ROAD SALT ALTERNATIVES AND PAVEMENT INNOVATIONS

A Literature Review

Project: Investigation of Road Salt Alternatives and Pavement Innovations

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Contents

Introduction

This report is Activity 1 of the Legislative-Citizens Committee on Minnesota Resources (LCCMR) 2018 funded project entitled "Investigation of Road Salt Alternatives and Pavement Innovations." The objective of the project is to investigate road salt alternatives (RSAs) and pavement innovations to reduce or eliminate the transport of chlorides into Minnesota's lakes, streams, and groundwater. According to the project work plan, Activity 1 is a review of previous research on road salt alternatives, pavement innovations, and pavement friction.

Previous studies have investigated the performance of RSAs with regards to the prevention of ice formation on the pavement surface (anti-icing), the reduction or elimination of ice or snow cover on the pavement surface (deicing), their environmental impact, their cost, production processes, and various other related topics. To maintain alignment with the focus of the funded project with respect to RSAs, this report focuses on their performance, environmental impact, and cost. With regards to pavement innovations, this report focuses on concrete and asphalt pavement innovations that are intended to enhance anti-icing, deicing, and road friction.

The organization of this report is such that it first introduces and discusses RSAs investigated and reported in the literature. Studies that specifically investigated the performance of RSA with respect to anti-icing, deicing, or road friction follow. Although the previously mentioned sections on RSAs include a general discussion of their environmental impacts such as biochemical oxygen demand (BOD) and corrosivity, some studies focused specifically on the impact of RSAs on specific environmental aspects (e.g. toxicology). These studies are reviewed in a separate section on environmental impact, which also includes a review of studies that have modeled the fate, transport, or impact of RSAs, mainly the BOD of calcium magnesium acetate (CMA) in streams and lakes.

Lastly, previous research on pavement innovations are discussed. This discussion includes a description of the pavement innovation technique and, depending on the study, covers issues such as anti-icing, deicing, road friction, energy requirements, and cost.

Road Salt Alternatives

To minimize the environmental impact of salts, many RSAs have been investigated over the past several decades on the basis of water solubility, their ability to lower the freezing point of water, corrosiveness, toxicity, cost, environmental impact, and flammability (Boice 1986). This section introduces and discusses these materials, most of which are organic compounds, and covers such issues as their cost, effectiveness, and general environmental impacts. Please note that there is a subsequent section devoted solely to studies that investigated a specific environmental impact of RSAs and that the current section presents a general overview of environmental concerns and findings for each of the RSAs presented.

Before beginning the discussion of RSAs that are intended to melt snow and ice, it is worthwhile to note that research has determined that abrasives (i.e. sand and grit) can be more effective at increasing road friction (Perchanok 2010) and provide longer lasting road friction if the abrasives are pre-wetted as they are placed on the road, heated to ~82 °C (~180 °F) just prior to placement, or mixed with hot water just prior to placement (Nixon 2001). These techniques help more abrasive stay on the road upon placement (i.e. not bounce off) and it helps abrasives stay on the road for a longer period of time because, upon placement without such treatment, a large fraction of the abrasives bounce off the road surface, are blown off by natural winds (D'Itri 1992), or are swept off in 10 to 100 vehicle passages (Nixon 2001).

Concerning the organic RSAs discussed in the literature, much focus has been on acetates-based products, formate-based products, glycol and glycerol, and succinate-based products. A discussion of these RSAs begins immediately below.

Acetate-Based Alternatives

As previously mentioned, one organic RSA is acetate (Boice 1986, Baltrenas and Kazlauskiene 2009), which includes potassium acetate, sodium acetate, and calcium magnesium acetate (CMA) (Fay and Muthumani 2017). Although most of the research has been completed on CMA, potassium acetate is currently favored in cold climates because of its improved level of service, i.e., it will melt snow and ice at lower temperatures than road salt and most other RSAs. The main advantage of acetate-based alternatives is that they are not as corrosive to most metals as salts (Ihs and Gustafson 1996, MDOT and Tetra Tech 2006, Fay and Muthumani 2017) and Ihs and Gustafson (1996) have stated that CMA also causes less freeze/thaw damage to pavements. Acetates are, however, corrosive to galvanized steel and they can cause damage to concrete and asphalt through alkali-silica reactions on aggregates and emulsification of asphalt binder (Fay and Muthumani 2017). With regards to steel, Baltrenas and Kazlauskiene (2009) found that magnesium acetate was three times less corrosive than calcium chloride and two times less corrosive than magnesium chloride. Boice (1986) found that the corrosiveness (and ice melting ability) of CMA depends on the ratio of calcium to magnesium, with optimum values from three to seven. In one study investigating aluminum corrosion, the potassium acetate corrosion rate was equal to that for chloride, although the corrosion rate for CMA was lower (Levelton Consultants 2008). Levelton Consultants (2008) also pointed out that many studies that have investigated the corrosivity of CMA were done on steel bars submersed in CMA, not of steel bars embedded in concrete exposed to CMA, which would more accurately represent the true exposure process. They also noted that concrete scaling is more dependent on the quality of concrete than on the deicer used.

With regards to cost, acetates are significantly more expensive than chloride-based deicers and, therefore, are mostly used at airports and where steel corrosion is a concern, such as at bridges. In fact, only 10-15% of department of transportations that responded to a survey indicated they use acetate in some way (Fay and Muthumani 2017). Acetates can be up to 20 times more expensive than chloride-based deicers (Boice 1986, Fay and Muthumani 2017) and Albright (2009) found that CMA is still more expensive than salts even when factoring in the cost of corrosion damage caused by salts. The lack of an economic and reliable production method of CMA contributes to the high cost (Boice 1986). Albright (2009) noted, however, that future advances in CMA production could result in a price drop of 20%. In one such method, Jin et al. (2010) converted a vegetable waste product into acetic acid and CMA. Electrodialysis was used to condense CMA from the acetic acid with 22% of the total organic carbon in the vegetable waste being converted to CMA.

In a study that investigated methods with the potential to reduce the total negative impact of deicing by considering the total life-cycle impact, Fitch et al. (2013) showed that CMA has higher total life-cycle environmental impacts than conventional rock salt and preemptive treatment of roads with salt brine and/or CMA. Most of the total life-cycle environmental cost of CMA was due to CMA production, which uses more energy and water and produces more greenhouse gases than chloride-based methods. As previously discussed, it also has a higher BOD.

Another drawback of acetates is that they are less effective than chloride-based deicers (Bang and Johnston 1998). For example, Boice (1986) found that it took 1.65 times the CMA to obtain and equivalent melting power of salt. Others have found or estimated different amounts of CMA are required to equal the effectiveness of chloride-based deicers, but every study has found more CMA (or acetate) is needed. For example, MDOT and Tetra Tech (2006) found that up to two times the amount of CMA was required for equal effectiveness and Fay and Muthumani (2017) stated values ranging from 1.3 to 1.5 times are typical when the temperature is below -6.7 °C (20° F).

Acetates also work more slowly compared to salts such as sodium chloride, they are less effective in freezing rain, dry snow, and light traffic and they also don't work well when applied to thick accumulations of snow or ice (Fay and Muthumani (2017). Ihs and Gustafson (1996), however, found that, in some cases, the effectiveness of CMA lasted longer than that of sodium chloride.

D'Itri (1992) noted that, in practical applications, powdered CMA was blown off the road surface due to winds (either natural or vehicle induced) and Boice (1986) noted that because CMA is lightweight it cannot penetrate snow and ice. CMA also absorbs moisture and can form sticky conglomerations (Boice 1986). The use of CMA in pellet form prevented winds from blowing the material off the surface of the road (D'Itri 1992) and allowed the Michigan Department of Transportation to more optimally use CMA. In a different application, acetates can also be used to pre-wet salts, which increases the effectiveness of the salt (MDOT and Tetra Tech 2006).

A summary of acetate-based deicers is shown in Table 1 below.

Table 1. Summary of information on acetates (modified from Fay et al. 2015).

Form	Application Rate	Cost*	Effectiveness
Sodium Acetate	Near 32° F (thin ice): 190-320 lbs/lane-mile. 10° F (1" ice): 600-1500 lbs/lane-mile	\$1000-\$1500 per ton or \$95-\$240 per lane mile	Excellent at melting. Works more quickly and at lower temperatures than NaCl
CMA	250-400 lbs/lane-mile	\$600-\$2000 per ton or \$75-\$400 per lane-mile	Similar to NaCl but requires more CMA to achieve similar results. Works more slowly. Not as effective in freezing rain and light traffic
Potassium Acetate	Deicing: 60-80 gal/lane-mile. Anti-icing: 25-60 gal/lane-mile.	\$600-\$1200 per ton or \$192-\$512 per lane-mile**	Activates quickly. Works more quickly than glycol and is less slippery

* Product cost only (does not include labor or other application related costs)

**Assumes density of 10.7 lbs per gallon

Environmental concerns regarding the use of acetates as RSAs include impact to soils, vegetation, aquatic life, and water bodies. Most studies have found or estimated minimal or no environmental impact of acetates when they are used as an anti-icing or deicing agent. For example, Albright (2009) concluded that CMA would cause negligible changes to soil permeability and fertility even at concentrations much higher than those expected in road runoff and there would be no negative impact on vegetation on land or on aquatic organisms. The only environmental threat, according to Albright (2009), would be BOD in "poorly flushed" waters in which CMA accumulates. Similarly, Baltrenas and Kazlauskiene (2009) stated that calcium acetate and magnesium acetate do not affect water bodies and do not build up over time and that the calcium and magnesium can improve both soil structure and fertility. The Transportation Research Board (1991) stated that CMA is likely to have no adverse effect on humans and few negative environmental impacts. CMA produced from alternative sources, such as municipal solid waste, however, could cause contamination and introduce other problems.

Other studies have found, however, that there could be some environmental impacts. For example, at high concentrations, CMA could affect certain kinds of algae and it could free aluminum and iron ions from the soil. The calcium and magnesium ions, however, when released through microbial degradation, could help neutralize acid rain (Boice 1986). The Minnesota Stormwater Manual (2018) also states that acetates would characteristically be absorbed by the soil but if they made it to the groundwater, they would be mobile, and they could impact surface waters. Small ponds and slow moving waters are the most likely water bodies to be impacted by acetates, especially from sodium acetate and potassium acetate, which are more mobile. Bang and Johnston (1998) noted that CMA may increase water hardness but that these ions tend to precipitate, which reduces the risk of groundwater contamination. Others, however, have reached different conclusions. For example, Ihs and Gustafson (1996) stated that CMA infiltration to groundwater can be significant and these substances should not be placed near groundwater. D'Itri (1992) found that CMA did not mobilize metal ions in the soil. In fact, it decreased the mobility of some.

Fay and Muthumani (2017) stated that the biggest environmental concern of acetates is BOD. Also, the Western Transportation Institute (2017) found that, in general, non-chloride deicers can temporarily impact BOD but will have limited or no long-term impact on water quality and aquatic species. If an acetate-based product were to have a high BOD and it was used frequently it could, however, have a greater environmental impact for an extended period. Ihs and Gustafson (1996) stated that the oxygen demand and decomposition of CMA is strongly dependent on temperature and, at low temperatures, CMA may last long enough to be carried to receiving water bodies. D'Itri (1992) found that CMA biodegradation in a soil was complete when temperatures were between 10 and 20°C (50 and 68 °F) but results were variable when temperatures were near 2 °C (35 °F). BOD due to acetate road application may also impact wastewater treatment plants (WWTP). Rabideau et al. (1987) found that if CMA were to replace chloride deicers in whole or in part, it would have significant impacts on WWTPs in Buffalo, NY due to increased aeration requirements (caused by the increased in BOD) and increased sludge handling.

A table (in modified form) from McKenney (2015) that summarizes negative environmental impacts of CMA (and, for comparison, sodium, calcium, and magnesium chlorides) on surface water, groundwater, soil, vegetation, and other aspects is shown in Table 2.

For studies that have investigated specific environmental impacts of BOD and other issues, see the “Environmental Impact” section later in this report.

Table 2. Negative environmental impact of CMA compared to conventional deicers (modified from McKenney 2015).

Deicer Environ-mental Impact on:	Calcium Magnesium Acetate (CMA)	Sodium Chloride	Calcium Chloride	Magnesium Chloride
Soils	Ca and Mg ions may exchange with metals in soil, which may release metals. Ca and Mg improve soil structure	Na ions can bind to soil, break down soil, and decrease permeability. Cl may form complexes with metals, increasing metal mobility	Cl may form complexes with metals, increasing metal mobility. Ca improves soil structure	Cl may form complexes with metals, increasing metal mobility. Mg improves soil structure.
Groundwater	Metals have potential to contaminate groundwater	Elevated chloride levels in groundwater	Metals have potential to contaminate groundwater	Metals have potential to contaminate groundwater
Surface Water	BOD can decrease oxygen levels in water, especially in lower waters of stratified bodies.	Elevated chloride levels, especially in small water bodies with high residence times near heavily salted areas. Can cause stratification and anoxia in bottom waters.	Elevated chloride levels, especially in small water bodies with high residence times near heavily salted areas. Can cause stratification and anoxia in bottom waters.	Elevated chloride levels, especially in small water bodies with high residence times near heavily salted areas. Can cause stratification and anoxia in bottom waters.
Vegetation	Little impact. Osmotic stress can occur at high concentrations.	Negative impact through traffic spray, osmotic stress, and nutrient imbalance. May influence spread of salt-tolerant non-native species	Osmotic stress and leaf scorch	Osmotic stress and leaf scorch
Wildlife	Little or no impact	Linked to salt poisoning in birds	Little or no impact	Little or no impact
Vehicles and Highway Structures	Increases conductivity which can increase corrosion. Less impact than chlorides	Initiates and accelerates corrosion of exposed metals. Exacerbates scaling	Similar to sodium chloride	Similar to sodium chloride. Cement paste deterioration due to reactions with Mg

Formate-Based Alternatives

Formates, like acetates, are a potential non-chloride based organic alternative to road salt. They have been researched much less than acetates and, therefore, there is much less available literature corresponding to the use of formates as an RSA. Like acetates, their main advantage is that they are not as corrosive as road salts (Baltrenas and Kazlauskiene 2009) and they can help reduce dependence on chloride-based products.

