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Review

Durability of Pavement Materials with Exposure to Various Anti-Icing Strategies

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Abstract: Anti-icing is a critical topic in durability assessment for pavement infrastructures, and it varies according to local policies. To provide sufficient information to winter maintenance agencies, and help compare the merits and shortcomings of each strategy, this review summarizes the widely used anti-icing strategies, including elastic surfaces or high-friction overlays, asphalt binders mixed with anti-icing additives, pavement heating technologies, deicers, and fixed automated spray technology, from academic and practical perspectives, as well as explore the impact of deicers on the durability of concrete materials. Furthermore, the costs of each method were compared to evaluate the feasibility of them. This review not only provides a summary of previous anti-icing strategies, but also sheds light on future research trends that may help address the challenges of current anti-icing strategies, and further enhance anti-icing efficiency and reduce life cycle costs.

Keywords: pavement; anti-icing strategies; cost; durability; sustainability

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1. Introduction

This review outlines currently applied techniques that are widely used for anti-icing activities. The performance and cost of various chemicals used for anti-icing and their corrosion impacts on the durability of highway infrastructure materials have been summarized. The main aim of this review is to synthesize the existing or ongoing research of (1) anti-icing strategies on pavement materials; (2) chemicals used for anti-icing strategies; and (3) corrosive effects on infrastructure and cost comparisons.

In recent decades, it has been widely accepted that the durability of pavement is significantly governed by anti-icing strategies in the cold region areas. To realize the sustainable development of pavement infrastructures, analyzing winter maintenance activities from the perspectives of materials and costs would be greatly beneficial to provide agencies with correct snow and ice control instructions. At present, the cost of ice and snow control is as high as hundreds of millions of dollars, U.S., in many countries across the world. For example, the annual cost of keeping the highways free of snow and ice in the United States was about $2.3 billion (between 1997 and 2005), and, when considering the corrosion and environmental impacts, the cost increased to at least $5 billion [1]. Local agencies will choose various anti-icing strategies that fit local conditions, to ensure smooth running of the highways. Typical anti-icing strategies include elastic surfaces or high-friction overlays, asphalt binders mixed with anti-icing additives, pavement heating technologies, de-icing chemicals, and fixed automated spray technology. For elastic surfaces or high-friction overlays, the cost and overlay materials are the main factors that confine their applications. The durability of the anti-icing additive mixed asphalt should be the primary concern of this strategy. For heating technology, although the ice melting efficiency is quite impressive, the construction process, materials design, durability, and costs are still the main challenges. Anti-icing chemicals have been extensively applied as snow and ice control strategies in cold regions, and, although showing promising efficiency, can cause severe damage to the structure of bridge pavements and other environmental impacts. This needs to be further investigated.

2. Anti-Icing Methods and Costs

This section summarizes several anti-icing methods that are applied to eliminate the ice or compacted snow on pavement surfaces. Such treatments provide effective strategies as snow and ice control methods. These methods would significantly reduce the cost of winter maintenance activities as most de-icing chemicals lose effectiveness, and abrasives or snowplowing are expansive and have relatively low efficiency.

A recent Strategic Highway Research Program reported the following benefits after anti-icing test programs were conducted by state DOTs (Departments of Administration) in Iowa, Missouri, Oregon, and Washington [2]:

- Snowplow trips were reduced by roughly one-third, resulting in less wear on equipment.
- Snowplowing was easily implemented, and at least three hours faster than conventional methods, which resulted in a reduction of labor costs.
- Fewer chemicals were needed by applying the treatment before snowfall, resulting in reduced costs and less chemical stress to the environment.

Kelting [3] reported a case study, which was conducted in Boulder, Colorado, and found that liquid anti-icing chemicals had a total application cost of $2500 per lane mile, as compared to $5200 per lane mile for conventional de-icing and sanding operations. Idaho's DOT reported that anti-icing retrofits showed a reduction in the annual average use of abrasives, labor hours, and vehicle crashes over five years [4].

Physical anti-icing methods include high-friction anti-icing polymer overlays, asphalt pavements containing anti-icing additives, heated pavements using energy transfer systems, and fixed anti-icing spray technology (FAST). These pavement anti-icing treatments may exhibit good reliability and incur less capital and maintenance costs [5]. The following sections will review these methods in detail.

2.1. Elastic Surfaces or High-Friction Overlays

The asphalt pavement can be modified to realize the high-friction surfaces that provide improved skid resistance in icy conditions. This friction modification was implemented by incorporating with open-graded or half open-graded asphalt concrete overlay and coarse aggregate (e.g., recycled ceramics particles) on asphalt pavements surface to facilitate the breaking and abrasion of compacted ice coverings on roads. Most recently, the durability of the open-graded friction surface layer was systematically reviewed by Wu [6]. It was summarized that, although the open-graded surface friction surface layer has many advantages, such as safety enhancement, cost-effective, and environmentally friendly benefits, it is still facing durability challenges, including rutting, raveling, clogging, cracking, delamination, and moisture susceptibility. In all of these mentioned durability challenges, the winter maintenance activity is a critical aspect that governs the service life of the open-graded friction surface. Due to its high air void content, the low thermal conductivity will lead to more frequent and severe frost and ice formation processes. As a result, the increased using of de-icing chemicals will result in an early age failure of the open-graded friction surface layer. Sharma [7] summarized the effects of utilizing polymers to improve the durability of open-graded friction surface layers. It was claimed that, by incorporating with polymers and crumbed rubber, or even waste plastics, the durability of the open-graded friction surface layer can be considerably improved if the quality of materials and the manufacturing process can be well controlled.

High friction anti-icing polymer overlays are effective at decreasing traffic risks, which are derived from the icy or slippery pavement surface. Meanwhile, further investigations are needed to study the high friction anti-icing polymer overlays, to guarantee durability and anti-icing efficiency. Commercially available polymer (named as Product A) is a surface covering material in which a specific polymer is applied to the paved surface and aggregates are applied to the surface. The aggregate acts as a hard sponge, acting as a slow-release mechanism for the liquid de-icing agent used. In this way, the cover can provide residual anti-icing benefits during application. After laboratory tests showed that medium-porosity limestone aggregate and calcium magnesium acetate (CMA) de-icing agent provided impressive residual anti-icing performance, the technology was patented and commercialized. An experiment was conducted at −4 °C with repeated application of compressed snow. The results show that, compared with granite aggregate and NaCl de-icing agent, the force required to reduce the snow accumulation is much greater, which requires reapplication of snow [8]. A frost test conducted at 1 °C, cooling aggregate samples to −7 °C, showed that the combination of limestone-CMA prevented the growth of frost [9]. In the winter of 2005–2006, field observations showed that Product A is generally better than the control section. Its advantages are (1) reduced snow and ice; (2) reduced chemical usage; (3) better snow removal effect during farming [10]. However, no road temperature below −9 °C was observed during that winter. In the winter of 2006–2007, Product A still performed better than the control section, but other conditions showed poor or worse performance. Similarly, most road surfaces have temperatures above −9 °C. However, on 7 December 2006, when the temperature of the Mitchell Bridge in Hibbing, Minnesota, was −20 °C, the Product A section was covered by 50% frost, and the control section was clear [11]. More information and documentation are needed to determine the advantages of Product A in extremely cold conditions.

Another strategy of elastic pavements was implemented by incorporating rubber particles as partial replacements of fine aggregate in asphalt binders during the construction process. To increase the resistance to the skid of pavements and provide “elastic aggregates which flex on the pavement surface under traffic” that can significantly improve the anti-icing efficiency [12], Product A devised and manufactured asphalt-based composites with the addition of 3–4% granulated tire rubber (1.6–6.4 mm particles) by weight of the mixture, along with some buffing and chopped fibers in the top course of hot-mix asphalt pavements. However, it was claimed that the addition of rubber could lead to challenges of the compaction status of asphalt [13].

The testing in practical cases and in laboratory conditions showed that another commercially available polymer (named as Product B) enhanced the low temperature cracking resistance, reduced the rutting resistance, and had a variable effect on the moisture susceptibility by comparing with the control pavements. Meanwhile, in practical cases surveyed by an FHWA (Federal Highway Administration) study, most of the pavements after coated with Product B exhibited the same rutting, cracking, and raveling resistance when compared with the control pavements [13]. It was reported by Alaska and New Jersey DOTs that the practical testing of Product B can result in a significant enhancement in the skid resistance of pavements, reducing vehicle-stopping distance during ice conditions and, thus, improving traffic safety [14]. Another example reported a case study in the northern cold regions of China, in which the crumb rubber was used to prepare asphalt-based elastic highway to prevent snow/ice pavement surface. It was claimed that the field performance of the rubber modified asphalt pavement, including the adaptability of gradation type, anti-freezing performance, ice-breaking performance, and anti-wearing performance was significantly enhanced by the appropriate incorporation of crumb rubber [15]. This result showed that the crumb rubber is an excellent mixture for anti-icing asphalt pavement.

The high-friction pavements were reported to be plagued by durability issues. Takeichi [16] evaluated three types of pavement that provide anti-freezing effects through high-friction surface texture and another eight types through pavement bending. The study indicated that the use of two approaches—one to cut pavements into lots of grooves and fill them with urethane resin, and the other to embed cylindrical or doughnut-shaped rubber into pavement surface at regular intervals—played a particularly positive effect on realizing excellent anti-freezing effectiveness. These two types of pavement systems were often applied in many special fields, such as intersections, and performed high anti-icing properties that were beneficial to pedestrians and vehicles.

The durability concern of high-friction overlays has been also proposed in the review [17,18], where several case studies of high-friction pavements of key locations, including horizontal curves or steep grades with excessive braking, high accident rates, and/or frequent wet-weather conditions, in cold regions of the U.S. were summarized from the perspectives of laboratory testing, field-testing, safety studies, and cost-benefit analyses. It was illustrated from most practical field tests that the use of high-friction overlay technology is effective at increasing the anti-icing performance of pavements; moreover, traffic accidents significantly descended. For increasing traffic safety, the South Dakota Department of Transportation installed a high friction surface treatment in 2014 and compared a three-year crash accident rate before and after the installation. It was found that the crash rate reduced from an average of 10 crashes per year to only two crashes per year. The collected data indicated that the installation of these overlays reduced automobile crashes by nearly 77%. In Minnesota, the high-friction overlays were applied to build a bridge pavement in July 2006 on southbound lanes in the City of Hibbing, to reduce vehicle skid. It was found from the survey that, after installation, the skid numbers remarkably decreased within 3 years. Young [19] installed a polymer-based overlay on asphalt pavements to enhance the anti-skid property; however, it was reported that the mean texture depth of the thin-bonded overlay tended to decrease by 13% of the overall overlay thickness after the pavements were in service for 9 months.

Furthermore, as claimed from the survey, the durability issue mainly resulted from the obvious friction loss between the treated overlays and automobiles. For example, the polishing effect caused by frequent traffic flow was indicated by the field test conducted in Sand Creek Bridge, Williston, North Dakota, demonstrating that the severe abrasion resulted in the significant reduction of the aggregate angularity and surface friction. This work claimed the short service life of high-friction overlay pavements. Moreover, the survey of the high-friction pavement constructed in Colorado also suggested that the texture depth of pavement reduced by 40% after only one year, and therefore, the anti-icing performance decreased. A similar result was given by the survey carried out in Mitchell bridges, Hibbing, Minnesota, which demonstrated that the aggregates on pavements suffered from repeated shearing from normal traffic polishing. This unexpected decrease in the field performance of high-friction overlays remarkably confined their application.

Although improving the friction of pavements was effective at increasing traffic safety during the heavy snow season, the less-satisfying long-term performance may significantly reduce the expectation of this technology. It was claimed by Evans that the pavements frequently suffered from the repeated wear force, such as plow blade shearing forces and normal traffic shear. The researcher predicted that the longevity of the overlay is limited to 3.5–5 years, and remediation was required to expand its service life [20].

Flintsch [21] indicated the rapid failure of high-friction overlays could be caused by a wide variety of issues, such as the raveling of the material, delamination, and the polishing of the aggregate. The deterioration in the compatibility of high-friction surface and pavement was closely controlled by the surface moisture of overlays. It was reported that high moisture content in the high-friction surface might hinder the pavement's ability to bond with the epoxy, thus causing raveling and peel-off problem; furthermore, the water trapped below the impermeable layer as the surface undergoes freeze–thaw action may lead to severe raveling.

Apart from the high friction surface, the efficiency of removing the ice layer on the asphalt pavement surface can be enhanced by using the so-called elastic surface, which mainly resulted from the filling of elastic materials, such as rubber or plastic polymers, in the asphalt matrix. This modification tends to alter the interaction between pavement and automobile tires, thus contributing to increase the surface friction of roadway or reduce the bonding connection of ice covering and road surface. Although the elastic pavement strategy generally doubles the cost of the asphalt mixture, the use of this strategy has brought broad interest in industrial fields after it was firstly introduced in the U.S. from Sweden in the late 1960s. The rubber-asphalt pavements exhibits good field performance when the temperatures reach no lower than −12 °C and the ice thickness is no thicker than 9 mm; the biggest challenge is that the agreement of the cost–benefit analysis has yet been conducted [22]. A survey by the Alaska DOT in 1998 [23] produced pliable rubber asphalt-based composites to reduce snow/ice accumulation on roads. However, their testing did not exhibit as high efficiency as was expected and obtained little financial benefit.

