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Review of road pavement heating methods

Abstract: The main aspect of winter maintenance is removing winter slipperiness. The article presents an overview of pavement heating methods that are an alternative to standard methods of dealing with snow and ice. Hydraulic, electric, microwave and induction heating was analyzed. The research and implementation of individual methods were presented.

Keywords: Heated pavements; Winter maintenance

Introduction

The author in her scientific work, the author deals with self-icing surfaces, i.e. those on which the surface can be automated, remotely eliminated winter slipperiness.

Winter slipperiness, so common in Poland, is a phenomenon that reduces the safety of road users. Winter maintenance is an annual challenge for managers. The deterioration of conditions usually occurs unexpectedly, often causing paralysis on the roads. GDDKiA guidelines [1] define winter road maintenance as work aimed at reducing or limiting traffic disruptions caused by weather conditions, such as winter slipperiness and snowfall. They include, among others preparation of materials for removing (and preventing) winter slipperiness, removing winter slipperiness, and mechanical removal of snow.

In Poland, chemicals and roughening materials as well as mechanical removal of snow and ice layers are used as standard. However, these solutions have a negative impact on the environment, users, and the construction of roads and facilities. [2-4].

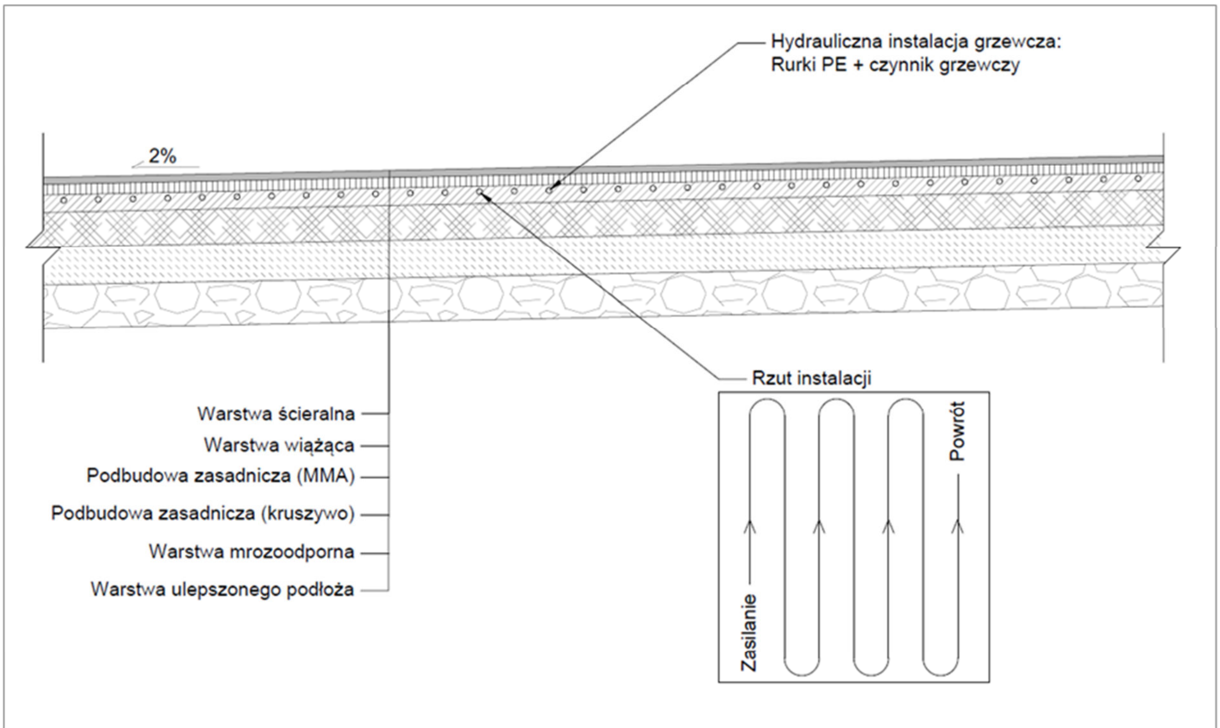
An alternative to standard methods may be the use of self-de-icing surfaces, i.e. surfaces whose structure allows for the removal of snow and ice through the generated heat. With the development of renewable energy sources, it seems more and more possible to popularize these solutions. Their widespread use would have a positive effect on the environment, extend the durability of the surface, and with appropriate programming, it would allow for quick removal of slipperiness.

