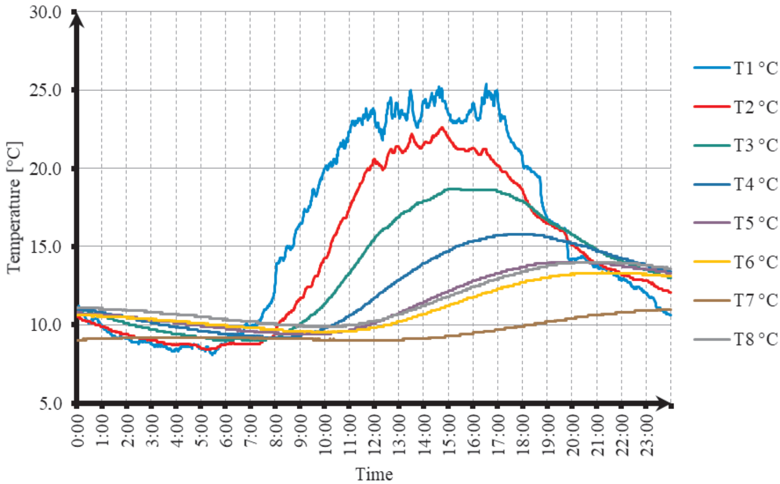

Fig. 7. Temperature gradient on 08/04/2017

During the four-year observation (2014-2017), it was noticed that, most frequently, the concrete slab surface temperature considerably exceeded the air temperature, as shown in Figure 8.

Analysing the above figures, one can state that the temperature distribution on the concrete slab surface during a twenty-four hour period is not the same and is not dependent only on the air temperature. Thermal transformation processes taking place in the concrete slab are much more complex and require more attention. During the day, the concrete slab temperature, especially the concrete slab surface temperature, depends on solar radiation intensity, air temperature, cloud cover, air humidity, concrete slab humidity, wind power and the temperature of the lower layers.

On the other hand, in the evening and in the morning, the concrete slab surface temperature depends primarily on air temperature, cloud cover, air humidity, concrete slab humidity, wind power, the temperature of the lower layers and skyward radiation. Despite the fact that the concrete slab temperature is affected by many factors, the average distributions of air temperature, concrete slab surface temperature and the average concrete slab temperature gradient can be determined on the basis of a large number of measurements.