Wu [24] attempted to enhance the abrasion resistance property of polymer overlays by incorporating with a hybridized fluorinated silicon-based copolymer, through enhanced self-crosslinking ability, strong self-adhesiveness, and high structural stability of the composite coatings in severe conditions. The final composites exhibited excellent hydrophobic properties and, thus, the increased anti-icing coating performance. More importantly, the abrasion test showed that the anti-icing performance maintained at a high level even after over 110 cycles of sandpaper abrasion and 20 icing/de-icing cycles, or suffering from various corrosive/organic conditions for more than 10 days. This result indicated that the incorporation of the silica-based copolymer could result in the increased abrasion resistance performance of the pavements.

A similar study was implemented in Sweden, Europe, where the polymer-modified asphalt binder was used as the waterproofing and aging resistance layer for the pavement. In this case, the layer was coated on a bridge, which experiences the temperature range from −40 °C to +30 °C. By collaborating with a German partner, the laboratory testing results showed that the tensile bonding strength was satisfactory and the bridge was following the requirements. The fatigue test results indicated that the waterproofing pavement well remained for all four polymer-modified systems and test temperatures. Besides, by using grit and steel ball robot blast equipment, only 10 tons of waste was produced compared with 250 tons of waste originating from manually operated blasting; this was satisfactory from the health and environmental perspective [25].

2.2. Asphalt Binder Mixed with Anti-Icing Additives

It was found that mixing anti-icing additives in asphalt binders is an effective approach to confine the ice formation on the surface of asphalt pavement. A study conducted in Italy used sodium chloride (NaCl) as the dominant additive on the asphalt mixture pavement and found that additives help in the delay in ice formation on the pavement surface, accelerating the melting process, and reducing adhesion between ice and the pavement surface.

One of the well-known chemical additives for anti-icing mixed asphalt pavement is the commercially available Product C (0.1–5 mm flake particles of 95% $CaCl_2$ and 5% sodium hydroxide) that was extracted from linseed oil or polyvinyl acetate. The Product C was often incorporated with the surface layer of fresh asphalt pavements, to enhance the anti-icing performance of pavements and bridge decks. Anti-icing additive pavement has been used in Europe, North America, and Japan since the 1970s. Laboratory studies have indicated that the addition of anti-icing additives could enhance the resistance of pavement to rutting at high temperatures, insignificantly decrease its temperature susceptibility, and increase the damage risk of moisture [13]. Proposed field-testing has revealed several conclusions on the field performance of the anti-icing additive pavements particularly at extremely cold temperatures [26–30].

The New York State DOT carried out a field test of the pavements with anti-icing additive in Albany, New York, in 1978, and it was investigated from their results that the pavements with anti-icing additives showed better anti-icing properties at temperatures higher than −7 °C. On the other hand, with decreasing temperatures, the anti-icing additive pavements exhibited an insignificant enhancement in the field performance as compared to control pavements [26].

The anti-icing efficiency of anti-icing additive pavements was dramatically determined by the service conditions. During warm and wet winters of Western Europe, New York

State, and Pennsylvania, the pavements had excellent self-de-icing performances. However, in areas that were drier and colder, such as Minnesota, Manitoba, and Illinois, the anti-icing additive pavements showed less satisfying anti-icing performances.

In a Colorado project, the effectiveness of de-icing was so slow that normal salting and sanding operations dominated in anti-icing performance [13]. Although the anti-icing additive pavement featured excellent field performance in terms of eliminating snow/ice covering, it was suggested that the high cost of the mixture might significantly confine its applications in practical cases. More seriously, the additional cost is not balanced by the benefit of reducing sanding and salting operations. However, the anti-icing additive pavement system is still meaningful and is worthy of more attention because it works for reducing traffic accidents. Another problem of the anti-icing additive pavement is the issue of raveling. A field test indicated some pavements tended to be exfoliative, which stressed the importance of better quality control of the pavements during pavement construction (especially compaction).

The feasibility of the anti-icing additive pavement has been proved. First of all, although the high water absorption ability of the pavement will result in slippery constructions, it can be effectively avoided by sand incorporation or water flushing [13]. Secondly, research by the Michigan DOT [31] concluded that the anti-icing additive achieves its effectiveness when the temperature is over −3 °C. Furthermore, heavy traffic (at least 5000 ADT—Average Daily Traffic) is required for anti-icing additives to reach their full de-icing potential. Moreover, the anti-icing additive featured little environmental risk and obvious reduction in salt usage, which impresses researchers.

However, the cost of anti-icing additives is high (USD $4000–$4500 per ton/2015), approximately 30–50 times the cost of asphalt materials (about USD $80–$150 per ton/2015). Other anti-icing additives are also commercially available in Japan and China [32], all of which aim to reduce the use of chemical deicers and improve the efficiency of mechanical removal. The main challenge of this technology is to balance the demand for controlled-release cement treatment to achieve the anti-icing functions.

Giuliani [33] developed sodium chloride-based anti-icing filler in asphaltic materials; it was demonstrated that, due to the presence of the de-icing agent, the formation of ice covering has been delayed. Moreover, the skid resistance result indicated that this technology exhibit an effective function in reducing frost formation. More importantly, the long-term performance measurement was conducted and it was found that the releasing de-icing chemicals tended to decrease with time, especially during warm and rainy seasons, which decreased the effectiveness of the de-icing fillers.

Ma [34,35] studied the de-icing performance of anti-icing asphalt mixtures with deicers; it was found that the bonding connection between ice and pavements could be weakened due to the releasing anti-icing additives from asphalt mixtures. However, it was proposed that the use of anti-icing additives exhibited negative influences on the rutting stability, thermal cracking resistance, and moisture susceptibility of asphalt mixture. To overcome this disadvantage, polyester fibers were incorporated with asphalt mixtures, and it was indicated that the polyester fibers are effective to minimize the negative influence of deicers, and the fiber modified asphalt mixture has much better engineering properties than the normal de-icing asphalt mixture. By this method, the anti-icing performance of asphalt pavements mixed with polyester fibers and its durability reached a balance.

2.3. Pavement Heating Technologies

The pavement heating technology aims to prevent icing or promote de-icing. According to the relative position of the heating source and the sidewalk, it can be classified as (1) internal heating (for example, geothermal heat pump [36]; (2) electrical resistance heating [37–40]; and (3) external heating (for example, microwave and infrared heating). Attempts have been made to use infrared heating lamps and insulated bridge pavements with polyurethane foam, but were found to be ineffective [41,42]. Figure 1 illustrates the cost estimates of various heating systems by the Iowa Department of Transportation [43].

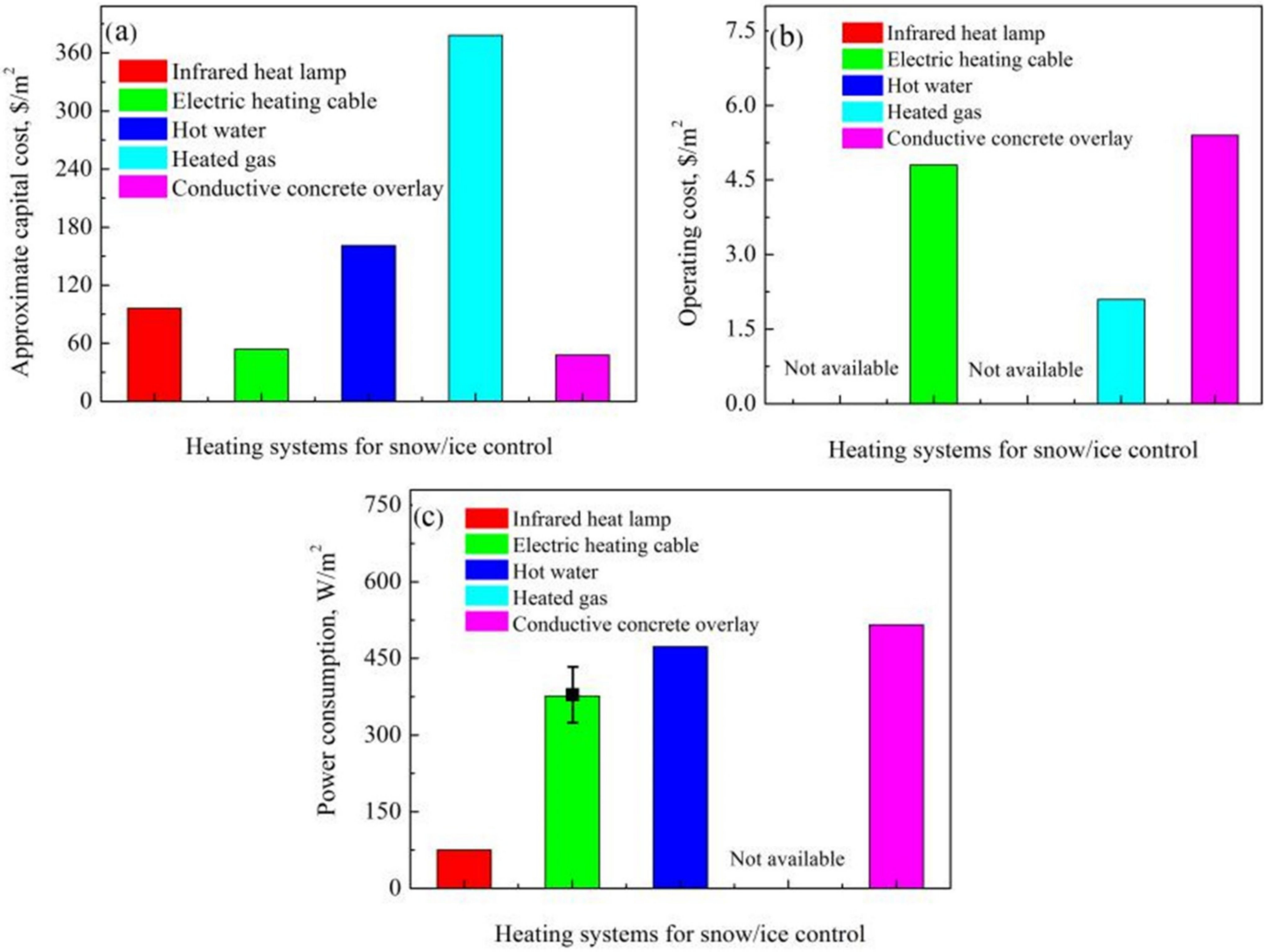

Figure 1. Estimated cost of various heating systems of (**a**) approximate capital cost, (**b**) the operating cost, and (**c**) the power consumption of various heating systems for snow and ice control [43].

Using cables as the electric heating elements has become popular in the manufacture of anti-icing pavements since this technology was firstly installed in practical cases, as early as the 1960s in Newark, New Jersey. Electric heating cables were embedded under pavement surfaces and were controlled by surface sensors that can perceive snow participation on roads. However, this approach was discarded due to several crucial problems. For example, the inaccurate detection of these sensors may mislead the heat resource, and the electric heating cables may be easily split off pavements by heavy traffic. These problems were stated by the Ladd Canyon Heating Project by the Oregon DOT, which tested the field performance of cables on a part of Interstate Highway I-84 in 2006 [44]. Apart from the high operation cost, the poor durability of electrical heating is the most significant reason that confines its application. To be more specific, the repeated traffic loading will cause damage to the cables so that the cables will lose their electric heating functions. Although no severe failures of the system can threaten the safety of the pavements, when the environment temperature below −7.2 °C, the system will become inefficient due to the damage of the cables.

In addition to cable, using conductive carbon fabric as a heating element of concrete pavement was explored by Mohammed [45]. In their work, carbon fiber fabrics in the forms of filament, woven fabric, and unidirectional fabric were embedded into the concrete matrix to manufacture anti-icing pavements, and it was reported that these carbon fabric-pavements exhibited satisfied anti-icing performance, the generated electric-heat was sufficient to heat samples from freezing temperatures of −20 °C to above 0 °C in a short period. The input power density, wetness of concrete, depth of the embedded carbon fabric, and ambient temperature are parameters of the anti-icing performance. However, this technology presented potential limitations. The weak connection between carbon fabric and copper electrodes hinders electric current flow and results in the generation of over-amount of heat, which is harmful to the long-term performance of anti-icing pavements.