Common forms are sodium formate and potassium formate, which are commonly used at airports for deicing airplanes. Formates are also corrosive to galvanized steel and damage concrete and asphalt but their main disadvantage is high cost.

With regards to environmental impacts, sodium formate can have some of the same negative environmental impacts as sodium chloride due to the release of the sodium ion (D'Itri 1992). Formate, like acetate, can increase water turbidity, hardness, and alkalinity. Formates will breakdown in topsoil, which can have a positive impact on plants at low concentrations but would be harmful at high concentrations.

Formates degrade in water and have a high BOD, which is more of a concern during spring runoff and warm weather (Fay and Muthumani 2017). BOD may be temporarily impacted but if the BOD and application rates are high, it could have a longer impact (Western Transportation Institute 2017).

A summary of formate-based RSAs is shown in Table 3 below.

Table 3. Summary of formate-based road salt alternatives (Modified from Fay et al. 2015).

Form	Application Rate	Cost	Effectiveness
Sodium Formate	Near 32° F (thin ice): 125-250 lbs/lane-mile. 10° F (1" ice): 400-1000 lbs/lane-mile	\$200-\$350 per ton or \$12-\$44 per lane mile (near 32° F, thin ice) \$40-\$175 per lane mile (10 °F, 1" ice)	Excellent at melting. Works more quickly and at lower temperatures than NaCl
Potassium Formate		\$1000-\$1600 per ton or \$62-\$200 per lane mile (near 32o F, thin ice) \$200-\$800 per lane mile (10 oF, 1" ice)	Similar to NaCl but requires more CMA to achieve similar results. Works more slowly. Not as effective in freezing rain and light traffic

Glycol and Glycerol

Glycol and glycerol are other organic, non-chloride based deicers that deice well and are typically used at airports. Both glycol and glycerol, which is a byproduct of biodiesel production, are not corrosive to steel and exert BOD when they break down in the environment (Fay and Muthumani 2017, Fortin et al 2014, Western Transportation Institute 2017). These products may be a carcinogen to plants, although the corresponding observations may have been influenced by airport sites that experienced high concentrations and high frequency of use. They can also negatively impact asphalt and concrete.

Overall, glycerin is less toxic than chloride, but in some situations they may affect plant cell metabolism, the functioning of enzymes, and fish fertility among other environmental impacts (Fay and Muthumani 2017).

Like the previous organic deicers discussed, these products are more expensive than chloride-based deicers and exert BOD in aquatic environments. The impact of BOD is not expected to be long-term, however, if a product has a high BOD and is used a lot, the BOD impact could exist for longer periods.

A summary of glycol and glycerol deicers is shown in Table 4 below.

Table 4. Summary of glycol and glycerol deicers (Modified from Fay et al. 2015).

Form	Application Rate	Cost	Effectiveness
Ethylene Glycol	50-2000 gal/lane-mile	$14-$40 per gallon or $700-$80,000 per lane mile	Very effective at deicing
Propylense Glycol		$10-$20 per gallon or $500-$40,000 per lane mile	
Glycerin	Varies depending on blend ratio. Typically used as an additive	$10-$30 per gallon	Used as ice inhibiting additive. Also provides anti-caking effect. Less expensive than gylcols.

Succinate-Based Alternatives

Succinate, or succinic acid, is a dicarboxylic acid that is used in the food and pharmaceutical industries. Succinate salts exist in nature and can be produced from fermentation, corn processing, and other processes. With regards to deicing, the most effective deicer has been potassium succinate (Fay and Muthumani 2017). Like the other organic deicers previously discussed, succinate is not corrosive to steel. It also is not corrosive to aluminum and causes no (or minimal) spalling of concrete (Fay and Muthumani 2017). In fact, when mixed with salt brine at 2% it reduced the corrosivity of the brine by 40%. Succinate BOD values are similar to values for acetate and formate and, like those materials, dissolved oxygen in receiving water bodies may temporarily be affected. Long-term impact is not expected unless application rates are high (Western Transportation Institute 2017).

A company, BioAmber, is working on producing a commercial potassium succinate deicer (Fay and Muthumani 2017). Because product manufacturing is not full-scale, the price of commercial potassium succinate has not yet been determined but BioAmber estimated that it could be similar to the cost of formate based deicers (Western Transportation Institute 2017). Fortin et al. (2014) has estimated costs could be up to $75 per lane-mile and $2.50 per gallon.

A summary table of the above RSAs and, for comparison, chlorides, is shown below in Table 5. Table 6 lists more detailed environmental impacts of some RSAs. Other literature that contains information similar to that discussed in this section and is related to general environmental impacts of RSAs include Fritzsche (1992), Fischel (2001), Ramakrishna et al. (2005), Fay and Shi (2012), and Fortin et al. (2014), among others.

Table 5. Summary of deicers (modified from Western Transportation Institute 2017).

Deicer	**Low Temperature Effectiveness (°F)**	**Relative Cost**	**Relative Toxicity**	**Environmental Impacts**	**Infrastructure Impacts**
Chlorides	NaCl: 15 $MgCl_2$: -5 $CaCl_2$: -15	Low	High	Accumulates in the environment. Impacts water quality and aquatic flora and fauna	Pavements and metals
Acetates	Kac: -26 NaAc: 0 CMA: 0	Moderate	Moderate	Moderate BOD	Pavements and galvanized steel
Formates	NaFm: 0 KFm: -20	High	Moderate	Moderate BOD	Pavements and galvanized steel
Glycols	-20	Moderate	High	High BOD	Limited
Succinates	Unknown	Unknown	Moderate	Moderate BOD	None known

Table 6. Environmental impacts of some RSAs (modified from Fay and Shi 2012).

Context / Deicer	Soil	Flora	Fauna	Surface & Ground Water	Human
Chloride-based	Cl, Ca, & K can mobilize metals. Na can ↓ permeability & ↑ density. Ca can ↑ permeability & aeration. Mg can ↑ stability & permeability. NaCl can ↓ fertility (which can ↓ plant growth & ↑ erosion)	Can cause leaf singe, browning, senescence, & osmotic stress	Little or no impact when ingested unless at extremely high concentrations. Can cause behavior changes and toxicity in birds and mammals by direct ingestion. > 250 mg/L can cause changes in community structures	Can ↑ hardness. Can cause density stratifications which can cause low DO at depth. Ca & K can mobilize metals. K can cause eutrophication	Skin & eye irritant. Sodium in drinking water can lead to high blood pressure. Can ↑ Cl, Ca, K, and Na concentrations above recommendations. Anti-caking agents may contain cyanide, a known carcinogen
Acetates & Formates	Ca & Mg can mobilize metals, ↑ stability & permeability. CMA degradation can ↑ pH	At low concentrations, acts as fertilizer. High concentrations can cause low yield, leaf browning, & senescence	High BOD can cause anoxic conditions in water. Can promote bacteria and algae growth. Kac & NaAc appear more toxic than CMA	Can leach metals into water. High BOD can lead to low DO. Can ↑ hardness and turbidity	Skin & eye irritant. Ca & Mg can increase water hardness
Glycols	Propylene glycol degradation may ↓ hydraulic conductivity in anaerobic soil	Can inhibit plant growth	Distrupts endocrine. Ingestion of concentrated fluid can cause death	Higher BOD than other deicers.	Distrupts endocrine. Ingestion of concentrated fluid can cause death
Urea	Can ↑ nitrate concentrations	Little information available	Little information available	Can ↑ nitrate. Urea additives can be toxic	Can ↑ nitrate concentrations in water

Other Road Salt Alternatives

The previously discussed RSAs are the most commonly mentioned and researched materials in the literature. Other materials, however, have been suggested and studied. Information on products such as urea, molasses, agricultural byproducts such as beet extract, and various commercial products consisting of different materials or material blends is available in the literature and is summarized below.

Laurinavicius et al. (2011) investigated potential RSAs and listed urea as potentially viable. D'Itri (1992) and Fortin et al. (2014) also discuss urea as a possible RSA. Urea is not corrosive to steel. Urea breaks down in the environment and will not accumulate, although it has a higher BOD than the other organic RSAs and is a fertilizer that contains nitrogen (Fortin et al 2014). According to Fortin et al. (2014), urea is most effective at melting ice from -10 to – 5 °C (15 to 23 °F). Urea, however, could be a significant source of nitrogen input to the environment (Findlay and Kelly 2011) and the nitrogen could act as a fertilizer. As a fertilizer, urea could cause algal blooms and other undesirable plant growth in water bodies (D'Itri 1992). Also, ammonia, which has relatively high toxicity to aquatic life, and nitrate formation from urea is of concern (D'Itri 1992) due to soil and water contamination. Laurinavicius et al. (2011) concluded that another material containing nitrate, calcium magnesium nitrate, is a potential RSA, but again, groundwater and soil contamination is a concern due to nitrate.

Molasses, an organic byproduct from sugar production, has also been used as a RSA. A patented molasses product called Geo-Melt in the United States and Safecote in Europe has been used in the United States, Great Britain, and Europe. Baltrenas and Kazlauskiene (2009) state that this product, when added to sodium chloride, helps the solution remain on the road seven times longer and can reduce salt use by 30-50%. It doesn't require any additional salt spreading or applicator equipment, which is convenient for road maintenance crews and municipalities. Adding 10% Geo-Melt to sodium chloride for road deicing increases the cost by 1.5 to two times. Geo-Melt should not be applied to low volume roads because, with low traffic volumes it can form a slippery layer before it mixes with the snow. No mention was made of environmental impact of Geo-Melt but the product does meet all British water quality standards (Baltrenas and Kazlauskiene 2009). McCullough (2010) investigated the use of Geo-Melt and found that users of the product felt it didn't last long enough on the road surface and, therefore, always required salt application in addition to Geo-Melt.

Harris et al. (1965) investigated low corrosivity deicers for airports and determined that the prime candidate was a mix of 75% tri-potassium phosphate and 25% formamide. Field testing was recommended as was further investigation into the effect the mixture had on concrete spalling. No other information on this mix was found in the literature.

Johnston and Huft (1992) suggested that mixtures of sodium salts and fatty acids with low molecular weights could be attractive RSAs. Advantages include the materials being non-toxic, non or only mildly corrosive, and biodegradable. Listed disadvantages include the cost and the release of sodium ions.

Jungwirth et al. (2014) developed and tested locally sourced brine alternatives for anti-icing winter roads in Alaska. The most successful mixes contained 2% potassium succinate, potassium acetate, or urea and corrosion inhibitors (potassium gluconate and sodium metalsilicate). While most mixes lost their effectiveness over time due to evaporation, two mixes that contained urea and an organic proprietary product called Boost, increased their effectiveness as time elapsed. The successful mixes were high-performing anti-icers with low corrosivity compared to conventional deicers and were made with byproducts from local distilleries or breweries.

In a report that summarized the experiences of the Michigan Department of Transportation's use of an agricultural (primarily from corn processing) byproduct based anti-icing agent in southwest lower Michigan from 1999 to 2002, Kahl (2002) noted that some drivers thought that, due to it's black color, the product used was black ice that had formed on the road surface. The agricultural byproducts were used as anit-icers and were initially applied at a rate of 35 gallons per lane-mile (~$30/lane-mile). Results showed these anti-icing practices maintained bare pavement longer, that salt use was reduced by 61%, and that the use of pure CMA with no salt would have cost $120/lane-mile. The study recommended that liquid agricultural byproducts be used as anti-icing agents prior to snowfall and the onset of ice formation, not as deicers.

In another study that investigated the use of bio-based RSAs, Nazari et al. (2016) developed a product that was designed to be environmentally friendly, contained no metals, and could be derived from an eco-friendly and cost-effective process. Locally sourced agricultural materials were mixed with 23% (by weight) salt brine and commercial additives that had little or no toxicity and the mixes were tested for their ice-melting capacity, ice-penetration rate, ability to protect asphalt and concrete, impact on friction coefficient of iced asphalt pavement, and anti-corrosion performance. A 23% by weight salt brine was used as the control. The main criteria for choosing the best performing anti-icer were the ice-melting capacity and the ability to increase the friction coefficient of iced asphalt pavement.

The top performing mix was a water-based solution made of 3% (by weight) of sugar beet extract, 0.67% sodium metasilicate, and 23% sodium chloride. This mix had a high ice-melting capacity and ability to increase the friction coefficient of iced asphalt at 25^{o} F. This mix also had a decent ice-penetration rate and low impact on Portland cement mortar scaling. It also had little impact on asphalt binder.

In his literature review, Albright (2009) discussed another agricultural based product, Ice Ban (or Magic Minus Zero). According to Albright (2009), Ice Ban was found to be an effective prewetting agent. Compared to salt it melted ice more quickly, penetrated more deeply, and was effective at lower temperatures than salt alone. The product has high concentrations of phosphorus and, although this phosphorus initially did not appear to be bioavailable, it was subsequently released through microbial action.

