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Analysis of the thermal characteristics of anti-icing driveway plates

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Abstract. This article presents the results of numerical analysis of the dynamic temperature distribution in driveway construction, for example, for emergency response vehicles - such as: ambulance, fire brigade, police and so on. It is assumed that the driveway is equipped with a heating mat, which is responsible for maintaining the road surface at a positive temperature. The purpose of this solution is to eliminate icing of the surface under difficult climatic conditions when the outdoor air temperature is negative. The presented calculations were performed in four stages. The first step involves comparing solutions containing different thicknesses of the heating plate from 6cm to 12cm. In the second stage - for the solution chosen from the first stage - a variable position of the heating mat in the plate is assumed. In the third stage two versions were compared: a solution with side insulation at the curb and without such insulation. Stage four contains a comparison of a driveway in the form of an overpass with a solution arranged directly on the ground. The whole analysis is designed to determine the best proposal for driveway construction - so that it is effective in terms of the energy delivered to the system, which is necessary to maintain a positive surface temperature.

1. Introduction

Thermal-humidity solutions are widely used in practical applications related to building constructions [1-3]. Due to the large number of variables influencing the work of structural and engineering components, proper temperature analysis is quite complex, often requiring complicated computational methods [4-5] or time consuming and costly empirical studies [5-6]. The development of information technology in recent years has enabled the improvement of software to model spatial structures under certain conditions [7]. This allows for the creation of virtual building constructions and the analysis of their work [8]. This concerns both construction, strength and carrying capacity issues [9] as well as geotechnical [10], heat [11] and humidity [12] issues. The use of numerical modelling greatly accelerates the process of finding optimal structures [13] and reduces the costs associated with the design process for engineering structures or buildings. There are known studies on the analysis of heated roads. They concern both the process of management of energy consumption [14] and the construction of heating systems [15]. However, there are no publications in the field of comparison of the adopted structural solutions for the efficiency of road heating systems.

This article attempts to use numerical modelling to properly design a driveway for emergency response vehicles, such as ambulance, fire brigade, police, military, etc. The task of these institutions is to respond efficiently and as quickly as possible to situations in which this emergency response is required, e.g. road accident, fire, natural disaster. Under Polish climatic conditions, during the winter season, the road surface is often iced due to the negative external air temperatures, which may delay or



hinder the operation of the abovementioned services. This is particularly important in the case of access roads and manoeuvring areas where the traffic volume is low and the external road cleaning services are delayed. The solution to the problem may be the use of a heated road surface. Such solutions are already widely used in Scandinavian countries and increasingly in temperate countries. The investment involved in the use of heated road surfaces is expensive and the operating costs associated with the proper functioning of such facilities are high. There is therefore a need to analyse available material and construction solutions to the fullest extent possible in the conceptual stage so that the end result of the project to be implemented is satisfactory from the investor's point of view.

The use of numerical modelling allows for a preliminary analysis of the correctness of the adopted solutions without the need for large investment funds. In the case of a heated driveway plate, the important information for the investor is the cost of operating the facility and the assurance that the adopted solution will work well in adverse weather conditions. In the case of analyses related to thermal issues and temperature distribution in building partitions - the main problem is the large number of variables influencing the results obtained. These variables can be: the physical characteristics of the materials used, the order of the layers, the geometrical dimensions of the individual components, and the variable load resulting from the placement of the designed construction in the external environment. Due to the stochastic nature of environmental loads such as outdoor air temperature, intensity of solar radiation, atmospheric precipitation, wind strength and direction, it is not possible to perform numerical analysis for every possible case that may occur in practice. The present study adopts the method of multi-comparison comparative analysis. It is based on the principle that for the adopted assumptions one variable is differentiated and selected cases are analysed. The most advantageous of the group of solutions obtained is the basis for the next step of adopting another variable and performing another comparative analysis for this variable. This methodology allows us to choose the proper design solution without the need to analyse a few thousand cases that would have to be considered in the case of a large number of variables. It should be stressed that there is no certainty that the adopted solution will be optimal. However, it should be in the group of solutions that will be near the optimum.