Apart from cable heating, electrically conductive fillers were applied to incorporate with the conventional concrete to achieve stable electrical conductivity of the concrete based composite to manufacture electrically conductive pavement. A thin layer of conductive concrete can produce enough electric-heat because of its high electrical conductivity. This can be utilized to prevent ice formation on the pavement surface when connected to a power source. Two types of conductive concrete were proposed and applied in practical cases due to their advantages and limitations: (1) conductive fiber-reinforced concrete, and (2) concrete containing conductive aggregates. Current progress shows the electric de-icing roadway system can be made by carbon nanofiber paper [46] or carbon/glass fiber hybrid textile [47]. The result of the field test indicated that this electrically conductive concrete exhibited high electrical conductivity, high electric-heat generation property, uniform and rapid heating, reliable performance, low cost, and/or improved service life. Due to the use of conductive materials, more sand and cement and less limestone were used than in conventional concrete [48].

The electrical conductive overlay is another way to realize the pavement heating technology. To explore the feasibility of applying conductive concrete as electric heating bridge pavements through small-scale experiments, Yehia [49] manufactured a conductive concrete deck for the Nebraska Department of Roads. Figure 2 gives material costs of conductive concrete versus conventional cement concrete. Their work indicated that using conductive concrete was much more cost-effective than that embedded with an electrical heating source. Furthermore, they constructed electric de-icing concrete bridge pavements by the use of 1.5 percent of steel fibers and 25 percent steel shavings, by volume, for the Roca Spur Bridge in Roca, Nebraska, and they illustrated that this method required a lower cost than other de-icing technology. The average energy cost was about only \$0.8/m^2 per snowstorm [50].

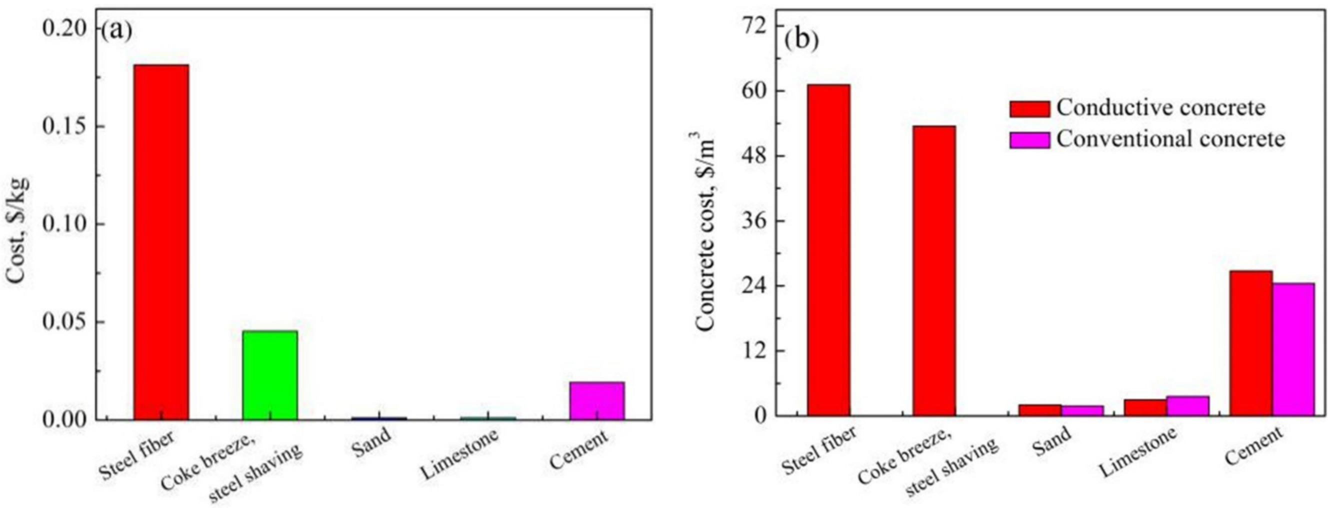

Figure 2. (**a**) Costs of conductive concrete materials and (**b**) Costs of conductive concrete materials versus conventional concrete materials, in 1998, USD [48].

Similar technology was applied in another work [51]. They prepared a conductive ultrathin bonded wearing course (CUBWC), which mainly consists of the conductive functional phases such as graphite, carbon fiber (CF), epoxy resin adhesive, as anti-icing pavements. They firstly considered the effects of CF length, CF content, and graphite content on the electrical characteristics of CUBWC, it was found that the most suitable fiber length was 2 mm and the optimum dosage of conductive fillers was 25% graphite (by mass) and 4% CF (by mass). Furthermore, they proposed that the electrical characteristics of CUBWC could be affected by the temperature of the composites, especially during the snow melting process. From their results, a positive temperature-resistivity coefficient was found in CUBWC samples, which is the resistivity values tend to increase with the increasing temperature because the thermal expansion degrees of carbon fillers and epoxy resin matrix is inconsistent at a high temperature. Therefore, the different expansion increased the distance between the adjacent conductive particles, leading some conductive pathways to cut off. However, the resistivity fluctuation caused by temperature was limited, and the resistivity values kept relatively stable. More importantly, the temperature-cycling test was further conducted to evaluate the long-term property of electric-heating overlays. It was illustrated that after two cycles, the heating up curve and the cooling curve were consistent with each other. This phenomenon showed that the internal structure of the composite system tended to be stable after repeated shrinkage and expansion of resin matrix, thus the resistivity variation of CUBWC became smaller after two temperature cycles. This work proved the feasibility of using carbon-epoxy resin as an electrically conductive overlay for snow/ice management on pavements.

After the construction of the de-icing Roca Bridge deck, its field performance was evaluated from 2003 to 2008. To avoid the disadvantage of chemical instability of steel shaving, carbon and graphite products were used to replace steel shavings in the conductive concrete mix design. From their long-term research, it was shown that the conductive concrete is effective to raise about 10 °C of the slab. However, the electrical conductivity efficiency of the concrete bridge pavements tended to significantly decrease during the service life of the bridge pavements, thus increasing the energy required and the cost. The total construction cost of the Roca Spur Bridge de-icing system was $193,175. The cost per unit of the surface area of the conductive concrete inlay was $635.1/m^2$. The construction costs of the various de-icing systems are compared in Figure 3. The operating cost of the Roca Bridge de-icing system was about $250 per major snowstorm [48]. Furthermore, the author concluded that achieving long-term stability of the electrical conductivity of concrete is the most challenging task. Moreover, because of the increasing electrical resistance, the higher electric voltage, higher operation cost, and lower efficiency were obtained in the Roca Spur Bridge deck, and the high electric power would put human beings at threat.

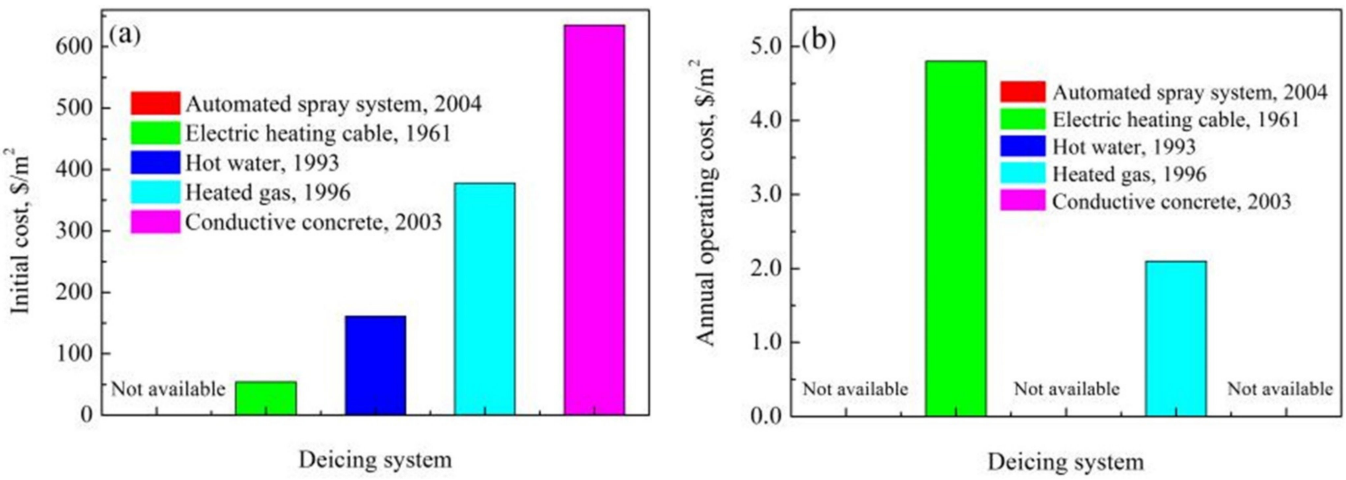

Figure 3. *Cont.*

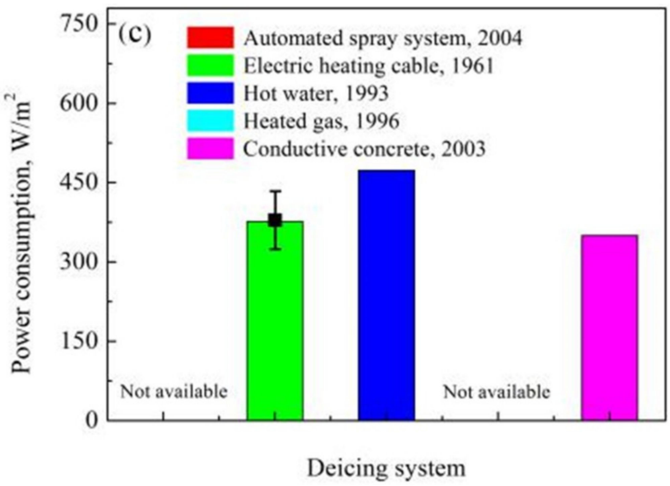

Figure 3. (**a**) Initial cost, (**b**) Annual operating cost and (**c**) Power consumption of different deicing systems [48].

The electrically conductive concrete system was also manufactured as airport runways. A representative example, a commercially available system that was constructed at O'Hare International Airport [52]. These anti-icing asphalt pavements were prepared by mixing graphite into the asphalt. The field performance of O'Hare International Airport was tested for four years, beginning in November 1994, and it was illustrated that the system exhibited effective self-de-icing property and good durability. Furthermore, it showed satisfying cost benefits, showing that the system would largely help to improve the exit efficiency, and possibly have a payback of the investment in 3 years. The results also indicated that this system could work well in severe conditions, even when the temperature was below −23.3 °C. In one of the winter seasons, for example, the temperature of pavement improved by −5.6 °C in extremely cold weather.

The addition, the electrically conductive fillers in the asphalt mixture do not only provide heating energy (via the electrical Joule energy), but also act as agents to realize induction heating by applying external microwave devices on the top of the pavement surface, regardless of the ice thickness. In recent years, the microwave de-icing performance of asphalt mixture was tested by using steel slags as aggregates. It was claimed that the steel slag aggregate is an excellent microwave absorbing material because of the high hyperactive (Fe_3O_4) and active (Fe_2O_3 and FeS) contents. The testing results show that the microwave heating efficiency is a parameter of the aggregate's size. The steel slag aggregates with sizes of 9.5 mm, 2.36 mm, and 0.6 mm were found to be the most effective sizes. Besides, the thermal conductivity and the uniformity of microwave heating on the asphalt mixtures decrease with the increasing content of steel slag. They suggested the optimized volume contents of steel slag are 40% and 60% [53].

Apart from the steel slag aggregates, the microwave induction heating performance of the asphalt mixture with the addition of steel wool fiber has been investigated. It was found that the contents and diameters of steel wool fiber are key factors that influence the induction heating efficiency. The increasing contents of the steel wool fibers will lead to the increase of the air void of asphalt mixture, and the increase of the diameter will result in a decrease of heating efficiency. However, the increasing of diameter is beneficial to enhance the heating uniformity of the asphalt mixture. It was reported that the optimized combination of contents and diameters of steel wool fibers for induction heating was 0.3% for 15–35 µm, 0.6% for 50–70 µm, and 0.9% for 75–125 µm. Moreover, it was stated that the thickness of the ice was not relevant to the ice-thawing efficiency [54].

Liu's study demonstrated that, except for the addition of microwave absorbing materials in asphalt mixture, the structural design is also an important strategy to enhance the induction heating efficiency of pavement. A magnetically conductive layer was applied to replace the lower part of the inductive asphalt mixture layer in the conventional induction heating asphalt pavement. The structural stability was tested, and the de-icing efficiency was evaluated. The results indicated that this novel structure could significantly enhance the de-icing efficiency by as much as over 80% without sacrificing the stability of the pavement structure [55].

Another multiple layer structure was developed to enhance the induction heating efficiency. In this structure, three sub-layers were designed, as the top layer was made of an electrically conductive asphalt mixture containing waste steel shavings, the medium layer was the asphalt mixture with a pre-embedded induction coil, and the bottom layer was constructed by a waterproof adhesive layer with magnetically absorbing material containing waste ferrites. It was reported that the optimum content of waste steel shavings in the top layer was 6%. The tensile strength and shear strength of the magnetically absorbing bottom layer reach about 90% of the traditional waterproof adhesive layer [56].

