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Heated Transportation Infrastructure Systems: Existing and Emerging Technologies

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Heated Transportation Infrastructure Systems: Existing and Emerging Technologies

Abstract

Ice and snow on pavement surfaces cost the U.S. national economy in snow removal, damaged pavement and lost man-hours due to travel delay. Common practices for removing ice and snow from pavement surfaces include spraying anti-ice chemicals on the ground and deploying snowplowing vehicles. These methods are labor-intensive, occasionally ineffective at extremely low temperatures and have associated environmental concerns with possible contamination of nearby water bodies. Heated pavement systems (i.e., the concept of supplying heat to the pavement through an external or internal source) melt snow and ice without the need for anti-ice chemicals and snowplowing vehicles. A vast majority of the existing heated pavement systems utilize electrical or geothermal (hydronic) heating technologies. The use of anti-icing coatings and mix designs to deter ice formation is a closely related, but distinct concept. The objective of this paper is to provide a comprehensive review of the current state of practice and research of existing heated transportation infrastructure systems (highway pavement, bridges and airport pavement) as well as provide an overview of the emerging technologies.

Keywords

heated pavements, icy roads, hydronic, conductive concrete, superhydrophobic, phase change materials

Disciplines

Civil Engineering | Construction Engineering and Management | Environmental Engineering

Comments

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HEATED TRANSPORTATION INFRASTRUCTURE SYSTEMS: EXISTING AND EMERGING TECHNOLOGIES

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Abstract

Ice and snow on pavement surfaces cost the U.S. national economy in snow removal, damaged pavement and lost man-hours due to travel delay. Common practices for removing ice and snow from pavement surfaces include spraying anti-ice chemicals on the ground and deploying snowplowing vehicles. These methods are labor-intensive, occasionally ineffective at extremely low temperatures and have associated environmental concerns with possible contamination of nearby water bodies. Heated pavement systems (i.e., the concept of supplying heat to the pavement through an external or internal source) melt snow and ice without the need for anti-ice chemicals and snowplowing vehicles. A vast majority of the existing heated pavement systems utilize electrical or geothermal (hydronic) heating technologies. The use of anti-icing coatings and mix designs to deter ice formation is a closely related, but distinct concept. The objective of this paper is to provide a comprehensive review of the current state of practice and research of existing heated transportation infrastructure systems (highway pavement, bridges and airport pavement) as well as provide an overview of the emerging technologies.

Key Words: HEATED PAVEMENTS / ICY ROADS / HYDRONIC / CONDUCTIVE CONCRETE / SUPERHYDROPHOBIC / PHASE CHANGE MATERIALS

Introduction

Ice and snow on transportation infrastructure systems cost the American economy in snow removal, damaged pavement and lost man-hours due to travel delay. Common practices for removing ice and snow from surfaces in transportation infrastructure include spraying large quantities of anti-ice chemicals on the ground and deploying a great number of snowplowing vehicles. However, these methods are labor intensive and have environmental concerns with possible contamination of nearby water bodies. Heated pavement systems using hydronic heating, electrical resistance and conductive concrete have gained attention as desirable alternatives to current methods of removing ice and snow.

Several approaches on heated pavements systems have been proposed for different transportation infrastructure applications. Each of these approaches has its own advantages and limitations. A method that holds promise for bridge systems may not always be promising for highway and airfield pavements and vice versa.

This paper first examines an overview, current state of practice and state of research of hydronic and electrical resistance based heated pavement infrastructure and anti-icing pavement coatings and mix design. The paper concludes with a discussion between hydronic and electrical resistance heated pavement and suggests the most promising heated pavement application for bridge decks, roadway pavement and airport runways. Recommendations for future heated pavement research are also presented at the conclusion of this paper.

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Hydronic Heating Systems

Overview

Hydronic heating systems utilize heated fluid carried by pipes embedded in the pavement to warm the pavement through conduction. Hydronic heating systems are typically closed loop systems where, after the fluid releases heat into the pavement, it returns to the heat source to be sent through the pipes again (Lund 2000). The fluid can be heated by a variety of sources from a boiler burning fossil fuels to more environmentally friendly options including geothermal wells and waste heat from industries. Geothermal heated hydronic systems tend to incorporate a heat pump to obtain a higher level of heat (Minsk 1999). The capacity of a hydronic heated pavement system to melt snow and ice depend on the materials and design of the system such as fluid temperature, pavement conductivity, pipe depth and pipe spacing. Higher fluid temperatures, greater pavement conductivity, shallower pipe depth and more compact pipe spacing are desirable for improved performance, but construction, heating and pumping costs and structural stability are constraints. Although the structural stability of pipes is a design concern, the embedded pipes have little impact on the stability of the pavement. Embedded pipes hardly provide any detriment to fatigue life of the pavement, and the location of maximum tensile stress still remains at the bottom of the pavement (Wang, et al. 2012).

The pipes carrying the heated fluid have evolved over time. In the United States, early versions of hydronic heating systems used steel, iron, or copper pipes. Steel and iron pipes are susceptible to corrosion if exposed and untreated by cathodic protection. Deicing salts sprayed on the pavement accelerate the corrosion process of these metal pipes. Currently in the US, PEX (cross linked polyethylene) pipes are the favored material for hydronic systems. PEX pipes are noncorrosive lightweight, flexible and structurally sound at to 93 °C and 552 kPa tensile stress (200 °F and 80 psi) (Lund 2000).

Portland cement concrete (PCC) pavements have been preferred over Hot-Mix Asphalt (HMA) pavements for hydronic systems owing to the fact that PCC has a greater thermal conductivity than HMA. Also, HMA is poured at 149 °C (300 °F) and compacted with rollers, which may damage the pipes set in place (Lund 2000).

Hydronic heated pavement systems have been demonstrated to work well with clean energy sources, e.g., geothermal, for a relatively low operation cost. However, hydronic systems include high initial cost for the intensive design and construction of the system and potential of catastrophic failure of the system due to leaky pipes (Fliegel, et al. 2010).

