Efficacy, Costs, and Impacts of Non-Chloride Deicers: An Educational Primer and Product Information Sheets

Final Report

CLEAR ROADS
research for winter highway maintenance

Western Transportation Institute

Project 1048127/CR21-03
September 2023

Pooled Fund #TPF-5(353)
www.clearroads.org

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
CR 21-03		

4. Title and Subtitle	5. Report Date
Efficacy, Costs, and Impacts of Non-Chloride Deicers: An Educational Primer and Product Information Sheets	September 2023
	6.
7. Author(s) Laura Fay, Karalyn Clouser, Neil Hetherington, Mathew Bell, Anna Price, Xianming Shi	8. Performing Organization Report No. CR 21-03
9. Performing Organization Name and Address Western Transportation Institute Montana State University PO Box 174250 Bozeman, MT 59717	10. Purchase Order No. 11. Contract or Grant No. No. 1048127
12. Sponsoring Organization Name and Address Clear Roads Pooled Fund Minnesota Department of Transportation Office of Research & Innovation 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899	13. Type of Report and Period Covered Final Report [March 2022 – September 2023] 14. Sponsoring Agency Code

15. Supplementary Notes

Project completed for Clear Roads Pooled Fund program, TPF-5(353). See www.clearroads.org.

16. Abstract (Limit: 250 words)

The objective of this project was to synthesize available information on non-chloride deicers to allow for a more comprehensive understanding by winter roadway maintenance professionals and allow for easy comparisons between products and with sodium chloride (as salt brine or rock salt). This was accomplished through a literature search that summarized research on non-chloride deicing products and identified 46 non-chloride deicing products, summarized research on applications of various heated pavement technologies, and summarized research on anti-icing and anti-bonding/water-repellent surface treatments. Two surveys of state and local transportation agencies and vendors and manufacturers of non-chloride deicing products were conducted, respectively. The survey of state and local transportation agencies identified non-chloride products used. An evaluation of the Clear Roads Qualified Products List (QPL) Specification Document and other standards and testing requirements was conducted, which suggests that a wealth of data is collected and available for review of non-chloride deicing products. A deeper evaluation of BOD, COD, nitrogen, phosphorus, cyanide, toxicity, and corrosion is provided, because these are of particular interest when considering non-chloride deicers. Subsequently, we developed educational primers, or two-page fact sheets, for key categories of non-chloride deicers – acetates, formates, glycols, and ag-based that serve as high-level overviews of information on non-chloride deicers that can be used to make informed decision when comparing products to sodium chloride as rock salt or salt brine. This work found non-chloride deicers to be a viable option in winter roadway maintenance operations and many transportation agencies across the country are successfully using these products.

17. Document Analysis/Descriptors	18. Availability Statement
Non-chloride deicers, educational primer, fact sheets, costs, impacts	No restriction. This document is available to the public through the Clear Roads Organization and the Minnesota Department of Transportation.

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	192	-0-

Efficacy, Cost, and Impacts of Non-Chloride Deicers: An Educational Primer and Product Information Sheets

FINAL REPORT

Prepared by:

Laura Fay
Karalyn Clouser
Neil Hetherington
Mathew Bell
Anna Price
Western Transportation Institute
Montana State University

Dr. Xianming Shi, P.E.
Consultant

September 2023

Published by:

Minnesota Department of Transportation
Office of Research & Innovation
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

ACKNOWLEDGMENTS

We would like to acknowledge the Clear Roads Technical Advisory Panel members- Doug McBroom, Patti Caswell, Jasmine Dondlinger, Laura Shanley, Craig Bargfrede, Jessica Andrews, Michael Nichols, and Tom Peters, and Greg Waidley from CTC & Associates. We would also like to thank the survey respondents from local and state transportation agencies and deicer vendors and manufacturers for providing key information.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Ac - acetate

Ag – agricultural by- or co-product

AIAP – anti-icing asphalt pavement

BOD – biochemical oxygen demand

Ca – calcium

$CaCl_2$ – calcium chloride

Cl - chloride

COD – chemical oxygen demand

CR – Clear Roads

Cy - cyanide

DO – dissolved oxygen

EG – ethylene glycol, $HO-CH_2CH_2-OH$

EPA – Environmental Protection Agency

FAA – Federal Aviation Administration

Fm - formate

hr - hour

K - potassium

KAc – potassium acetate, CH_3COOK

KFm – potassium formate, HCOOK

Mg - magnesium

$MgCl_2$ – magnesium chloride

N - nitrogen

NaAc or NAAC – sodium acetate, CH_3COONa

NaCl – sodium chloride

NaFm – sodium formate, HCOONa

O – oxygen

OD – Oxygen Demand

P - phosphorus

PCR – percent corrosion rate

PG – propylene glycol, $CH_3CH(OH)CH_2OH$

QPL – Qualified Product List

Su - succinate

TKN – Total Kjeldahl Nitrogen

TOD – Total Oxygen Demand

UV – ultraviolet

WRM – Winter Road Maintenance

EXECUTIVE SUMMARY

The objective of this project (CR21-03) was to synthesize available information on non-chloride deicers to allow for a more comprehensive understanding by winter roadway maintenance professionals and allow for easy comparisons between non-chloride products and sodium chloride (as salt brine or rock salt). This was accomplished through a literature search, which summarized research on and identified 46 non-chloride deicing products, summarized research on applications of various heated pavement technologies, and summarized research on anti-icing and anti-bonding/water-repellent surface treatments.