As a novel de-icing strategy, although induction heating has many advantages, including high efficiency, environmentally friendly, and a significant reduction of labor cost, there still have several challenges that need to be concerned. First, the long-term performance of the induction-heating pavement was barely reported. The reduction of bonding strength between the aggregates and the asphalt is still unclear, and the aging problem of the asphalt binder with exposure to the microwave was little investigated. Second, the structural design needs to be further investigated. The thickness of the magnetic layer, the electrical conductive performance, and the percolation of the fillers are all critical factors that determine the induction heating efficiency.

Despite the aforementioned anti-icing methods being effective in the prevention of snow/ice accumulation, a large amount of additional energy is required to achieve such satisfied anti-ice/snow performance, which will cause huge energy consumption. Therefore, to solve this problem, using natural energy, including solar energy and wind energy as melting systems, was invented in Japan. The renewable nature energies used in Japan are summarized by Hiroshi [57]; for example, utilizing underground water source or steam, storing heat underground, circulating it under pavements, and using electricity produced by wind power. This system necessitates higher capital costs than electric heating technologies, but it achieves cost benefits (i.e., maintenance costs and environmental protection).

To combine the advantages of both nature energy and electric source, an anti-icing airfield runway was built in Arkansas that can heat itself by using solar energy and electric heat. The concrete overlay panels (4 m $\times$ 3.048 m) were manufactured by the incorporation of graphite powder and steel fiber and equipped with a solar energy supply. The field test illustrated that only solar energy is insufficient to heat the whole pavements and restricting energized pavement sections only to the pavement surface. The field-testing results also demonstrated the conductive concrete systems should only be implemented on the runway section where heavy snow removal equipment is hard to operate, instead of the whole pavements, because of the high implementation cost. Moreover, it was previously proposed that the satisfying strength of conductive concrete is required before the implementation [58].

Furthermore, geothermal energy has been seen as a heating source through heat pipe or direct hot water to melt ice/snow on roads, sidewalks, bridge pavements around the world. It was agreed that using geothermal energy has cost-benefits, i.e., heating airport runways with geothermal sources can be paid in 2–5 years [59]. The approach can be achieved by "either transfer the heat through pipes in the pavement by a flow of warm liquids or from direct geothermal water or through the use of heat exchanger systems or hot runoff liquids from local industry or power plants." The field experiment of using geothermal energy was conducted by storing waste heat from a local steel factory into a borehole for heating pavements [60]. This method is cost-effective as compared to the mechanical snow removal method, and it was estimated that the system will pay for itself in 1–2 years if only the runway is heated, and in 5–10 years if the entire surface area is heated.

The application of geothermal energy in practical cases was illustrated by Morita [61] in Japan that they constructed the Gaia snow-melting system to transfer geothermal heat for de-icing ice/snow. The first system was installed in Ninohe, Iwate Prefecture, in 1996, and it showed that even at low temperatures in cold seasons (the average temperature is −8.3 °C), the system can effectively melt compacted snow/ice layers and is environmentally friendly. However, they also proposed that further improvement would be required to maintain the system and have good anti-icing performance on very cold days [61]. This technology has many advantages, such as the reduced consumption of fossil fuels (and thus, less CO_2 emission), reduced consumption of electricity with a higher coefficient of performance, and reduced urban heat island effect with heat exhaust placed underground [62]. The next application was proposed—that they directed the tunnel spring water and hot spring water to the highway for melting snow on roads where the average minimum temperature was around −18 °C and the average annual accumulated snowfall depth of 500 cm [53]. The test indicated that this approach could effectively remove the snow/ice accumulation on roads. Moreover, this design exhibited higher construction costs (1.15 to 1.24 times the cost of conventional, electric-powered road heating) and lower operating costs (22 to 46 percent of the conventional systems).

No construction problem was found for installing the heat pipe system. The cost data of this system are summarized by Hoppe [63]. Operating costs for the heat pipe system are lower than those for an electrical or hydronic system. The heating system does not seem to have any adverse effects on the durability of the bridge pavements. Apart from Japan, geothermal energy has also been frequently applied in the U.S. for controlling snow/ice on roads. Because there are only few geographical locations with geothermal fluids above 37.8 °C, heat pipe technologies are commonly built to transfer warm water in the U.S. In 1972, some alternative anti-icing methods were summarized by Murray and Eigerman (1972) [64], and their estimated costs are illustrated in Figure 4. It shows that a high cost was required for geothermal heating technology; more specifically, geothermal snow melting without a heat pump (around \$215.3/m^2), ground source heat pumps (\$376.7/m^2 for typical highway bridge pavements systems), and "hydronic" geothermal heating (\$1076.4 to \$1614.6/m^2 for the deck and heating system). Due to the high cost of this technology, it was only used for significant cases, such as bridge pavements and airports [65]. A representative example of the field test was a heat pipe system in New Jersey, where a circulated ethylene glycol-water mixture between pipes was embedded 0.051 m below the pavement surface and a horizontal grid was buried 0.9144 to 3.9624 m below the pavement on 0.61 m levels. Compared to an electric heating system, this design needs a higher cost because of the significant cost of excavation to place the ground pipes [66]. Another field test using geothermal energy was conducted in Virginia, where a two-lane bridge pavement on Route 60 over the Buffalo River in Amherst County was conducted and the Freon HCFC 123 was used as the working fluid. The testing results indicated that using heat pipe technology to prevent snow/ice accumulation is practical and the anti-icing performance was highly related to the efficiency of the working fluid. Furthermore, these heat pipe systems feature easy installation and low cost. The cost data of this system are summarized in Hoppe's study (listed in Table 1) [63]. Moreover, it was also proposed that this system did not exhibit any side effects on the durability of the bridge pavements.

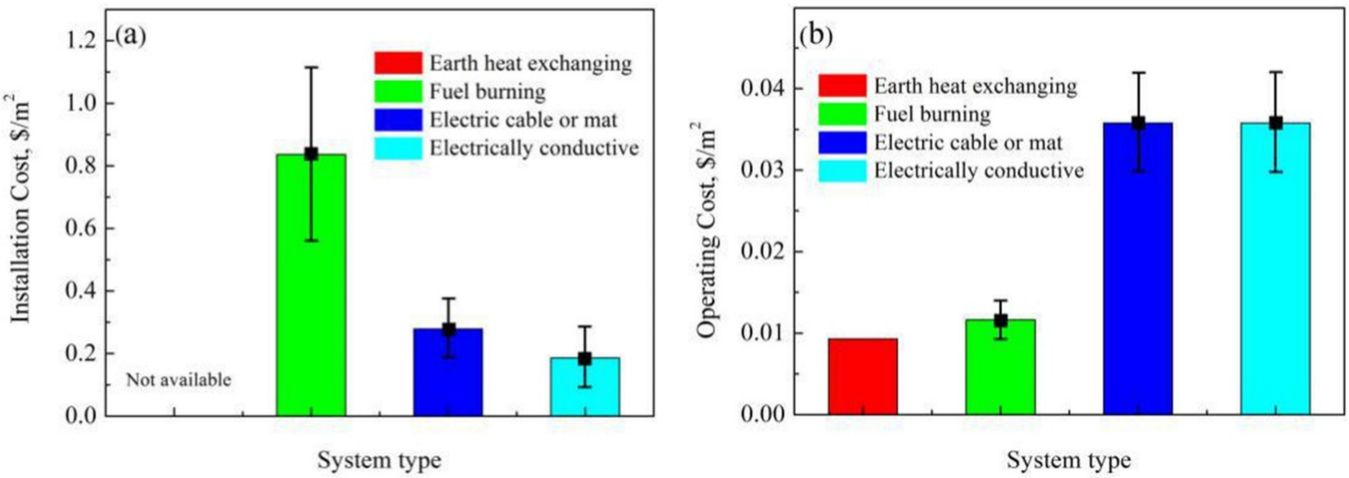

Figure 4. Pavement heating system installation costs (**a**) and operating costs (**b**) per season, in 1972, USD [63].

Table 1. Cost Data of a Geothermal Heating System in Virginia in 2000 [64].

Item	Cost, USD
Construction	\$323/m^2 (deck area); \$181,500 total
Retrofit	\$18.73/m^2
Operating	\$18/h (gas); \$312/year (electricity)
Maintenance	\$500/year

2.4. De-Icing Chemicals

Anti-icing chemical features reduce the freezing point of water, thus decrease the formation of ice, and prevent the formation of bonds between the road surface and the ice. Therefore, the decrease in the freezing point of road anti-icing chemicals is usually determined through experiments [67]. Although liquid chemicals are most frequently applied as a de-icing agent, solid chemicals can be potentially used in some cases. There are mainly five chemicals that can be used for anti-icing operations in North America: sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), potassium acetate (KAc), and calcium magnesium acetate (CMA). Furthermore, deicers extracted from agricultural products can be implemented solely or together with other chemicals [68]. Maintenance personnel from Kansas and New Jersey estimated in interviews that using anti-icing agents could save 15–20% of costs. Moreover, Coleman (2014) presented that using chemicals had other advantages including the ease of farming, better road conditions for customers, and safety [69]. However, implementing deicers at extremely low temperatures poses a potential risk of structural damage. More specifically, when the temperature is lower than the eutectic temperature of the deicer, road conditions may become worse due to the refreezing of the road surface.

Chloride-based salts are the most commonly used chemicals for reducing the freezing point of water. According to a 2007 survey, DOTs in most states depended on chloride salts and abrasives for winter highway maintenance [70]. Sodium chloride (NaCl) or rock salt is the most widely used chemical because of its high storage and low cost [71]. Apart from using it as de-icing agent for pavements, it can also be used as a rock salt for de-icing or added to sand or other abrasives to prevent freezing. The Salt Research Institute recommends that the application rate of NaCl should be 100 to 300 pounds of solid matter per lane mile (30 to 90 kg per lane km) and 45 to 165 gallons per lane mile (105 to 388 L per lane km) 23% of the liquid brine. However, at a pavement temperature of −12 °C, NaCl is hardly used and has little effect [72].

The eutectic temperature is the lowest temperature at which the de-icing solution remains liquid, which depends on the concentration of the deicer, and is usually expressed as a weight percentage of the solution. After the snow or ice melts, and a de-icing agent will be diluted in the melting water, which may cause the solution to re-freeze, which leads to a significant difference in the eutectic temperature of the deicer. Figure 5 shows a comparison of the eutectic temperature and effective temperature of some commonly used deicers. Most chemicals will lose their functions before reaching the eutectic temperature. When the temperature drops below −9 °C, NaCl and CMA are no longer cost-effective, and the help of other deicers may be needed to achieve the goal of controlling snow and ice. Other options used in the U.S. and Nordic countries include mixing NaCl with liquid $MgCl_2$ or $CaCl_2$. In addition, it has been shown that mixing rock salt with carbohydrate by-products, such as corn derivatives or sugar beets, can increase traction. When winter becomes more severe, it may be necessary to develop low-temperature modified high-performance brine [73–78].

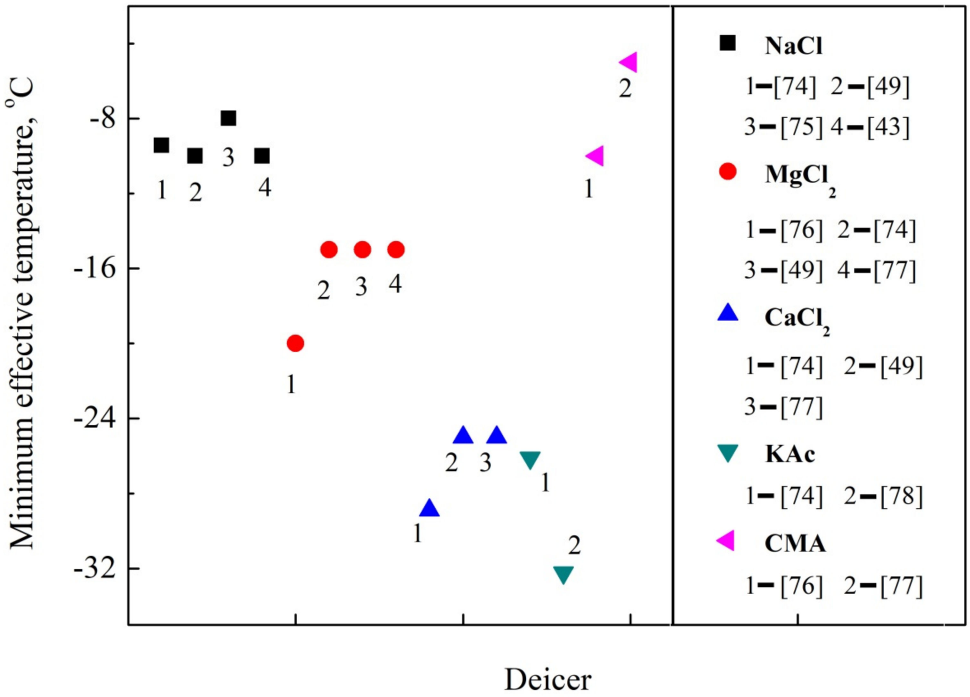

Figure 5. Eutectic temperature vs. effective temperature for several deicers [43,49,74–78].