Current state of practice

Hydronic heated pavement has been used in practice since the completion of the Klamath Falls Bridge in 1948 (Lund 2000). Hydronic heated pavement has since spread globally with high concentration of use in Nordic countries and Japan. Hydronic heated pavement is primarily used in bridges, but it has recently been utilized to heat aircraft parking stands in Nordic countries (Barbagallo 2013).

In 1948, the first application of heated pavement in the United States resulted in a hydronic heating system constructed into a 137 m long (450 ft.) bridge deck in Klamath Falls, Oregon. A half-ethylene-glycol-half-water solution circulated through 19 mm-diameter (3/4 in) iron pipes located 7.5 cm (3 in) below the pavement surface and 45 cm (18 in) on center. Ethylene glycol acted as antifreeze for the fluid. The solution was heated by a 62 °C (143 °F) geothermal well through a heat exchanger before being pumped through the deck. The pump, which required electricity to run, was the only operation cost of the heated pavement. The Klamath Falls hydronic system initially had the heating capacity to keep the bridge clear for a snowfall intensity of 76 mm per hour at an air temperature of -23 °C (3 in per hour at -10 °F). In 1992 the temperature of the geothermal well dropped from 62 °C to 37 °C (143 °F to 98 °F), and the well was rehabilitated. In 1997, the hydronic system failed from leaks in the iron pipes caused by corrosion. A replacement geothermal-powered hydronic system was installed into the bridge after the

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failure. The new system used 19 mm (3/4 in) diameter PEX tubes imbedded 7.6 cm (3 in) deep in an 18 cm (7 in) thick concrete layer. The PEX tubes were placed 36 cm (14 in) on center in a double overlap pattern. In 1999, the total cost of the reconstruction project was approximately \$430,000, and the annual operation and maintenance cost was \$3,000 and \$500 respectively (Lund 2000). Today, the United States has hydronic and heat pipe bridges in operation in Oregon, Nebraska, Texas, Virginia, Wyoming and New Jersey.

The Gardermoen International Airport contains 35 hydronic heated aircraft parking stands ranging from 600 m² to 780 m² (6,500 – 8,400 ft²) in size. The hydronic system is geothermally-heated through Aquifer Thermal Energy Storage (ATES), which also heats and cools the terminal buildings as shown in Figure 1. The hydronic system is also supplemented by one electric and four oil fired and boilers to reach the design heating performance of 248 w/m² (79 BTU/(hr·ft²)). ATES operates when temperatures fall between -8 °C and 2 °C (18 °F and 35 °F) and takes about four hours to start up. The hydronic heated aircraft parking stands averaged from \$275,000 to \$375,000 to build, and the annual operation cost for each stand amounted to around \$16,500. Gardermoen International Airport considers the heated stands a necessity because of quicker aircraft turnaround times and safety of ground crews and passengers. Gardermoen currently has 10 larger heated stands under construction, which would increase their heated pavement area to 36,836 m² (396,500 ft²) (Barbagallo 2013). Arlanda International Airport, located in Stockholm, Sweden, also uses ATES to heat 54 aircraft parking stands, which cover an area of over 92,900 m² (1,000,000 ft²) (Barbagallo 2013).

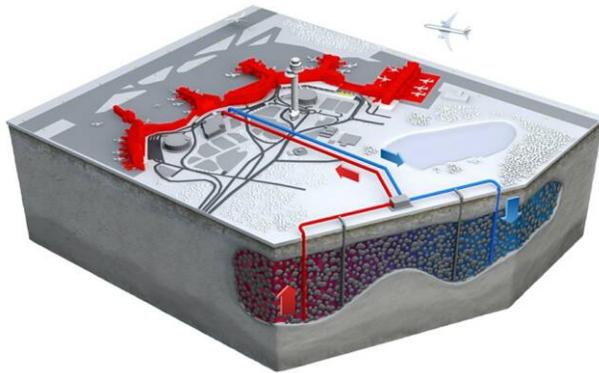


Figure 1 - ATES heats the airport terminal and the aircraft parking stands (Underground Energy, LLC 2009)

Current state of research

Much of the current research studies involving hydronic heating systems focus on developing the technology into efficient solar energy harvesters. Hydronic solar energy harvesters collect and store heat from the summer to be used to heat the pavement in the winter. The Swiss-based Solar Energy Pilot Project (SERSO) has been acting as a prototype of the technology for over two decades. Current research indicates that hydronic systems can be designed to harvest up to 30% of solar energy in the summer months.

In the early 1990s, Switzerland developed the Solar Energy Pilot Project (SERSO) to combat hot pavement in the summer and ice formation in the winter. SERSO oversaw the design and construction of a 1,300 m² (14,000 ft²) bridge located on Road 8 at Därligen, Switzerland. SERSO combined a hydronic pavement heating system with a heat sink in the form of a 55,000 m³ (1.94 million ft³) sandstone rock formation (Eugster 2007). A total of 160 individual stainless steel pipes, each 34 m (112 ft.) long, spaced 23 cm (9.5 in) on center, were placed at a depth of 7 cm (2.75 in) below the asphalt pavement surface. The pipes ran to the heat sink rock formation, which consisted of 91 bore hole heat exchangers 65 m (213 ft) deep. A service building, located between the bridge surface and heat sink, pumps a glycol-water

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solution back and forth between the bridge asphalt pavement and heat sink. Plan and profile views of the SERSO system are shown in Figure 2. The total cost of the project including research was approximately \$3 million. The initial cost of future projects utilizing similar systems to SERSO is expected to be half as much (Lund 2000).