We conducted two surveys of a) state and local transportation agencies and b) vendors and manufacturers of non-chloride deicing products. The survey of state and local transportation agencies identified non-chloride products used. The overwhelming majority of agencies were using sugar beet-derived products, typically as an additive to chloride-based brines. [Note that agriculturally base additives, like beet products, are generally used as additives to chloride-based liquids and solids.] Non-chloride deicers reportedly used by transportation agencies included Biomelt AG-64, Calcium Magnesium Acetate (CMA), Potassium Acetate (KAc), Sand, Sodium Formate (NaFm), and SPC-5000. Information on gallons used, cost, application method and rates, and temperature range used are provided. Agencies indicated the major reason for using these non-chloride deicers was (their) better performance and reduced impacts on the environment and infrastructure. Agencies also indicated that they conducted little to no additional testing to assess the performance of these products. Success stories from agencies highlighted cost saving observed, reduced corrosion impacts, better residual performance, and others. The vendor survey received responses, in the form of data requested, from Cryotech, EnviroTech Services, Inc., Fyve Star, Hawkins Inc., Nachurs Alpine Solutions, LLC, New Deal Deicing, OMEX, and Smith Fertilizer and Grain. Information provided by these companies included the product name and description, average cost, environmental test results, performance test results, and a list of additional documents provided for 20 unique non-chloride deicers.

The evaluation of the Clear Roads Qualified Products List (QPL) Specification Document and other standards and testing requirements revealed that a wealth of data was collected and available for review of non-chloride deicing products. The evaluation also determined that additional testing was not necessary for consideration by Clear Roads at this time.

A deeper evaluation of biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrogen, phosphorus, cyanide, toxicity, and corrosion are provided, because these are of particular interest when considering non-chloride deicers. Overall, BOD values for chlorides were the lowest, with formates and ag-based additives moderately higher, with acetates, succinates, and glycol much higher, and urea having the highest BOD. Generally, COD values followed a similar trend to BOD for the various deicer types. Nitrogen is an essential nutrient but at elevated concentrations can impact the near-road environment. Nitrogen is a primary component in urea and may be present in other deicing materials. Phosphorus is also an essential nutrient but at elevated concentrations can impact the near-road environment. Phosphorus can be present at elevated concentrations in deicers and ag-based additives.

Cyanide can be present in anti-caking additives used in deicers and in ag-based additives, which can lead to cyanide loading around storage facilities and in the near-road environment. Toxicity of deicers is highly variable as a function of the species of interest, components of the deicing material, and concentration. Past work identified chlorides as the least toxic and acetates as more toxic, in the following order: $NaCl < CaCl_2 < MgCl_2 <$ Acetates < Glycols < Formates. Corrosion of metals, or corrosion protection, is commonly associated with non-chloride deicers. The corrosion risk of deicing materials varies greatly as a function of material type, pavement type, and metal type.

Performance testing of non-chloride deicers was evaluated and the influence of deicers on pavement friction was reviewed. In the U.S., pavement friction values (μ) above 0.6 are typically considered safe, friction values 0.6 – 0.4 may trigger a watch or warning that road condition is becoming more slippery, and friction values below 0.4 are considered slippery and commonly result in winter roadway operations. This general guidance can be used by Clear Roads when reviewing friction data provided for QPL consideration. Ice melting capacity test methods were reviewed, and of the methods available, the mechanical rocker test appears to provide the most accurate and precise results, but limited data was available using this test method for many non-chloride deicing products.

A special group of Clear Roads members that works with the QPL may choose to work towards the following:

1. Clear Roads requires a wealth of data be provided by the vendor for QPL evaluation. Consider developing guidance on how these data can be assessed and which guidelines to follow (further clarification on test methods is needed, units to use, etc.).
2. Consider modifying the corrosion testing requirement to include galvanized steel and stainless steel.
3. Consider looking into the limits allowed for phosphorus, nitrogen, and cyanide.

The outcomes of this project include the contents of this final report document and the standalone educational primers (two-page fact sheets) for key categories of non-chloride deicers – acetates, formates, glycols, and ag-based. The developed factsheets serve as high-level information sources on non-chloride deicers that can be used to make informed decisions when comparing products to sodium chloride as rock salt or salt brine.

The following conclusions may be made – non-chloride deicers are a viable option in winter roadway maintenance operations. Many transportation agencies across the country are successfully using these products. Non-chloride deicers provide varying benefits depending on the composition, including performing at colder temperatures, increased corrosion protection, reduced (environmental) impacts, and residual (performance) benefits on the roadway. On the other hand, the same non-chloride deicers can have increased (detrimental) impacts relative to those of salt (rock salt or salt brine) such as with BOD, COD, and toxicity, and typically at an increased cost. There is not a clear way to say one deicing product is better than another. For this reason, each non-chloride deicing product should be evaluated individually based on an agency’s needs and priorities.

Future work could conduct ice melting capacity testing (using the mechanical rocker test or other test method) for non-chloride deicers (read: sodium acetate, calcium magnesium acetate, sodium formate, potassium formate, and ethylene and propylene glycols) to serve as baseline values for these products. Future work could investigate the feasibility of BOD evaluation at colder temperatures and/or for longer periods of time to more closely mimic winter conditions, and/or take dilution into account in the test method. Additional work needs to be done to better understand the toxicity of all deicing products as it relates to dilution, species, water and soil chemistry, water temperature, and exposure duration.

1 Introduction

The objective of this project was to synthesize available information on non-chloride deicers to allow for a more comprehensive understanding by winter roadway maintenance professionals and allow for easy comparisons between non-chloride products and sodium chloride (as salt brine or rock salt). This was accomplished through a literature search, survey, and evaluation of standards and testing requirements. The outcomes include the contents of this final report document, and standalone educational primers (two-page fact sheets) for key categories of non-chloride deicers which are provided in detail in this document.

2 Methodology

2.1 Literature Search

A literature review was conducted, which focuses on identifying recently completed and in-progress research on non-chloride deicers, specifically laboratory and performance data, impacts, performance relative to sodium chloride, and cost in North America and abroad. The literature review also involves the synthesis of data collected from manufacturers and vendors on available non-chloride deicers and performance and environmental data on these products. The third section of the literature review focuses on non-chloride deicing using heated pavements and provides a summary of the research efforts of the last decade. The fourth section focuses on anti-icing/anti-bonding water repellant surface treatments.

Information was found using the following databases: Google Scholar, Transportation Research Information Service, ISI Web of Science, and Montana State University Library, documents published by state DOTs, Clear Roads, university transportation centers (UTCs), Strategic Highway Research Program (SHRP), Federal Highway Administration (FHWA), National Cooperative Highway Research Program (NCHRP), PIARC, American Public Works Association (APWA), and AASHTO; as well as keyword searches via Google.