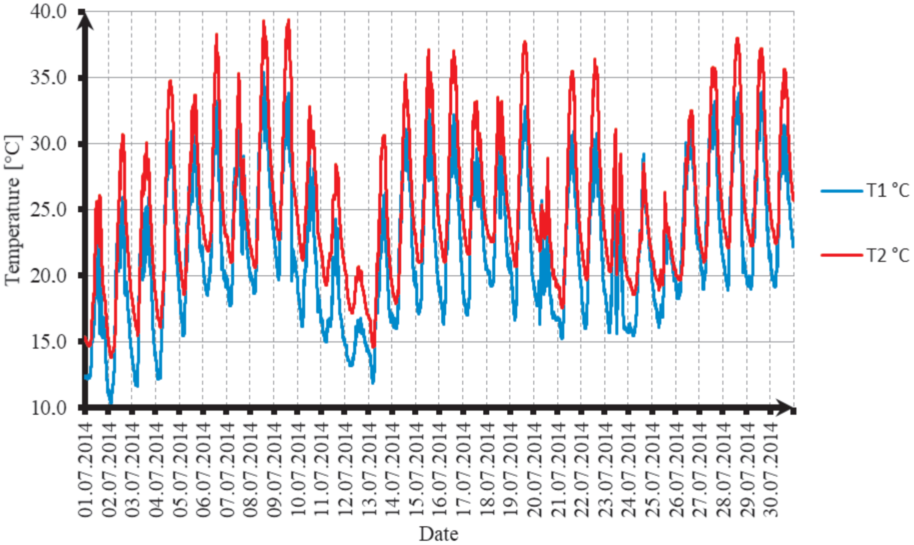

Fig. 8. Gradient of air temperature and slab surface temperature in July 2014

3.1. Temperature gradient in concrete slab

One of the parameters determining the thermal stress value in the cement concrete pavement is the temperature gradient in the concrete slab. This gradient expresses the change in temperature per one unit of the pavement thickness. Its value varies throughout a twenty-four hour period (day and night) and throughout the year. The current calculation methods use the gradient values determined on the basis of the experimental research conducted in the United States between 1930 and 1935. This value of 0.66°C/cm was determined for the climatic conditions in which the average slab surface temperature was 19.7°C and the maximum recorded temperature on the concrete slab surface was 44.7°C. Between 2014 and 2017, the average concrete slab surface temperature at the measuring stand was 11.64°C, and the maximum concrete slab surface temperature was 41.6°C. The average concrete slab surface temperature in Polish climatic conditions is almost twice lower than the average concrete slab surface temperature for which the temperature gradient in the concrete slab was determined. Figure 9 shows an example distribution of the temperature gradient during a twenty-four hour period (day and night) in 2016.

The highest value of the temperature gradient was obtained in July and it was 0.25°C/cm. Slightly lower values of the gradient were obtained in May and April, while much lower values were obtained in August, September and March. One should bear in mind that the temperature gradient does not depend on the maximum temperature of the concrete slab surface but on the largest difference between the concrete slab surface temperature and the concrete slab bottom temperature.

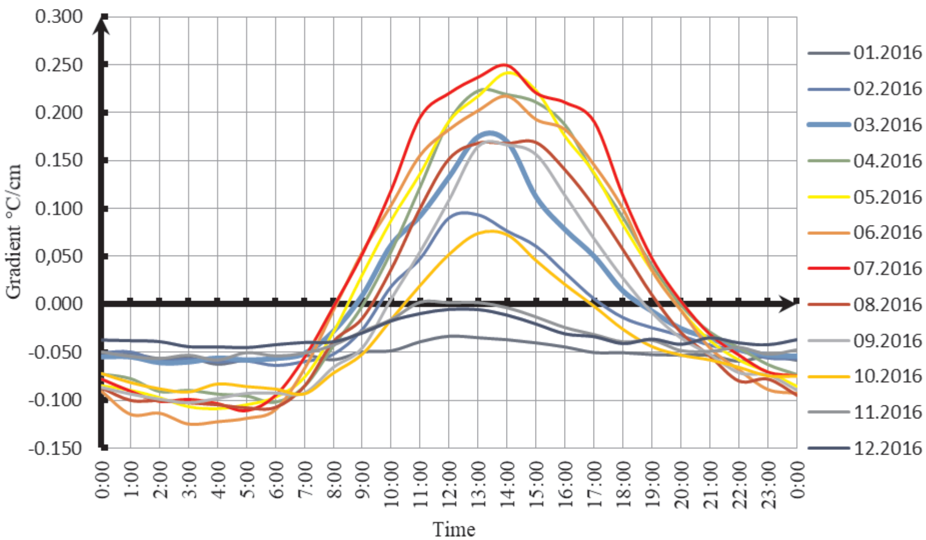

Fig. 9. Temperature gradient distribution during a twenty-four hour period (day and night)

Figure 10 shows the distribution of the maximum temperature gradient and the minimum temperature gradient for individual years during the measurement period, while Figure 11 shows the value of the maximum temperature gradient and the minimum temperature gradient in the analysed measurement period.

On the basis of the presented diagrams, one can state that the distributions of the maximum and minimum values of the temperature gradient for individual years are similar. This is because the temperature gradient does not only depend on the temperature value but above all on the coefficient of heat transfer inside the concrete and the time the given temperature affects the concrete surface.

Analysing the annual summary of the maximum temperature gradient (Fig. 11), one can state that its value in the successive years is very similar and ranges from 0.23°C/cm to 0.31°C/cm, which is twice as low as the value currently used in the thermal stress calculations.