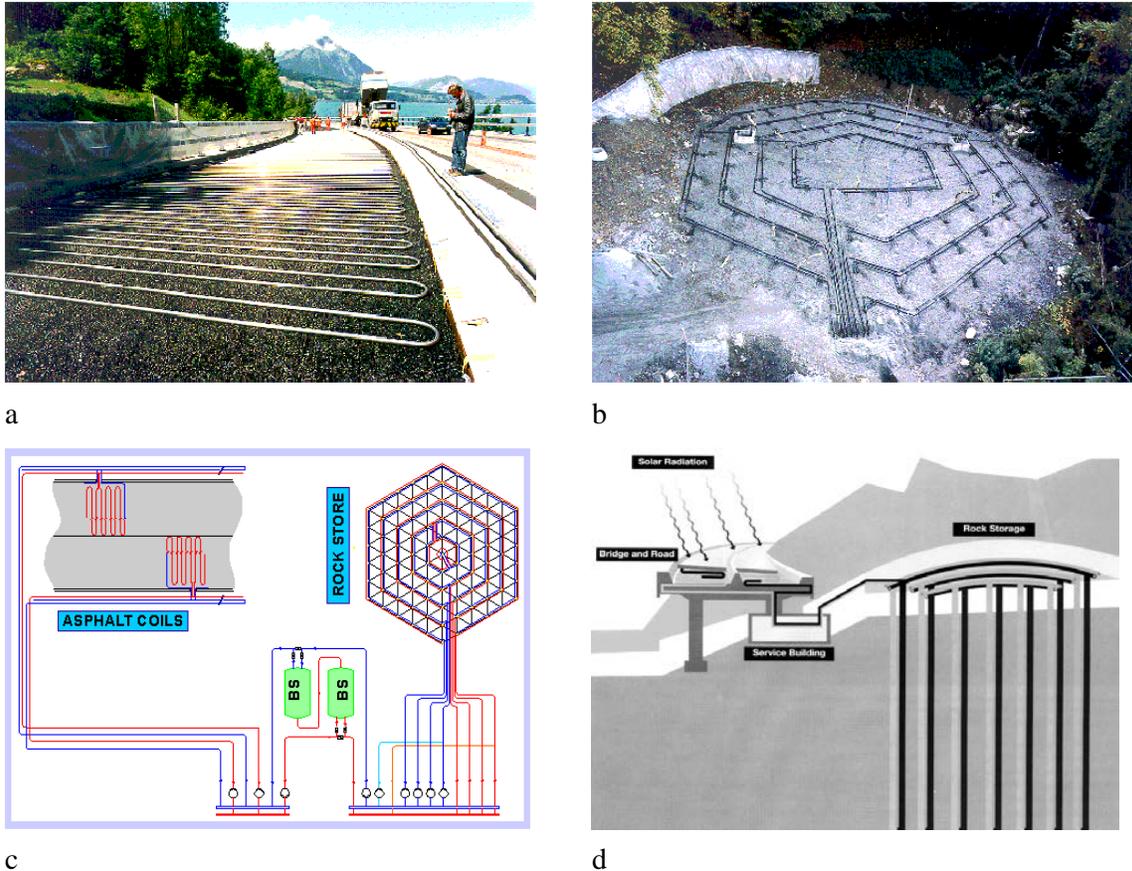


Figure 2 - a) Stainless steel pipes (SERSO: Energy from the road n.d.) b) Sandstone rock formation heat sink (SERSO: Energy from the road n.d.) c) Plan view of SERSO system (SERSO: Energy from the road n.d.) d) Profile view of SERSO system (Lund 2000)

During the summer the bridge deck can reach 60 °C (140 °F). About 20% of the summer solar radiation can be collected by the deck-pipes resulting in 150,000 kWh (510 million BTU) of collected energy. Thermal energy losses within the system amount to 35% of the collected heat with the remaining thermal energy being stored in the heat sink (Lund 2000). The stored heat is then used in the winter to deter ice and snow formation on the bridge deck by keeping the surface temperature just above 0 °C (32 °F). Researchers working on the SERSO project discovered the most energy efficient operation of the system during the winter time was to apply a continuous stream of moderate amount of heat in advance and during winter storms instead of high rates of heat to combat ice formation during storms. This moderate heating strategy eliminates the need for a heat pump in the system. The SERSO hydronic system operates just under 1000 hours during each summer and winter season (Eugster 2007).

Taking a cue from SERSO, hydronic heating research is concentrated on using pavement as an energy harvester in the summer to be used for preventing snow and ice formation on pavement surface during the winter. Using pavement as a solar energy harvester has an additional bonus of reducing the pavement temperature during the summer, which is particularly advantageous for reduced rutting of

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asphalt pavement. Pavement systems and especially asphalt pavement, which can reach 60 °C (140 °F) during warm days, already collect heat (Van Bijsterveld, et al. 2001). Researchers are developing strategies to harness and store that heat to be used during the winter.

The capacity of a hydronic system to collect solar energy in the summer follows the same criteria as heating the road in the winter: pavement conductivity, pipe depth and pipe spacing. Researchers from Jilin University in China conducted experiments on the heat harvesting ability of hydronic systems with a variety of pipe spacing magnitudes (Gao, et al. 2010). In their experiment, three 1.2 m x 0.6 m (4 ft x 2 ft) cement-concrete slabs were cast with pipe spacings of 9 cm, 12 cm and 15 cm (3.5 in, 4.7 in and 5.9 in). Water was used as the pipe fluid, and tests were conducted on sunny days in August 2008 when the natural solar radiation intensity ranged from 300 to 1000 W/m² (95 to 317 BTU/(hr·ft²

cm and 15 cm (3.5 in, 4.7 in and 5.9 in) pipe spacing were 258 W/m², 232 W/m² and 154 W/m² (82 BTU/(hr·ft²), 74 BTU/(hr·ft²) and 49 BTU/(hr·ft²)) respectively. The Jilin University researchers concluded that with a small enough pipe spacing, a hydronic road system embedded in a concrete slab could harvest up to 30% of solar radiation (Gao, et al. 2010). Current hydronic systems utilize 100 to 700 W/m² (32 to 222 BTU/(hr·ft²)) of heat energy for deicing and anti-icing purposes. Hydronic systems are effective as energy harvesters, but storing and insulating that water volume until winter are major concerns.