The article discusses the research and implementation in the field of heating: hydraulic, electric, microwave and induction, and indicates the potential direction of development of the issue.

Hydraulic heating

The most popular are surfaces heated by means of a hydraulic system located in the road structure. The factor flowing through it causes the pavement to heat up. Such an installation can be powered both by an air source or ground source heat pump, as well as directly by geothermal energy. A cross-section of an exemplary road structure in this technology is shown in Fig. **1**.

In 1948, the first such investment was made in Klamath Falls, Oregon. The installation, made of 135 m long iron pipes placed in a cement concrete pavement, was supplied with a geothermal well. The structure operated without the need for renovation for a period of almost 50 years. Then, during the overhaul of the pavement structure, the system was rebuilt with corrosion-resistant PEX pipes [5]. In Switzerland, in 1994, the bridge in Därligen was put into operation, with a hydraulic system on the surface, powered by a ground heat store. Thanks to the installation of 91 vertical geothermal probes made at a depth of 65 m, it was possible to store the heat received from the surface in the summer season and use it in the winter [6]. In Fukui (Japan), in 2006, a bridge was built over the Asuwa River, where the energy obtained from the pavement in the summer was stored thanks to the installation of 378 piles with a heat exchanger near the riverbank, and then it was used to melt snow and ice in the winter [7]. In Iceland, the main source of energy on the island is geothermal energy. Every year, the number of sidewalks and roads heated with it increases. In 2019, most newly constructed buildings in geothermal energy-rich areas have de-icing systems. The heated area in 2018 was approximately 1.2 million m^2 [8].



1. An example of a cross-section of a hydraulically heated pavement

In places of the previously installed installations, winter temperatures reached -10 °C. Zhao et al. [9] from Harbin, China, focused on the operation of the system at lower temperatures, as their region's average winter temperature is around -16.9 °C and the lowest can drop even below -25 °C. For the purposes of the research, a system was constructed with the path dimensions of 5x5 m, powered by a ground heat pump with 10 exchangers reaching a depth of 10 m. Based on the results obtained, the researchers conclude that in order to increase the heating rate, the temperature of the flowing liquid should be above 30 °C. The fluid flow should be selected to achieve the lowest possible energy consumption and the best possible energy efficiency.