McCullough (2010) gave a more thorough summary of Ice Ban and its performance as an anti-icer and deicer. That investigation reported that Ice Ban melted more ice than magnesium chloride at all temperatures tested and it also melted ice more quickly. Furthermore, as the temperature dropped, all products became less effective at melting ice, but this effect was less for Ice Ban. Ice Ban melted as much or more ice than magnesium chloride even when Ice Ban was applied at temperatures 5.5 °C (10 °F) colder than magnesium chloride. Findings from McCullough (2010) include:

1. Ice Ban penetrated ice more quickly and deeper than magnesium chloride,
2. Ice Ban did not appear to be corrosive to metals or asphalt,
3. Friction test results after Ice Ban application on asphalt and concrete pavements had results similar to wet pavement results,

4. Dried Ice Ban on pavement did not decrease the skid resistance of asphalt but with concrete pavement skid resistance decreased slightly but remained within acceptable safety limits,
5. Field tests showed Ice Ban provided equal or better performance in all applications except one. That application was in Nebraska when Ice Ban was sprayed in a freezing rain (no liquid application is recommended, however, during a freezing rain),
6. Field tests confirmed previous lab experimental results that showed Ice Ban melts more ice more quickly than magnesium chloride,
7. Field tests confirmed previous lab experimental results that showed Ice Ban is less corrosive than salt, and
8. Salt that is pre-wet with Ice Ban is more effective than salt alone.

ASCE (1999) is an extensive study that investigated the effectiveness, corrosivity, and ease of use of Ice Ban. This report also notes that Ice Ban provided equal or better performance than control materials in almost every case. The low corrosivity of Ice Ban was also noted as was the fact that, in some cases, Ice Ban lowered corrosion rates to values less than the corrosion rate of pure water. The impact on concrete scaling was similarly low and was much better than the other deicing agents tested (chlorides and acetates). ASCE (1999) does note, however, that users sometimes had difficulty in using and applying Ice Ban due to it's high viscosity and presence of solids, both of which lead to clogged nozzles and applicators.

A study by Roosevelt and Fitch (2000) determined that the Virginia DOT should not use Ice Ban M50 as a pre-wetting agent for snow and ice control because of the cost and operational problems associated with its use. The study found that Ice Ban M50 was more effective than a similar amount of magnesium chloride or sodium chloride and it was less stressful to roadside vegetation than any other chemical tested. There were problems, however, with consistency (product composition would change from batch to batch), mold, and product stability. Although the product was not recommended for use, it was recommended to conduct further tests on Ice Ban. McCullough (2010) found that users of Caliber, another commercial product, believed it was cleaner and much improved compared to Ice Ban. No further information on Caliber, however, was found in the literature.

Beet products and byproducts have also been investigated and used as RSAs. For example, in Arkansas, rock salt pretreated with BEET 55C ®, a natural beet product, has been used (McKenney 2015). Also, many states in the mid-west have used "Beet Heet", a sugar beet molasses-based commercial product that increases the ability of rock salt to melt ice (Rhodan and Sanburn 2014). It was estimated that about 175 municipalities in the mid-west were using “Beet Heet” in 2014.

Some RSA products investigated were a combination of previously discussed materials. For example, researchers at the South Dakota Department of Transportation developed Ice Shear ™ which is a deicing mixture of equimolar sodium acetate and sodium formate (Bang and Johnston 1998). It has low corrosivity and is an effective deicer (Johnston and Huft 1992). The sodium ion in Ice Shear ™ is more soluble than the calcium and magnesium in CMA and both acetate and formate promote bacterial growth. Drawbacks to this product include the fact that Ice Shear ™ may deplete oxygen with its high BOD. Bang and Roseland (1989) found that Ice Shear ™ decomposed quickly when temperatures were warm but decomposition rates were slow when temperatures were near freezing. Bang and Johnston (1998) evaluated the environmental effects of Ice Shear ™ and investigated its behavior in soil and water. Their results indicated that Ice Shear ™ chemical compounds are biologically oxidized and that biodegradation during transport is quick enough to dilute the concentrations of organic salts in highway runoff. Thus, concentrations reaching receiving waters were expected to be reduced. The tolerance of aquatic life to the product is high (overall it has a low toxicity) and it causes no harm to lab animals through skin contact or inhalation (Bang and Roseland 1989). Also, Bang and Johnston (1998) found that Ice Shear ™ is relatively harmless to Rainbow Trout and roadside vegetation. At low concentrations in soils the product may act as a fertilizer for plants. Lettuce, however, is not tolerant of Ice Shear ™ but other broadleaf vegetation is tolerant.

Finally, some reports suggested that methanol may have potential as an RSA (Dunn and Schenk 1980; D’Itri 1992) but methanol has limited effectiveness due to relatively rapid evaporation (D’Itri 1992).

Performance of Road Salt Alternatives

This section reviews literature in which the performance of RSAs has been directly evaluated. Performance with regards to anti-icing, deicing, road friction, corrosivity, and other performance related issues have been investigated by various authors. Some of the investigations have been performed under controlled laboratory conditions while other studies have been conducted in the field. It is important to note that Muthumani et al. (2014) and Fay and Shi (2011) state that laboratory test results don't always accurately portray performance in the field due to varying temperatures, traffic, wind, differences in snow properties, pavement type, and pavement condition, etc. Because ice melting ability is a key performance issue of any RSA, a summary of the conditions that drive the ice melting process is given immediately below, just before the review of research that has investigated the performance of RSAs.

Wahlin and Klein-Paste (2017) investigated ice melting rates and the corresponding driving forces of deicers. The ability of a material to melt snow or ice is linked to the freezing point of the material. In general, a lower freezing point should mean a greater ability to melt snow and ice. There are, however, large differences in ice melting performance among materials with the same freezing point. These differences appear to be due to differences in the diffusivity of the material in water. The diffusive flux, which is a product of the driving force and diffusivity, correlated well with the rate of ice melt. This indicates that the chemical melting rate was rate-limited by mass diffusion. Fick's Law for diffusion, which is valid for very dilute solutions, however, could not be related to the rate of ice melting. The correlation between diffusive flux and ice melting rate existed only when using methods appropriate for non-ideal solutions in which the chemical potential, not the concentration gradient as used in Fick's Law, is the driving force. This indicates that properties such as chemical potential and activity are better descriptors of ice melting than concentration. With that background information, a review of the performance of RSAs follows.

Performance of Acetates, Formates, Glycol/Glyercol, and Succinates

Fay and Shi (2011) tested chloride-based products, a sodium acetate/sodium formate blend, CMA, and other RSAs for ice melting, ice penetration, ice undercutting, and their impact on freeze-thaw resistance of Portland cement concrete. Road friction following deicer application was also assessed as was corrosivity and thermal properties. Four deicers, all liquids, were identified as best performing. Two of the best performing were magnesium chloride based products, one was an agricultural product (containing magnesium and/or calcium chloride), and one was potassium acetate.

The magnesium chloride and CMA products had the least impact on Portland cement concrete and the potassium acetate product had the coldest effective temperature (followed by a magnesium chloride product). The agricultural product resulted in the lowest friction coefficient on both ice covered and deiced concrete. Acetates where not corrosive to steel but were corrosive to galvanized steel.

Based on the results of Western Transportation Institute (2017), Fay and Akin (2018) investigated the effectiveness of potassium succinate as a RSA. Results indicated that potassium succinate is similar to sodium chloride with regards to improving winter road friction. Potassium succinate, however, was found to be effective only down to -5 °C (23 °F), whereas salt brine was effective down to -10 °C (15 °F). This result is contrary to the value published by the Western Transportation Institute (2017) that lists the effective low temperature for succinates as -20 °C (-4 °F), although this result was based on results of just one test method. The Western Transportation Institute (2017), however, also states that the effective low temperature for succinates is “unknown” due to the uncertainty in the single value of -20 °C (-4 °F) obtained from just one test method. Also, the ice melting rate of potassium succinate was slightly less than that of salt brine. Based on these results, Fay and Akin (2018) suggest that potassium succinate can be a viable RSA at or above -5 °C (23 °F).

Fortin et al. (2014) stated that potassium acetate works at the lowest temperature of all acetates (-28.9 to 0 °C; -20 to 32 °F) while formates and potassium succinate are also effective in this temperature range with formates having the lowest BOD of all the non-chloride dicers. Urea has one of the highest BODs of non-chloride deicers and is effective from -9.4 to 0 °C (15 to 32 °F).

Shi et al. (2009) evaluated the performance of potassium acetate, sodium acetate/formate-blends, and potassium formate as compared to sodium chloride, magnesium chloride, and sand-salt mixes. Lab tests were conducted for ice melting, penetration, and undercutting of ice. Like Fay and Shi (2011) found, the four best performers were liquids. The best performers from high to low rank were 1. A magnesium chloride blend, 2. Apex Meltdown (which is magnesium chloride based), 3. A blend of magnesium chloride and Ice Ban, and 4. CF7 (a commercial product that is potassium acetate based). CF7 had the coldest effective temperature (followed by

Apex Meltdown) but CF7, sodium chloride, and IceSlicer (another commercial product) were the most harmful to concrete.

Wahlin and Klein-Paste investigated the effect of deicing chemicals on the hardness of snow. Dendritic snow was mixed with six different solutions in equilibrium with ice and then compressed. After compression, hardness of the snow was measured. Snow mixed with potassium formate was 25% softer than snow mixed with sodium chloride whereas the urea/snow mix was 20% harder than the sodium chloride/snow mix. This could impact the required amount of chemicals needed to achieve the same hardness, which could impact chemical usage in practical applications.

Performance of Other RSAs

Some studies have investigated the performance of other RSAs such as molasses-based products or agricultural products. For example, Fu et al. (2012) compared two liquid molasses-based materials with salt brine for use as pre-wetting agents and, in separate tests, as anti-icing agents. Pre-wetting involved spraying salt with a solution of the molasses-based product before road application. Pre-wetting the salt helps the salt adhere to the road surface and provides moisture, which salt needs for effective deicing, on cold, dry days. When used as an anti-icing agent, the materials were sprayed directly on the road surface before a snowfall event. Results showed that, when used as pre-wetting agents, none of the materials performed better than the others for 85% of the tests. For the remaining 15% of the tests, results were mixed and there was no consistent material that outperformed the others. When used as anti-icing agents, the two molasses-based products resulted in higher friction values than salt brine. The molasses materials were applied at a lower rate yet outperformed the salt brine by up to 10% with regards to friction.

Muthumani, et al. (2015) compared agriculturally derived products and complex chloride minerals in a laboratory investigation by measuring the degree to which products lower the freezing point of water and improve the ice melting capacity, weaken the ice bond to pavement, improve product longevity on the road surface, prevent ice formation, influence absorbance of sunlight on performance, and reduce corrosion of carbon steel. A best practices manual was developed which included storage guidelines, material handling and loading, storage and mixing, brine production equipment, application methods and guidelines, anti-icing and direct liquid application, and identified issues with agriculturally derived products.

Hosseini et al (2017) compared the road friction performance of RSAs with conventional brine (a 23% sodium chloride solution). The RSAs tested were Snowmelt (a fully bio-based product), Fusion (a mixture of a bio-based product and chloride salt), and Caliber M1000 (another mix of a bio-based product and chloride). Tests, which were performed in a parking lot in Ontario, Canada, were done at three different application rates (3, 6, and 9 liters per 1000 ft^2). The application rate did not affect product performance and treated sections had from 10 to 40% increased friction as compared to untreated control sections. There was no statistical difference, however, in the performance of each of the three products.

Lee et al. (2017) investigated the performance of chloride-based and organic-based materials mixed with chlorides with respect to ice melting and their impact on steel and concrete. Hazardous components of the products were also compared. Field tests showed that most of the organic products met South Korea’s corrosion, concrete freeze-thaw, and environmental requirements. Field tests also showed that chloride products were more effective than the organic products except when temperatures were below -17.2 °C (1 °F), at which point no product was effective. Lab test results agreed with field test results in that the organic-based materials were not as effective as chloride products. Liquid organic-based materials were effective deicers, however, but solid organic-based materials were not.

Specific Environmental Impact of RSAs

Although environmental impacts of RSAs were previously discussed, many studies investigated specific impacts of RSAs on water bodies, soil, or organisms. A thorough review of such studies was beyond the scope of the previous sections and would have cluttered the broad discussion in those sections. The work, however, is significant, relevant, and contributes much to the field of RSAs and, as such, is reviewed in this section. A sub-section at the end of this section covers studies that involve modeling the fate of RSAs (mainly CMA) in the environment.

In a general study that investigated three different deicing management techniques to determine possible methods to reduce phosphorus and sediment export to a lake, Albright (2009) investigated the impact of: 1. Abrasives with just enough salt to avoid clumping (the abrasives were fines with high phosphorus content), 2. Reduced abrasives and increased salt use along with liquid Ice Ban applied in spot applications, and 3. Use of only pre-wetted salt and Ice Ban applied in spot applications. Each of the three strategies were implemented for a period of one to six years and phosphorus and sediment export to the lake was recorded. The third technique (only pre-wetted salt with some Ice Ban application) resulted in the lowest phosphorus and sediment loading. In was noted, however, that chloride concentrations in the lake were increasing and this strategy would likely increase this trend.