2. Tools and design principles

Calculations were carried out in the Adina program [16] using the finite element method (hereinafter abbreviated FEM). The FEM method enables the creation of structures: one-, two- and three-dimensional elements that form part or all of a building construction. The program allows analysis of the work of structures created working under load. The analysis may concern endurance issues as well as thermal or flow issues. The program allows the creation of component elements of a solid-state structure as well as fluid in the form of liquid or gas. This is particularly important for issues related to temperature distribution and heat flow. In order to properly exploit the capabilities of the software, the appropriate calculation procedure with the following steps is applied:

- select the appropriate module for analysis (strength, temperature, flow),
- generate the structure of the construction being analysed, paying particular attention to the correct mapping of the geometrical features of the real model,
- determine the required physical characteristics of the component materials applied,
- adopt boundary conditions, related to the way the burden is applied, the constraints of the model, etc.,
- adopt a division into groups of elements and define for them the way of subdivision, by which a finite element grid is created; particular attention should be paid to the way the grid is created - so that nodes in adjacent elements, surfaces or linear dimensions overlap, ensuring continuity of the model,
- perform calculations for the selected calculation module; in the case of non-stationary issues, the initial conditions and, depending on the load, the length of the time step, should be taken into account,
- analyse the results obtained, properly but in a critical way, leading to interpretation of the results.

For the basic model, the following design assumptions were adopted:

2.1 Module

During the analysis, the Adina CFD module was used for calculations. This is a model for both heat and flow analysis.

2.2 Structure of the construction

A three-dimensional numerical model of the heated driveway structure was built in the computational program. It was assumed that the length of the driveway would have a constant cross-section, therefore a 1000 mm long section of the construction was modelled. This consists of the following:

- reinforced concrete structure - consists of a plate of 300 mm thickness and 5000 mm width and a restrictive curb, also of 300 mm thickness and a height selected such that the upper edge of the curb is 80 mm above the top surface of the road.
- in the roadway between the curbs - on the upper surface of the construction plate, the following finishing layer is designed: 12-mm thick waterproofing, 100-mm thick extruded polystyrene, 60- to 120-mm thick concrete screed, 3-mm thick resin surface.
- the 300 W/m² heating mat is located in the concrete screed layer.

2.3 Physical characteristics of materials used

The physical properties of the materials used in the numerical model are shown in the Table 1. The heating mat is made of copper cabling embedded in a plastic casing. The power of the mat at the level of 300 W/m² was assumed on the basis of an exemplary solution used in practical implementation. For all materials, a reference temperature of +20°C is assumed.

Table 1. Physical properties of materials in the numerical model.

Material name	Density	Heat conduction coefficient	Specific heat
—	kg/m ³	W/(m·K)	J/(kg·K)
reinforced concrete (construction plate and curb)	2500	1.70	840
waterproofing	1000	0.18	1460
extruded polystyrene	30	0.04	1460
concrete screed	2400	1.70	840
heating mat	8800	370	380
resin surface	1200	0.20	1400

2.4 Boundary conditions

After creating the model structure, the relevant material characteristics were assigned to individual elements and a model of the impact from the external environment was derived. For this purpose, the boundary conditions on the outer surfaces of the model associated with the outdoor air temperature were determined. In the baseline model, a constant value of outdoor air temperature was assumed at -5°C, while the heat flow in the analysed construction was modelled as a non-stationary process. The Special Boundary Condition function was used to load the external surfaces. This allows the modelling of radiation and convection phenomena occurring on the solid surface in contact with the liquid or gaseous environment. Condition III was used, which defines the ambient temperature and heat transfer coefficients. In the case of convection, the mean wind speed is assumed to be 2 m/s. For such assumed wind speed values, the value of the convection coefficient on the exterior surfaces of the model was assumed. In order to limit the number of possible cases, fixed values for boundary conditions for all stages of analysis were assumed (Table 2):