A summary of the identified relevant literature is provided in Chapter 3: Literature Review and the annotated bibliography is provided in APPENDIX A - Annotated .

2.2 Surveys

Two surveys were developed using Qualtrics, a web-based survey tool. The first survey aimed to collect information from local, state, and international winter maintenance agencies. The second survey aimed to collect information from deicer product manufacturers and vendors. The developed surveys were distributed on October 25, 2022 to the Clear Roads Technical Panel and Members states, the Snow & Ice List Serv, the Transportation Research Board (TRB) Winter Maintenance Committee, vendors and manufacturers of non-chloride deicers, and other relevant transportation agencies and organizations. The surveys were closed on November 28, 2022.

A summary of the survey results is provided in Chapter 4: Survey Results. The survey questionnaires and detailed responses are provided in Appendix B – Survey Instruments & Detailed Results.

2.3 Evaluation of the Clear Road Qualified Products List Specification Document

The Clear Roads Qualified Product List (QPL) Specification Document was evaluated for products that are categorized as non-chloride or non-chloride additives. This includes the following QPL categories:

- Category 3 – Liquid Calcium Magnesium Acetate
- Category 7 – Solid Calcium Magnesium Acetate

- Category 12 – Other Acetates
- Category 13 – Liquid Products with Greater than 30% Organics
- Category L – Experimental Category for Liquid Products
- Category S – Experimental Category for Solid Products
- Category A4 – Additive for Liquid Deicing Products and Pre-Wet Materials

Data required in the QPL Specification Document were evaluated for products from the various categories of the QPL listed above and for non-chloride products not included in the QPL. Information collected in the literature review and survey was used to determine if sufficient information is available to compare the efficacy and environmental impacts of non-chloride deicers, or if additional environmental and performance testing should be conducted for some of these products.

The proceeding evaluation can be found in Chapter 5 - Evaluation of Clear Roads Qualified Product List (QPL) Specification Document.

2.4 Educational Primers

Information on non-chloride deicer groups – acetates, formates, glycols/glycerol, and agriculturally derived (a.k.a., ag-based) deicers, was developed into two-page primers or fact sheets, presenting information on costs, recommended use, and impacts in a succinct and accessible format. All information presented in the primers was captured in previous tasks. We developed the two-page primers for a general non-technical audience including transportation agency staff, the general public, state and local legislators, and media outlets.

The two-page primers can be found in Chapter 6 - Educational Primers.

3 Literature Review

3.1 Research on Non-Chloride Deicing Products

The following section summarizes information identified on non-chloride deicers, including impacts on the environment, infrastructure, and performance. Common categories of non-chloride deicers include acetates (e.g., sodium acetate (NaAc), calcium magnesium acetate (CMA)), formates (e.g., sodium formate (NaFm), potassium formate (KFm)), glycols (e.g., ethylene (EG), and propylene glycol (PG)). Agriculturally derived (ag-based) products are also commonly referred to as non-chloride but are typically blended with chlorides. Many other non-chloride deicing products and blends exist. In this effort, 46 non-chloride deicing products were identified and are summarized in Table 1.

3.1.1 Environmental Impacts

The environmental impacts of non-chloride deicers vary for each product. Common environmental impacts associated with non-chloride deicers include elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD), and increased toxicity to aquatic organisms. The following section highlights work identified that addresses these concerns.

A few studies have examined the oxygen demand and/or toxicological effects of acetate deicers. Alaskan lakes that were dosed with CMA at runoff concentrations found it did not persist, was rapidly consumed by organisms, caused lower dissolved oxygen concentrations for several months, stimulated algae growth, and may have stressed salmonid species (LaPerriere & Rea, 1989). A field investigation of CMA impacts on water quality in Oregon streams found no measurable effects on BOD (USGS, 2000). Corsi et al. (2009) quantified the toxicity of KAc and NaFm in aquatic organisms and found that it was driven by the material, except for in one species where toxicity was caused by additives in the deicer.

Corsi et al. (2012) found that PG aircraft deicers featured higher 5-day biochemical oxygen demand (BOD5) than EG, such that PG aircraft deicers had higher degradation rates. They also found that acetate-based pavement deicers had overall lower BOD and COD than aircraft deicers, and NaFm pavement deicers had lower COD than acetate-based deicers. Acetates were found to degrade more than glycols in fresh and marine waters. The work also investigated the influence of BOD test temperature and length on the results, and found longer test periods and warmer temperatures produced higher values because a lag occurred as the microorganisms adjusted to new food sources.

As part of CR 11-02, Pilgrim (2013) conducted toxicity testing of common roadway deicers and found potassium chloride to be the most toxic, followed by $MgCl_2$, then $CaCl_2$, with NaCl as the least toxic. The commonly used ag-based roadway deicer, a blend of salt brine and sugar beet juice (typically at 80/20 v/v) has BOD5 and COD values of 25.82 mg/L and 277.94 mg/L, respectively (Nazari & Shi, 2019). In contrast, an ag-based deicer consisting of 0.89 wt.% grape pomace extract, 4.57 wt.% glycerin, 4.54

wt.% sodium formate, 0.19 wt.% sodium metasilicate, and 18.4 wt.% NaCl, has significantly lower BOD5 and COD values of 2.77 mg/L and 135.17 mg/L, respectively.

3.1.2 Infrastructure & Equipment Impacts

An attribute commonly associated with non-chloride deicers is reduced (detrimental) impacts to infrastructure and equipment. While this is the case for some non-chloride deicers, the impacts vary for each product. The following section highlights work completed in this field.