Horner (1988) investigated CMA in the environment and recommended that, to prevent DO depletion, CMA not be used in watersheds where road runoff can directly reach receiving water bodies that have less than 100:1 dilution available in the runoff season. Other recommendations and conclusions included:

1. Provide a vegetated drainage course between roads where CMA is applied and receiving water bodies (at least 25% of acetate and butyrate can be removed in five meters of overland flow in vegetation but cation removal cannot be assumed in three meters),
2. Avoid CMA use where course soils overlay sensitive aquifers,
3. Avoid CMA use where soils are contaminated with metals because CMA may mobilize metals,
4. Dilute CMA by at least 4-times in order to keep concentrations below water quality standards,
5. CMA can increase soil permeability by up to 20 times depending on the soil type and CMA concentration,
6. Complete CMA degradation occurs in soils within two weeks at 10 and 20 °C (50 to 68 °F) but it takes two to four weeks at 2 °C (35.6 °F),
7. A soil depth of 3 cm was enough to degrade CMA in lab experiments,
8. There can be a lag of up to one week before CMA degradation begins,
9. Plants can withstand 2500 mg/L of CMA in soil but this concentration may be deadly to seedlings if immediately exposed,
10. Spraying or flooding plants with water containing 3000 mg/L of CMA does not affect the plants, and
11. In water, the ultimate BOD is about 75% of the CMA added.

Brenner and Horner (1992) investigated the impact of CMA, with respect to DO, on terrestrial and water ecosystems. Specific goals were to determine the BOD of CMA, determine the effect of temperature on degradation rate, determine if there is any BOD from contaminants in corn-based CMA, compare lab results to field results, and predict impact of full-scale CMA application on the DO of receiving waters and recommend ways to minimize the impact. It was estimated that the high range of CMA in road runoff could be 100 mg/L. This concentration completely depleted DO within two days at 20 °C while 10 mg/L of CMA depleted 4.5 mg/L and 7.0 mg/L of DO for reagent grade CMA and corn-based CMA, respectively. This indicates a larger BOD in corn-based CMA, which could be attributed to butyrate that was present in the corn-based CMA (both CMA products had equal acetate concentrations).

The DO depletion rate was a strong function of temperature and seemingly followed an Arrhenius relationship. Tests were conducted at 2 °C, 6 °C, 10 °C and 20 °C (35.6 °F, 42.8 °F, 50.0 °F and 68.0 °F). The standard, first-order BOD equation did not fit well at low temperatures (2 °C and 6 °C) due to a lag, however, and an alternative log curve was proposed. DO depletion due to CMA was tested in microcosms and in ponds and, although DO depletion occurred, it did not occur to the same extent as in lab experiments. This was likely due to reaeration of the microcosm, which could occur in the field but did not occur in the laboratory. In support of this theory, one pond, when ice covered, experienced a much larger drop in DO with a relatively small inflow of CMA. Recommendations to limit the impact of CMA included no application in areas were receiving water bodies are close to the road, where or when water bodies are ice covered, where CMA will not be diluted, and where there are fish that are sensitive to low DO. No application was also recommended when there may be late spring storms because water temperatures would be higher and this would likely lead to increased degradation rates and greater DO depletion.

To assess for DO depletion, Brenner and Horner (1992) suggested obtaining information on typical winter snowfall, water content of snow, typical amounts of deicer applied, volumes of runoff and runoff patterns after a thaw, distance from roads to receiving water bodies, permeability of soil, volumes of lakes and flow rates of streams, types of fish and spawning habits in nearby water bodies, and knowledge of potential for under-ice DO depletion in water bodies.

Horner and Brenner (1992) focused on environmental impacts of CMA other than BOD and DO depletion and included such topics as CMA transport characteristics, CMA fate in the environment, and its impact on terrestrial and aquatic ecosystems. With respect to soil, the only significant impact found was that CMA increases soil permeability. Lab studies showed potential acetate mobility, but field studies showed only minor evidence of this. CMA can also, through ion exchange with calcium and magnesium, release certain metals from the soil. Field results showed less of a tendency to do so and less consistency than lab studies. Also, the amount of metals released would not cause environmental problems. The authors noted, however, that the actual behavior in roadside soils is not known. At concentrations in the soil that were much higher than those expected in road runoff, no adverse effects were observed except when the high concentration was in the root zone, which killed seedlings.

Through a literature review and limited laboratory studies, Winters et al. (1984) reviewed the toxicity of CMA and found that it is less toxic to rainbow trout and fathead minnows than sodium chloride. A concentration of 5000 mg/L of CMA was found to slightly delay the hatching of rainbow trout but it did not affect the number of eggs hatched. Water flea reproduction was significantly inhibited at 250 mg/L CMA and at 125 mg/L sodium chloride. CMA, however, was found to be more toxic to algae than sodium chloride, but at concentrations under 50 mg/L CMA there was no harmful impact to algae. Overall, sodium chloride did more damage to plants than CMA, although one plant (Russian Olive) was damaged less by sodium chloride. CMA transport through the soil resulted in some removal of iron, aluminum, and nutrients from the soil. At concentrations likely to be generated in deicing applications, CMA may have less of a negative impact on the environment than sodium chloride.

Buteau et al. (1992) performed toxicity tests on Chevron's Ice-B-Gone ® Deicer, which was a pellet form of CMA. Acute oral toxicity, sub-chronic toxicity, acute inhalation toxicity, acute dermal toxicity, skin irritation, eye irritation, and skin sensitization tests were performed on rats and the latter two tests were also performed on human volunteers. All tests showed a low level of toxicity. CMA was found to be a slight eye irritant but not a skin irritant or skin sensitizer.

Goldman and Lubnow (1992) investigated the impact of CMA on 10 lakes in northern California with respect to microbial processes. Concentrations of 10 mg/L CMA appeared to increase chlorophyll in one lake and a concentration of 1 mg/L resulted in statistically higher chlorophyll concentrations in another lake. During the summer, eight out of the ten lakes showed no response to CMA at doses of 0.1, 1.0, and 10 mg/L CMA but bioassays in the late spring and early winter showed slight responses to CMA. Temperature, weather, and the standing stock of microbial populations were the most important variables that influenced algae populations. The authors theorized that increases in water temperature likely increased microbial activity and bacterial mineralization, which, in turn, could have caused the increases in chlorophyll.

Tanner and Wood (1999) investigated the effect of CMA application by the Oregon Department of Transportation on Bear Creek, which is in the Cascade Mountains. The road on which CMA was applied and Bear Creek run parallel to each other for about one mile and the creek is close to the road. At the time of the study, the road received CMA applications several times a year. The creek is small with a flow rate of approximately 4 cfs and it receives runoff directly from the road and shoulder. CMA (96% pure) was mixed with water at a dilution factor of 0.33 by weight and applied at 35 gallons per mile. Streamflow, rainfall precipitation, stream DO, pH, specific conductance, and water temperature were monitored continuously through the winter of 1998-99. No effect was observed with respect to calcium concentration, BOD, or magnesium concentration. BOD was small in water samples taken before CMA application and also in those taken after CMA application. Five-day BOD was 0.1 to 1.5 mg/L and twenty-day BOD was 0.2 to 2.0 mg/L.

Some studies have investigated the impact of RSAs on groundwater quality. For example, Granato et al. (1995) took groundwater samples at test sites next to Route 25 in Massachusetts and analyzed them for major trace chemicals. Groundwater concentrations were higher down gradient from the road as compared to samples taken up gradient. This suggests that the road (and possibly deicing agents) are affecting groundwater quality. One site was particularly impacted by both CMA and road salt. Results suggest, but are not conclusive, that there is potential mobilization due to winter recharge, ion exchange, acidification from road salts, and mineral weathering caused by deicing chemicals. No chemical concentrations exceeded national primary drinking water standards, but chloride and manganese exceeded secondary standards and surface water recommendations were exceeded for chloride, cadmium, and copper.

Hellstén and Nystén (2003) investigated the migration of sodium chloride, calcium chloride, magnesium chloride, CMA, potassium acetate, and potassium formate in aquifers. Potassum formate caused fewer negative impacts to infiltrated water than chloride and acetate. For example, overall results showed more metals were leached from the soils by sodium chloride than by acetate or formate. CMA, however, leached more arsenic, lead, nickel, and zinc than formate and formate leached more molybdum and chromium than acetate or chloride. Although metals were leached from the soil, only manganese and sodium exceeded European Union drinking water standards.

Jain (2018) used experimental mesocosm to investigate the impact chloride and acetate salts of sodium and calcium had on soil permeability and the retention of copper in the soil. Results showed that chloride-based salts reduced permeability and acetate-based salts had minimal impact on permeability. Acetate-based salts, however, increased organic removal in the soil (as measured by chemical oxygen demand), which may indicate microbial growth. Also, less copper was retained by the soil when salt was included in the runoff.

Hellstén et al. (2005) monitored groundwater chemistry in an aquifer to determine the fate of potassium formate on an aquifer scale. Formate did not enter the saturated zone through the vadose zone because of biodegradation in the topsoil. Thus, no undesirable changes in groundwater chemistry were observed.

Some studies have specifically investigated the impact of deicers on metal mobility in soils. For example, Amrhein et al. (1992) investigated the impact of deicers on metals leaching from roadside soils. Roadside soil samples were taken, placed in 50 mL syringes that acted as columns, and tested under laboratory conditions. Two sets of experiments were performed. In one set, 175 mL of a sodium chloride-CMA solution was run through the columns followed by 105 mL of distilled water (to represent snow melt water). In the second set of experiments, 90 mL of the sodium chloride-CMA solution was run through the soil columns followed by 90 mL of distilled water. Slightly more nickel, chromium, cadmium, lead, and iron were leached when high CMA concentrations were used. This suggests effects of ligand complexation (chloride versus acetate) and competitive ion exchange on metal mobilization. Solubilization of cadmium was mostly controlled by competitive cation exchange and complexation by chloride and acetate. High concentrations of CMA leached more cadmium than sodium chloride leached and more than dilute salt solutions leached. Concentrations of lead, chromium, nickel, cadmium, and copper in leachate never exceeded drinking water regulations but copper, nickel, and iron concentrations often exceeded limits set to protect freshwater life. Sodium tends to destroy soil structure and increase organic matter mobility, thereby increasing chances of metal mobility. The calcium and magnesium in CMA increases soil permeability and soil structure and reduces the dispersion of organic matter and clays. Horner and Brenner (1992), however, found that there was less tendency and consistency for the release of metals through ion exchange due to CMA application in the field as compared to laboratory studies.

Burkett and Gurr (2004) followed up on a modeling study performed by Scarsbrook et al. (1996; discussed below) by performing field tests. Preliminary field tests indicated that, of the four streams modeled, the smallest stream (baseflow of 1.8 cfs; 0.05 m^3/s) would need a CMA application of 110 g CMA/m^2 on a nearby road to result in a 20% reduction in DO from saturation. In full-scale field tests an average application rate of 30 g CMA/m^2 was applied to the road and the stream DO never dropped below 90% saturation. There was also no noticeable effect on benthic growth or aquatic invertebrates. No impact was noticed on a beech or tea tree forest or in fernland or grassland. No impact on soil chemistry was observed and increases in phosphorus and exchangeable calcium and magnesium were insignificant with decreases in values being as common as increases. Observed benefits of CMA application over sand/grit application were 1. A reduction in accidents, 2. A decrease in travel time during icy conditions, 3. A 24% increase in friction when CMA was used in place of sand, and 4. Less road closures.

Finally, Rasa et al. (2005) investigated the impact of sodium chloride and potassium formate on the mobility of cadmium in roadside soils. Formate elevated the soil pH, which increased the fraction of cadmium adsorbed onto oxide surfaces to up to 80%. Sodium chloride, however, increased the water soluble fraction of cadmium due to cation competition and the formation of cadmium-chloride complexes.

Deicer Impact on Specific Species

Other studies on the impact of RSAs have investigated their impact on a specific species of plant or organism. For example, Robidoux and Delisle (2001) investigated the environmental impact of sodium formate, CMA, sodium chloride, on three plants (barley, red fescue grass, Kentucky bluegrass) and an earthworm (Eisenia fetida). It was concluded that, overall, the toxilogical impact of sodium formate was approximately the same as sodium chloride with both having a larger impact than CMA. The authors noted, however, that due to the fact that more CMA is required for the same deicing effect as sodium chloride or sodium formate, the total impact of using any of the three deicers may be similar.

Joutti et al. (2003) tested sodium chloride, calcium chloride, magnesium chloride, potassium formate, potassium acetate, and CMA with different bioassays. Bioassays were an onion plant root elongation test, a duckweek growth inhibition text, an enzyme inhibition test, and a microbial test (luminescent bacteria, BioTox test). Overall, the organic chemicals were more toxic than the inorganic salts. The rank of toxicity, according to the root elongation and growth inhibition tests, were, from most toxic to least toxic: potassium formate, potassium acetate, CMA, calcium chloride, sodium chloride, and magnesium chloride. CMA could not be tested for the other two bioassays due to the turbidity of the samples.

Dougherty and Smith (2006) investigated the effect of sodium chloride, magnesium chloride, calcium acetate, magnesium acetate, sodium ferrocyanide, and sodium formate on tadpoles of two frog species and one toad species. Some salt compounds negatively affected some tadpoles but the acetates, sodium ferrocyanide, and sodium formate did not. All the concentrations tested were less than 170 mg/L and it was noted that higher concentrations may result in more of an impact.