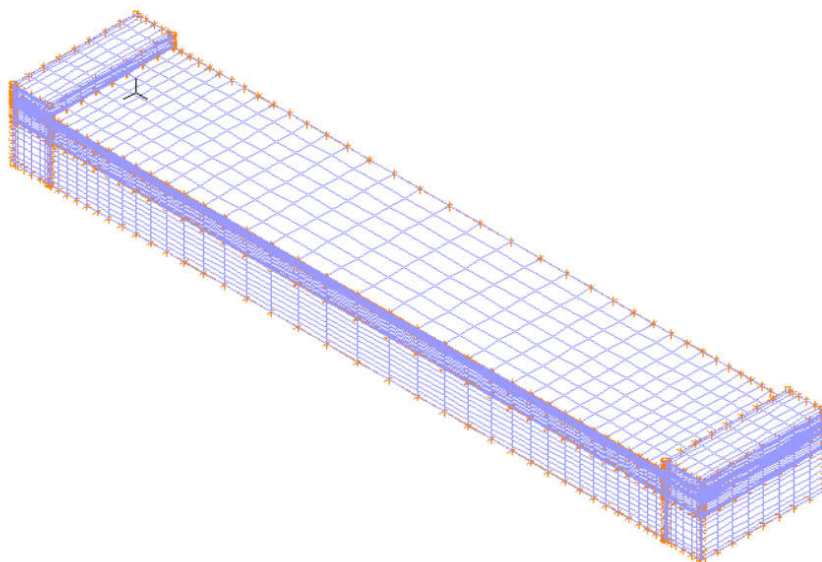
Table 2. Constant values in numerical analysis.

Name	Symbol	Unit	Value
Stefan-Boltzmann constant	σ	$\text{W}/(\text{m}^2 \cdot \text{K}^4)$	$5,67 \cdot 10^{-8}$
Emissivity coefficient	ε	-	0.9
External air temperature	T_e	$^{\circ}\text{C}$	-5
Convection heat transfer coefficient	h_{ce}	-	12
Heating mat power	q	W/m^2	300

2.5 Division into groups of elements

For each material group, a separate group defining a subdivision of finite elements was created. The FEM grid was made up of octagonal elements in the shape of a cuboid. The use of such a shape allows for more precise numerical results than for four-node elements. A one-meter-long section of the driveway was adopted for analysis.

The Figure 1 shows the construction of the basic model with its division into finite elements.

**Figure 1.** Construction of the basic model.

2.6 Initial conditions and time function

The maximum unfavourable initial conditions were set up - full cooling of the analysed construction. This means that the initial temperature value for the whole construction is assumed to be -5°C . The loading temperature was assumed at -5°C (as the most unfavourable from -5°C to $+5^{\circ}\text{C}$). It was assumed that with a higher air temperature, there will be no icing, while at a lower temperature the precipitation will occur in the form of snow and also will not cause icing. For non-stationary analysis, a time step of 20 minutes was adopted. In the case of analysis of thermal phenomena occurring in building constructions, this is sufficient to obtain results with the required accuracy. For the first 24 hours, a heating period is established using a heating mat with full heating power ($300 \text{ W}/\text{m}^2$). After this period, heating periods were cyclical: switching off the heating –causing the structure to cool - for 7 hours and reheating for 5 hours. The entire analysis of each variant covered a total of 96 hours (4 days).

3. Results and discussion

3.1 Stage I – different thicknesses of concrete screed

The first stage contains a comparison of cases differing in the assumed thickness of the concrete screed. Four variants of the screed were adopted: 6 cm, 8 cm, 10 cm and 12cm. In each of these variants it is assumed that the heating mat is located 6 cm from the upper surface of the screed. The results suggest that the most preferred solution for the first stage is a 12-cm thick screed, thus the thickest of the proposals adopted. Compared to other variants, the surface of the driveway heats up the slowest, which is an undesirable feature. It is more important, however, that the heat accumulated in the screed slows down the cooling process. This is important at critical moments just before the end of the cooling cycle, when the road surface temperature is the lowest and can lead to icing. The minimum surface temperature of a given cycle for the 12-cm thick screed variant is higher than that obtained for other variants. The graphic distribution of the temperatures obtained in each variant for the analysis time equal to the end of the first cooling cycle (31 hours from the start of the process) is shown in the figure (Figure 2).