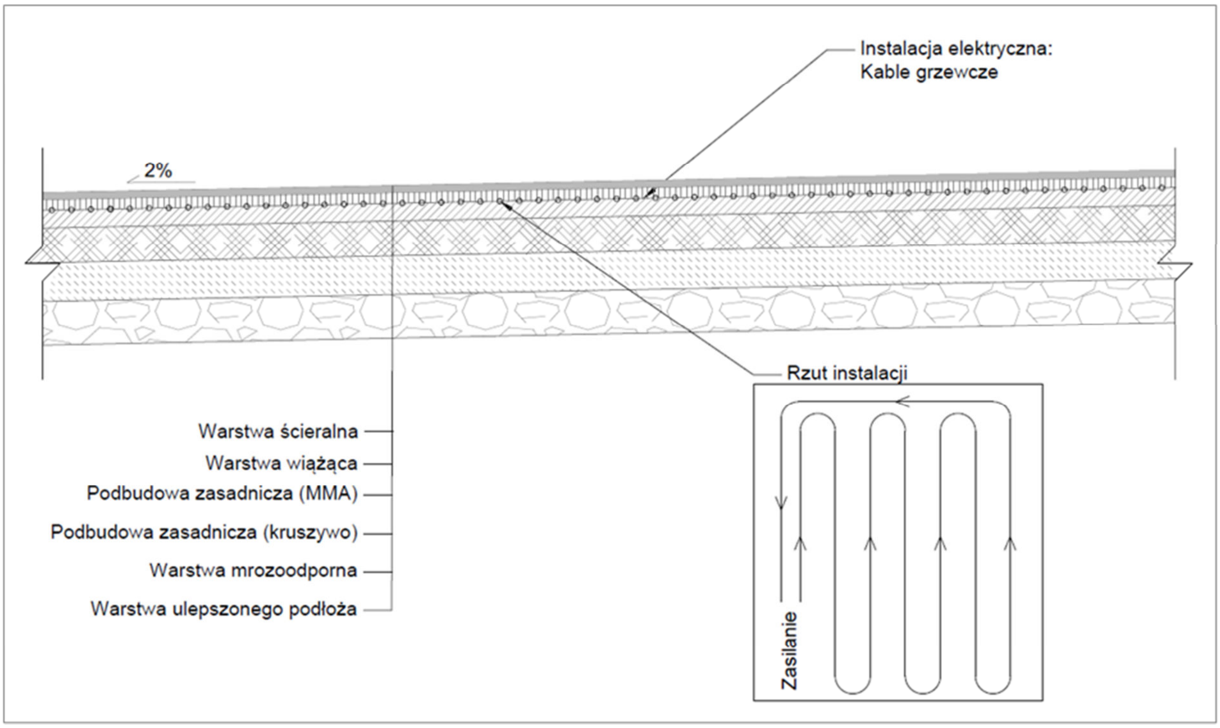
The operation of surface hydraulic energy systems, both those accumulating heat and those transmitting heat to the surface in winter, is influenced by many factors, including the ability to conduct heat between the installation and the surface, the depth of the installation, material, shape, dimensions, pipe spacing, type of working fluid used, the interaction between the surface and the pipe, temperature, and flow of the working fluid [10,11].

The time needed for the system to operate decreases with the increase of the thermal conductivity of the pavement layer, the increase of the pipe diameter, and the reduction of the installation depth and its spacing. A spacing of 25 cm and a depth of 4 to 10 cm are optimal [12].

The issue of hydraulic heating supplied directly from geothermal sources was dealt with by Ho et al. [13]. The performed numerical analysis showed that for the North Dakota region, where the air temperature in winter ranges from -5 °C to -25 °C, the temperature of the factor (water) must be 50-60 °C. The numerical analysis of the hydraulic system for very cold areas of China carried out by Zhao et al. [14] showed that the suggested pipe spacing should be 120 mm (the tests carried out for 160 mm did not give positive results).

Electric heating

Another solution is surfaces heated with cables or electric mats. They are usually powered directly from the grid, but with the development of photovoltaic panel technology, new power options appear. An exemplary solution scheme is shown in Fig. **2**.



2. An example of a cross-section of an electrically heated pavement

As early as in the 1860s, electric heating was used on the platform [15]. The first electrical installations were very expensive. Heating systems had to be in constant readiness to efficiently heat the pavement when needed, which resulted in high demand for electricity. In Japan, during the winter periods between December 1992 and March 1994, an electric heating system was tested based on probabilistic snowfall data generated by the Japan Meteorological Association. The operation of the system was checked at actual intersections. It was shown that in two consecutive winter periods, additional data allowed to reduce energy consumption by 29.7% and 61.6% [16].

Rao et al. [17] tested concrete containing conductive components, allowing to achieve stable electrical conduction. An overlay made of a thin layer of concrete with the addition of graphite and steel fibers, connected to the electricity can generate heat to prevent ice formation. The technology was first used on a large scale in China on two parking ramps, each 41 m long. Despite problems arising at the installation stage, it was successfully put into operation and obtained the power values appropriate for de-icing: 200-300 W/m^2.