Hanslin (2011) investigated the impact of CMA, potassium formate, and sodium chloride on the growth and stress responses of tree saplings. Tests were conducted in pots with five species of saplings and different concentrations of the deicers. Increasing concentrations (zero to 13.3 mmol/L soil) caused negative responses but results varied with species. Root growth decreased in two species and leaf biomass decreased in four of the five species. There was no impact on specific leaf area, relative chlorophyll content, height increase, or chlorophyll fluorescence. Overall, the organic deicers did not have less impact on saplings than sodium chloride did during active growth.

Harless et al. (2011) conducted 96 hour acute toxicity tests on larval wood frogs for urea, sodium chloride, magnesium chloride, potassium acetate, calcium chloride, and CMA. Larval were least sensitive to urea, sodium chloride, and magnesium chloride and were most sensitive to

CMA, potassium acetate, and calcium chloride. Toxicity varied greatly and the authors suggested more research be done to determine effects on other species.

Schuler et al. (2017) investigated the effect sodium chloride, magnesium chloride, ClearLane ™ and two salts mixed with GeoMelt ™ (a proprietary blend containing beet juice) and Magic Salt ™ (a proprietary blend of magnesium chloride mixed with a distillation byproduct) had on food webs in experimental aquatic communities. Sodium chloride had little effect but the organic additives reduced DO and, after microbial breakdown, transformed phosphorus to a usable form that resulted in an increase in algae. More algae lead to more zooplankton. Magnesium chloride reduced compositional differences of zooplankton and, at low concentrations, increased the number of amphipods. The authors concluded that RSAs can alter ecosystems.

A summary of the studies that investigated specific environmental impacts of RSAs is given in alphabetical order in Table 7 below.

Table 7. Major conclusions from studies investigating specific environmental impacts of RSAs.

Study Citation	Major Conclusions	Comments
Albright 2009	Pre-wetted salt with Ice Ban was best of three methods to reduce phosphorus export to a lake.	Increase in Cl^- in lake would be accelerated.
Amrhein et al. 1992	CMA can leach metals from soil.	
Brenner & Horner 1992	Should not use CMA where water bodies are close to road, are ice covered, are not diluted, and where fish are sensitive to low DO.	Suggest obtaining additional watershed info such as typical snowfall, water content of snow, soil permeability, etc.
Burkett & Gurr 2004	Field tests showed that road application of 30 g CMA/m^2 did not drop BOD of 1.8 cfs stream below 90% saturation. Also had limited or no other environmental impacts.	
Buteau et al. 1992	Ice-B-Gone form of CMA has low level of toxicity.	
Dougherty & Smith 2006	Salts negatively impacted tadpoles but acetates and sodium formate did not.	
Goldman & Lubnow 1992	CMA did not affect 8 of 10 lakes in summer but CMA impacted algae populations in late spring & early winter.	
Granato et al. 1995	Groundwater adjacent to road can be impacted by CMA and road salt.	
Hanslin 2011	During active growth, organic deicers did not have less impact on saplings than sodium chloride.	
Harless et al. 2011	Larval wood frogs were most sensitive to CMA, potassium acetate, CaCl, and were least senstive to urea, NaCl, and $MgCl_5$.	Recommended additional tests on other species.
Hellstén & Nystén 2003	In soil, acetate and formate leach less metals than sodium chloride. Potassium formate causes less negative environmental impact on infiltrated water quality than chloride and acetate.	
Hellstén 2005	Potassium formate was degraded in soil and did not impact groundwater.	
Horner 1988	Should not use CMA where road runoff directly enters water body with dilution factor < 100.	See body of this report for additional conclusions.
Horner and Brenner 1992	CMA increases soil permeability and can release metals.	
Joutti et al. 2003	Organic deicing chemicals are more toxic than non-organic salts	
Rasa et al. 2005	Formate application to soil increased pH, which increased the fraction of cadmium bound to the soil.	
Robidoux & Delisle 2001	Toxilogical impact of sodium formate is about equal to sodium chloride and both have larger impact than CMA.	More CMA is needed to get the same deicing effect.
Schuler et al. 2017	Organic deicers can alter ecosystems.	
Tanner & Wood 1999	CMA road application had no impact on a small creek (~4 cfs) that ran parallel to the road.	Investigated impact on BOD and calcium and magnesium concentrations.
Winters et al. 1984	CMA is less toxic to rainbow trout and fathead minnows than NaCl. CMA is more toxic to algae than NaCl but, overall, NaCl is more toxic to plants.	

Environmental Modeling Studies

Some documents reported on model studies to determine the fate and/or impact of roadway deicers in the environment. For example, Lindstrom (2006), who modeled the fate of chloride using a model for the unsaturated groundwater zone and a different model for the saturated zone, showed that aquifer chloride concentrations will increase and take several decades to decrease even if all chloride use is stopped. The only model studies found in the literature that investigated RSA fate, transport, and/or impact focused on CMA. Since Task 2 of this project involves such a model, a discussion of those studies is included below.

D'Itri (1992) modeled the effect of CMA road applications on surface waters by using rate and empirical coefficients from other studies and assuming that CMA applied to a road surface is either: 1) Transported by runoff to adjacent soil where it begins to degrade, or 2) Stored in a snow bank until it is released into the ground via snowmelt. Direct runoff from the road to receiving water bodies was not considered. The loss of acetate in the soil was modeled using the non-point source model *Simulator for Water Resources in Rural Basins-WQ* (SWRRBWQ). CMA degradation in receiving water bodies was modeled using first order equations for CMA and DO, again with rate constants from previous studies. Model results showed a 70% loss of CMA per 10 feet of runoff distance if CMA is applied directly to the soil or 50% if it is added to the snow pack. D'Itri (1992) plotted percent CMA remaining versus distance from the edge of a two-lane road with shoulder assuming the road runoff is delivered to a 10 foot wide buffer zone. This plot, which is reproduced as Figure 2, shows that CMA is totally degraded after 40 feet. D'Itri (1992) concluded that CMA input to a water body is not likely to be significant unless the water body is close to the road.

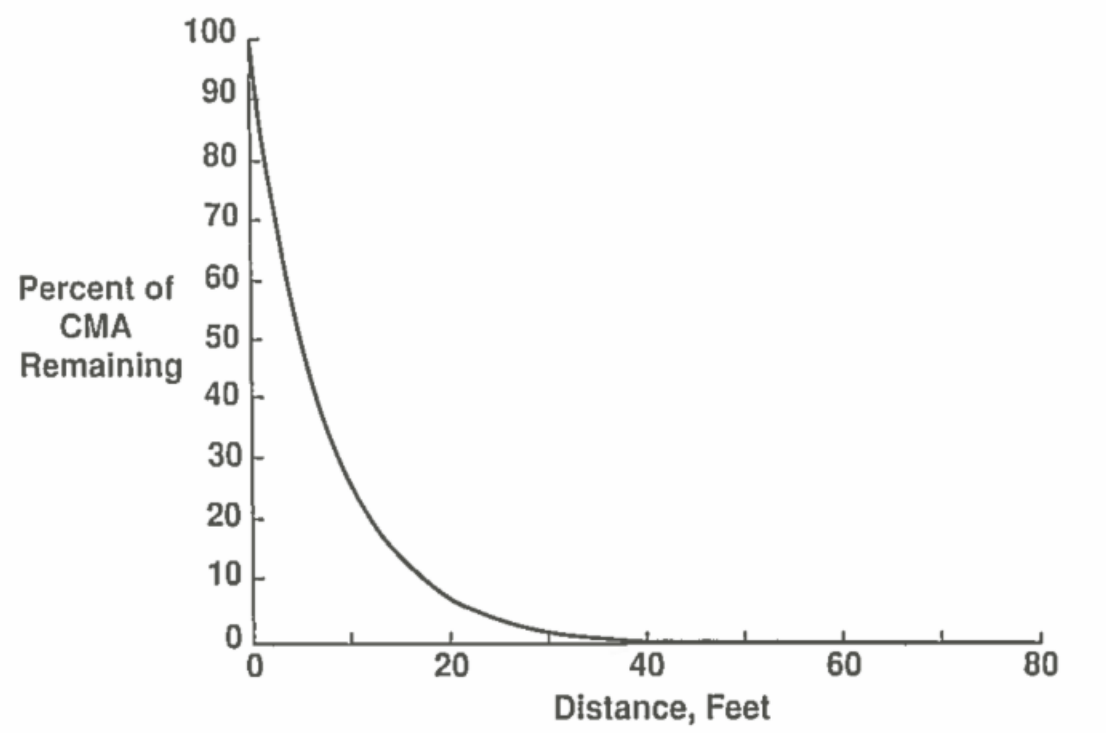

Figure 1. CMA remaining from distance of roadway assuming a two-lane road with shoulder delivers runoff and CMA to a 10 foot wide buffer (D'Itri 1992).

Additionally, the D'Itri (1992) model was conservative in that it ignored flow through the receiving water body, which could bring in more oxygen and, thus, help replenish some of the depleted DO. Model runs were conducted for receiving ponds from 1 to 14 hectares in size and from 2 to 8 meters in depth. Biodegradation was simulated by adjusting the biodegradation rate for a temperature of 20 °C (68 °F) with temperature dependence functions from other studies. Results showed that a 1 acre pond with a depth of 2 m (i.e. the worse case scenario) with an annual loading of 60 g BOD/m^2 would have a maximum DO deficit of about 2 mg/L. This deficit would occur during the winter when other DO sinks would not be present and the results would not be compounded. D'Itri (1992) also found there would be no significant impact of CMA on lake phytoplankton. This research indicates that, once CMA or other organic alternatives enters the soil, it will have a limited influence upon DO concentration in receiving water bodies.

Scarsbrook et al. (1996) modeled the impact of CMA road application in a national park area in New Zealand. The model, which implemented a Streeter-Phelps DO model for CMA impact on four streams, was used to test six scenarios. Four scenarios used estimates of BOD delivery rates (directly to the streams) and BOD values based on data from two rain events in

1995 to model CMA impact on stream DO levels. The two other scenarios estimated the mass of CMA road application required to cause a 20% drop in stream DO (from saturation) under average flood conditions and under short duration floods.

Model results showed the two largest streams were not at any risk even for the worst case scenario of 100% CMA delivery to the stream in a 5 hour runoff event. But the critical CMA burden (i.e. causing a 20% drop in DO from saturation) for the smallest stream (baseflow of 0.05 m^3/s; Burkett and Gurr, 2004) was only 35 g CMA/m^2. For larger streams, this value was 153 g CMA/m^2 or above. Also, of the first four scenarios, the smallest streams were significantly impacted under three of the four model scenarios. Scarsbrook et al. (1996) recommended that field investigations be performed in order to estimate the amount of CMA carried to the streams by runoff, the amount lost in the soil, and the resulting DO values in the streams (so that the model could be refined and critical CMA values be reassessed). As previously discussed, Burkett and Gurr (2004) did some additional field tests related to Scarsbrook et al. (1996).

These two modeling studies indicate that the most important impact upon DO concentration would be due to direct runoff into the receiving water body.

Abrasives

Historically, sand has been applied to road surfaces in an attempt to increase friction between the road surface and vehicle tires. Numerous studies, however, have found that any increase in friction caused by sand placed on the road surface is usually quickly diminished due to the particles bouncing off or being blown off the road due to winds induced by passing vehicles (e.g. Salimi et al 2014, Saltan et al. 2014). Dahlen and Vaa (2001), for example, found that sand removal from the road surface can occur after the passing of just 50 vehicles. Nixon (2001) stated that this can occur with “light” vehicle passage, especially in colder weather. Schlup and Ruess (2001) also found this to be true and added that abrasives visible on the road surface can give drivers a false sense of security and cause them to drive too fast for conditions. Finally, Keyser (1973) found that abrasives less than 300 microns in size do almost nothing to increase road friction.

Studies have also found abrasives cost more than salts and cause more negative environmental impacts. For example, Fay and Shi (2012) stated that, in order to attain a reasonable level of service, the environmental impacts of abrasives are more detrimental than that of salt. Abrasives can exacerbate the stress on roadside vegetation and soil (Fay and Shi 2012) and they are a significant risk to water quality and can threaten aquatic species (Staples et al. 2004). They can also increase water turbidity, clog streams and drains, reduce water body oxygenation, affect food chains, and reduce fish reproduction (Staples et al. 2004). Abrasives less than 10 microns in size can contribute to air pollution (Fay and Shi 2012) and their use can be limited in air quality non-attainment regions (Chang et al. 2002). Schlup and Ruess (2001) concluded that salts have less overall negative impact on the environment than abrasives and that, in a study of three Swiss cities over two winters, the cost of abrasives was six to 10 times more than that of salts. These studies have not considered the long-term impact of chloride on toxicity in fresh water bodies. In the Minneapolis-St. Paul metropolitan area, for example, the U.S. Environmental Protection Agency’s chronic (~long-term) chloride toxicity criteria are frequently surpassed, and some water bodies have also surpassed the acute (~short term) toxicity criteria (MPCA, 2014).

Although many studies have found that sand, when applied using conventional methods, does not last long on the road surface, other studies have determined that alternative placement methods can increase the longevity of the impact of abrasives on road surfaces. For example, Nixon (2001) stated that prewetting sand at the tailgate of the truck just prior to placement can help the sand stay on the road and that heating the sand just prior to placement can have the same effect. When the sand is prewet the water, upon freezing, can freeze the particles to the road surface and when abrasives are heated it will cause a small portion of ice to melt, which, upon refreezing, will help adhere the sand to the surface. Ihs (2002) also noted this effect when spraying sand with hot water just prior to distribution.