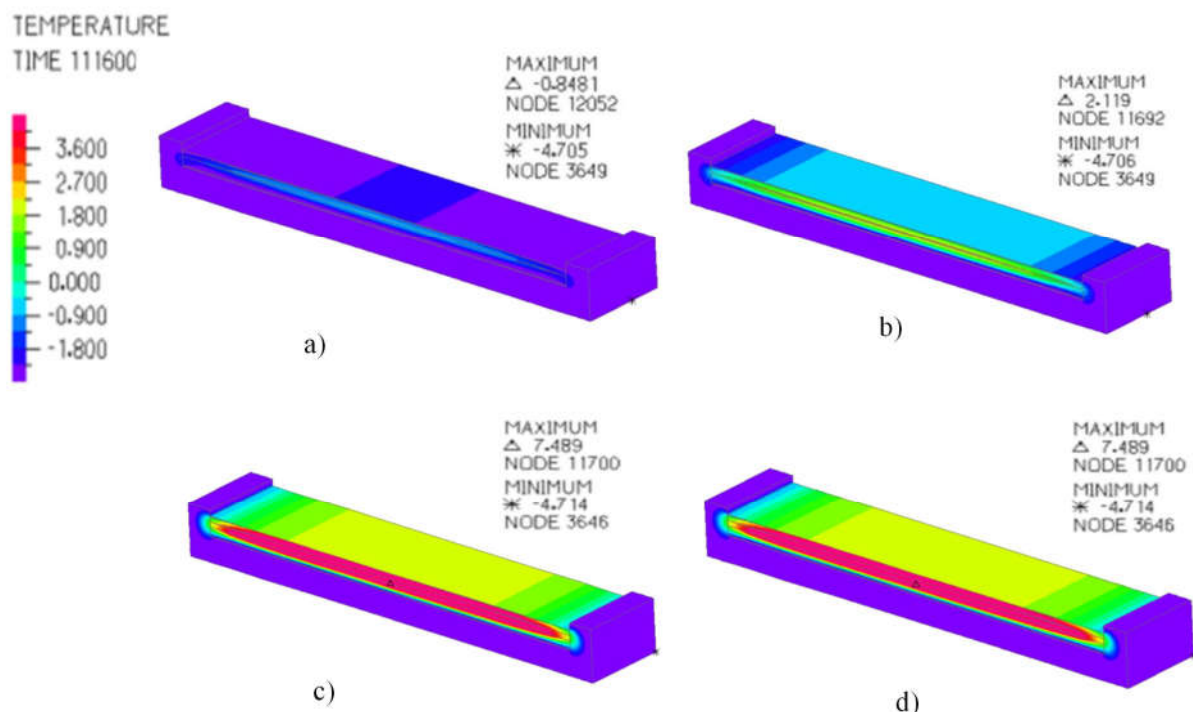


Figure 2. Temperature distribution for stage I (31 hours from the start of the process); 6-cm thick screed (a); 8-cm thick screed (b); 10-cm thick screed (c); 12-cm thick screed (d).

3.2 Stage II – different depth of installation of the heating mat in the concrete screed

In the second stage - for the adopted 12-cm thick screed (based on the results from the first stage), the depth of placement of the heating mat in the screed was varied. Five variants of the position were taken, at a depth measured from the top level of the screed: 4 cm, 6 cm, 8 cm, 10 cm and 12 cm. This analysis stage did not produce the expected effects of differences between variants. The resulting temperature values were similar in the analysed variants. The most advantageous version was the one where the heating mat was the lowest. However, it should be borne in mind that in the case of a badly thermally insulated bottom surface of the screed, the effect may be opposite to that expected. The graph (Figure 3) shows the temperature distribution at the midpoint of the surface for each variant of the second stage.