Researchers from Delft University of Technology in the Netherlands recommend using a confined aquifer with low permeability to store the harvested heat energy (Van Bijsterveld, et al. 2001). They suggest a hydronic harvesting and heating system where groundwater from a confined aquifer is pumped up to collect the thermal energy in the pavement in the summer, which is then pumped down to a separate confined aquifer for storage until winter. For a sustainable system, the storage aquifer must not permanently alter the groundwater temperature and groundwater table depth. The hydronic system should be designed to prevent pollution and changes of oxygen levels of the groundwater. A major drawback to this hydronic heating storage strategy is finding appropriate confined aquifers and ground water systems (Van Bijsterveld, et al. 2001).

Other strategies for storing the harvested thermal energy include utilizing an insulated tank or heat sink similar to the SERSO. An insulated tank has a limited volume to store the heated fluid, which may not last through the winter months. Heat sinks have high initial costs. Despite the storage challenges, using pavement as an energy harvester is a green alternative to using a boiler-heated hydronic system.

Electrical Heating System

Overview

Electrically heated pavement systems work by passing a current of electricity through a conductor embedded in pavement or conductive pavement. The energy lost due to electrical resistance is converted into heat, which warms the pavement (Yehia and Tuan 2000). Electrically heated pavement can be utilized wherever electricity is readily available. However, the high voltage caused by the electrically heated pavement is a safety concern. If dangerous voltage levels exist at the surface of the electrically heated pavement, the pavement must be insulated (Fliegel, et al. 2010). Also, the operation cost of using electricity to heat pavement deters wide use of this technology. Based on the accumulated knowledge of material properties and development of new materials, researchers are attempting to create safe and more affordable electrical heating systems.

Current state of practice

Commercial electrical resistance based heating systems are available in the market. The commercial systems tend to be for pedestrian and private use such as sidewalks and driveways.

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An electrically conductive asphalt pavement system (with the commercial name SnowFree®) was developed by Superior Graphite in 1995, which incorporates copper cables embedded in a conductive asphalt layer consisting of 25% synthetic graphite (Lopez 2012). In collaboration with the Federal Aviation Administration (FAA), a conductive asphalt concrete system pavement system was installed on 697 m² (7500 ft²) of taxiway at Chicago O'Hare International Airport (Lavitt 1995). Copper cables, alternating between live and ground were placed at intervals of 4.88 m (16 ft) and cast within a 5 cm (2 in) layer of the graphite infused asphalt concrete. The asphalt mix appropriately attained the FAA AC 150/5370-10F P-401 standard (FAA 2011a) for airport surfaces. During the 3.5-year duration of the study, 200,000 aircraft traveled on the graphite infused asphalt concrete, and no significant cracking was observed. The system's performance was evaluated for 3.5 years from 1995 to 1999. Throughout the evaluation period, the conductive asphalt concrete system consistently produced a power density of 484 W/m² (153 BTU/(hr·ft²)) while in operation. The study reported that an estimated operating cost of \$2,400/hr (value in 2003 dollars) would run the conductive asphalt concrete system for a 10,000 foot-long runway. Although the conductive asphalt concrete system satisfactorily cleared snow and ice, the FAA deemed that the operating cost was high, and no other airport has utilized this technology to date (Lopez 2012).

Current state of research

With the increasing knowledge of material properties and development of new materials, electrically heated pavement systems have the potential to make great improvements in heating capacity and energy efficiency.

Normal-weight concrete has an electrical resistivity that ranges from 654,000 to 1,100,000 Ω·cm (257,000 to 433,000 Ω·in). With the addition of conductive materials to the mix design the pavement can become electrically conductive with a resistivity around 400 Ω·cm (160 Ω·in) (Tuan 2008). Researchers at the University of Nebraska developed an electrically conductive concrete mix composed of steel fibers and shavings, sand, 13 mm (½ in) limestone and portland cement (Yehia and Tuan 2000). The addition of steel fibers and shavings caused the price of this conductive concrete to be greater than five times more expensive than conventional concrete. The conductive concrete mix met the 28 days ASTM and AASHTO specifications for strength, workability and durability. In 2000, the researcher casted two 1.2 x 3.6 m (4 x 12 ft) slabs consisting of a 9 cm (3.5 in) thick layer of the conductive concrete to compose deicing and anti-icing experiments. Two steel plates were embedded along the edges of the slab to act as electrodes. The average power of the slabs was about 590 W/m² (187 BTU/(hr·ft²)), and gradual, uniform heating was achieved during the experiment (Yehia and Tuan 2000). Through their experiments, the researchers noted that there weren't many sources of steel shavings, and the shavings gathered from fabricators are usually contaminated with oil. In 2001, the researchers successfully replaced the steel shavings with carbon and graphite products (Tuan and Yehia 2002).

The new conductive concrete mix developed by the researchers consisted of 1.5% steel fibers and 25% carbon product by volume. This mix had greater compressive and flexural strength but slightly less electrical resistivity than the steel shavings mix. The steel-carbon mix performed well enough in lab testing for the Nebraska Department of Roads to select it for the deck material for the Roca Spur Bridge in 2001 (Tuan 2008).

The Roca Spur Bridge deck is 46 m long and 11 m wide. A 25.6 cm thick standard reinforced concrete deck provided the base to the conductive concrete overlay. PVC pipes and junction boxes, which ran along the centerline of the bridge, carried the power cords within the reinforced concrete. The conductive concrete was cast and saw-cut into 52 isolated slabs 1.2 m x 4.1 m x 10.2 cm large on top of the reinforcing concrete. The electrodes were two angle irons running along the length of each slab. The workability and finishing properties of the conductive concrete were similar to PCC, and therefore no special crews were needed to caste the concrete. Figure 3 displays the deck construction of the Roca Spur Bridge. The total cost of construction for the Roca Spur Bridge was \$193,175 (Tuan 2008).