FinnRA (1991) found that heating the sand to 80 °C (176 °F) prior to placing it in a truck for distribution did not make a statistical difference in friction. They also found that heated abrasives of up to 250 °C (482 °F) increased the coefficient of road friction from 0.22 to 0.37 but the value dropped back to 0.22 in less than 24 hours. Hallberg and Henrysson (1999) found that an application method called Hottstone ®, which applied 2 to 5 mm aggregate at greater than 180 °C (356 °F) could increase friction for several days. Another method called Friction Maker ™ applied 0 to 8 mm sand with hot water at 90 °C (194 °F) and also increased friction for several days. The Friction Maker ™ was cheaper than applying a salt/sand mix on a per application basis and the Hottstone ® method was about 30% more expensive than applying a salt/sand mix on a per application basis. Nixon (2001) recommended that field trials be performed in Iowa to test application of abrasives using three different methods. The methods were 1. Pre-wetting the abrasives at the back of the spreader, 2. Heating abrasives to ~180 °C (356 °F) prior to placement, and 3. Mixing abrasives with hot water at ~90 °C (194 °F).

Dahlen and Vaa (2001) found that using heated abrasives or adding warm water to sand can allow the sand to stay on the road even after more than 2000 vehicles pass by and that using warm-wetted sand can reduce overall sand use by 40% to 50%. The most extensive report on using warm and/or wet sand was Perchanok et al. (2010) who reported on the Hot Water Sander, a material spreader developed in Sweden that prewets sand with water at 95 °C (203 °F) as it's being spread on the road. Tests in Scandanavia demonstrated that the sand could stay on the road for more than 10 hours whereas conventionally applied cold and dry sand would be blown away within minutes. Based on tests in Norway, this method is expected to increase the coefficient of friction values by 0.1 and this increase is expected to last two times longer than conventionally applied sand. Overall O&M costs and environmental footprints are also expected to be lower, although the authors also estimated the capital and operating cost over the equipment life span to be 1.5 times conventional equipment.

Perchanok et al. (2010), however, did note that the method has several practical concerns. The listed concerns were:

1. While in operation, a fog cloud formed around the spinner, severely reducing visibility behind the spreader. This is a safety concern.
2. The operational speed is 15 mph (24 km/hr), which is lower than conventional spreaders. This is another safety concern.
3. Sand is discharged at the rear end of the spreader, which means the vehicle could be on an unsanded road.
4. The operating range of the spreader is reduced by 40 % compared to conventional spreaders of the same load capacity, due to the load of water.
5. In order to prevent sand from freezing in unheated stockpiles, conventional sand with approximately 3% added salt was used.

Abrasives can still be an effective means of winter road maintenance. For example, Ihs (2002) stated that Sweden uses crushed stone aggregate (0-5 mm) in urban areas and they also use sand (0-8 mm) with ~3% salt by weight. On roads with speed limits above 43.5 mph (70 km/hr), the maximum size of abrasive used is 4 mm. Norem (2009) studied traffic accident data from Sweden to determine the effectiveness of winter maintenance options. The study found that salted roads were more accessible than sanded roads, but no conclusions could be drawn nationwide regarding a safety comparison between salted and sanded roads. That is because roads were safer on salted roads in central and southern Sweden but in the cold winters of northern Sweden, the number of accidents was higher on salted roads. Norem (2009) recommended that salting should be avoided in areas and in periods when the frequency of road surface temperatures below −8 °C (18 °F) exceeds 20%. In these climates, the warm-wetted sand method, Norem (2009) concludes, is likely better for improved friction. Norem (2009) also stated that warm-wetted sand is favorable on roads with traffic volumes less than 2,000 average annual daily traffic and in periods with stable winter conditions.

In an investigation into the impact of sand spreading rates, Salimi et al. (2014) found that sand spread at a low rate (354 lb/lane-mile; 100 kg/lane-km) did not improve friction but sand spread at a medium rate (886 lb/lane-mile; 250 kg/lane-km) and a high rate (1428 lb/lane-mile; 420 kg/lane-kg) did improve friction by 23% and 43%, respectively.

Wang et al. (2015) investigated the wear of asphalt pavement due to the application of winter sand and winter salt. By simulating applications and wear, it was determined that sand removed bitumen from the pavement and polished the aggregate, which reduced road friction of the bare pavement over the long-term. Salt only impacted the bitumen on the surface of aggregate and the aggregates were only minimally polished. Thus, the salt treated specimens had a higher friction coefficient than the sand treated specimens.

Finally, Saltan et al. (2014) evaluated a new machine, the Ice Melter Experiment Mechanism (IMEM), that evaluated the impact abrasives have on snow or ice surfaces. The IMEM measures the amount of ice melted as the pressure from an experimental wheel is rotated over abrasives on the ice surface. As the wheel rolls over abrasive particles, it pushes them into the ice, which can melt a portion of the ice. The IMEM was used to evaluate a conventional limestone sand and, for comparison, a new abrasive, which was a pumice waste from the Isparta-Karakaya region of Turkey. The limestone sand performed better in that it melted more ice. At wheel loads of 3, 4, 5, and 6 kg, the sand melted 93%, 105%, 59%, and 48% more ice, respectively. The sand, however, was removed from the ice surface by the simulated traffic. Although the pumice melted less ice, once broken into small pieces by the wheel, it remained on the ice surface where it had a longer impact on road friction. Saltan et al. (2014) suggested that, since pumice is used as a fertilizer, rain runoff containing pumice may be beneficial to roadside vegetation. It should be noted, however, that it would also likely add to nutrient loads, which are a main target of most stormwater management plans.

Pavement Innovations

To prevent ice formation on roads and melt or otherwise remove snow and ice from road surfaces, researchers have looked beyond what can be applied to the road surface to what can be done to improve pavement designs to achieve this objective. Most of the research has focused on the following four innovations: 1. Adding materials to the pavement mix design so the pavement can be more effectively heated, 2. Adding deicing agents to the mix design, which are released over time and aid in deicing, 3. Adding pipes to the pavement cross-section so that the pipes can be heated, often by warm liquid moving through them, which can melt snow and ice on the pavement surface, and 4. Applying a hydrophobic coating to the surface of the pavement in order to reduce ice adhesion strengths. These, and one other study which investigated making asphalt with a polyurethane binder instead of conventional asphalt, are reviewed below.

Pavement Heating by Adding to the Mix Design

Yang et al. (2012) investigated placing manufactured carbon fiber tape in concrete sidewalks to heat the tape with electricity. The system was effective in melting snow and ice on the surface. With an electricity cost of \$0.20/kW-hr, the average cost of heating the pavement when the air temperature was -11 °C (11.5 °F) was \$0.0292/m^2-cm. Units are per square meter of pavement area and per centimeter of accumulated snow depth. Costs would increase with colder temperatures and greater wind chill, but the authors concluded that the method could be viable for bridge decks, parking lots, and sections of road that are susceptible to icing.

A similar technique for heating pavement, called electrically conductive concrete, involves adding conductive materials to the pavement mix design. This allows the pavement to be more efficiently heated by an external power source. Typical conductive materials are steel fibers, graphite powder, or carbon particles (Abdualla et al. 2016), among others. Additional required components include electrodes, a power supply, and temperature sensors. In this design, an electric current applied through electrodes embedded in a conductive layer on top of conventional pavement is used to heat the top layer of pavement and melt snow and ice. The ability of the pavement to melt snow and ice depends on the resistivity of the conductive materials. Values required for deicing are typically less than 1000 ohm-cm (Abdualla et al. 2016). Electrode types reported in the literature include steel, perforated steel, perforated stainless steel, and galvanized iron. A good bond between the pavement and the electrode is also necessary for effective heating.

Abdualla et al. (2016) investigated requirements needed for electrically conductive concrete to be a cost-effective deicer. The underlying conventional pavement layer was 5 cm thick and had grooves on top to promote a good bond with the overlying conductive pavement layer. A 5 cm thick conductive layer with 0.75% (by volume) of 6 mm long carbon fibers provided a resistivity of 50 ohm-cm. There was also an insulating layer underneath the pavement. Tests investigated the ability of the pavement to melt 2.5 cm of snow on the surface. An AC power source of 80 volts and 11 amps was used. Abdualla et al. (2016) recommended using AC power as it enables electrons to find different pathways into the conductive materials, which more evenly distributes heat throughout the conductive layer. The power required to melt the 2.5 cm of snow was 0.54 kW-hour/m^2 and cost \$0.065/m^2, which Abdualla et al. (2016) claimed were the lowest values reported in the literature thus far. The low power requirement and associated cost were attributed to the low resistivity of the conductive layer. The authors concluded that the keys to having a well performing, cost-effective electrically conductive layer are low resistivity, electrodes that are bonded well with the conductive layer, and cost-effective thermal insulation. Additional studies investigating electrically conductive pavement are discussed below.

Li et al. (2013) investigated adding carbon nano-fiber polymer as a thermal source (powered by solar energy), a carbon nanotube cement-based thermal conduction layer, and insulating layers to a Portland cement pavement in order to remove snow and ice from the pavement surface. Laboratory and field tests were performed and the system did melt snow and ice on the surface. Based on laboratory test results, the maximum cost of deicing with the system was estimated to be \$0.29/m^2. With carbon nano-fiber polymer being a relatively new material at the time of publication, Li et al. (2013) suggested that material costs will likely decrease in the future.

Galao (2014) also investigated carbon nano-fibers in cement but did not incorporate solar power. In these studies, cement paste with carbon nano-fibers ranging from zero to five percent by weight and voltages of 50, 100, and 150 volts were applied. Specimens with 1 or 2% carbon fibers could achieve high temperatures but required 150 volts. Specimens with 5% nano-fibers, casted as shotcrete, could increase temperatures by about 20 °C (36 °F) with only 65 volts. Heating rates were up to 10 °C (18 °F) per minute. Specimen sizes were 0.10 m by 0.10 m and power consumption to raise the middle of the most effective 5% carbon nano-fiber specimens from 20 °C to 30 °C (68 °F to 86 °F) ranged from about 0.0005 kW-hr to 0.0007 kW-hr. With an average cost of \$0.20/kW-hr, the cost to increase the center temperature of the 5% carbon nano-fiber specimens from 20 °C to 30 °C (68 °F to 86 °F) would range from approximately \$0.01 to \$0.014/m^2. No other information on power consumption was given.

For use at airports, Lai et al. (2014) investigated cement concrete with a steel mesh and carbon fiber heating wires 5 cm below the surface and spaced 10 cm apart. With a power supply of 350 W/m^2, the design could melt 2.7 cm thick layer of snow in two hours with air temperatures of -3 to -1 °C (26.6 to 30.2 °F). At \$0.20/kW-hr and 350 W/m^2 for two hours, the estimated cost is \$0.07/m^2.

Pan et al. (2014) investigated the impact of insulating layers between the bottom of asphalt pavement and the conductive (i.e. heated) layer. In a heated pavement system, the insulating layer causes more heat to transfer to the top of the pavement and melt more snow and ice than without the insulating layer. Three materials were tested to determine which one performed the best as an insulating layer. Those materials were slurry seal, expanded shale, and an unnamed waterproofing material. The waterproofing material had a lower thermal conductivity (0.3081 W/m-°C) than the expanded shale (0.6518 W/m-°C) and slurry seal (1.592 W/m-°C) with increased snow and ice removal.

Wu et al. (2015) investigated using steel fibers, carbon fibers, and steel fiber-graphite together in a concrete mix to increase the conductivity of the concrete for deicing purposes. The optimum mix used 1% steel fiber, 0.4% carbon fiber, and 4% graphite (all by volume). The mix demonstrated low resistivity (322 ohm-cm) and high power density. The temperature increased

8.7 °C (15.7 °F) after 2.5 hours when subject to 27 volts and 21.8 °C (39.2 °F) after two hours when subject to 44 volts. Wu et al. (2015) concluded that this design showed potential for snow melting and/or deicing applications.

Lai et al. (2015) also investigated heating pavement to melt snow and ice but used heating cables installed in the structural layer of the road. The cables were placed on a course gravel asphalt in a zig-zag fashion with a fine gravel asphalt layer placed on top. The design is intended for use on bridges and in tunnels and mountain roads and research included laboratory tests, field tests, and a numerical simulation. Results indicated that the design can melt snow and ice with a power input of 200 to 400 W/m^2 when the air temperature is between -20 and 0 °C (-4 °F and 32 °F). With an average cost of $0.20/kW-hr, the cost to melt snow in this air temperature range would be $0.04/m^2 to $0.08/m^2 for every hour of heating. In the study with air temperatures ranging from -7 °C to -11.3 °C (19.4 °F to 11.7 °F), up to five hours were required to raise the pavement surface temperature to values above freezing. A total power cost estimate for the five hours of heating is from $0.20/m^2 to $0.40/m^2.

In a laboratory setting, Galao et al. (2016) investigated the feasibility of highly conductive carbon fibers in concrete as a self-heating material for ice prevention and melting. It was concluded that with an applied voltage difference of 20 volts, pavements in the field could increase their temperature to above 0 °C (32 °F) when they were initially at -15 °C (5 °F). Power required in the laboratory experiments was 300-500 W/m^2. Using the $0.20/kW-hr estimate and assuming heating occurs for five hours (laboratory tests in this study ranged from 3.6 to 8.3 hours of heating), the total power cost would range from $0.30/m^2 to $0.50/m^2.