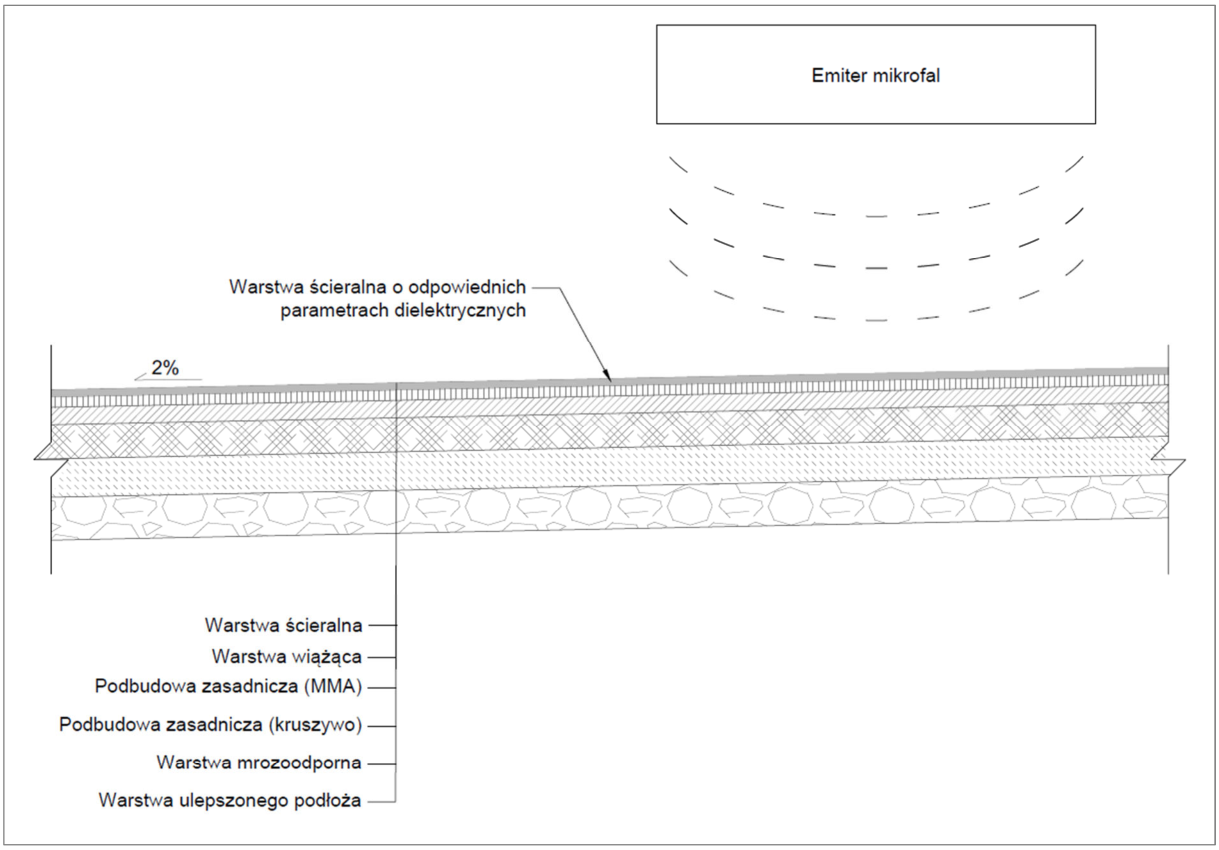
Pan et al. [18] indicated the potential for the use of conductive asphalt. They highlighted the need to perform tests on larger samples in the laboratory and on a real scale to observe the influence of temperature and load for further technology development. The conductivity of the asphalt binder depends mainly on the distribution of the conductive filler in the asphalt binder. Important aspects when designing and making such mixtures are: the method of adding the ingredients and their mixtures, the appropriate content of free space in the VMA mineral mixture, and the appropriate soil framework. It should be remembered that the additives improving the electrical conductivity can simultaneously affect the strength parameters of the mixtures, depending on their shape, composition, and how compatible they are with the mixture/asphalt. Conductive fillers increase the viscosity of asphalts, which at the same time increases the mixing temperature ensuring adequate coverage of the aggregate with the binder.