Figure 6 illustrates the eutectic curves of some commonly used de-icing agents, i.e., their solution concentration-related freezing point temperature, which demonstrates that NaCl usually exhibits the best performance above −9 °C, but it does little to melt snow when the temperature is below −21 °C. At extremely low temperatures (−9 °C and lower), other chlorides and acetates are badly required as supplementary deicers to melt ice, because of their lower freezing points [79]. A study was recently conducted to observe the physical mechanisms of wet de-icing pavements using NaCl. Compared with the theoretical value of freezing point, studies have found that 60% lower salt concentration can result in remarkable snow-melting performance [80]. The difference is attributed to the fact that the chemical substance weakens the ice bonding with the sidewalk, so that the ice formed is weakly bonded on the pavements, which is easily damaged by the shear traffic force. Apart from the NaCl, calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$) have been widely studied. At low temperatures, $CaCl_2$ and $MgCl_2$ have better ice melting performance than salt brine, and many DOTs use them as anti-icing or pre-wetting salt solutions for rock salt [81]. However, $CaCl_2$ and $MgCl_2$ lack economic benefits as compared to NaCl, which may bring difficulty for their application. Furthermore, the $CaCl_2$ and $MgCl_2$ have another disadvantage; the residues of deicers will absorb more water than NaCl, potentially leading the pavements into dangerously slippery conditions [82–84].

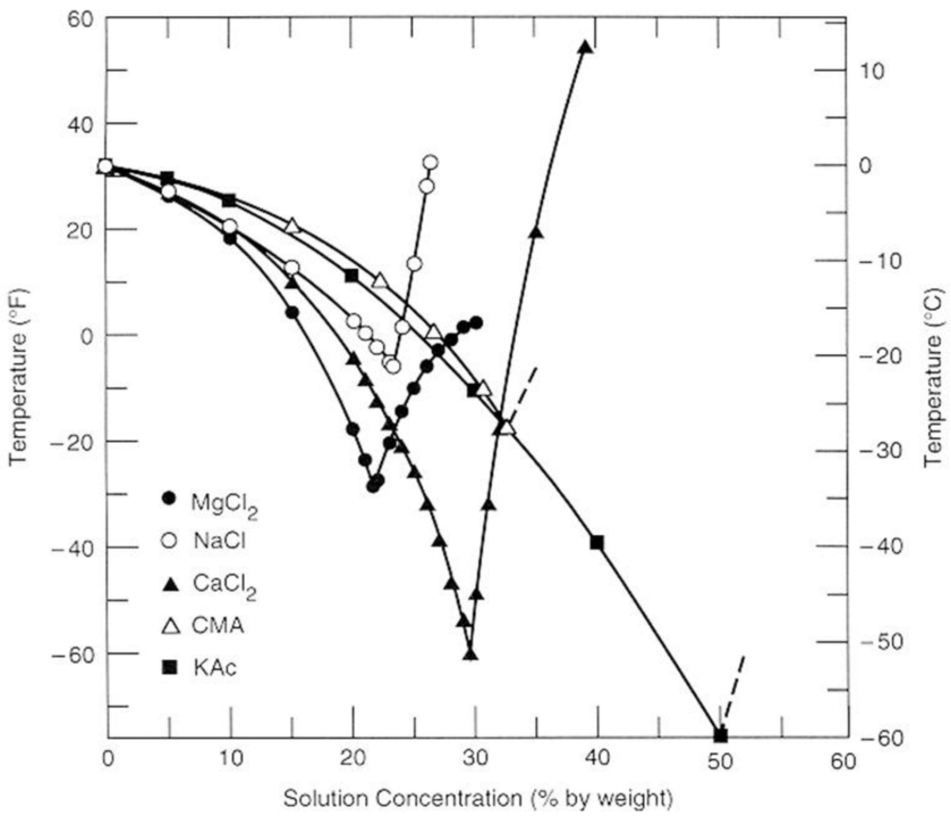

Figure 6. Freezing point of common road chemicals.

The functions of these deicers were previously investigated in many studies, and it was revealed by the field studies that $CaCl_2$ is more effective in snow management than NaCl because it can attract water and cling on the road [85]. Furthermore, another site test was conducted by the Maine DOT to evaluate the effectiveness of various snow control methods on interstate highways during the low-temperature snowstorm in January 2011, which lasted about 7 to 8 h [86]. It was found that mixing pre-moistened sand with 70/30 brine and a proprietary $MgCl_2$ blend is more cost-effective than the other two methods (three applications of salt or early salting followed by sanding). In Alberta, Canada, when the environment drops between −18 °C and −12 °C, workers mix salt with a small amount of sand and then add a large amount of liquid de-icing agent ($MgCl_2$ or $CaCl_2$) to melt the ice on the road piece. Experimental data show that, compared with NaCl, the amount of $CaCl_2$ required to reach the comparable anti-icing performance between −17.8 and −12.2 °C within an hour was much less, and the introduced chloride ion will be reduced by 5 times, and the cation will be reduced by 10 times [87]. The higher de-icing efficiency of $CaCl_2$ was proved by another research that, under conditions between −9 and −15 °C, applying $CaCl_2$ as deicer could result in more undercutting of ice on pavement than NaCl [88]. However, a different result was given by a laboratory study. It was demonstrated that the de-icing ability of various chemicals at −5 °C followed the order of NaCl > $CaCl_2$ > CMA > Urea, while the rate at which the deicers debonded snow from pavement complied the consequence of $CaCl_2$ > NaCl > Urea > CMA [89]. Granular $CaCl_2$ was often combined with NaCl to further increase the effectiveness of NaCl in cold conditions, because $CaCl_2$ acts quickly, dissipates heat, and uses moisture in the air to form saltwater [90]. Mitchell [91] reported a case study in Illinois that discovered the effectiveness of mixing salt with 10–15% $CaCl_2$. It was found that the additives extend the effective life of the brine and lower the minimum effective temperature. Another field study was conducted to investigate the difference in efficacy between pure brine and a mixture of brine and CMA. Researchers have observed that saltwater containing CMA lasts longer on the road. In addition, a study was conducted in Baltimore where the use of $MgCl_2$ for anti-icing operations was suspended due to slippery road conditions.

Based on a Colorado study, it was claimed that $MgCl_2$ (liquid), $CaCl_2$ (liquid), potassium acetate, and other commercially available de-icing agents, unspecified Agro-based, and sodium acetate and sodium acetate present the lowest effective temperature. In contrast, they believed that abrasives, potassium formate, and sodium chloride are the least effective products [92].

Coleman [69] reported that KAc and calcium magnesium acetate (CMA) are both effective as anti-icing chemicals at significantly low temperatures. A survey conducted in Virginia found that $MgCl_2$ and $CaCl_2$ were both beneficial for snow removal [93]. It was also reported that, for anti-icing chemicals, the increase of the anti-icing effectiveness leads to cost enhancement. It was claimed that the cost of the salt brine is about 5 cents/gallon, while the $CaCl_2$ or $MgCl_2$ is about 40 to 50 cents/gallon [94]. For the KAc based salt, the price will be as high as $2.5/gallon, and thus it can only be used in critical infrastructures, such as bridges pavements, or airports because the corrosive effect on rebar is far less than chloride-based salts [69]. Figure 7 summarizes the approximate cost of common deicers from many references.

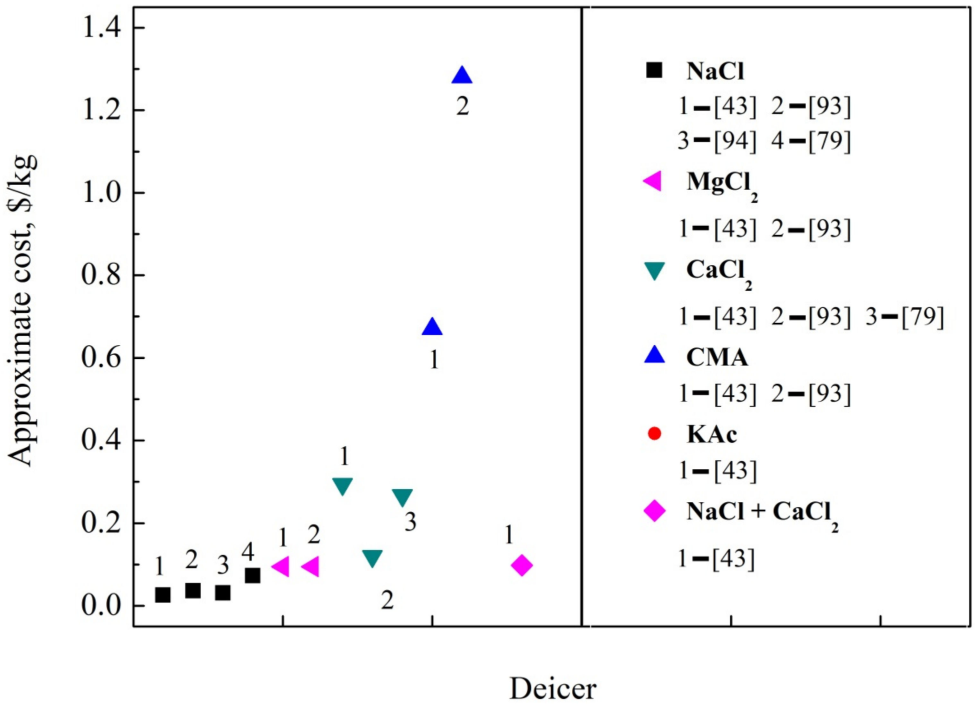

Figure 7. Approximate Cost of Common Deicers [43,79,93,94].

Some organic materials can perform as enhancers of the chemical deicers for the ice/snow control, including the agricultural by-products (ABP) or organic by-product, popularly used additives are including corn syrup, corn syrup and other corn derivatives, beet juice-sugared or de-sugared; lignin/lignosulfonate; molasses (usually from sugar cane); brewer/distiller by-product; and glycerin. Various agricultural-based chemicals can be used alone or as additives to other winter maintenance chemicals [68].

Agriculture-based additives increase costs, but may increase the snow-melting capacity of deicers, reduce the corrosiveness of chemicals, and/or have a longer life than standard chemicals when applied on the pavements [95]. In addition, agriculture-based additives utilize renewable resources and have little impact on the environment. Alkoka [96] studied a de-icing product called Magic, which is a mixture of ABP and liquid $MgCl_2$. The product can effectively work within the condition as low as −28.9 °C [96]. Pesti [97] used brine and liquid corn salt on the Nebraska highway and evaluated the cost of this program, it was found that liquid corn salt achieves bare pavement conditions faster than salt brine and saves road user costs [97]. Fu [98] conducted field tests on two different beet molasses-based materials (30% beet juice + 70% brine) and normal brine (23% NaCl) as a pre-wetting agent and anti-icing agent in Burlington, Canada. The results show that the pre-wetting property of the mixture at low temperature is not significantly improved. Even though it is more costly than ordinary brine, organic materials can reduce the amount of chloride released into the environment. However, the results of this study are limited to application rates and observed winter conditions [98]. The Swedish National Road and Transport Institute examined the friction characteristics of the three mixtures. The brine used for pre-wetting salt made with 30% beet powder does not significantly improve friction. In the case of mixing sand and hot water, longer-term performance is observed [99]. Shi [100] has developed a systematic method to assist maintenance agencies in selecting or developing their deicers, which integrates available information on all aspects of the deicer and incorporates agency priorities.

Recently, freezing point depressants of bio-derived materials have been developed for airport runways and road applications. Approximately 0.35 kg of crude glycerol will be generated when each gallon of biodiesel was produced. Therefore, this by-product is under the urgent requirement to increase the cost-benefit [101,102]. In addition, crude glycerin is also a very cost-effective de-icing addictive because it costs US $0.02 per gallon. However, the purification of crude glycerin is needed for ice/snow control. The incorporation of succinate and glycerin will enhance the de-icing performance of salt brine to a level equivalent to $MgCl_2$ or KAc at a lower cost. At the same time, it is cost-effective, as it reduces the usage rate, the corrosion of metals, and the impact on concrete or asphalt materials. These chemical mixtures were very cost-effective for snow de-icing on certain road weather conditions. For example, it was found that "Supermix" (85% salt water, 10% Deicer, and 5% $CaCl_2$) above −9.4 °C shows a positive field performance when 40 gallons per lane mile of de-icing were used above −16.7 °C at 10 gallons per ton [103]. Some counties in Ohio have found that mixing brine with 10–15% agricultural-based products or less than 10% $CaCl_2$ "can considerably increase the amount of salt remaining on higher volume pavements when anti-icing and lower the effective working temperature of brine when pre-wetting at the spinner" [104]. Taylor valued the effectiveness of the brine mixtures made of glycerol, NaCl, $MgCl_2$, and commercial deicers, and it was concluded that a mixture of 80% glycerol and 20% NaCl exhibited the best laboratory performance and low negative effects [105]. However, this finding should be further concerned because the high viscosity of this mixture can prevent ice when diluted, but it will reduce its effectiveness. Besides, the use of glycerin may pose a potential risk to water quality.