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The researchers attempted alternating power to the slabs in a checkerboard fashion to save on operating costs. The checkerboard approach could not keep up with snow accumulation, so all slabs were turned on during snow events. The Roca Spur Bridge could keep pace with snow melting and de-icing with all slabs turned on. Over four years of operation, the electrical conductivity remained constant, and no maintenance was required on any of the electrically conductive slabs (Tuan 2008).

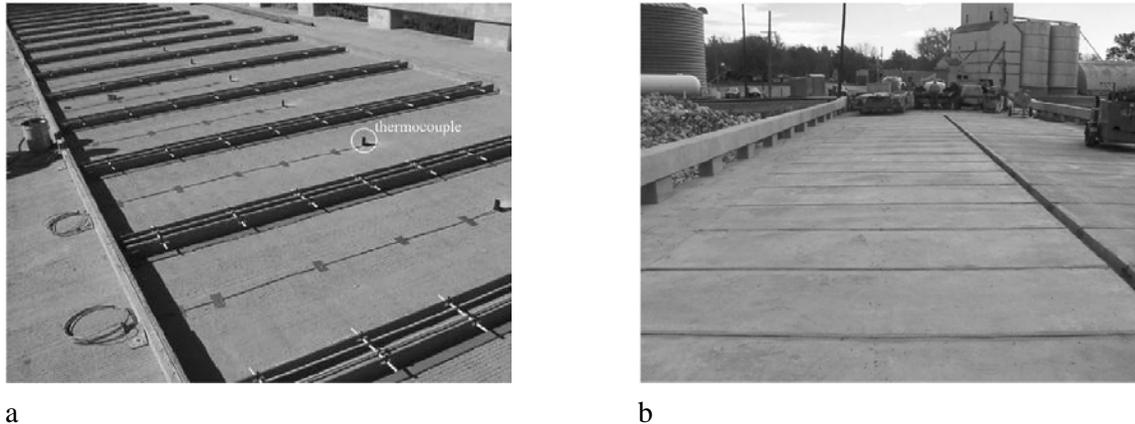


Figure 3 - a) Formwork and wiring for conductive concrete b) Saw-cut conductive concrete slabs (Tuan 2008)

The cost of using steel in an electrically conductive concrete matrix is very high. Some other research studies have identified chemical electroconductive fibers (CEF) that can replace steel and other costly metals in conductive concrete. Researchers have found that the CEF lignin, which usually is developed from wood, when paired with glass fibers closely parallels steel fibers in conductivity and strength (Piskunov, et al. 2008).

CEF must fulfill many requirements in order to replace metal fibers in conductive concrete. Along with high electrical conductivity and appropriate resistance, CEF must have high strength, low moisture absorption, high bond strength with the binder and compatible coefficient of thermal expansion with the surrounding material. CEF must also be chemically inert and abundant (Piskunov, et al. 2008). These requirements have made finding the appropriate CEF difficult.

Cement-matrix and polymer-matrix composite concrete have a huge constructability advantage over hydronic and conductive-wire heating systems because the placing of these conductive matrix systems is nearly identical to casting concrete. Composite concretes also provide multiple options for conductive material to be used in the matrix. The high material costs and inadequate strength have limited the use of cement-matrix and polymer-matrix composite concrete, but material advances may give rise to greater composite concrete use.

Following the shift made by the University of Nebraska researchers to carbon products, the University of Alaska (Anchorage) and University of Houston researchers explored carbon fiber tape as the resistive element in electrically conductive concrete. Carbon fiber tape was selected as the resistive element for its lightweight and high tensile strength and thermal conductivity (Yang, et al. 2012).

The researchers developed three 1.8 x 1.2 m slabs with the carbon fiber tape spaced 7.6 cm (3 in) apart (see Figure 4). The carbon fiber tape was connected to copper strips, which acted as electrodes. A thermally-conductive, electrically-nonconductive epoxy was spread on the carbon fiber tape to prevent electrical leakage into the PCC (Yang, et al. 2012).

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Figure 4 - Construction of conductive slab with carbon fiber tape (Yang, et al. 2012)

The carbon fiber tape panels reached a peak temperature of 11 °C (52 °F) during operation in sub-freezing temperatures, which melts snow effectively. The carbon fiber tape heated the slab uniformly as the range of temperatures on the surface of the slab was within 3 °C (5.4 °F) (Yang, et al. 2012). Table 1 compares the carbon fiber tape to the steel fibers and carbon particles based electrically conductive concrete mix developed for the Roca City Bridge (Tuan 2004). Carbon fiber tape is a promising resistive element for conductive concrete, but large scale testing of the strength, durability and constructability of carbon fiber tape infused concrete need to be performed.

Table 1 - Comparison of steel fibers and carbon particles based electrically conductive concrete and carbon fiber tape (Yang, et al. 2012)

Deicing System	Installation Cost per m ² (USD)	Annual Operating Cost per m ² per storm (USD)	Power Density (heat output) (W/m ²)
Steel fibers and carbon particles (Tuan 2008)	205	0.74	350
Carbon fiber tape (Yang, et al. 2012)	145	0.09	127

Anti-Icing Pavement Coatings and Mix Design

Overview

Another approach to ice-free roadways is to prevent ice forming on or sticking to the pavement altogether. Spraying anti-icing chemicals on pavement surfaces is an example of a pavement coating that helps prevent ice formation. After their application to the pavement surface or mix, anti-icing coatings and mix designs do not require any input of manmade energy, so there is no operating cost associated with these technologies. This portion discusses current state of practice and current state of research for anti-icing pavement coatings and mix designs that are permanent fixtures of the pavement.

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Current state of practice

The current state of practice for anti-ice chemical spraying systems are automated spigots mounted on or near the pavement surface that supply a stream of anti-icing chemicals to the pavement (see Figure 5). These spigots can be activated by road-condition sensors or remotely by transportation officials. Although the road-condition sensors are convenient by being totally automated, reliability issues continue to persist. Anti-icing spigot systems are advantageous for areas where road crews have difficulty accessing during winter weather (Barrett and Pigman 2001). These spigot systems have the same drawbacks as the manually placed anti-icing chemicals including environmental concerns and ineffectiveness in extreme cold weather. The initial and installation costs of the automated spray systems are approximately \$600,000 (Barrett and Pigman 2001). The annual operation and maintenance costs add up to around \$44,000 (Tuan 2008). Several state DOT's including California, Kentucky, Minnesota, Montana, Nebraska, Pennsylvania, and Texas make use of their products (Boschung 2013a).