Sassani et al. [19] investigated the use of carbon fibers in electrically conductive concrete for surface de-icing applications. The special mixture must contain the right amount of carbon fibers to arrange them in a way that allows conduction from the heating system of the road. The permeability test allowed for the determination of the appropriate amount of fibers. The authors showed that the mixtures can be used for de-icing pavements, with the recommendation of using fibers in the amount of 1% by volume. They recommend an insulating layer of cement concrete with low thermal conductivity (e.g. lightweight aggregate) below the installation. The authors have checked that the initial values of the energy transfer coefficient drop from about 66% to 50% to stabilize at this level.

Microwave heating

Microwaves are waves with a frequency in the range of 100 MHz to 100 GHz. Heating with microwaves can be defined as the direct conversion of energy into the material during the heating process. The material's ability to absorb energy from microwaves is described by the dielectric properties of the materials. The movement of the dipole, i.e. the water molecule, changes depending on the state of aggregation. For liquid water, this movement occurs at GHz (microwave) frequencies, while for ice it occurs at kHz (long radio waves). As a result, microwave heating will not work on ice, but it will work very well on water formed from melting ice [20]. An example of the pavement cross-section is shown in Fig. **3**.

Liu et al. [21] investigated the dielectric properties of materials intended for road surfaces. An increase in the efficiency of microwave heating and an improvement in the dielectric properties of pavement concrete with an increase in the w/c coefficient and the sand point was found. Additionally, attention was drawn to a significant increase in these parameters after adding graphite. The addition of graphite in the amount of 15% of the cement mass increased the heating efficiency from 0.65 °C/s to 1.63 °C/s for the microwave source at a height of 20 mm.



3. An example of a cross-section of a surface structure heated with microwaves

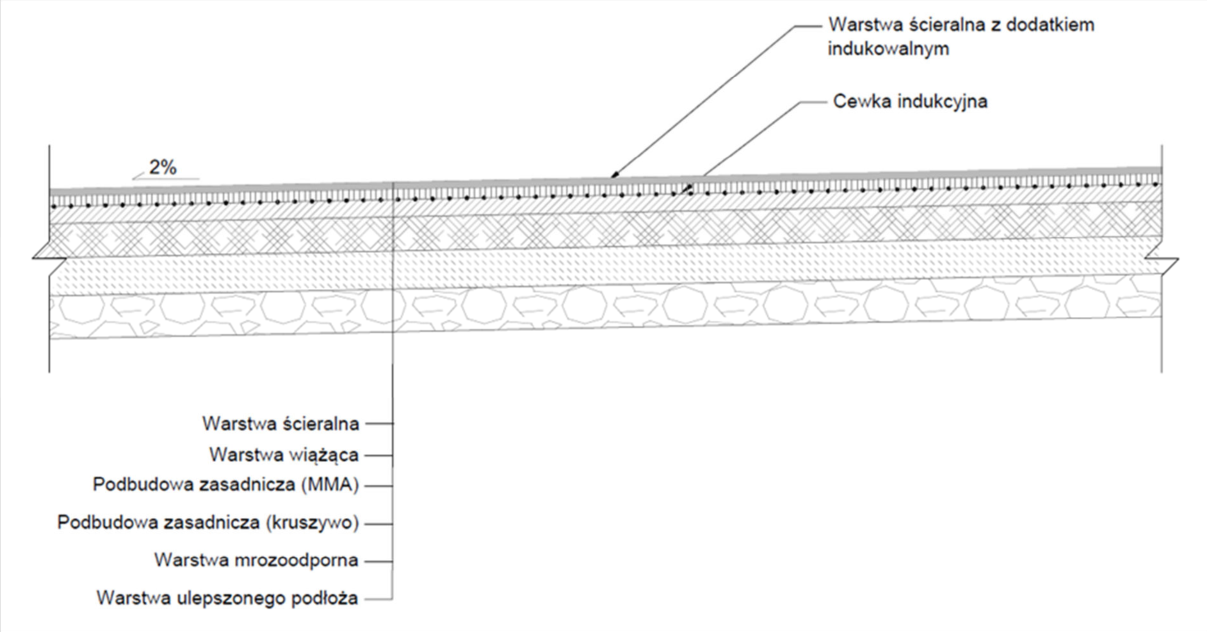
Gulisano et al. [22] focused in their research on improving the dielectric properties of mixtures by adding slags from an arc furnace. For more precise results, it was decided to test asphalt mortars (grain size up to 2 mm). Part of the limestone aggregate was replaced with slags (5% and 10% by volume), and the results showed an increase in the dielectric constant from 3.8 to 5 in the entire tested frequency range. Additionally, it was recommended to use 5.8 GHz for pavement layers up to 7 cm thick and 2.45 GHz for higher thicknesses.