Earlier work by Shi et al. (2009) found the most elevated freeze thaw damage to concrete was from KAc, followed by NaCl, NaAc/NaFm blend, KFm, and then CMA and $MgCl_2$, if based solely on the mass loss from scaling. However, the mass loss data and visual observation of concrete fail to tell the full story when the concrete exposure involved $MgCl_2$. Xie et al. (2019) found that degradation by $MgCl_2$ (along with frost damage) often peaked inside concrete, elusive to visual inspection. They also found that cumulative field exposure to (~30 wt.%) $MgCl_2$ deicer induced significantly compromised splitting tensile strength (as high as 50%) and caused a reduction in microhardness (up to 60%, commonly at a depth of 25 to 50 mm) of concrete bridge deck samples cored from the State of Oregon, often without visible surface distress. Xie et al. (2017) reported that relative to NaCl, field exposure to KAc deicer caused more damage to concrete decks, partially due to the use of reactive aggregate. Concrete specimens with non-reactive aggregate were fabricated and subjected to freezing/thawing (F/T) and wetting/drying (W/D) cycles. In addition to calcium (Ca) leaching, needle-shaped and rod-shaped precipitates formed in concrete samples after F/T and W/D cycles in NaCl and KAc, respectively. For the laboratory concrete specimens, KAc induced notably more reduction in their compressive strength than NaCl. In addition to the physical attack on the concrete by internal stress buildup induced by the F/T cycles, NaCl deicer could chemically react with calcium and hydroxide ions in the concrete pore solution and ettringite (a cement hydrate) to form oxychloride and trichloroaluminate crystals, respectively (Egüez Álava et al., 2016; Farnam et al., 2015a, 2016). $MgCl_2$ deicer could react with cement hydration products to generate multi-phase crystals, such as $Mg(OH)_2$ and $Mg_3(OH)_5Cl\cdot(H_2O)_4$, which could lead to the internal damage of concrete (Farnam et al., 2015b; Xie et al., 2019). $CaCl_2$ deicer could also react with cement hydration products, evidenced by the reduced $Ca(OH)_2$ content, calcium leaching and formation of calcium oxychloride crystals (Jones et al., 2020; Qiao et al., 2021a; Qiao et al., 2021b).

Glycol was found to have similar freeze-thaw damage to concrete pavement as NaCl at low concentrations, whereas higher concentration reduced the impacts (Haiyan et al., 2010). Overall, commercial aircraft deicers had a larger negative impact on freeze-thaw damage to concrete than pure glycol. Furthermore, Anastasio et al. (2015) found more damage to airport asphalt pavements from NaFm than NaCl. Glycerol has been shown to reduce impacts to concrete and asphalt pavements when added to brines (Shi & Jungwirth, 2018).

Damage to the asphalt mixture in the presence of deicers was typically greater than in the presence of only water, especially when the asphalt pavement underwent freeze-thaw cycles (Dore et al., 1997; Xu and Shi, 2018). The deicers seemed to reduce the strength and elasticity of asphalt mixture, exacerbating the freeze-thaw damage (McCutchon et al., 1992). Premature deterioration of asphalt pavement due to the use of acetate/formate-based deicers was found at some Nodic airports. Typical symptoms included degradation and disintegration of asphalt pavement, softening of asphalt binders, and stripping of asphalt mixes occurring together with loose aggregates on the runways (Nilsson, 2003; Shi , 2008). A laboratory investigation also confirmed that the use of acetate/formate-based deicers could accelerate the degradation of asphalt mixture through emulsification of the binder (Pan et al., 2008). Yang et al. (2018) discussed the impact of non-chloride deicers on asphalt mastic based on their hydrophilic-lipophilic properties. Compared with more lipophilic potassium propionate (PP) and KAc, higher concentrations of hydrophilic dipotassium succinate (DS) and KFm on the asphalt binder surface featured larger contact angles, which consequently resulted in lower wettability and lower moisture susceptibility.

At the time of this report there is insufficient data in the published domain on ag-based deicer impacts on pavements to state any clear conclusions. Nazari & Shi (2019) optimized an ag-based deicer based, in part, on reduced impacts to cement paste and carbon steel, which consisted of 0.89 wt.% grape pomace extract, 4.57 wt.% glycerin, 4.54 wt.% sodium formate, 0.19 wt.% sodium metasilicate, and 18.4 wt.% NaCl. Fan et al. (2023) investigated whether and how a common ag-based additive, beet root juice, altered the detrimental effects of chloride brines on the durability of cement concrete, by evaluating the frost resistance of ordinary Portland cement (OPC) concrete in various chloride brines. The presence of beet root juice in NaCl or $MgCl_2$ greatly slowed the ingress of Cl^- ions and mitigated the leaching of Ca^{2+}, thus effectively mitigating the scaling-induced mass loss, strength reductions, and gas permeability change of the concrete. In other words, beet root juice showed great potential in mitigating the deicer scaling induced deterioration of OPC concrete, especially when blended with the NaCl solution, likely by increasing the viscosity of the deicer solution and depositing a protective film on the concrete surface.

Corrosion protection is a key attribute associated with many non-chloride deicers. Ag-based additives have been shown to provide corrosion protection (Muthumani et al., 2016; Shi & Jungwirth, 2018; Nazari et al., 2019). Nazari et al. (2017) found that the presence of sugar beet by-product in 30 wt.% $MgCl_2$ could form a (temporary) organic protective layer on the surface of both coated and bare carbon steel samples, with much greater anticorrosion benefit for bare coupons. Nazari et al. (2020) found that sugar beet juice mitigated the corrosion rate of C1008 carbon steel, gray cast iron GCCL35, and Type 65-45-12 ductile cast iron samples in the presence of diluted 23 wt.% NaCl at dilution ratios of 1:90 and 1:30. However, for 30 wt.% $MgCl_2$ solution, the sugar beet juice only reduced the corrosion rate at the 1:30 dilution ratio. The effect of solution type on the protectiveness of an organic passive layer could be related to the effect of ionic strength on the solubility of beet juice molecules. Glycerol has been used as a brine additive to reduce corrosion to metals (Shi & Jungwirth, 2018). CMA was found to be less corrosive to automotive steel, aluminum alloys, stainless steel, and combined metals than NaCl (Slick, 1998). Acetate-based deicers are frequently used on bridge decks to prevent corrosion (TRS, 2017).

Typical corrosion testing asses impacts to mild steel but work by Caplan & Cohen (1953) found that EG causes corrosion to galvanized steel.