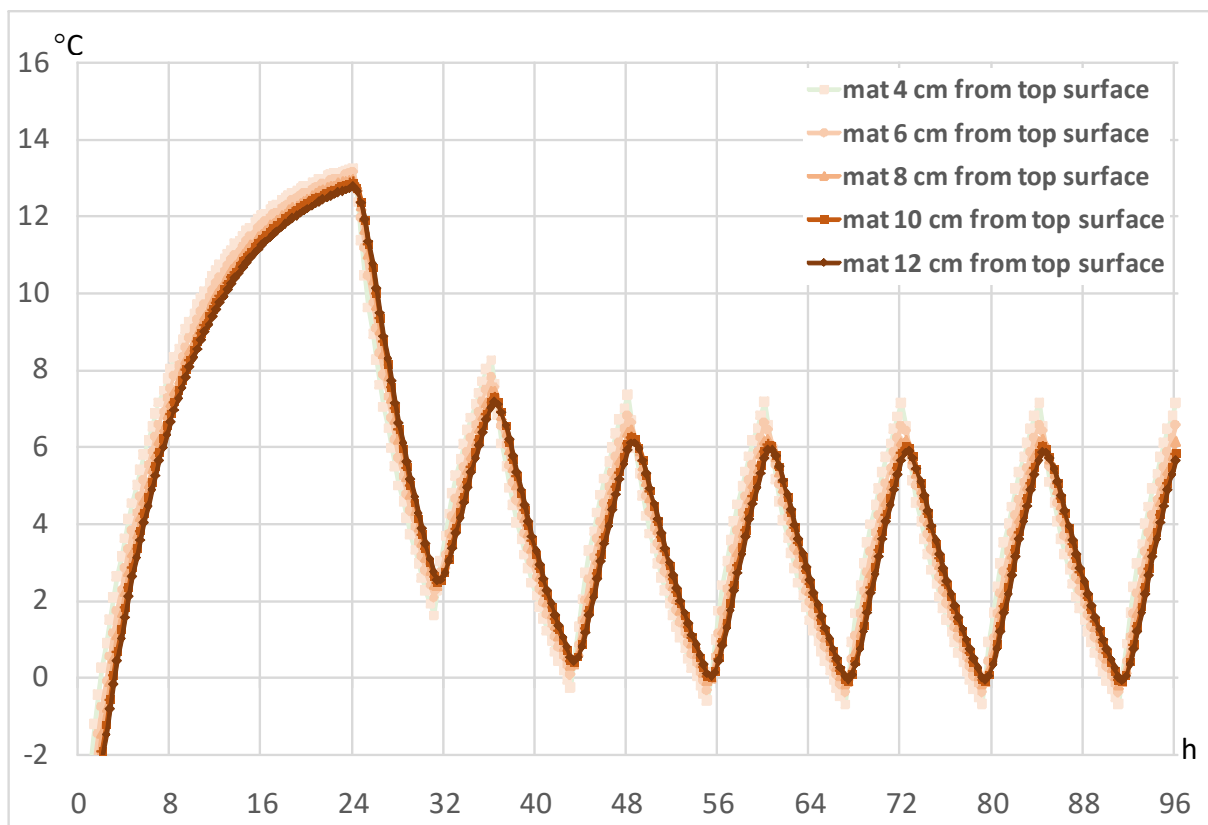


Figure 3. Temperature distribution at the midpoint of the surface for each variant of the second stage.

3.3 Stage III – thermal insulation between screed and curb

In Step 3, two variants were analysed. The first of them assumed a driveway structure identical to the best solution obtained during the second stage. The second variant introduced the use of thermal insulation with extruded polystyrene in the space between the concrete screed and the curb. It is assumed that such use of insulation would limit the escape of energy supplied by the heating mat to the massive structure of the curbs, which in this case acted as thermal bridges. Thin insulation of 1 cm thickness was proposed along both curbs. The results show that there are no significant differences between the two variants in the central roadway. The temperatures obtained for the middle of the surface are similar in both cases. Significant differences appear in the area of the surface near the curb. In the case of the first variant, a very high decrease in the temperature value is observed compared to the centre of the roadway. A significantly more favourable temperature system was obtained for variant 2. The results are shown in Figure 4.