Gao et al. [23] pay attention to the increase in the free space content in the asphalt mix with the increase in the amount of steel wool fibers. The authors recommend choosing thinner fibers, they generate less free space. However, care should be taken, because the smaller the diameter of the steel wool fibers, the more unevenly the surface is heated. The optimal contents of steel wool are: 0.3% for wool #000, 0.6% for wool #0 and 0.9% for wool #2.

Induction heating

Induction heating is the process of heating an electrically conductive element through electromagnetic induction, the operating frequency of which is in the range 1 kHz - 1 MHz [20]. Neither snow, ice, nor a standard mixture are such materials. The solution is to add electrically conductive elements to the surface mixture, which, under the influence of induction, will heat up and melt the layer of snow or ice. The scheme of the solution is shown in Fig. **4**.

Xu et al. [24] focused on the deicing properties of asphalt mixtures containing steel wool fibers. They tested the de-icing rate for standard and modified mixtures - the results show a significant positive effect of the amount and length of added fibers.



4. An example of a cross-section of an induction-heated pavement structure

Liu et al. [25] developed a new structure of asphalt pavements containing electrically conductive and magnetically absorbing layers. The top layer (electrically conductive) contained the addition of steel chips, 6% by weight of the aggregate was selected as a recommended value.

Liu et al. [26] compared the effects of induction heating and microwave heating. They showed that with similar power and method of radiation, heating with induction is fast, but at the same time heterogeneous in the longitudinal direction, while microwave heating is slow but uniform. The effective depth of heating was much greater when microwaves were used.

Unusual solutions

Asfour et al. [27] presented the concept of non-standard hydraulic heating. In the presented model, on both sides of the pavement, there are tanks: upper and lower, a pump, and insulation of the wearing course and the substructure. The heated liquid flowed through a binder layer of porous asphalt. The simulations showed effectiveness in various weather conditions.

Lei et al. [28] proposed a method of heating existing bridges. PEX tubing loops attached to the underside of the bridge plate were insulated along the length of the pipeline, thus creating a heating system. The achieved results confirmed the operation of the system in mild winter conditions.

Xiang et al. [29] presented the concept of a photovoltaic-thermal pathway. The system consists of a transparent surface, photovoltaic modules, and asphalt concrete with a network of heating pipes. The analysis of the created mathematical model showed an increase in energy efficiency compared to the previously known photovoltaic road system.

Summary

The range of alternative methods of combating winter slipperiness includes both very traditional methods, such as hydraulic heating, and very innovative methods, such as microwave and induction heating.

Hydraulic methods are the most developed and most frequently used problem in projects, although they still require optimization.

Electric heating is also a technology that has been known for a long time. With the development of alternative energy sources, the potential of this method has increased.

In recent years, more and more research work has been related to both microwave and induction heating technology. These are undoubtedly promising methods, but their commercialization requires further research and the development of reliable implementation methods.

The variety of systems will allow to perfectly adapt to the situation. The author plans in her work to create guidelines to help choose a solution suitable for the location and needs. Additionally, when planning the implementation of a self-icing surface, it should be taken into account whether the technology of laying a layer of asphalt concrete or cement concrete pavement will not damage the installation. In the case of cement concrete, remember to fasten the installation in an appropriate way so that the elements do not fall down or flow out. On the other hand, too high a temperature of the asphalt mixture may damage cables or pipes, therefore it should be taken into account when choosing materials for the construction. An important aspect is also the process of compacting the layer made, it is necessary to check whether the standard methods will not damage the installation.

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