3.1.3 Performance

Many non-chloride deicers have varying influences on deicing performance, such as improving ice melting ability, working at colder temperatures than salt, and providing residual (performance) benefits to name a few. The performance of each non-chloride deicer needs to be assessed individually. The following section highlights work assessing performance of various non-chloride deicing products.

Work by Cuelho et al. (2010) found that the use of ag-based products aided in reducing the effort required to plow snow off pavement samples when compared to salt, KAc, $MgCl_2$, and $CaCl_2$ deicing products. Muthumani et al. (2014) found more ag-based products remained on pavement samples after trafficking and plowing, showing these products had a residual effect. They also found ultraviolet (UV) exposure increased ice melting for all product types, but more so for darker ag-based products. Nazari & Shi (2019) optimized an ag-based anti-icer based in part on ice melting, which consisted of grape extract, glycerin, sodium chloride, sodium metasilicate, and sodium formate. Work on ag-based deicers by Taylor et al. (2014), found greatest deicing performance measured as freezing point, ice melting, skid resistance, and viscosity from an 80% glycerol and 20% NaCl blend.

Work by Nilssen et al. (2018) found solid deicing chemicals had higher ice melting capacity than liquid solutions; NaCl had the highest in solid form and $CaCl_2$ had the highest in liquid form. CMA was found to reduce slip resistance, or improve grip, on many pavement types when compared to NaCl (Sahaf & Moradzadeh, 2015). Ice undercutting testing was used to assess performance of various deicers and FreezGard CI Plus, a $MgCl_2$ based liquid, performed the best after 30 minutes (Lammers, 2021).

Levulinic acid (sodium, magnesium, and calcium levulinate) from sorghum grain was tested in the lab to determine its deicing properties (Ganjyal et al., 2007). Sodium levulinate was found to have the best freezing point range, from 27°F to 5°F, and melt the most ice, which showed its potential for use in the field as a deicer. Laboratory analysis of potassium succinate found it could work as a deicer down to 23°F and had slightly lower ice melting rates than NaCl (Fay & Akin, 2018). Using unbaked dolomite rock as a source of calcium and magnesium nitrates and adding carbamide at a blend ratio of 1:2.01 worked as a deicer down to -25.6°F (Akhmedov et al., 2018). Successful field trials occurred with this product.

3.2 Heated Pavements Research

The following reports and journal papers were identified and provide information on a non-chloride deicing option for heating pavements. Investigated heated pavement technologies included geothermal heating, electrical resistive heating, and external heating (wind, solar, microwave and infrared) (Shi & fu, 2014).

Carbon fiber tape was investigated for use as heating panels embedded in concrete and performed satisfactorily during deicing and anti-icing operations (Yang et al., 2012). Energy costs were sensitive to air temperature and wind chill. Overall, the carbon fiber tape heating system showed high energy efficiency and cost effectiveness. Suggested applications include sidewalks, parking lots, bridge decks, street crossings, and culverts in cold regions. Wu et al. (2015) tested carbon fibers imbedded in concrete and found the dosage and uniformity of carbon fibers were key factors in its effectiveness. They also found that adding sand reduced air gaps and improved effectiveness. Overall, Wu et al. found conductive concrete provided low resistivity and high power and had potential in snow melting and deicing. Electrically conductive carbon fiber cloth, with an ethylene propylene diene monomer (EPDM) rubber composite and aluminum silicate fiber cloth thermal insulation layer, was investigated to heat pavements and was found to have good temperature durability, mechanical stability, and uniform heat production capacity (Han et al., 2019). To verify this technology, actual deicing and snow melting experiments should be conducted. Follow up work by Wei et al. (2020) incorporated graphite into the rubber composite EPDM, used a heat generating carbon fiber cloth layer, and an aluminum silicate fiber cloth, which proved to be stronger than the no-graphite test in tensile and shear strength and thermal conductivity. The mechanical properties met requirements for road use. Mohammed et al. (2019) tested three different forms of carbon fiber, cable filaments, and woven and unidirectional fabrics in concrete and generally found the method to be a viable option for deicing and preventing snow accumulation. They found the cable filament was more advantageous than other forms tested. Carbon nanotubes embedded in concrete 40 inches apart were found to effectively deice in the lab and field (Kiim et al., 2020).

Conductive composite overlays made of carbon fibers in a polyurethane rubber sheet, with gravel bonded on the surface as a wearing layer and an aluminum foil film on the bottom for adhesion and insulation, was tested by Yang et al. (2018). The composite overlay was found to melt ice and frost, have high electrothermal conversion efficiency, excellent flexibility, and serve as a friction wearing layer. Applications include use on accelerated construction projects. Yan et al. (2021) investigated the use of a wearing surface with graphite for deicing, which performed well mechanically and served effectively as a wearing coarse and at melting ice.

Hydronic heating from district heating and cooling systems was studied and the temperatures were suitable for heated pavement applications (Blomqvist et al., 2019). Additional analysis and modeling found the system could be modified for increased energy efficiency and reduced greenhouse gas emissions.

Electrically heated steel pipes embedded in concrete approximately 6 inches deep and 6 inches apart were able to melt 2 inches of snow in 5 hours at a heating power of 533 watts (Liu et al., 2019a). A large-scale field test of electrically conductive heated concrete found flat bar and smaller diameter electrodes were more cost-effective, but larger sized electrodes increased energy efficiency (Malakooti et al., 2021). Recommendations from this work included heating pavement prior to the snow event and use of this technology on bridge decks and at rest areas. Asphalt with steel slag and Teflon-carbon fiber for heating was a stable heat source that deiced better than steel slag alone when embedded at 1.5 inches and spaced 4 inches apart (Jiao et al., 2022). The design could be optimized for energy consumption and environmental conditions.