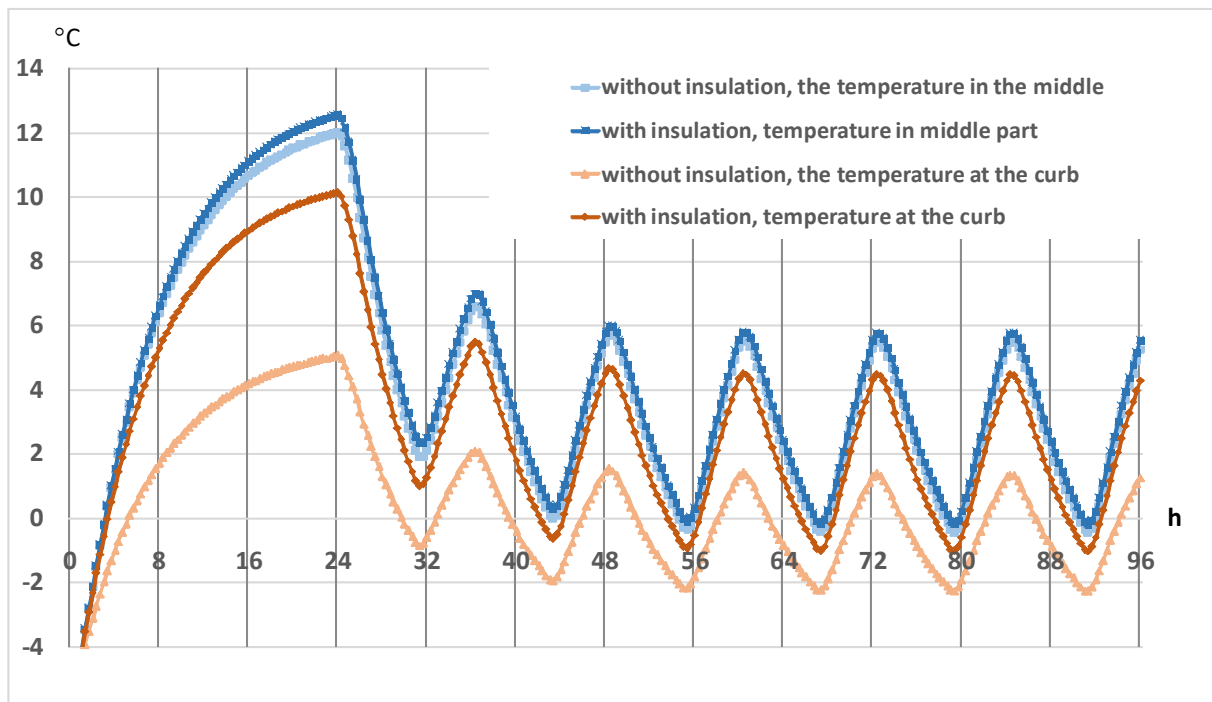


Figure 4. Temperature distribution at the midpoint of the surface and at the curb for the two variants of the third stage.

An exemplary temperature graph for the analysis time equal to the end of the second cooling cycle (43 hours from the start of the process) is shown in Figure 5.