Developing deicer compositions using sustainable resources, such as by-products of agricultural processes, offers many advantages. This approach is beneficial to the environment by reducing waste, decreasing impact, and creating environmentally safe deicers. Janke developed an environmentally friendly deicer or anti-icing agent from a by-product of a wet milling process of corn called "steep water". The deicer formulation is non-corrosive, inexpensive, water-soluble, and readily available in large quantities. Tests have shown that successful inhibition is achieved with the addition of these "steep water" soluble to chloride salts [106]. Similarly, Kharshan demonstrated the successfully increased corrosion protection of carbon steel using corn extracts [107]. It is suggested that an amount of 20 to 60 gallons per lane mile of the "steep water" deicer be applied to effectively clear snow and ice from roadways. When applied to roadways, the "steep water" deicer is not easily removed by passing vehicles or wind and remains in contact with the road, which provides continued de-icing performance with decreased application rates. Ice melting tests were conducted on a 0.089 m thick snow comparing "steep water" concentrated at 50% by weight of a dry substance to an industrial salt/sand mixture. The "steep water" demonstrated higher melting performance than the salt/sand mixture for both duration and strength. In addition, the "steep water" deicer also showed active ice melting at temperatures as low as −13 °C, whereas the salt/sand mixture ice melting stopped around

−7 °C [106]. Montgomery et al. proposed a deicer formulation, derived from corn steep water, in which glucose and corn steep water is combined with sodium hydroxide to form a biodegradable deicer solution with a freezing point around −26 °C [108]. Furthermore, corrosion testing resulted in little effect on mild steel. Mild steel bolts were immersed in and sprayed with various concentrations of "steep water" and showed no oxidation after four months [106]. Janke [109] proposed a non-corrosive, environmentally safe deicer composition made from vintners condensed soluble acquired from the processing of wine. This wine by-product deicer has a freezing point of −29 °C and is primarily a carbohydrate-based product [109].

Manitoba's search for alternative environmentally friendly de-icing agents led to an alcohol by-product produced by a nearby Crown Royal™ whiskey plant that was found to be effective. Other de-icing agents containing sugar beet by-products are also being explored [86]. A two-year study for the Colorado DOT found NaCl (liquid brine or solid), abrasives (non-volcanic), and $MgCl_2$ blend have the lowest cost per lane mile, whereas, pre-wet abrasives, CMA, potassium acetate, and potassium formate were considered more costly per lane mile. Moreover, a CDOT staff survey respondent mentioned that Clearlane had been very useful because it worked in very cold temperatures [110]. Cuelho [111] established best practices for removing snow and ice from roadways through laboratory and field experiments. The work found that anti-icing materials improved the ability of a plow to remove snow from the pavement surface, even at temperatures lower than −10 °C. $CaCl_2$ performed best on asphalt surfaces at all temperatures, while KAc performed best on concrete at all temperatures (−18 °C, −12 °C, −9 °C, and −1 °C).

Kelting and Laxon recently recommended the use of anti-icing because it can decrease costs by greater than 50% compared to conventional de-icing [3]. Infrastructure damage resulting from winter highway maintenance activities is substantial. Repairing the damage caused by snow and ice control operations could cost state and local agencies $5 billion each year [1]. As of 2014, there were 610,749 bridge pavements in the U.S., approximately 24 percent of which were structurally deficient [112]. The estimated cost of installing corrosion protection measures in new bridge pavements and repairing old bridges in the Snowbelt states ranges between $250 million and $650 million annually [72]. A study estimated that 3500 to 7000 bridge pavements would be damaged due to salts; the total cost to repair 1/10 of the bridge pavements would be between $50 million to $200 million per year [113]. Parking garages, pavements, roadside infrastructures, and non-highway objects near winter maintenance activities are also exposed to the corrosive effects of road salts. Finally, it should be noted that any repairs to the infrastructure translate to costs to the user in terms of construction costs, traffic delays, and lost productivity. Indirect costs are estimated to be greater than ten times the cost of corrosion maintenance, repair, and rehabilitation [114]. It is important to note that this is a generalized estimation for the nation.

2.5. Fixed Automated Spray Technology

Fixed automated spray technology (FAST) system is another technique for anti-icing pavements, which is typically installed at key and remote locations. Unlike the previously stated anti-icing strategies, which focus mainly on changing the pavement materials and heating the pavement surface through different sources, FAST applies the liquid deicers once a road's conditions or temperature threshold is reached to prevent ice formation.

This system is coupled with road weather information systems (RWIS) and reliable weather forecasts to spray deicers and promote the paradigm shift from being reactive to proactive in fighting winter storms. There are sensitive structures and critical segments of the roadway network that need to be free of snow and ice promptly before the winter maintenance vehicles can travel to the site and treat them.

During the winter season, accidents often occur on bridge pavements or shaded areas where the surface temperature tends to be lower than adjacent areas and creates potentially hazardous driving conditions, such as frequent frost and black ice [115,116]. With conventional mobile operations, the levels of service and traffic safety are also difficult and costly to maintain for locations far from winter maintenance sheds [117], or for areas that experience a high traffic volume. In the latter case, traffic congestion may delay the arrival of winter maintenance vehicles to the site in need of treatment [118]. In highly congested traffic areas, it is difficult to maintain the materials on the road, while it is desirable to implement the deicers before the frost. FAST is a technological solution designed to provide quick, effective service delivery to high-risk locations prone to icy conditions and/or with high traffic volumes, while reducing the amount of labor and materials needed through timely prevention of ice formation to the pavement or bonding or packing of snow. Indirect benefits from FAST may include reduced corrosion and environmental impacts and reduced travelers' delay and stress. A conceptual study indicated that eliminating even one accident a year would provide a benefit-cost ratio greater than 1 for two automated FAST systems installed on bridge pavements for the Minnesota Department of Transportation (MnDOT) [119]. Another study indicated a benefit/cost ratio of 2.36 for a proposed FAST installation on a section of I-90 in Washington State, assuming a 60 percent reduction in snow and ice-related accidents [120].

FAST systems have been used in Europe more extensively than in North America. Since the mid-1980s, hundreds of automated anti-icing systems have been used throughout Europe as established tools to battle snow and ice conditions on highways, bridge pavements, and airports. In North America, FAST is a relatively new technology that has gained popularity since the late 1990s [121]. All nine respondents to the FAST survey conducted for this research project installed their first FAST system in 1995 or later, either as a test and evaluation project or based on regional deployment needs. FAST systems aim to deliver the anti-icing chemical to key locations in a controlled manner, using pumps, piping, valves, and nozzles (or discs). The ideal application would be fully automated, using the pre-programmed logic and real-time input from many atmospheric and pavement sensors on-site. When the sensors detect ice presence or an imminent frost or icing event, the nozzles will be automatically triggered to spray the anti-icing chemical at a pre-determined rate and pattern.

While the concept is intuitive, its implementation is complex because the FAST system "integrates sensing technology, fluid mechanics, data processing, and communications technology with the concrete and asphalt of a highway facility" [122]. Systems with less automation are often deployed in the United States, particularly those with the capabilities of automatic detection and remote activation. Such systems sacrifice some of the FAST benefits for better system reliability. For instance, the fully automated FAST system may be able to treat short-duration frost events whereas the remotely activated FAST system cannot. Additionally, the fully automated system can improve the level of service at the installation site even when winter maintenance personnel are not available.

A complete FAST system includes the spray subsystem that delivers the anti-icing chemical onto the road surface and the control subsystem that triggers the spraying action. The spray subsystem consists of the following components:

- Reservoirs to store an appropriate amount of anti-icing chemicals in an accessible area.
- A set of pumps to deliver the chemical through the piping of the hydraulic system, which connects the nozzles to the reservoirs through valves.
- A series of spray nozzles that deliver the chemical to various point locations.
- RWIS or atmospheric and pavement sensors on-site for early frost or ice warning.
- A remote processing unit (RPU) that can store a certain amount of data preset by the agency, as well as observational data collected from the sensors for an extended period.
- A software application to display the FAST data in graphic and tabular formats and to manage users and their privileges.
- Electronically controlled automated and manually operated triggering devices to spray deicers.

FAST is not a solution for the entire road network, but rather for key locations where it can derive the maximum benefits. Selection of the proper site is crucial to the success of any FAST system installation. The site should have unique characteristics, such as high winter accident statistics, remote location away from the regular maintenance routes, or very high traffic volumes [123]. A report summarizing the experience of the Kentucky Transportation Cabinet recommended that the FAST system be used in the following areas and/or conditions: (1) crash-prone areas; (2) isolated structures that require the de-icing truck to travel an unreasonable distance to treat; (3) remote areas that are difficult to reach in bad weather; or (4) bridge pavements over water which may be more susceptible to freezing moisture [116]. A methodology and a decision support tool were developed for the Nebraska Department of Roads to prioritize FAST installations on candidate bridge pavements, considering accident history, bridge alignment, weather, traffic, and bridge distance from maintenance yard, among others [124].

3. Conclusions

This review synthesized the available literature or ongoing research on the performance and cost of various anti-icing strategies on the durability of pavement materials. The chemicals used for anti-icing strategies and the corrosive effects on infrastructures were compared. Several key findings are as follows:

- Open-graded high friction surface can facilitate the breaking and abrasion of compacted ice covering on roads. Although the benefits of this strategy are observable, the durability challenges, including rutting, raveling, clogging, cracking, delamination, and moisture susceptibility are remaining. Using high-friction polymer overlays are effective at decreasing the traffic risks. By combining the medium-porosity limestone aggregates and the liquid de-icing agent, the high-friction polymer overlay provides an impressive anti-icing performance. However, the maximum service temperature was only about −10 °C. For the temperature of the overlay, if the surface temperature was as low as −20 °C, half of the overlay was covered by frost. Adding rubber particles to the asphalt binder can significantly enhance the elasticity of the pavement. This elastic pavement can provide a condition to break the bonding between the pavement and ice. However, the challenge of this technology is the compaction status of asphalt will be sacrificed. It was claimed that the durability of the high-friction polymer overlay is questionable, but a Sweden case indicated that it is an effective approach to eliminate the water damage of pavement.
- The asphalt binder mixed with anti-icing additives can effectively confine the ice formation on the surface of the asphalt pavement. However, besides the high cost of the anti-icing additives, it was found that the application of anti-icing additives had some negative impacts on the rutting stability, thermal cracking resistance, and moisture susceptibility of asphalt mixture. In addition, the release of the de-icing chemicals tended to decrease with the extension of service time, especially during warm and rainy seasons.
- Heating strategies, including electrical heating, pipe heating, and geothermal heating are effective methods to realize ice and snow control. However, the cost of transforming the energy from the heating source to the pavement surface is quite high. Apart from the high operation cost, the repeated traffic loading will cause damage on the cables, which leads to the damage of the electric heating functions. For the conductive carbon fabric, the weak connection between carbon fabric and the copper electrodes hinders electric current flow and results in the generation of over-amount of heat, which is harmful to the long-term performance of anti-icing pavements. Although induction heating has many advantages, the long-term performance of the induction-heating pavement was barely reported, and the structural design needs to be further investigated.
- The anti-icing chemical will reduce the eutectic temperature of the liquid solution and prevent the bonding between the road surface and the ice. However, the corrosive effect of anti-icing chemicals on the durability of pavement materials and metal parts is always a long-standing challenge. In addition, the application of anti-icing chemicals

will pose negative environmental problems, which should be systematically concerned. Fixed automated spray technology (FAST) system is a good method to minimize the application of anti-icing chemicals. By combining with road weather information systems (RWIS) and reliable weather forecasts, the negative impact of the anti-icing chemicals on the durability of infrastructures and ecosystems can be significantly alleviated. Although the FAST system is intuitive, its implementation is complex because this system requires the combination of sensing technology, fluid mechanics, data processing, and communications technology with the concrete and asphalt of a highway facility. Sometimes, an effective system needs to sacrifice some benefits of FAST to reach good reliability.