Another method of heating asphalt mixed with embedded steel wool using microwave reported the optimal steel wool percent and mix design for heating uniformity, ice thawing time, and ice thickness (Gao et al., 2019). Overall, they found a larger diameter steel wool helped improve heating uniformity. Magnetite was added to concrete for microwave heating experiments by Huang and Xu (2019). They found the magnetite improved mechanical properties and deicing efficiency. As magnetite concentration increased, so did compressive and flexural strength and absorption and heating efficiency of the concrete. Graphite was added to concrete and was found to increase microwave deicing efficiency, and the cost and time required for deicing was significantly improved (Liu et al. 2019b). Liu et al. (2020) tested the microwave heating efficiencies of graphite, iron black, and silicon carbon added to concrete. Ferric aluminum and hydroxy iron power mixed with asphalt were also tested for microwave deicing. When considering cost and deicing efficiency, the ideal mix had 1% ferric aluminum and 5% hydroxy iron; additional testing to determine pavement durability was recommended (Ding et al., 2021). Lu et al. (2021) added carbon fiber to concrete to test its microwave deicing capabilities and found that while more carbon fiber allowed for better deicing performance, as little as 1% could be used, which balanced mechanical properties, deicing, and cost. Carbon fiber modified concretes were tested by Ning et al. (2022) and longer carbon fibers (0.6 cm) and higher concentrations (2%) had the highest microwave heating.

3.3 Anti-icing or Anti-Bonding/Water-Repellent Surface Treatments

Another category of non-chloride roadway deicing options is anti-bonding surface treatments. These treatments consist of applying a surface treatment on the pavement as a chemical and/or the blending of a chemical in the pavement mixing process. The success of these anti-bonding strategies is marked by their ability to reduce the amount of plow force (ice adhesion) required to remove bonded snow and ice from pavement. Similarly, hydrophilic and hydrophobic coating are used for similar purposes on aircraft, space shuttles, winter turbines, powerlines, and roadways. Key attributes of these treatments include friction, water contact angle, wettability, interfacial shear strength. They also include properties of that material, in this case the roadway surface, such as roughness and texture, air entrapment, permeability, and absorption capacity. All attributes can influence ice adhesion (Tiwari, 2020).

Anti-icing asphalt pavements (AIAP) that have salt-storage additives have been developed and tested. Summary work by Zhang et al. (2021) noted these pavements improve driving conditions by facilitating snow removal, but the salt-storage additives could compromise the integrity of the asphalt pavement. Zhang et al. noted that the release rate of stored salt could be difficult to control. Zhang and Shi (2021) developed and tested an AIAP asphalt with zeolite aggregate containing $CaCl_2$ coated with a micro-epoxy layer. They were able to achieve both anti-icing and mechanical performance, including slower salt release and reduced impacts to the asphalt pavement. A promising anti-icing application was under freezing fog conditions. The theoretically anti-icing service life was calculated to be at least 3.4 years. Modeling work by Zhang et al. (2022) found that a 16 mm thick asphalt pavement overlay with salt storage additive could function for 5 years at a minimum pavement temperature of 27.7°F.

Tazawa et al. (1992) found that increasing the deformability of the asphalt concrete, through the introduction of rubber in the mix design, was an effective method of decreasing interfacial bonding between ice and the pavement surface.

Sprinkel et al. (2009) compared roadway test sections of various overlay treatments, one of which was designed to absorb/hold deicing material, on interstates and bridges. They found that these treatments could prevent frost, ice, and snow on the roadway when compared to traditional concrete pavements. Additionally, these overlay treatments were found to serve as a wearing layer and increased skid-resistance of the pavement.

Wright et al. (2016) found that both sodium formate and sodium silicate, when used as filler in bituminous materials, moved to the pavement surface and reduced ice adhesion, but also found that sodium silicate reduced the pavement durability. Work by Al-Kheetan et al. (2020) found the concrete samples with lower water/cement ratios were more resistant to freeze-thaw damage. When water/cement ratios were higher and sodium acetate was added the damage was exacerbated but when water/cement ratios were lower and sodium acetate was added, the pavement was provided additional protection.

Song et al. (2019) investigated the use of inexpensive, non-fluorinated, and robust superhydrophobic concrete (S-concrete) coating and found the material had surface mechanical strength, remained effective after scratching and abrasion, and provided good anti-icing ability, low ice adhesion strength with pavement, and high corrosion resistance on concrete. Work by Shen et al. (2020) using mortar concrete with 1H,1H,2H,2H-Perfluorodecyl triethoxysilane (PFDTES, $C16H19F17O3Si$) mixed in found it had low water permeability, low ice adhesion strength, and low ice accumulation. The material did not degrade with mechanical nor weather exposure. Work by Wang et al. (2022) developed an anti-icing surface coating from biochar and titanium nitride nanoparticles that showed great anti-icing properties and had photothermal properties.

Mundo et al. (2020) found that coating and impregnation using polyurethane and silane/siloxane were effective at preventing water ingress creating hydrophobic pavement conditions and had icephobic characteristics. Additionally, they found embedding nano-powders in hydrophobic emulsions could create hydrophobic coatings and icephobic characteristics.

3.4 Summary of available non-chloride deicing products

A preliminary list of 46 deicing products that are sold as non-chloride deicers for roadway and airport applications are summarized in Table 1. The table includes the following information product name, vendor/manufacturer, and deicer material along with summary information on whether the product is on the Clear Roads QPL, if sold as a non-chloride deicer despite including chlorides, links to product information pages, if technology summary sheet and Safety Data Sheet (SDS) are available, and other explanatory notes. Note that there are likely similar products with different names. The goal was to identify as many non-chloride deicing products as was feasible.

Table 1. Summary of non-chloride deicing products described by product name, vendor/manufacturer, deicing material, and links to additional resources, etc.