Figure 5 - Boschung FAST - Fixed Automated Spray Technology (Boschung 2013b)

Current state of research

Phase change material admixtures, freezing point depressant absorbing aggregates and superhydrophobic coatings are emerging areas of research to prevent ice from forming on pavement surfaces. Each area of research provides a different strategy to prevent ice from forming on pavement. Phase change materials prevent ice adhesion by maintaining the pavement temperature above freezing during freezing conditions. Freezing point depressants lower the freezing point of water. Anti-icing chemicals are an example of freezing point depressants. Superhydrophobic coatings prevent water from adhering to the surface.

When a material undergoes a phase change from gas to liquid or liquid to solid and vice versa, it remains at a constant or near-constant temperature until enough energy (heat) is acquired to change phases. Researchers are testing concrete mixtures with phase change material (PCM) additives to reduce the number of freeze/thaw cycles a pavement undergoes throughout the year (Bentz and Turpin 2007). Many materials are available with a phase change just above freezing, which would deter the pavement temperature from dipping below freezing. Table 2 displays the simulated reduction in freeze thaw cycles if PCMs are added to concrete pavement. In milder climates, PCMs can eliminate pavement from reaching 0 °C (32 °F), which would prevent frost accumulation. PCMs would be less beneficial in areas with harsh winters where many weeks go by without a high above the freezing point. In these areas, PCMs would be reducing the number of freeze/thaw cycles during the fall/winter and winter/spring changeover (Bentz and Turpin 2007).

Freezing point depressants lower the temperature (below 0 °C) at which water freezes. The ambient temperature must be below 0 °C (32 °F) for water to phase-change into ice. Anti-ice chemicals sprayed on roadways are examples of freezing point depressants (Carroll and Dempsey 2007).

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Certain textured aggregates can absorb the freezing point depressants and could be resistant to ice accumulation for multiple winter storms instead of applying anti-ice chemicals to pavement before each storm. Chicago O'Hare International Airport tested the textured aggregate on 61 m (200 ft) of taxiway during the 2004/2005 winter. At the end of the study, the freezing point depressant coating on the texture aggregate had no noticeable improvement over adjacent sections, which were not covered in freezing point depressants. Snow stuck to the treated textured aggregate in equal amount as the adjacent pavement for each snowstorm (Carroll and Dempsey 2007). These results indicate that freezing point depressant coatings shouldn't be considered for ice prevention.

Table 2 - Simulated reduction in annual number of freeze/thaw cycles due to the presence of a PCM in the concrete (Bentz and Turpin 2007)

US City	Number of freeze-thaw cycles for control concrete	Number of freeze-thaw cycles for PCM Concrete	Simulated reduction with PCM (%)
Kansas City, MO	81	63	22.2
Tampa, FL	4	0	100.0
Lubbock, TX	71	44	38.0
Tucson, AZ	16	3	81.3
Cheyenne, WY	131	106	19.1
Pierre, SD	100	75	25.0
Seattle, WA	34	18	47.1
Fresno, CA	20	5	75.0
Baltimore, MD	104	71	31.7
Bridgeport, CT	104	83	20.2
Alpena, MI	107	81	24.3
Waterloo, IA	86	61	29.1
Total Cycles	858	610	28.9

A surface is considered superhydrophobic if water has a contact angle larger than 150° and will roll off the surface that is less than 5° from the horizontal. Superhydrophobic surfaces tend to have micro-nano-hierarchical texture along with a water-repelling chemical composition (Kulinich, et al. 2010). Researchers have yet to determine if superhydrophobic surfaces can also prevent ice formation. Researchers conducted an experiment where supercooled microdroplets of water were sprayed in a wind tunnel onto a superhydrophobic surface (Kulinich, et al. 2010). The experiment was meant to imitate freezing rain falling on the surface. The tested superhydrophobic surface deteriorated between icing/deicing cycles because the ice damaged the asperities (nano-level unevenness) of the surface. The researchers concluded that ice adhesion on a dry surface can be delayed, but ice causes damage to the surface once it adheres. In a humid environment, ice can actually be anchored into the superhydrophobic surface (Kulinich, et al. 2010). A superhydrophobic coating would be compatible with heated pavement system after the ice has melted, but questions of the durability of the superhydrophobic coating and possible ice-anchoring need to be addressed.

Discussion and Recommendations

Table 3 compares the benefits of hydronic and electrical resistance heated pavement systems. Both technologies have been successfully implemented in practice by achieving their design goals of either

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deicing or anti-icing. The cost data for both systems were generated from literature (Lavitt 1995, Minsk 1999, Eugster 2007, Fliegel, et al. 2010, Tuan 2008, Yoshitake, et al. 2011, Barbagallo 2013). The generated cost data were adjusted into November 2013 monetary values based on the U.S. Department of Labor Consumer Price Index (US BLS 2013) for discussion.

Electrical resistance heating systems with an average cost of \$400/m² (\$37/ft²) does hold an advantage over hydronic heating systems, which cost \$750/m² (\$70/ft²), for having a substantially lower initial cost. The initial cost is dependent upon the design costs and construction costs. The design and construction considerations for electrical resistance heating systems only consist of wire and electrode placing as the conductive concrete is cast just like a concrete overlay. Hydronic heating systems are much more design and construction intensive with pipe spacing and depth and pump considerations.

The average operation and maintenance costs for hydronic systems and electrical resistance heating systems are \$14.02/m² (\$1.30/ft²) and \$18.14/m² (\$1.69/ft²), respectively. The operation and maintenance cost for hydronic systems are highly dependent on the heat source with the average cost of boiler heating and geothermal heating being \$23.48/m² (\$2.18/ft²) and \$7.72/m² (\$0.72/ft²), respectively. The operating cost for geothermal systems is dependent on the size of pump needed for the well depth.