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References

1. Federal Highway Administration. *How Do Weather Events Impact Roads?* Federal Highway Administration: Washington, DC, USA, 2005.
2. National Cooperative Highway Research Program. *Environmental Stewardship Practices, Procedures, and Policies for Highway Construction and Maintenance*; NCHRP 25-25; National Cooperative Highway Research Program: Washington, DC, USA, 2009.
3. Kelting, D.L.; Laxson, C.L. *Review of Effects and Costs of Road De-Icing with Recommendations for Winter Road Management in the Adirondack Park*; Report # AWI2010-01; Adirondack Watershed Institute: Paul Smiths, NY, USA, 2010.
4. Goodwin, L.C.; Pisano, P. *Best Practices for Road Weather Management*; Road Weather Management: Washington, DC, USA, 2003.
5. Shi, X.; Strong, C.; Larson, R.; Kack, D.; Cuelho, E.; El Ferradi, N.; Seshadri, A.; O'Keefe, K.; Fay, L. *Vehicle-Based Technologies for Winter Maintenance: The State of the Practice*; Western Transportation Institute: Bozeman, MT, USA, 2006.
6. Hao, W.; Yu, J.; Song, W.; Zou, J.; Song, Q.; Zhou, L. A critical state-of-the-art review of durability and functionality of open-graded friction course mixtures. *Constr. Build. Mater.* **2020**, *237*, 117759.
7. Sharma, S.; Goyal, T.K. Utilization of Polymers in Improving Durability Characteristics of Open-Graded Friction Course Layer: A Review. In *Sustainable Civil Engineering Practices*; Springer: Singapore, 2020; pp. 81–88.
8. Adams, E.E.; Alger, R.G.; Chekan, J.P.; Williams, F.D.; Valverde, R. Persistence of Reduced Snow to Pavement Shear-Strength for 2 Aggregate Materials Treated with CMA and NaCl. In *Chemical Deicers and the Environment*; Lewis Publishers: Chelsea, MI, USA, 1992; pp. 481–493.
9. Alger, R.G. *Anti-Icing Coatings and Methods*; Michigan Technological University: Houghton, MI, USA, 2005.
10. Nixon, W. *An Analysis of the Performance of the SafelaneTM Overlay during Winter 2005–2006*; Cargill: Wayzata, MN, USA, 2006.
11. Nixon, W. *An Analysis of the Performance of the SafelaneTM Surface Overlay during Winter 2006–2007*; Cargill: Wayzata, MN, USA, 2007.
12. Stuart, K.; Mogawer, W. *Laboratory Evaluation of Verglimit and Plusride*; Federal Highway Administration: Washington, DC, USA, 1991.
13. Zhang, H.; Han, S.; Liu, H. A summary of asphalt concrete pavement for deicing and snow melting technology. *Helongjiang Jiaotong Keji* **2008**, *3*, 8–9.
14. Shi, X.; Huang, J.; Yang, Z. Pavement Treatments for Sustainable Winter Road Maintenance. In *Sustainable Winter Road Operations*; John Wiley & Sons: Hoboken, NJ, USA, 2018; p. 402.
15. Tan, Y.Q.; Zhou, C.X. *Anti-Icing Performance of Asphalt Pavement Mixed with Crumb Rubber*; World Scienctific Publishing: Singapore, 2012.
16. Takeichi, K.; Sato, I.; Hara, F.; Yamamoto, C. Performance of Various Antifreezing Pavements by Field Test. *Transp. Res. Rec. J. Transp. Res. Board* **2001**, *1741*, 114–123. [CrossRef]

17. Akin, M.; Fay, L.; Shi, X. Friction and Snow—Pavement Bond after Salting and Plowing Permeable Friction Surfaces. *Transp. Res. Board* **2020**, *11*, 794–805. [CrossRef]
18. Akin, M.; Zhang, Y.; Shi, X. *Pavement Surface Treatments for Ice-Prone Locations in the Illinois Highway System*; Illinois Center for Transportation: Rantoul, IL, USA, 2018.
19. Young, L.M.; Durham, S.A. Performance of an Anti-Icing Epoxy Overlay on Asphalt Surfaces. *J. Perform. Constr. Facil.* **2013**, *27*, 836–840. [CrossRef]
20. Evans, J.F. *Evaluation of the SafeLane™ Overlay System for Crash Reduction on Bridge Deck Surfaces*; U.S. Department of Transportation: Washington, DC, USA, 2010.
21. Flintsch, G.W.; de León Izeppi, E.; McGhee, K.K.; Roa, J. *Field Performance Evaluation of High-Friction Surfaces*; Virginia Tech: Blacksburg, VA, USA, 2010.
22. Zhang, H. Research on the Antifreezing Asphalt Mixture by Crumb Rubber Modified. Master's Thesis, Chang'an University, Xi'an, China, 2009.
23. Wyant, D.C. *Final Report: Exploring Ways to Prevent Bonding of Ice to Pavement*; Virginia Transport Research Council: Charlottesville, VA, USA, 1998.
24. Wu, Y.-L.; She, W.; Shi, D.; Jiang, T.; Hao, T.-H.; Liu, J.; Zhang, Q.-C.; You, J.; Li, R. An extremely chemical and mechanically durable siloxane bearing copolymer coating with self-crosslinkable and anti-icing properties. *Compos. Part B Eng.* **2020**, *195*, 108031. [CrossRef]
25. Edwards, Y. *Polymer Modified Water Olymer Modified Water Olymer Modified Waterproofing and Pavement System for the High Coast bridge in Sweden*; VTI Report; Swedish National Road and Transport Research Institute: Linköping, Sweden, 2001.
26. Shi, X.; Fu, L. (Eds.) *Sustainable Winter Road Operations*; Wiley Blackwell: Hoboken, NJ, USA, 2018.
27. Maupin, G. *Field Investigation of Verglimit*; Virginia Highway and Transportation Research Council: Charlottesville, VA, USA, 1986.
28. Kiljan, J. *Verglimit Evaluation (Boulder)*; Colorado Department of Highways: Denver, CO, USA, 1989.
29. Turgeon, C. *Evaluation of Verglimit (A De-Icing Additive in Plant Mixed Bituminous Surface)*; Federal Highway Administration: Washington, DC, USA, 1989.
30. Lohrey, E. *Field Evaluation of an Experimental Bituminous Pavement Utilizing an Ice-Retardant Additive-Verglimit*; Federal Highway Administration: Washington, DC, USA, 1992.
31. Current Deicing Practices and Alternative Deicing Materials. Available online: http://www.michigan.gov/documents/ch2-deice_51438_7.pdf (accessed on 18 February 2014).
32. Akin, M.; Jiang, H.; Xianming, S.; Veneziano, D.; Williams, D. *Snow Removal at Extreme Temperatures*; Final Report. 99085/CR11-04; Western Transportation Institute: Bozeman, MT, USA, 2013.
33. Giuliani, F.; Merusi, F.; Polacco, G.; Filippi, S.; Paci, M. Effectiveness of sodium chloride-based anti-icing filler in asphalt mixtures. *Constr. Build. Mater.* **2012**, *30*, 174–179. [CrossRef]
34. Ma, T.; Geng, L.; Ding, X.; Zhang, D.; Xiaoming, H. Experimental study of deicing asphalt mixture with anti-icing additives. *Constr. Build. Mater.* **2016**, *127*, 653–662. [CrossRef]
35. Ma, T.; Ding, X.; Wang, H.; Zhang, W. Experimental Study of High-Performance Deicing Asphalt Mixture for Mechanical Performance and Anti-Icing Effectiveness. *J. Mater. Civ. Eng.* **2018**, *30*, 4018180. [CrossRef]
36. Mitchell, M.R.; Link, R.E.; Seo, Y.; Seo, U.; Eum, J.; Lee, S.-J. Development of a Geothermal Snow Melting System for Highway Overlays and Its Performance Validations. *J. Test. Eval.* **2011**, *39*, 592–602. [CrossRef]
37. Yehia, S.A.; Tuan, C.Y. Thin Conductive Concrete Overlay for Bridge Deck Deicing and Anti-Icing. *Transp. Res. Rec. J. Transp. Res. Board* **2000**, *1698*, 45–53. [CrossRef]
38. Yehia, S.; Tuan, C.Y.; Ferdon, D.; Chen, D. Conductive concrete overlay for bridge deck deicing: Mixture proportioning, optimization, and properties. *ACI Mater. J.* **2000**, *97*, 172–181.
39. Chang, C.; Ho, M.; Song, G.; Mo, Y.-L.; Li, H. A feasibility study of self-heating concrete utilizing carbon nanofiber heating elements. *Smart Mater. Struct.* **2009**, *18*. [CrossRef]
40. Yang, T.; Yang, Z.; Singla, M.; Song, G.; Li, Q. Experimental Study on Carbon Fiber Tape–Based Deicing Technology. *J. Cold Reg. Eng.* **2012**, *26*, 55–70. [CrossRef]
41. Axon, E.; Couch, R. Effect of insulating the underside of a bridge deck. In *Highway Research Record*; U.S. Department of Transportation: Washington, DC, USA, 1963.
42. Zenewitz, J.A. *Survey of Alternatives to the Use of Chlorides for Highway Deicing*; Engineering Research and Development Bureau: Washington, DC, USA, 1977.
43. Zhang, J.; Das, D.; Peterson, R. Selection of effective and efficient snow removal and ice control technologies for cold-region bridges. *J. Civil Environ Archit. Eng.* **2009**, *3*, 1–14.
44. Joerger, M.D.; Martinez, F.C.; ODOT Research Unit. *Electric Heating of I-84IN LADD Canyon, Oregon*; SPR 304-461; Oregon Department of Transportation: Salem, OR, USA, 2006.
45. Mohammed, A.G.; Ozgur, G.; Sevkat, E. Electrical resistance heating for deicing and snow melting applications: Experimental study. *Cold Reg. Sci. Technol.* **2019**, *160*, 128–138. [CrossRef]
46. Zhou, X.-M.; Yang, Z.; Chang, C.; Song, G. Numerical Assessment of Electric Roadway Deicing System Utilizing Emerging Carbon Nanofiber Paper. *J. Cold Reg. Eng.* **2012**, *26*, 1–15. [CrossRef]
47. Song, S. Deicing Method Based on Carbon/Glass Fiber Hybrid Textile. US Patent 20120132634A1, 31 May 2009.