Name	Vendor	Type	CR QPL List	Chlorides Present	Composition	Link	SDS (MSDS) Downloaded	Runway Deicer	Notes
Bare Ground Clear Way Non Chloride Potassium Formate Liquid Deicer	Bare Ground Solutions				Potassium Formate (60-75%) Water (25-40%)	https://www.bareground.com/product/winter/bare-ground-clear-way-non-chloride-potassium-formate-liquid-deicer/	Y		SDS downloaded
Bare Ground Jet Way Sodium Formate Granular Deicers	Bare Ground Solutions				Sodium Formate (>98%)	https://www.bareground.com/product/winter/runway-and-rail-switch-deicers/bare-ground-jet-way-sodium-formate-granular-deicer/	Y		SDS downloaded
Clear Way Non Chloride Potassium Acetate	Bare Ground Solutions				Potassium Acetate	https://www.bareground.com/product/winter/ice melt/clear-way-non-chloride-potassium-acetate/			
Entry	Branch Creek Solutions				Potassium Formate (45-54%) Water (40-49%) Adjuvant Blend (Proprietary)	https://chloridefree.com/commercial/	Y		SDS, resource guide downloaded
GreenBlast	Cargill	Additive for Liquid Deicing Products and	x			No information found online on this product			

Name	Vendor	Type	CR QPL List	Chlorides Present	Composition	Link	SDS (MSDS) Downloaded	Runway Deicer	Notes
		Pre-Wet Materials							
CF-7	Cryotech	Other Acetates	x		Potassium Acetate (50%) Water (50%) Corrosion Inhibitors (<1%)	https://www.cryotech.com/products/cf7-liquid-deicer?app=pavement	Y		fact sheet, SDS downloaded
CMA	Cryotech	Solid Calcium Magnesium Acetate	x		Calcium Magnesium Acetate (96%) Moisture and Water-Insoluble Oxides/Hydroxides (<4%)	https://www.cryotech.com/products/cma-solid-deicer?app=pavement	Y		fact sheet, SDS downloaded
CMAK	Cryotech	Other Acetates	x			No information found online on this product			
E36	Cryotech				Potassium Acetate (50%) Water (50%) Corrosion Inhibitors (<1%)	https://www.cryotech.com/products/e36-liquid-runway-deicer	Y	Y	fact sheet, SDS downloaded
LC17	Cryotech				Propylene Glycol (10-50%) Potassium Acetate (10-50%) Corrosion Inhibitors (<1%)	https://www.cryotech.com/products/lc17-liquid-runway-deicer	Y	Y	fact sheet, SDS downloaded

Name	Vendor	Type	CR QPL List	Chlorides Present	Composition	Link	SDS (MSDS) Downloaded	Runway Deicer	Notes
Liquid CMA 25%	Cryotech	Liquid Calcium Magnesium Acetate	x						listed under the solid CMA on the Cryotech website
NAAC	Cryotech				Sodium Acetate - Anhydrous (97%) Corrosion Inhibitors (<1%)	https://www.cryotech.com/products/naac-solid-deicer?app=pavement	Y		fact sheet, SDS downloaded
QS50	Cryotech				Sodium Acetate - Anhydrous (30-70%) Sodium Formate (30-70%) Corrosion Inhibitors (<2%)	https://www.cryotech.com/products/qs50-solid-deicer	Y	Y	fact sheet, SDS downloaded
Apogee	Envirotech Services Inc.				Water (Balance) Proprietary Organic Based Components (75-85%) Proprietary Performance Additive (2-6%)	https://envirotechservices.com/products/anti-icing-deicing/ultra-low-based-products/	Y		brochure, SDS downloaded
Boost SB	Envirotech Services Inc.	Additive			Organic Agricultural By-Product (Proprietary)	https://envirotechservices.com/products/anti-icing-deicing/salt-brine-additives-products/	Y		SDS downloaded

Name	Vendor	Type	CR QPL List	Chlorides Present	Composition	Link	SDS (MSDS) Downloaded	Runway Deicer	Notes
					Water (Proprietary)				
SOS AP	Envirotech Services Inc.	Additive for Liquid Deicing Products and Pre-Wet Materials	x	x	Water (66-76%) Magnesium Chloride (24-34%) Shield AP Corrosion Inhibitor (<1%) Performance Additive (Proprietary)	https://envirotechservices.com/sos/	Y		SDS downloaded
SOS Inhibited	Envirotech Services Inc.	Additive for Liquid Deicing Products and Pre-Wet Materials	x	x	Water (66-76%) Magnesium Chloride (24-34%) Shield AP Corrosion Inhibitor (<1%) Performance Additive (Proprietary)	https://envirotechservices.com/sos/	Y		SDS downloaded
SOS-C Inhibited	Envirotech Services Inc.	Additive for Liquid Deicing Products and Pre-Wet Materials	x	x	Water and Non-Hazardous Components (Balance) Calcium Chloride (25-	https://envirotechservices.com/sos-c/	Y		SDS downloaded

Name	Vendor	Type	CR QPL List	Chlorides Present	Composition	Link	SDS (MSDS) Downloaded	Runway Deicer	Notes
					35%) Proprietary Corrosion Inhibitor (2-10%)				
Safeway KA Hot	Fyve Star				Potassium acetate (50%)	https://www.fyvestar.com/wp-content/uploads/2019/01/7.-SafewayKAHOTcg.pdf		Y	Available Upon Request
Safeway SF	Fyve Star					https://www.fyvestar.com/wp-content/uploads/2019/01/6.-Safeway_SF-Tech-Sheet-copy.pdf		Y	Available Upon Request
NC 3000	Glacial Technologies	Other Acetates	x			No information found online on this product			
Aqua Hawk KA-50 Deicer	Hawkins	Liquid Potassium Acetate Deicer				https://www.hawkinsinc.com/groups/oil-field-chemicals/potassium-acetate-deicer-supplier/		Y	
Liquid Potassium Formate, 53%	Hawkins			x	Potassium formate (51-53%)	https://www.hawkinsinc.com/groups/oil-field-chemicals/liquid-potassium-formate-53/		Y	
Magic Minus Zero (Brine Enhanced)	Innovative Surface Solutions	Additive for Liquid Deicing Products and Pre-Wet Materials	x	x		https://www.innovativecompany.com/environmentally-friendly-liquid-deicer.php			