Table 3 - Evaluation of advantages between hydronic and electrical resistance heated pavement

Heated Pavement Technology	Initial Cost	Operation and Maintenance Cost	Constructability	Durability	Safety	Potential for Innovation	Green Energy
Hydronic Heated Pavement		✓			✓		✓
Electrical Resistance Heated Pavement	✓		✓	✓		✓	

As each implemented technology is relatively new, it is difficult to quantify the durability of the heated pavement systems. Electrical Resistance is considered and reported to be more durable in Table 3 because if repairs need to be made to an electrically conductive concrete overlay it can be patched up with more conductive concrete. It is possible for the electrical wires within the pavement to be severed or disconnected from an electrode, which would require cutting into the concrete for repair. Hydronic pipe systems have the potential for pipe leakage, which would require pipe repair or replacement and could impact the structural integrity of the pavement. Heat output of wells in geothermally-heated hydronic systems may deteriorate over the pavement lifespan as in the case of the Klamath Falls Bridge. The well would then need to be rehabilitated or replaced by a boiler. Electrical resistance poses the safety concern of electrical shock to pedestrians (in the case of sidewalks and crosswalks) if designed and operated incorrectly. Table 3 also displays that electrical resistance based concrete has more potential for innovation. Searching for a cost-effective electrically conductive concrete mix design is a relatively new research area while boilers and pumps are a more established technology.

Hydronic systems can use geothermal heat and operate as an energy harvester, which is why Table 3 indicates hydronic as the greener option. Both technologies can utilize green electrical power. In fact, some researchers have suggested lining roadways with photovoltaic cells and battery banks to provide electricity to electrically conductive pavement (Yehia and Tuan 1998). Wind turbines near the pavement could provide electricity in a similar manner, but wind turbine couldn't be used around airports

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except in FAA-certified areas. Much like developing a cost-effective electrically conductive concrete, finding a cohesive green energy for heated pavement has great potential for innovative research.

Bridges

Electrical resistance based heated system tends to be the appropriate choice in more instances than hydronic systems for heating bridge deck surfaces. The relatively lower initial cost of electrical resistance heated pavement is a significant advantage it holds over hydronic systems. Obtaining funding for the construction electrical resistance based heated pavement would be easier and faster than hydronic systems. Electrical resistance based heated pavement can be constructed anywhere the electrical grid reaches. Geothermally-heated systems, which appear to have lower operating and maintenance cost than electrical resistance based systems, are limited to areas that have easily accessible groundwater or, better yet, geothermally active zones. Boiler-heated hydronic systems tend to have a greater operating and maintenance cost than electrical resistance based heated system.

Roadways

Currently, the cost of constructing, operating and maintaining long spans of heated pavement roadways is too costly to recommend either electrical resistance or hydronic heated pavement. For high-priority, critical sections of the roadway, electrical resistance based heated pavement will be the more appropriate choice using the same reasoning mentioned for bridges. Phase change material admixtures have the potential to be utilized on future roads. PCMs can deter ice from forming on the roadway for periods of time with an additional benefit of reduced freeze/thaw cycles the pavement experiences. If PCMs emerge as a viable admixture, they can be expected to work as standalone systems or in conjunction with heated pavement systems as hybrid systems.

Airport runways, taxiways, ramps and parking lots

The FAA has design objectives set for any heated pavement system used on runways. The objectives include a "no worse than wet" pavement condition, "surface temperature above freezing point prior to the start of expected snow accumulation" and "maintaining surface temperature above the freezing point until snow accumulation has ceased" (FAA 2011b). The control of the heating system must be automated, have "ground fault protection devices" and "fluid temperature and pressure monitoring sensors for hydronic system" (FAA 2011b).

Electrical resistance heating systems also cannot interfere with proximate communication or navigation devices. Both technologies must obtain AC 150/5370-10 and AC 150/5320-12 construction standards for rigid pavement and skid-resistant surfaces before runway implementation. Whether hydronic, electrical resistance or neither heating system is chosen will be decided in a case by case basis for each airport.

Currently, researchers at Iowa State University 's FAA Center of Excellence for General Aviation are working on a FAA-sponsored project to develop heated airport pavement systems by considering conductive concrete, superhydrophobic surfaces and PCM technologies.

Conclusions

Hydronic and electrical resistance heated pavement systems are currently used in practice on bridges and airport taxiways and stands. Current state of research for hydronic systems utilizes the system as a solar energy collector in the summer to provide energy in the winter months. For electrical resistance heated pavements, researchers are testing various conductors and composite concrete to create cost efficient and sustainable heated pavements. Another avenue for deicing pavement is applying phase change materials, freezing point depressants or superhydrophobic coatings to the pavement.

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The future applications of each technology are as variable as the technologies themselves. For most bridges, electrical resistance heated pavement appears to be the best option. Electrical resistance heated pavement is suitable in a wider range of scenarios and typically has a lower initial cost compared to hydronic systems. Phase change material admixtures applied to roadways appear to be an effective way to reduce how often the roads are covered with ice without adding an operation cost. Application of heated technology on airport runways should be determined on a case-by-case basis, but all technologies must first pass strict construction codes. As the true cost of anti-icing chemicals and snow plowing equipment become more apparent, heated pavement technology has the potential to become the top choice for deicing infrastructure.