Bai et al. (2017) investigated the use of two parallel and horizontal layers of stainless steel fibers within concrete for heating purposes. The concrete mix included graphite, silica fume, and the stainless steel fibers. The following four concrete specimens were tested:

1. Plain concrete,
2. Same as 1 but with a double layer of stainless steel fibers,
3. Same as 2 but with steel fibers in concrete mix, and
4. Same as 2 but with graphite in concrete mix.

The resistivity of the specimens with the double layer of steel fibers was less than 30,000 ohm-cm and was still increasing with time after 56 days. Graphite and steel fibers added to the concrete mix further reduced resistivity to less than 200 ohm-cm and, after three weeks of increasing resistivity, the resistivity began to decrease with time. With this design, a 6 mm layer of ice was melted in 100 minutes with a power input of 800 W/m^2 at -20 °C (-4 °F). Most of the energy consumed was due to the heating of the concrete, not melting the ice. Also, it was determined that the ambient temperature is the most important factor in determining the time required for deicing.

Another method of heating pavement involves adding particles that absorb microwaves to the pavement mix design. This allows the pavement to be heated by a microwave unit on a passing vehicle that is also equipped to remove snow and ice as discussed below. In this process the ice is not melted because it does not absorb microwaves (Lu et al. 2017) but the pavement is heated, and this weakens the bond between ice and pavement. The weakened bond allows the vehicle, which is equipped with a crusher, to more easily grind and/or crush the ice layer so that it can be removed by a blade or shovel (also on the vehicle), all with less damage to the pavement. A schematic of this process from Gao et al. (2017) is shown in Figure 1 below.

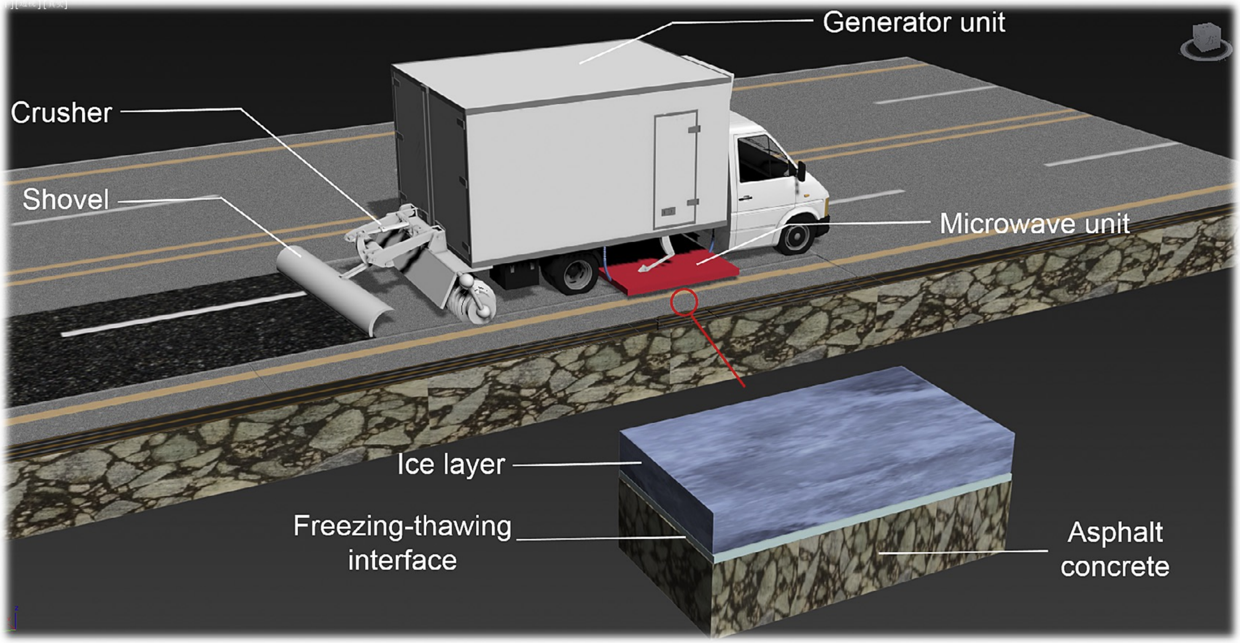

Figure 2. Schematic showing a microwave heating unit for ice removal from asphalt (from Gao et al. 2017).

In an investigation into the properties of an asphalt pavement for microwave ice removal, Wang et al. (2016) used magnetite as an aggregate in the asphalt due to its high microwave adsorption properties. The magnetite microwave heating efficiency was over 6 times that of conventional basalt aggregate. Properties of the asphalt with magnetite aggregate were examined and it was determined that it had adequate properties for use in roads. The actual ice melting ability of the pavement was not tested.

Lu et al. (2017) investigated ice removal from a concrete pavement after it was microwaved. Different microwave frequencies were tested and results showed that using 5.8 GHz as compared to 2.45 GHz decreased the microwave penetration depth from 118 mm to 53 mm and increased the deicing efficiency by more than five times. Adding 10% black iron oxide (by weight) to the pavement mix design increased the microwave efficiency by 1.8 times.

In an attempt to increase the microwave heating efficiency of pavements, Gao et al. (2017) investigated partially replacing conventional aggregate with steel slag. The microwave heating capacity of steel slag was found to be dependent on particle size with sizes of 0.6, 2.36, and 9.5 mm being the most effective. The heating uniformity and thermal conductivity of the pavement was found to decrease with an increase of steel slag content while the surface temperature increased with an increase in steel slag content. As a balance between heating uniformity/thermal conductivity and surface temperature, the authors recommended a steel slag content between 40 and 60% (by volume of total aggregate) for optimum performance. Tests were performed in a laboratory with a 850 W, 2.45 GHz microwave oven. Specimens were heated until a layer of ice that was initially adhered to the specimen surface fell off. No details were given regarding how long specimens had to be microwaved for this to occur, but graphs showing pavement surface temperature as a function of time in the microwave indicate it was less than 10 minutes. Figures in Gao et al. (2017) show specimens that appeared to be about 10 cm in diameter. Actual specimen size, however, was not given and, therefore, an estimate of the cost per pavement surface area is not possible.

Deicers in the Pavement Mix Design

Another innovation in pavement anti-icing and deicing has been the incorporation of anti-icing and/or deicing agents in the pavement itself. These agents help prevent ice formation or aid in the melting of snow and ice on the pavement surface. After the agents at the pavement surface dissolve into water or are otherwise transported away from the surface, agents from below the surface move to the surface through diffusion (and/or other processes discussed below) and help in the anti-icing, deicing process. Peng et al. (2015), however, showed that chloride anions added to a pavement as anti-icing agents can be retained in the pavement rather than released.

Giuliani et al. (2012) investigated the use of a sodium chloride-based anti-icing filler (at 5.7% by weight) in asphalt and compared results to pavement with conventional calcareous filler. The anti-icing filler caused a delay in frost formation and icing, an acceleration of melting, and it reduced the adhesion strength between the ice and asphalt. After about 20 days about 65% of the original salt content had been released. The authors claimed, however, that the overall durability is expected to be “high” due to diffusion that moves salt from the asphalt body to the surface.

Wright (2013) investigated how the addition of sodium formate and sodium silicate to asphalt mixes impacts asphalt properties such as compactibility, stiffness, fatigue, permanent deformation, and skid resistance as compared to conventional asphalt. Reductions in ice adhesion and freezing point were also investigated. Studies showed that these additives do not negatively impact asphalt properties when subject to standard tests but that they may increase susceptibility to deterioration in the presence of water, which may reduce service life. The additives also reduced the freezing point and the ice adhesion strength. The study also investigated the transfer of the additives to the surface and found that the transfer is dependent on the ambient relative humidity and the number and arrangement of surface voids (chemical transfer is greatest in surface voids). Transfer to the surface was found to typically occur when the relative humidity was greater than 70%, which is the point at which the chemicals absorb water from the atmosphere. With regards to freezing point reduction, at 3 and 5% (by weight) these additives reduced the freezing point to -1.6 and -2.1 °C, respectively.

Liu et al. (2014) studied properties of asphalt made with a commercially available Chinese anti-freeze product that contained chloride salts. The study, which mainly focused on the impact of the anti-freeze on asphalt properties, did find that the anti-snow and ice performance of the pavement increased with the addition, but details were limited.

Wang et al. (2017) also studied asphalt properties but of asphalt containing salt storage aggregate at zero, 5, 10, 15, and 20% (by weight). The salt storage aggregate was made from 90% pure sodium chloride, glass powder, and maifanite powder. To make the aggregate the materials were mixed and milled, heated to 750 °C (1382 °F), crushed, cooled and formed. It was determined that all the asphalt mixes tested could meet standard asphalt specification requirements and that salt migrates to the surface due to osmotic and capillary pressures where it can gradually melt snow and ice.

Liu et al. (2015) studied the salt releasing characteristics of asphalt made with a salt product subject to static and dynamic loading. The salt product was provided by a Chinese company and contained SiO_2, NaCl, $CaCl_2$, Al_2O_3, CaO, and other unspecified substances. The release of salt depended on the loading cycle. Under static loading salt release plateaued but if dynamic loading was then applied, the salt release rate increased.

A high elastic asphalt pavement (created by adding a high elastic modifier to conventional asphalt) that contained the deicing agent Mafilon (which replaced 70% of the mineral fillers) was investigated by Luo and Yang (2015) for rutting performance, low temperature performance, moisture damage resistance, snowmelt performance, and deicing performance. The high elastic asphalt with deicer performed better than conventional asphalt with regards to rutting and low temperature performance but was slightly weaker in moisture damage resistance. The high elastic asphalt with deicer also had a higher snowmelt speed and a weaker ice bond on the surface. Four hours after snowfall, snow thickness on the elastic pavement was 5 mm while on conventional asphalt it was 22 mm. Also, after the snowfall stopped, an ice layer formed on only half of the Mafilon pavement surface area but it formed over the entire conventional pavement surface area. Finally, at an ambient temperature of -5 °C (23 °F), a saturated sponge did not freeze to the surface of the modified asphalt, which indicates that the deicer prevented the surface from freezing.

Another study by Ma et al. (2016) also investigated the effect of commercial chloride-based, anti-icing additives on pavement properties. Contrary to Luo and Wang (2015), the additives were found to be detrimental to rutting stability, thermal cracking resistance, and moisture susceptibility of the pavement. Polyester fibers, when added to the mix, however, reduced this negative impact to a level such that the pavement performed in a satisfactory manner. The mix with anti-icing additives and polyester fibers provided some snowmelt and weakened the bond between ice and pavement.

Farnam et al. (2015) investigated the use of two products with high enthalpies of fusion (~130-170 J/g) and freezing temperatures of 2 to 3 °C (35.6 to 37.4 °F) when placed in concrete cement. The objective of the design was to improve snowmelt and anti-icing properties of the pavement. The high enthalpy of fusion materials store heat which reduces ice and snow on the surface. The two products, paraffin oil (a petroleum product) and methyl laurate (a vegetable product) were tested in two configurations. In the first configuration, the material was placed in lightweight aggregate which was placed in the mortar and, in the second configuration, the material was placed in tubes that were embedded in the mortar. The paraffin oil in the mortar did melt snow and ice and it worked well. The methyl laurate, however, damaged the mortar and didn't release heat due to a reaction with the mortar. When placed in the embedded tubes, both materials worked well. Heat releases were enough to melt 22 to 36 kg of pure ice per cubic meter of mortar on the surface of the pavement at temperatures ranging from approximately -1 °C to -3 °C.

Farnam et al. (2017) followed up their previous work with a second study that used paraffin oil in two ways. One was placing the oil in lightweight aggregate that was used to make concrete and the second was by placing the oil in metal pipes that were embedded in the pavement slab during casting. Both methods showed the ability to melt snow and ice on the pavement surface, but the pipe method released heat more rapidly than the aggregate method and, thus, melted snow and ice more quickly. The authors claimed that results indicated that both methods could reduce or eliminate the need for deicing salts or chemicals, especially in weather conditions that have recently dropped below freezing.

Peng et al. (2015) investigated making Mg-AlCl layered double hydroxide (LDH) from Mg-$AlCO_3$ and investigated its performance related to deicing. Mg-AlCl(LDH) was more effective than Mg-$AlCO_3$ (LDH) in decreasing the freezing point of water. At temperatures below the freezing point it can weaken the adhesion forces between the ice and asphalt. As was previously mentioned, tests also showed that chloride anions can be retained in the asphalt and not released into the environment.

Chen et al. (2018a) investigated the performance of anti-freezing asphalt with regards to the adhesion strength between ice and asphalt. In this asphalt mix design, mineral fillers were replaced with anti-freezing fillers that released salt after a snowfall or, more specifically as shown by Wright et al. (2016), under high relative humidity conditions (greater than 60-70%). The anti-freezing filler used consisted of CaO, Al_2O_3, SiO_2, Na_2O, K_2O, Fe_2O_3, and other substances and was used in different specimens to replace 33%, 67%, and 100% of the conventional aggregate (it is not clear if this was by weight or volume). The asphalt was also modified with a styrene butadiene styrene block polymer to improve rheological properties. The released salt helped to melt ice and snow. The technique did not melt all of the snow and ice but it did lower the adhesion strength between ice and pavement by up to 80%. Long-term ice adhesion (simulated by washing and drying cycles), however, greatly increased in strength, indicating that the effective life of the deicing ability of the pavement may be limited.