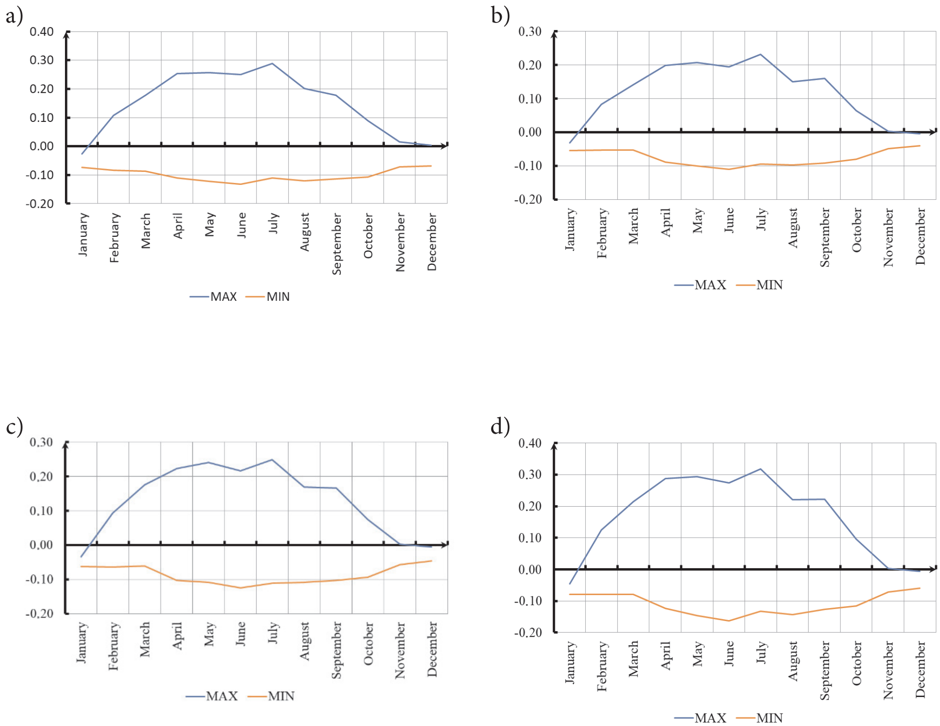

Fig. 10. The distribution of the maximum and minimum temperature gradient in 2014 (a), 2015 (b), 2016 (c) and 2017 (d)

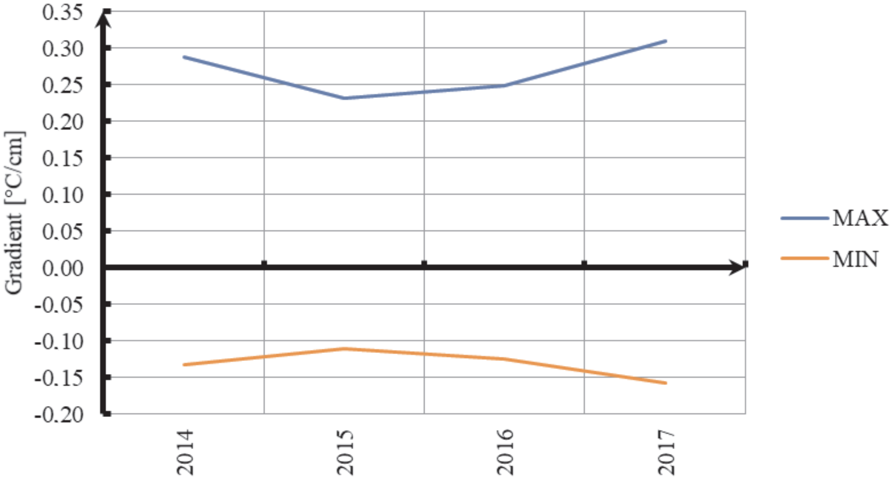

Fig. 11. The distribution of the maximum and minimum temperature gradient in the analysed measurement period

In order to verify the available analytical methods [2, 3], the measured temperature gradient values and the calculated temperature gradient values are juxtaposed in Table 1 and in Figure 12. The calculations were made for the average air temperatures and the slab surfaces determined for each month in which the maximum temperature gradient values were recorded in the concrete slab.