References

- Barbagallo, D. 2013. "RPD 155 Heated Pavements." Presented in *FAA ANG-E262 REDAC Committee Meeting*, March 19, 2013
- Barrett, M. L., and J. G. Pigman. 2001. *Evaluation of Automated Bridge Deck Anti-icing System*. Kentucky Transportation Center, University of Kentucky, KY.
- Bentz, D. P., and R. Turpin. 2007. "Potential Applications of Phase Change Materials in Concrete Technology." *Cement & Concrete Composites* (Elsevier Ltd.) 29: 527-532.
- Boschung. 2013a. *Clients*. Accessed April 26, 2013. www.boschungamerica.com/clients.
- Boschung. 2013b. *FAST - Fixed Automated Spray Technology*. Accessed April 26, 2013. www.boschung.com/en/fast/.
- Carroll, N. M., and B. Dempsey. 2007. *Anti-Icing Pavement Coating Study at Chicago O'Hare International Airport*. Final Report DOT/FAA/AR-06/58, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, IL.
- Eugster, W. J. 2007. "Road and Bridge Heating Using Geothermal Energy. Overview and Examples." *European Geothermal Congress*. Unterhaching: European Geothermal Congress.
- Federal Aviation Administration (FAA). 2011a. "Item P-401 plant Mix Bituminous Pavements." *AC 150/5370-10F - Standards for Specifying Construction of Airports*, Federal Aviation Administration, Landover, MD.
- Federal Aviation Administration (FAA). 2011b. "Airside Use of Heated Pavement Systems." *AC 150/5370-17 - Standards for Specifying Construction of Airports*, Federal Aviation Administration, Landover, MD.
- Fliegel, J., J. Flyer, M. Katz, A. Le, T. Ngo, K. Roberts, A. Santoro, C. Sun, and T. Weyforth. 2010. *Design and Evaluation of a Retrofittable Electric Snow Melting System for Pavements*. Gemstone Program Final Report, Department of civil and Environmental Engineering, University of Maryland, College Park, MD., 118.
- Gao, Q., Y. Huang, M. Li, Y. Liu, and Y. Y. Yan. 2010. "Experimental Study of Slab Solar Collection on the Hydronic System of Road." *Solar Energy* 84 (12): 2096-2102.
- Kulinich, S. A., S. Farhadi, Nose K., and X. W. Du. 2010. "Superhydrophobic Surfaces: Are they really Ice-repellent?." *Langmuir* (American Chemical Society) 27 (1): 25-29.
- Lavitt, M. O. 1995. "Runway Heating System Could Melt Snow Away." *Aviation Daily* (McGraw-Hill, Inc.) 142 (14): 80.
- Lopez, R. 2012. "Interest Warms up in Heated Runway Systems: The FAA's Funding of Two Heated Runway Concept Trials has Reawakened Interest in This De-icing Technology." *Jane's Airport Review*: 14-16.
- Lund, J. 2000. *Pavement Snow Melting*. Klamath Falls, Geo-Heat Center, Oregon Institute of Technology, OR.

Reference to this paper should be made as follows: Ceylan, H., Gopalakrishnan, K., Kim, S., and Cord, W. (2014). "Heated Transportation Infrastructure Systems: Existing and Emerging Technologies," The 12th International Symposium on Concrete Roads, Prague, Czech Republic, September 23-26, 2014.

- Minsk, L. D. 1999. *Heated Bridge Technology: Report on ISTEA Sec. 6005 Program*. U.S. Department of Transportation.
- Piskunov, V., O. Volod'ko, and A. Porhunov. 2008. "Composite Materials for Building Heated Coverings of Roads and Runways of Airdromes." *Mechanics of Composite Materials* (Springer Science+Business Media, Inc.) 44 (3): 215-220.
- Tuan, C. Y. 2004. *Conductive Concrete for Bridge Deck Deicing and Anti-icing*. Final Report, Nebraska Department of Roads, University of Nebraska-Lincoln, NE., 153.
- Tuan, C. Y. 2008. "Roca Spur Bridge: The Implementation of an Innovative Deicing Technology." *Journal of Cold Regions Engineering* (ASCE) 22 (1): 1-15.
- Tuan, C. Y., and S. A. Yehia. 2002. "Airfield Pavement Deicing With Conductive Concrete Overlay." *Federal Aviation Administration Technology Transfer Conference*.
- Tyco Thermal Controls LLC. 2012. "ElectroMelt." *Raychem*. Accessed 4 16, 2013. <http://www.thermal.pentair.com/products/heating-cables/self-regulating/?id=tcm:432-27747&catid=tcm:432-17783-1024>.
- Underground Energy, LLC. 2009. *ATES - Aquifer Thermal Energy Storage*. Accessed May 30, 2013. <http://www.underground-energy.com/ATES.html>.
- U.S. Bureau of Labor Statistics (USBLS). 2013. *U.S. Department of Labor Consumer Price Index*, Accessed 12 01, 2013. <http://www.bls.gov/cpi/>.
- Van Bijsterveld, W. T., L. J. Houben, A. Scarpas, and A. A. Molenaar. 2001. "Using Pavement as Solar Collector: Effect on Pavement Temperature and Structural Response." *Transportation Research Record: Journal of the Transportation Research Board* 140-148.
- Wang, H., S. Wu, and G. Wang. 2012. "Research on Structural Performance of Conductive Asphalt Pavement Buried Tubes in Moving Load." *Journal of Testing and Evaluation* (ASTM Int'l) 40 (5): 1-7.
- Yang, Z., T. Yang, G. Song, and M. Singla. 2012. *Experimental Study on an Electrical Deicing Technology Utilizing Carbon Fiber Tape*. Department of Civil Engineering, Alaska University Transportation Center, University of Alaska Anchorage, Anchorage, AK., 1-59.
- Yehia, S. A., and C. Y. Tuan. 1998. "Bridge Deck Deicing." *Crossroads 2000 Conference*. Ames. 51-57. <http://digitalcommons.unomaha.edu/civilengfacproc/1>.
- Yehia, S. A., and C. Y. Tuan. 2000. "Thin conductive concrete overlay for bridge deck deicing and anti-icing." *Transportation Research Record: Journal of the Transportation Research Board* (Transportation Research Board of the National Academies) 1698: 45-53.
- Yoshitake, I., N. Yasumura, M. Syobuzako, and A., Scanlon. 2011. "Pipe Heating System with Underground Water Tank for Snow Thawing and Ice Prevention on Roads and Bridge Decks." *Journal of Cold Regions Engineering* 25(2): 71-86.