48. Tuan, C.Y. *Implementation of Conductive Concrete for Deicing*; University of Nebraska: Lincoln, NE, USA, 2008.
49. Yehia, S.; Tuan, Y. Bridge Deck Deicing. In Proceedings of the Crossroads 2000 Conference, Iowa, NE, USA, 19–20 August 1998.
50. Tuan, C. *Conductive Concrete for Bridge Deck Deicing and Anti-Icing*; Project No. SPR-PL-1(037) P512; Nebraska Department of Roads: Lincoln, NE, USA, 2004.
51. Sun, D.; Sun, G.; Zhu, X.; Xiao, F.; Dai, Z.; Liu, F. Electrical characteristics of conductive ultrathin bonded wearing course for active deicing and snow melting. *Int. J. Pavement Eng.* **2017**, *20*, 1299–1308. [CrossRef]
52. Derwin, D.; Booth, P.; Zaleski, P.; Marsey, W.; Flood, W. Snowfree®, Heated Pavement System to Eliminate Icy Runways. *Management* **2003**, *2012*, 3–16.
53. Gao, J.; Sha, A.; Wang, Z.; Tong, Z.; Liu, Z. Utilization of steel slag as aggregate in asphalt mixtures for microwave deicing. *J. Clean. Prod.* **2017**, *152*, 429–442. [CrossRef]
54. Gao, J.; Guo, H.; Wang, X.; Wang, P.; Wei, Y.; Wang, Z.; Huang, Y.; Yang, B. Microwave deicing for asphalt mixture containing steel wool fibers. *J. Clean. Prod.* **2019**, *206*, 1110–1122. [CrossRef]
55. Liu, K.; Xu, P.; Wang, F.; Jin, C.; Huang, M.; Dai, D.; Fu, C. Deicing efficiency analysis and economic-environment assessment of a novel induction heating asphalt pavement. *J. Clean. Prod.* **2020**, *273*, 123123. [CrossRef]
56. Liu, K.; Fu, C.; Dai, D.; Jin, C.; Li, W.; Li, S.; Xu, X. Induction heating performance of asphalt pavements incorporating electrically conductive and magnetically absorbing layers. *Constr. Build. Mater.* **2019**, *229*, 116805. [CrossRef]
57. Hiroshi, T.; Nobuhiro, T.; Nobuo, K. Development of highway snow melting technology using natural energy. In Proceedings of the 10th PIARC International Winter Road Congress, Lulea, Sweden, 16–19 March 1998.
58. Heymsfield, E.; Osweiler, A.; Selvam, P.; Kuss, M.L. Developing Anti-Icing Airfield Runways Using Conductive Concrete with Renewable Energy. *J. Cold Reg. Eng.* **2014**, *28*, 04014001. [CrossRef]
59. Athmann, T.; Bjornsson, R.; Borrell, P.; Thewlis, P. Geothermal Heating of Airport Runways. Available online: http://emerald.ts.odu.edu/Apps/FAAUDCA.nsf/AcevesDADEFullProposal.pdf?OpenFileResource (accessed on 18 February 2014).
60. Hellström, G. UTES for Snow Melting For Airport Runways in Sweden. Available online: http://www.egec.org/news/egec_restmac_workshop.htm (accessed on 27 November 2007).
61. Morita, K.; Tago, M. Operational characteristics of the Gaia snow-melting system in Ninohe, Iwate, Japan. In Proceedings of the World Geothermal Congress, Kyushu-Tohoku, Japan, 28 May–10 June 2000.
62. Yasukawa, K. *Direct Use of Geothermal Energy in Japan*; Institute for Geo-Resources and Environment: Tokyo, Japan, 2007.
63. Murray, D.M.; Eigerman, M.R. *A Search: New Technology for Pavement Snow and Ice Control*; US Environmental Protection Agency: Washington, DC, USA, 1972.
64. Hoppe, E.J. Evaluation of Virginia's First Heated Bridge. *Transp. Res. Rec. J. Transp. Res. Board* **2001**, *1741*, 199–206. [CrossRef]
65. Lund, J.W. Reconstruction of a pavement geothermal deicing system. *Geo-Heat Cent. Q. Bull.* **1999**, *20*, 14–17.
66. Lund, J. Available online: https://www.osti.gov/etdeweb/servlets/purl/895225 (accessed on 3 April 2014).
67. *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals*; ASTM Standard C672/672M-12; ASTM International: West Conshohocken, PA, USA, 2012.
68. Nixon, W.A.; Williams, A.D. *A Guide for Selecting Anti-Icing Chemicals*; Version 1.0; The University of Iowa: Iowa City, IA, USA, 2001.
69. Coleman, M. The Economics of Anti-icers. *AGRIS* **2014**, *39*, S3–S9.
70. Fay, L.; Shi, X. Laboratory Investigation of Performance and Impacts of Snow and Ice Control Chemicals for Winter Road Service. *J. Cold Reg. Eng.* **2011**, *25*, 89–114. [CrossRef]
71. Fischel, M. *Evaluation of Selected Deicers Based on a Review of the Literature*; Colorado Department of Transportation: Denver, CO, USA, 2001.
72. Committee of the Comparative Costs of Rock Salt and Calcium Magnesium Acetate for Highway Deicing. *Highway Deicing: Comparing Salt and Calcium Magnesium Acetate*; National Research Council: Washington, DC, USA, 1991.
73. Wieringa, J. *North American Winters in Europe: Focus on High Performance!* Industry Match: Groningen, The Netherlands, 2010.
74. Burkheimer, D. Effective Temperature of Deicing Chemicals. *Snow & Ice Factsheet*, 2006; 20.
75. Norem, H. Selection of Strategies for Winter Maintenance of Roads Based on Climatic Parameters. *J. Cold Reg. Eng.* **2009**, *23*, 113–135. [CrossRef]
76. Resource Concepts Inc. *Survey of: Alternative Road Deicers*; FHWA-SA-95-040; Nevada Department of Transportation: Carson City, NV, USA, 1992.
77. Shi, X.; Fay, L.; Yang, Z.; Nguyen, T.A.; Liu, Y. Corrosion of Deicers to Metals in Transportation Infrastructure: Introduction and Recent Developments. *Corros. Rev.* **2009**, *27*, 23–52. [CrossRef]
78. Myhra, T. Deicing and Anti-Icing Decisions for Runways and Ramps. In Proceedings of the FAA Alaskan Region Airports Conference, Anchorage, AK, USA, 8–9 May 2012.
79. Rubin, J.; Garder, P.; Morris, C.; Nichols, K.; Peckenham, J.; McKee, P.; Stern, A.; Johnson, T. *Maine Winter Roads: Salt, Safety, Environment and Cost*; The University of Maine: Orono, ME, USA, 2010.
80. Klein-Paste, A.; Wåhlin, J. Wet pavement anti-icing—A physical mechanism. *Cold Reg. Sci. Technol.* **2013**, *96*, 1–7. [CrossRef]
81. Baroga, E. *2002–2004 Salt Pilot Project*; Washington State Department of Transportation: Olympia, WA, USA, 2005.
82. Perchanok, M.S.; Manning, D.G.; Armstrong, J. *Highway De-Icers: Standards, Practice, and Research in the Province of Ontario*; Ontario Ministry of Transportation: Downsview, ON, Canada, 1991.

83. Center for Watershed Protection. The Stormwater Manager's Resource Center, Stormwater Management Fact Sheets. Available online: http://www.stormwatercenter.net/ (accessed on 18 February 2014).
84. Wasstrom, R. Before the Storm: Knowing How and When to Apply Salt and Other Chemicals Makes Crews More Effective Once the Snow Flies. *Public Works* **2007**, *138*, 11.
85. Warrington, P.D.; Phelan, C. *Roadsalt and Winter Maintenance for British Columbia Municipalities, Best Management Practices To Protect Water Quality*; Water BC: Victoria, BC, Canada, 1998.
86. CTC & Associates. *Snow and Ice Control at Extreme Temperatures*; Wisconsin Department of Transportation Bureau of Highway Operations: Madison, WI, USA, 2011.
87. Brandt, G.H. *Environmental Degradation by De-Icing Chemicals and Effective Countermeasures: Potential Impact of Sodium Chloride and Calcium Chloride De-Icing Mixtures on Roadside Soils and Plants*; National Academy of Engineering: Washington, DC, USA, 1973.
88. Blackburn, R.R.; Bauer, K.M.; McElroy, A.; Pelkey, J.E. Chemical undercutting of ice on highway pavement materials. *Transp. Res. Rec.* **1991**, *1304*, 230–242.
89. Trost, S.E.; Heng, F.J.; Cussler, E.L. Chemistry of Deicing Roads: Breaking the Bond between Ice and Road. *J. Transp. Eng.* **1987**, *113*, 15–26. [CrossRef]
90. *Using Salt and Sand for Winter Road Maintenance*; Wisconsin Transportation Bulletin No. 6; Wisconsin Transportation Information Center: Madison, WI, USA, 1996.
91. Mitchell, G.F.; Richardson, W.; Russ, A. *Evaluation of ODOT Roadway/Weather Sensor Systems for Snow & Ice Removal Operations/RWIS Part IV: Optimization of Pretreatment or Anti-Icing Protocol*; Ohio Research Institute for Transportation and the Environment: Athens, OH, USA, 2006.
92. Roosevelt, D.S. *A Survey of Anti-Icing Practice in Virginia*; Virginia Department of Transportation: Charlotesville, VA, USA, 1997.
93. Levelton Consultants Limited. *Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts*; Transportation Research Board: Washington, DC, USA, 2007.
94. Shi, X.; Fay, L.; Gallaway, C.; Volkening, K.; Peterson, M.; Pan, T.; Creighton, A.; Lawlor, C.; Mumma, S.; Liu, Y. *Evaluation of Alternative Anti-Icing and Deicing Compounds Using Sodium Chloride and Magnesium Chloride as Baseline Deicers, Phase I*; Colorado Department of Transportation: Denver, CO, USA, 2009.
95. Kahl, S. Agricultural By-Products for Anti-Icing and De-Icing Use in Michigan. In Proceedings of the 6th International Symposium on Snow Removal and Ice Control Technology, Spokane, WA, USA, 7–9 June 2004; pp. 552–555.
96. Alkoka, M.; Kandil, K. Effectiveness of using organic by-products in decreasing the freezing point of chemical solutions. New Challenges for Winter Road Service. In Proceedings of the 11th International Winter Road Congress, Sapporo, Japan, 28–31 January 2002.
97. Pesti, G.; Liu, Y. *Winter Operations—Abrasives and Salt Brine*; University of Nebraska: Lincoln, NE, USA, 2003.
98. Fu, L.; Omer, R.; Jiang, C. Field test of organic deicers as pre-wetting and anti-icing agents for winter road maintenance. In Proceedings of the TRB 91st Annual Meeting Compendium of Papers, Washington, DC, USA, 22–26 January 2012.
99. Möller, S. *New Technology and New Methods in Winter Road Maintenance*; VTI Rapport Issue No. 569; Swedish National Road and Transport Research Institute: Linköping, Sweden, 2007.
100. Fay, L.; Volkening, K.; Gallaway, C.; Shi, X. Performance and impacts of current deicing and anti-icing products: User perspective versus experimental data. In Proceedings of the 87th Annual Meeting of Transportation Research Board, Washington, DC, USA, 13–17 January 2008.
101. Pachauri, N.; He, B. Value-added utilization of crude glycerol from biodiesel production: A survey of current research activities. In Proceedings of the ASABE Annual International Meeting, Portland, OR, USA, 9–12 July 2006.
102. Thompson, J.C.; He, B.B. Characterization of Crude Glycerol from Biodiesel Production from Multiple Feedstocks. *Appl. Eng. Agric.* **2006**, *22*, 261–265. [CrossRef]
103. DeVries, R.M.; Hodne, B. Chloride Cocktail: Department in Illinois Finds Good Results Mixing Their Own Deicer/Anti-Icer. *Roads Bridges* **2006**, *44*, 8.
104. Ohio Department of Transportation. *Snow & Ice Practices*; Ohio Department of Transportation: Columbus, OH, USA, 2011.
105. Taylor, P.; Verkade, J.; Gopalaakrishnan, K.; Wadhwa, K.; Kim, S. *Development of an Improved Agricultural-Based Deicing Product*; Iowa State University: Ames, IA, USA, 2010.
106. Janke, G.A.; Johnson, W.D., Jr. Deicing Composition and Method. U.S. Patent US5965058A, 12 October 1999.
107. Kharshan, M.; Gillette, K.; Furman, A.; Kean, R.; Austin, L. *Novel Corrosion Inhibitors Derived From Agricultural By-Products: Potential Applications In Water Treatment*; NACE International: Houston, TX, USA, 2012.
108. Montgomery, R.; Yang, B.Y. Biodegradeable deicing composition. Patent WO2004031317A1, 15 April 2003.
109. Janke, G.A.; Johnson, W.D., Jr. Deicing Composition and Method. U.S. Patent US5709813A, 20 January 1998.
110. Shi, X.; Akin, M.; Pan, T.; Fay, L.; Liu, Y.; Yang, Z. Deicer Impacts on Pavement Materials: Introduction and Recent Developments. *Open Civ. Eng. J.* **2009**, *3*, 16–27. [CrossRef]
111. Cuelho, E.; Harwood, J.; Akin, M.; Adams, E. *Establishing Best Practices for Removing Snow and Ice from California Roadways*; California Department of Transportation: Sacramento, CA, USA, 2010.
112. *Highway Bridges by State and Highway System 2014*; Federal Highway Administration: Washington, DC, USA, 2014.
113. *Highway Deicing: Summary of Cost and Use Issues*; Special Report 235; National Research Council: Washington, DC, USA, 1991.
114. Yunovich, M.; Thompson, N.G. Corrosion of highway bridges: Economic impact and control methodologies. *Concr. Int.* **2003**, *25*, 1.

115. Friar, S.; Decker, R. Evaluation of a Fixed Anti-Icing Spray System. *Transp. Res. Rec. J. Transp. Res. Board* **1999**, *1672*, 34–41. [CrossRef]
116. Barrett, M.L.; Pigman, J.G. *Evaluation of Automated Bridge Deck Anti-Icing System*; University of Kentucky: Lexington, KY, USA, 2011.
117. Christillin, M.; Ardemagni, C.; Trombella, G. The Buthier Viaduct—A Different Approach to Road Network Maintenance in Winter. In Proceedings of the 10th PIARC International Winter Road Congress, Lulea, Sweden, 16–19 March 1998.
118. Ward, B. Evaluation of a fixed anti-icing spray technology (FAST) system. In Proceedings of the 81st Annual Meeting of the Transportation Research Board, Washington, DC, USA; 2002.
119. Keranen, P. Automated bridge deicers for increased safety and decreased salt use in Minnesota. In Proceedings of the 10th PIARC International Winter Road Congress, Lulea, Sweden, 16–19 March 1998.
120. Stowe, R. A benefit/cost analysis of intelligent transportation system applications for winter maintenance. In Proceedings of the Transportation Research Board 80th Annual Meeting, Washington, DC, USA, 7–11 January 2001.
121. Fixed, Automated Anti-Icing Spraying Systems. Snow and Ice Pooled Fund Cooperative Program. Available online: http://www.sicop.net/FAST%20Project.pdf (accessed on 18 February 2014).
122. Bell, G.T.; Nixon, W.A.; Stowe, R.D. *A Synthesis to Improve the Design and Construction of Colorado's Bridge Anti-Icing Systems*; Colorado Department of Transportation: Denver, CO, USA, 2006.
123. Civil Engineering Research Foundation. *Evaluation of the FreezeFree Anti-Icing System*; Sage Publications: Thousand Oaks, CA, USA, 2005.
124. Khattak, A.J.; Pesti, G.; Kannan, V. *Guidelines for Prioritizing Bridge Deck Anti-Icing System Installations. Phase I and Phase II Report*; The National Academies of Sciences, Engineering, and Medicine: Washington, DC, USA, 2003.