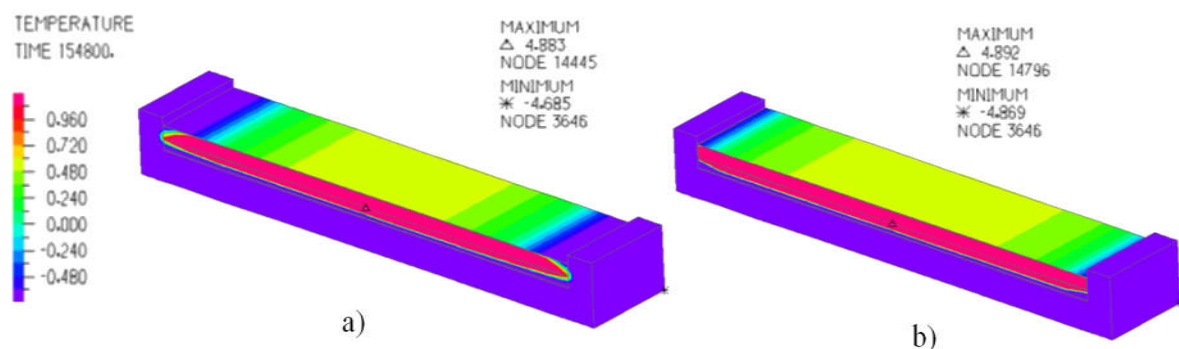


Figure 5. Temperature distribution for stage III (43 hours from the start of the process); variant without insulation(a), variant with insulation between curb and screed (b).

3.4 Stage IV – comparison of an overpass with a structure on the ground

In stages 1 ÷ 3 driveways were analysed which were exposed to cold air on the whole outer surface. Such a construction may be an example of a section of an overpass located in a span between support elements. In the fourth stage, the most advantageous third-stage solutions with a similar construction, but directly on the ground, were compared. A soil depth of 2.0 m (Figure 6) was taken into account in the calculation.

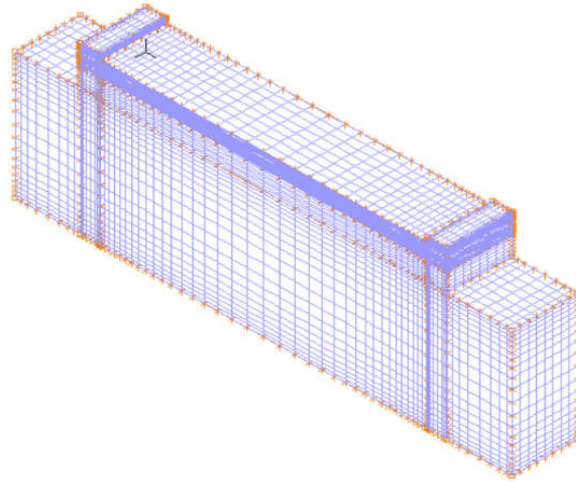


Figure 6. Model of driveway structure on ground with a depth of 2m.

This variant ensures that the bottom surface of the structure is partially protected against heat loss through the layers of soil adjoining it. It is assumed that at a depth of two meters the soil temperature is $+8^{\circ}\text{C}$. The conductivity coefficient of the ground was assumed to be $0.2 \text{ W}/(\text{m}\cdot\text{K})$, while the bulk density was $1200 \text{ kg}/\text{m}^3$. Under the assumed model, calculations were made, with the extension of the analysis period by an additional 7 days preceding the relevant time step. The introduction of these additional seven days was intended to obtain in the model a temperature distribution that corresponds to the initial stationary state for the assumed boundary conditions in the analysed structure.

The fourth stage results did not give a clear answer to the question of whether the placement of the structure directly on the ground would result in tangible benefits associated with lowering the heating costs of the driveway at the operational stage (assuming the same heating cycle as in the case of the overpass). The decisive factor here is that during the cooling cycle the upper surface of the roadway - in direct contact with the cold air outside - is cooled at a similar rate as in the case of the overpass. Excess heat at the heating stage passes over a longer period of time through a layer of thermal insulation in the downward direction, so this energy remains not fully utilized at the cooling stage due to the inertia of the system. Figure 7 shows the temperature distribution in step 4 models for the time step corresponding to the end of the third cooling cycle (the difference in the time value results from the period of 7 days preceding the analysed period adopted in model 2 – the declared time unit in the model is seconds).