TABLE 1

Summary of temperature gradient values

Year	The average maximum temperature gradient	The average temperature gradient determined according to the assumptions specified in [3]	The average temperature gradient determined according to the assumptions specified in [2]
	[°C/cm]	[°C/cm]	[°C/cm]
2014	0.286	0.071	0.124
2015	0.232	0.054	0.089
2016	0.249	0.051	0.119
2017	0.310	0.075	0.138
AVERAGE	**0.269**	**0.063**	**0.118**

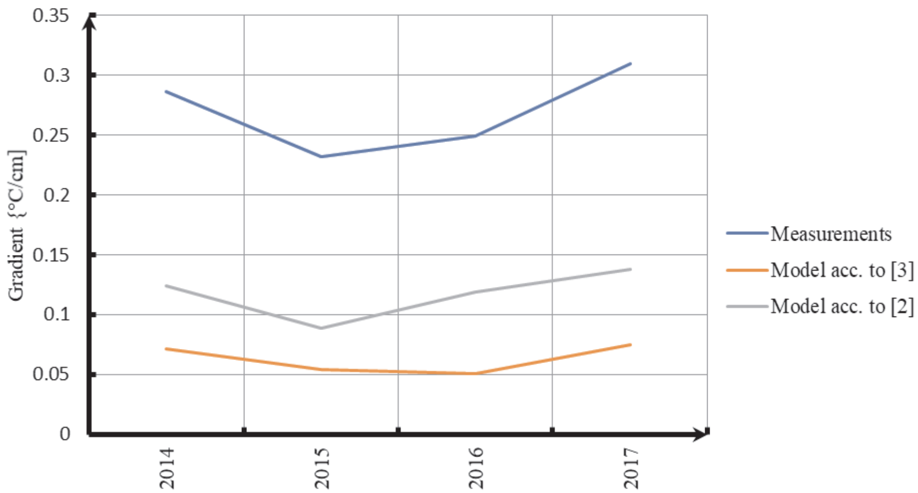

Fig. 12. Comparison of the results obtained by analytical methods with the measurement results

The presented calculations show that the temperature gradient determined by analytical methods is much lower than the temperature gradient determined on the basis of the experimental research. The discrepancy of the results is affected by numerous parameters determining the temperature value in the concrete slab, which were not subject to measurements, as well as by the accuracy level of the calculation model.

For the purpose of simplification, the model was validated using an average temperature distribution during a twenty-four hour period (day and night) that does not correspond to the highest values of the concrete slab surface temperature.

The measurement results presented and their comparison to the theoretical models lead to the conclusion that in order to ensure more accurate modelling of the temperature distribution inside the concrete slab, the currently used calculation models should be modified, as the calculation results are 2.5 times lower than the experimental research results.

4. Conclusion

This paper presents a method for measuring the temperature distribution inside a concrete slab. The purpose of the method is to ensure the most accurate representation of the actual road system. The aim of the research was to determine the temperature gradient in the concrete slab that has a direct impact on the fatigue life of the pavement structure. Based on the research conducted, it has been concluded that the currently used gradient value does not correspond to Polish climatic conditions. The measured temperature gradient value is twice lower than the value used in the calculations. It should also be noted that the results obtained using the calculation models for the temperature distribution inside the concrete slab also differ from the measurement results.

In the next stage of the research, solar radiation intensity is planned to be included in the calculation models and the vertical temperature distribution in a concrete slab is planned to be verified.

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G. ROGOJSZ

Analiza gradientu temperatury w betonowej nawierzchni drogowej

Streszczenie. W artykule przedstawiono wyniki badań doświadczalnych, które są kontynuacją badań prowadzonych w ramach pracy doktorskiej. Badania doświadczalne polegały na pomiarze temperatury na różnych głębokościach wewnątrz płyty betonowej, w tym na jej powierzchni, oraz pomiarze temperatury powietrza. Pomiar rozkładu temperatury prowadzono na płycie betonowej o wymiarach zbliżonych do rzeczywistych płyt drogowych. Celem realizowanych badań było określenie gradientu temperatury w płycie betonowej w polskich warunkach klimatycznych oraz weryfikacja dostępnych metod analitycznych.

Słowa kluczowe: gradient temperatury, nawierzchnia betonowa, naprężenia termiczne w nawierzchni betonowej

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