In a study of railway asphalt, Fang et al. (2017) also added anti-freeze additives to asphalt mix designs and tested asphalt properties. Additives tested included hydrated lime, fly ash, red clay brick powder, Portland cement, and an expansive water sealing agent. In tested mix designs the additives replaced 50% of the conventional fillers. The study found that the expansive agent was not an appropriate filler because moisture damage resistance was considerably reduced. A filler mix of hydrated lime (40%), fly ash (20%), red clay brick powder (20%), and Portland cement (20%) was found to be satisfactory, however, and this mix improved water damage resistance and, the authors claimed, enhanced asphalt anti-freeze ability, although no anti-freezing performance data was provided.

Hydronic Pavements

Another way to provide heat to a pavement in order to melt snow or ice is to embed pipes or tubes in the pavement and heat the pipes either by electricity or by circulating warm liquid through the pipes. Liquids used include brine, oils, and glycol-water, among others (Adl-Zarrabi et al. 2016). With either heating method, heat is transferred to the pavement surface where it can melt snow and ice or prevent the formation of ice. Pavements with such pipes or tubes are, by definition, called hydronic pavements. This section reviews publications regarding research into hydronic pavements.

Wang et al. (2010) investigated variables such as fluid temperature, pavement slope, and idling (or preheating) time on the design and performance of hydronic pavements. Slopes of 9 or 18° allowed melted slurry to drain out of the snow. This weakened the capillary effect in the snow and increased the total snow melt time. Compared to horizontal pavement, slopes of 9 and 18° and increased the time required to melt 27 mm of snow by 25.9% and 53.7%, respectively. These results corresponded to tests in which the pavement was preheated to 11.2 °C (52.2 °F). The authors noted that the impact of slope may be greater without preheating.

Chen et al. (2011) investigated the use of fluids in the pipes of hydronic asphalt pavement. In this investigation, heat was collected in the summer and stored for use in the winter to melt ice. In addition to melting ice in the winter time, the design can help prolong asphalt life because it moderates the temperature of the asphalt and reduces the extreme temperature swings experienced by conventional asphalt. In this study, graphite powder was added to the asphalt mix design to increase the thermal conductivity of the asphalt. Numerical simulations suggested placing the pipes between asphalt layers at a depth of 4 or 10 cm with a spacing between pipes of 18 to 40 cm. In experimental runs, snow melt times were longer than expected – 200 or more minutes to achieve completely bare pavement – but it was demonstrated that 25 °C (77 °F) water in the pipes of a hydronic pavement application can be used to melt snow on the surface of an asphalt pavement.

Adl-Zarrabi et al. (2016) also investigated the impact of hydronic pavement design parameters on pavement snow and ice melting performance. Modeling results showed that if pipe spacing is greater than 20 cm, the time required to melt increases rapidly. Thus, the authors recommended a pipe spacing of less than 20 cm. Also, if the embedded pipe depth is less than 10 cm, the impact of embedded depth is negligible. Pipe spacing had a larger impact on melt performance than pipe depth. In their model, the cost-effectiveness of using solar panels to heat stored fluid was investigated. It was determined that this is not justifiable due to added costs and complexity. Other important design parameters that were not investigated as part of the study included liquid flow rate, size of pipes, and the available amount of solar energy that can be harvested.

Mirzanamadi et al. (2018) also investigated hydronic pavement that used a heating fluid along with the practice of storing summer heat for winter use. Results of a numerical model were compared to data from a field installation for model validation. Numerical model results indicated that the performance of the system will improve as pipe spacing is decreased, embedded depth of pipe in the pavement is decreased, when larger pipes are used, and when the pavement has lower emissivity. As others have found, the distance between the pipes had the largest impact on snow melt performance.

Through simulation, Liu et al. (2017a) also investigated optimum design of hydronic concrete cement pavement but with electrically heated pipes. Optimum values of pipe spacing and embedded depth were 10 cm and 6 cm, respectively. It was also suggested that power input could be varied depending on if the time required to heat the pavement was important (i.e. high power, short heating time) or if efficiency was important (i.e. low power, longer heating time, but higher efficiency). Liu et al. (2017b) used simulation and laboratory experiments to show that the method could be effective with a power consumption of 100 to 400 W/m as long as the heating pipe spacing is between 10 and 25 cm, the pipe depth is between 6 and 12 cm, and the wind velocity is less than 15 m/s.

Hydrophobic Pavements

Some researchers have investigated the effectiveness of hydrophobic materials used as coatings on asphalt or concrete pavements as a means to reduce ice adhesion strength. For example, Ceylan et al. (2016) sprayed polytetrafluoroethylene (PTFE) in layers on asphalt pavement and found that the ice-repelling performance (as measured by water contact angles) was impacted by the spray time and PTFE dose. The authors concluded that spraying PTFE on asphalt has potential as an ice-repellent surface.

Sobolev et al. (2013) applied superhydrophobic siloxane admixtures to concrete surfaces in order to repel ice. The best water repellent materials (measured by the contact angle) were obtained using polymethyl-hydrogen-siloxane with a small amount of fibers (such as silica fume). The fibers and the extent of the dilution of the emulsion were found to be parameters that greatly influenced the level of hydrophobicity. Diluted emulsions (5% active material) allowed the fiber to produce a hierarchical surface of fibers and aggregates so the material had superhydrophobic properties. When tested, coated mortar specimens had ice shear strengths of about 30 kPa, which was about 10% of value corresponding to uncoated specimens.

Others have, however, found that the ice-repellent performance of hydrophobic surfaces is not long-lasting. Ahlborn and Poehlmann (1976) found that a traffic paint with silicone rubber and a weather proofing material with the same silicone rubber were effective in reducing ice adhesion strengths. They also found, however, that the material was worn off the road surface after 150,000 to 300,000 vehicles drove over the surface. Kulinich et al. (2010) found that the hydrophobic surfaces on pavements are gradually damaged through icing/deicing cycles and that the ice-repellent properties deteriorate over time. It was also determined that the hydrophobic surfaces were less effective during humid conditions due to the condensation of water on the surface, which resulted in much stronger ice adhesion strengths. In a literature review, Chen et al. (2018c) made similar conclusions mostly due to the fact that ice-repelling surfaces are worn off over time due to tire abrasion and that the micro-structure of hydrophobic surfaces are also vulnerable and consumable. Chen et al. (2018c) concluded that hydrophobic surfaces for pavements must still be researched and improved. Thus, although hydrophobic surfaces may have potential as an anti-icing method, the technology appears to still be in the research and development stage and not ready for implementation.

Other Pavement Innovations

The performance of a pavement made with aggregate and polyurethane binder (in place of traditional asphalt binder) with regards to anti-icing and deicing was investigated by Chen et al. (2018b). The polyurethane pavement was compared to the traditional asphalt pavement made with the same aggregate and particle size distribution. The two pavements had similar thermal conductivity values, but the polyurethane pavement had a much higher specific heat capacity. Results indicated the polyurethane pavement can significantly retard the formation of ice on the pavement surface. The pull-off strength and the shear strength at the ice/pavement interface in the polyurethane pavement was about 50 to 55% of that in the conventional asphalt pavement. The authors suggested that polyurethane pavement can provide better anti-icing and deicing performance and increase winter safety as compared to conventional asphalt. No mention, however, was made of the cost.

Observations and Recommendations

The use of road salt in Minnesota has caused chloride concentrations in many lakes, streams, and shallow groundwater bodies to increase to levels that have caused impairment. Similar trends have been observed in other locations within the United States and the world. In an effort to reduce chloride concentrations, research has been performed on road salt alternatives and pavement innovations with the objective of preventing the formation of road ice or melting snow and ice once it is on a roadway. This report is a review of literature associated with such research and is Task 1 of a Legislative-Citizens Committee on Minnesota Resources (LCCMR) 2018 funded project entitled "Investigation of Road Salt Alternatives and Pavement Innovations." This project seeks to reduce or eliminate the transport of chloride into Minnesota's lakes, streams, and groundwater. The report reviews previous published research that has investigated the topics of road salt alternatives (RSAs) and pavement innovations, and their environmental impact, with respect to anti-icing and deicing, and pavement friction.

Most potential RSAs are organic based products. Of all the RSAs investigated, the most heavily investigated and reviewed is calcium magnesium acetate (CMA). CMA, however, is not effective at lower temperatures than road salt, and therefore does not offer intrinsic advantages over road salt. Other commonly reported RSAs include other forms of acetate, formate-based products, glycol and glycerol, and succinate-based products. The current trend is to move to potassium acetate, which is effective at lower temperatures than road salt. In general, all of these products have higher monetary costs than road salt, are less corrosive to steel, and have a relatively high BOD. Other RSAs have been investigated and most of those are also organic based. They mostly consist of agricultural byproducts such as molasses, beet juice, corn processing products, and urea, which typically are applied with a chloride-based salt, although at reduced application rates.

Studies that have investigated the performance of RSAs with respect to anti-icing, deicing, or road friction have been reviewed. In general, RSAs are less effective in terms of quantity required than conventional road salts and, if equal performance (as compared to road salt) is desired, a greater amount of RSA must be used. Some studies, however, have found that using RSAs in combination with road salt (as an anti-icer or deicer) can increase salt effectiveness and, therefore, can reduce chloride use.

Due to their organic nature and eventual degradation, a common environmental concern of RSAs is BOD. In fact, some authors state it is the main concern with respect to RSAs. The many studies that have investigated the BOD of RSAs have generally concluded that the depletion of dissolved oxygen caused by RSAs will typically be small unless relatively large amounts of RSAs are transported to a small water body close to the roadway. Warmer temperatures or ice cover on the receiving water body can increase the impact due to faster degradation rates and the prevention of surface reaeration, respectively. Also, the conclusion that there will typically be a relatively small impact on dissolved oxygen has been supported for calcium magnesium acetate by at least two model studies.

Other studies have investigated the toxicological effect of RSAs on specific species of plants, invertebrates, or animals. Although toxicological impact has generally been found to be minimal and most investigators have concluded that organic RSAs have low toxicity, some have found direct negative effects on certain species and have recommended additional research. In particular, Pilgrim (2013) reports that a commercial potassium acetate product (CF-7) is more toxic to fathead minnows and an invertebrate than a number of chloride-based de-icing and anti-icing compounds.

The use of abrasives, such as sand and grit, to increase winter road friction was also reviewed. Although abrasives can cause negative environmental impacts ranging from increased water turbidity, lack of oxygenation, and decreased fish reproduction rates to air pollution, abrasives are still used for winter road maintenance. Small particles, which are the most difficult size to remove from stormwater runoff, likely cause most of the environmental impact but have also been shown to contribute minimally to increased road friction. Sweden uses larger particles (up to 4 and 8 mm diameter), which are easier to remove from stormwater runoff through settling and/or filtration processes. Also, simply placing abrasives on the road surface has been shown to be ineffective due to the fact that most of the abrasive particles either bounce off or are blown off the road relatively quickly. Pretreating the sand with hot water and/or by heating it just prior to road application, however, has been shown to cause an increase in road friction that can last for several days. An improved application of abrasives may be sufficient where speeds are low, such as residential streets and parking lots. This would reduce chloride use substantially.

Most pavement innovations designed with the intention of reducing the need for road salt can be grouped into one of the following four categories: 1. Adding conductive elements to the pavement mix design so the pavement surface can be more efficiently heated, 2. Adding anti-icing or deicing agents to the pavement mix design that are released at the pavement surface over time, 3. Hydronic pavements, which incorporate heating pipes into the cross-section of the pavement, and 4. Hydrophobic pavement coatings to reduce ice adhesion strengths. All have shown potential as a method to reduce dependence on road salts, but no full-scale applications have been documented. One pavement innovation with potential for future research is hydrophobic pavements, which require more research, including an assessment of how well they would work in field applications.

Overall, whether by RSA or pavement innovations, much research has been performed with the intention of ultimately reducing or eliminating the use of road salt. Although many studies have shown potential, further research is needed to fully optimize the implementation of pavement innovations in full-scale, practical applications. RSAs are more expensive and require more mass per road mile than chloride-based products, have high BOD, exhibit some toxicity, and can alter ecosystems. However, they result in clear roads during the winter months, similar to road salt, and they will likely not have long-term impacts as opposed to chloride-based salts. In addition, potassium acetate is currently being deployed for anti-icing at low temperatures, so some RSAs also can improve the level of service provided. Thus, it is our recommendation that the environmental impact and friction enhancement of RSAs, in particular potassium acetate, be further explored.

Although abrasives have been shown to have negative environmental impacts, those impacts can likely be reduced by selecting particles of larger size, which can be removed more easily than smaller particles. Because small particles do nothing to increase road friction, there will likely be no drop in effectiveness. Furthermore, the increase in road friction with pre-treated abrasives (either wetted or heated) has been shown to last for several days. Unlike chemical based RSAs, the abrasives will have little or no impact on BOD, little or no toxicity on aquatic life, and may be able to be collected after the winter and used again the following year. If the use of abrasives and corresponding pre-treatment methods are optimized for use on low speed locations, effective winter road maintenance on these locations with minimal chemical and biological impact, including the reduction of chloride in the environment, may be possible.

There is no one treatment that will reduce chloride load to our lakes, rivers and groundwater. Some countries in northern climates have successfully reduced their chloride load through the use of road salt alternatives, in improvements across design of pavements and design and placement of roads, bridges, and sidewalks, in optimizing the physical form (liquid or granular) of the material applied, the timing of the material applied, the amount of material applied, the spread pattern of material applied and the chemical make up of the material applied, and finally in improvements in mechanical snow/ice removal equipment. Such efforts would create a more efficient and effective winter maintenance industry.

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