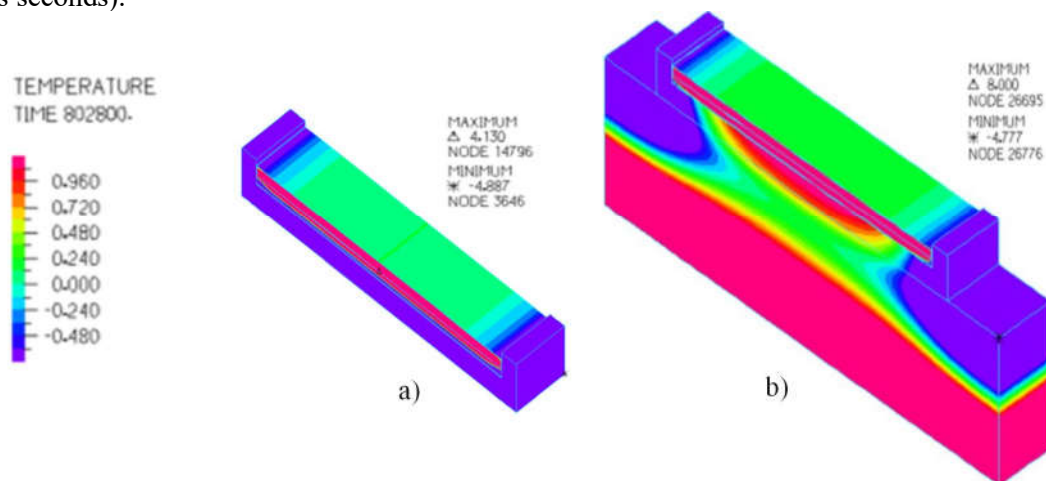


Figure 7. Temperature distribution for stage IV (55 hours from the start of the process); section of overpass(a), structure located on the ground(b).

It is evident that the differences in temperature on the upper surface of the roadway for both cases are small. The increased temperature of parts of the reinforced concrete structure under the surface of the thermal insulation for the variant located directly on the ground indicates a poorly chosen length of heating cycle compared to the cooling time for this case.

4. Conclusions

The energy consumption in practice will depend on the surface of the driveway, heating time and power (in case of using the power consumption controller). In this study, the same heating time was assumed as well as the same surface area and full heating power for each of the analyzed cases. As a result of the numerical tests carried out for the defined calculation models, the following conclusions can be drawn:

- The thickness of the screed, which is subject to heat and makes up the accumulation layer, is important for the operation of the entire system. Screeds with higher thicknesses heat up more slowly but maintain a stable temperature of the road surface.
- The depth of installation of the heating mat in the screed is of secondary importance. It may have significance for the speed of achieving a positive surface temperature during the first heating cycle and also in the case of an insufficiently insulated bottom surface.
- The use of insulation to protect the screed from the curb eliminates the impact of the thermal bridge and significantly improves the functioning of the system in the zone close to the curb.
- Given the possibility of using both exposed and partially enclosed constructions (e.g. by the ground) it is worthwhile to apply division of the entire system into sections in such a way that it is possible to use separate programming and selection of heating cycles for particular sections due to the occurrence of differences in boundary conditions in them.

The results presented in this paper concern a narrow group of variants selected from a very large number of possible cases. For the purposes of these considerations, certain constraints are assumed, e.g. constant driving conditions or constant ambient temperature of -5°C . Because in practice the ambient temperature is dynamically changing, it is therefore worth proposing a solution that works dynamically with the heating system. It seems that it would be a good solution to use temperature sensors that indicate the current temperature distribution of the surface and the environment. These types of solutions are already being used on our roads, and drivers constantly receive information on changing road conditions. A signal from the sensor should be transmitted to the energy management network in real time. In the event of a drop in the air temperature, the sensor would send information to the system that the heater should be switched on, or increased in intensity on a specified stretch. In a similar way, the system could respond, for example, to rainfall, which may increase the cooling of the surface by dampening it. For testing such a system, numerical modelling using the finite element method can be used.

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