Name	Vendor	Type	CR QPL List	Chlorides Present	Composition	Link	SDS (MSDS) Downloaded	Runway Deicer	Notes
Magic Minus Zero (Concentrate)	Innovative Surface Solutions	Additive for Liquid Deicing Products and Pre-Wet Materials	x	x		https://www.innovativecompany.com/environmentally-friendly-liquid-deicer.php			
ProMelt Ultra 2000 Inh	Innovative Surface Solutions	Experimental Category for Liquid Products	x	x	Magnesium Chloride (24%) Proprietary Ingredients (12%)	https://www.innovativecompany.com/liquid-deicer-anti-icing-frost-prevention-2000.php	Y		spec sheet and SDS downloaded
Liquid Ice Melt	Interstate Products, Inc.				Ethylene Glycol (25-35%) Methanol (20-30%) Diethylene Glycol (1-5%)	https://store.interstateproducts.com/products/liquid-ice-melt-5-gallon-pail.html	Y		SDS downloaded
Beet Heet Concentrate	K-Tech	Additive for Liquid Deicing Products and Pre-Wet Materials	x	x	Calcium Chloride (Proprietary) Agricultural Based Organic (Proprietary) Magnesium Chloride (Proprietary) Potassium Chloride (Proprietary)	https://northernsalt.com/beet-heet-liquid-de-icer/			

Name	Vendor	Type	CR QPL List	Chlorides Present	Composition	Link	SDS (MSDS) Downloaded	Runway Deicer	Notes
Beet Heet Concentrate MN	K-Tech	Additive for Liquid Deicing Products and Pre-Wet Materials	x	x		https://www.ktechcoatings.com/content/winter-products			
Alpine Ice-Melt	Nachurs Alpine Sol. Ind.	Other Acetates	x		Proprietary, Product TDS lists this as a 50% w/w potassium acetate solution	https://www.nasi-tm.com/alpine-ice-melt	Y		tech data sheet, SDS downloaded
Alpine RF-11	Nachurs Alpine Sol. Ind.				Proprietary, Product TDS lists this as a 50% w/w potassium acetate solution	https://www.nasi-tm.com/alpine-rf-11	Y		tech data sheet, SDS downloaded
Alpine RF-14F	Nachurs Alpine Sol. Ind.				Water (Proprietary) Potassium Formate (Proprietary) Corrosion Inhibitor (Proprietary)	https://www.nasi-tm.com/alpine-rf-14	Y		tech data sheet, SDS downloaded
GEN3 6-4	Nachurs Alpine Sol. Ind.				Glycerin (30-60%)	https://www.nasi-tm.com/gen3-64	Y	Y	tech data sheet, SDS downloaded

Name	Vendor	Type	CR QPL List	Chlorides Present	Composition	Link	SDS (MSDS) Downloaded	Runway Deicer	Notes
NASi FormiKlear	Nachurs Alpine Sol. Ind.				Potassium Formate (Proprietary) Water (Proprietary) Corrosion Inhibitor (Proprietary)	https://www.nasi-tm.com/formiklear	Y		tech data sheet, SDS downloaded
NEWDEAL	New Deal Deicing	Sodium acetate/formate Blend			Sodium Formate (68-78%) Sodium Acetate (20-30%) Proprietary Corrosion Inhibitors (<2%)	https://newdealdeicing.com/products/	Y	Y	tech data sheet, SDS downloaded
Isoway	Omex Environmental	Other Acetates	x		Potassium Acetate (26% w/w)	https://omexcanada.com/products/specialty-products/46-isoway			product sheet downloaded
Ice Guard	Ossian				Potassium Acetate (Proprietary) Water (Proprietary) Organic Additive (Proprietary) Corrosion	https://ossian.com/liquid-deicers/ice-guard/	Y		tech data sheet, SDS downloaded

Name	Vendor	Type	CR QPL List	Chlorides Present	Composition	Link	SDS (MSDS) Downloaded	Runway Deicer	Notes
					Inhibitors (Proprietary)				
Select Liquid Deicer	Ossian				Potassium Acetate (50%) Water (50%) Corrosion Inhibitors (<1%)	https://ossian.com/liquid-deicers/select/	Y		tech data sheet, SDS downloaded
CMA	Peters Chemical Company				Hydrated Calcium Magnesium Acetate (Proprietary) Water Insoluble Material (<4%)	https://www.peterschemical.com/calcium-magnesium-acetate/	Y		SDS Link: https://www.peterschemical.com/calcium-magnesium-acetate/msds-calcium-magnesium-acetate-cma/
Asset	Secure Winter Products				Potassium Formate (25-35%) Adjuvant Blend (15-25%)	https://securewinterproducts.com/products/asset/	Y		SDS downloaded
Zero Ground	Secure Winter Products				Sodium Formate (>98%) Entry Chloride Free (<2%) Corrosion Inhibitor & Colorant (<2%)	https://securewinterproducts.com/products/zeroground-chloride-free/	Y		SDS downloaded

Name	Vendor	Type	CR QPL List	Chlorides Present	Composition	Link	SDS (MSDS) Downloaded	Runway Deicer	Notes
Beet 55+	Smith Fertilizer and Grain	Liquid Products with Greater than 30% Organics	x		Proprietary	https://www.sfgroadmaintenance.com/products/beet-55/	Y		basic info, PDS, and SDS downloaded
SC CMA 25%	Sure Crop Farm Services	Liquid Calcium Magnesium Acetate	x			No information found online on this product			
Viper 2.0	UltraViolet				Hydrated Calcium Magnesium Acetate (Proprietary) Water Insoluble Material (<4%)	https://www.ultravioletusa.com/viper-products	Y		SDS Link: https://www.ultravioletusa.com/_files/ugd/b063f1_3b849a9a58124adaa405ea6e701de278.pdf
Viper Elite	UltraViolet				Potassium Acetate (50%) Water (50%) Corrosion Inhibitors (<1%)	https://www.ultravioletusa.com/viper-products	Y		SDS downloaded
Enviro-Melt	Valtec Industries				Urea (98%)	https://valtecindustries.com/products/enviro-melt-non-chloride-ice-melt-pellets	Y		SDS downloaded

4 Survey Results

4.1 Transportation Agency Survey

A total of 26 people responded to the transportation agency survey who provided information on 23 transportation agencies across the US. Twelve agencies (46% of respondents) indicated they use a non-chloride deicer, which, for the purposes of this survey, included any products used for anti-icing, deicing, or pre-wetting operations (see Table 2). These 12 agencies represented 2 cities, a county department of transportation, and nine state departments of transportation (Figure 1).

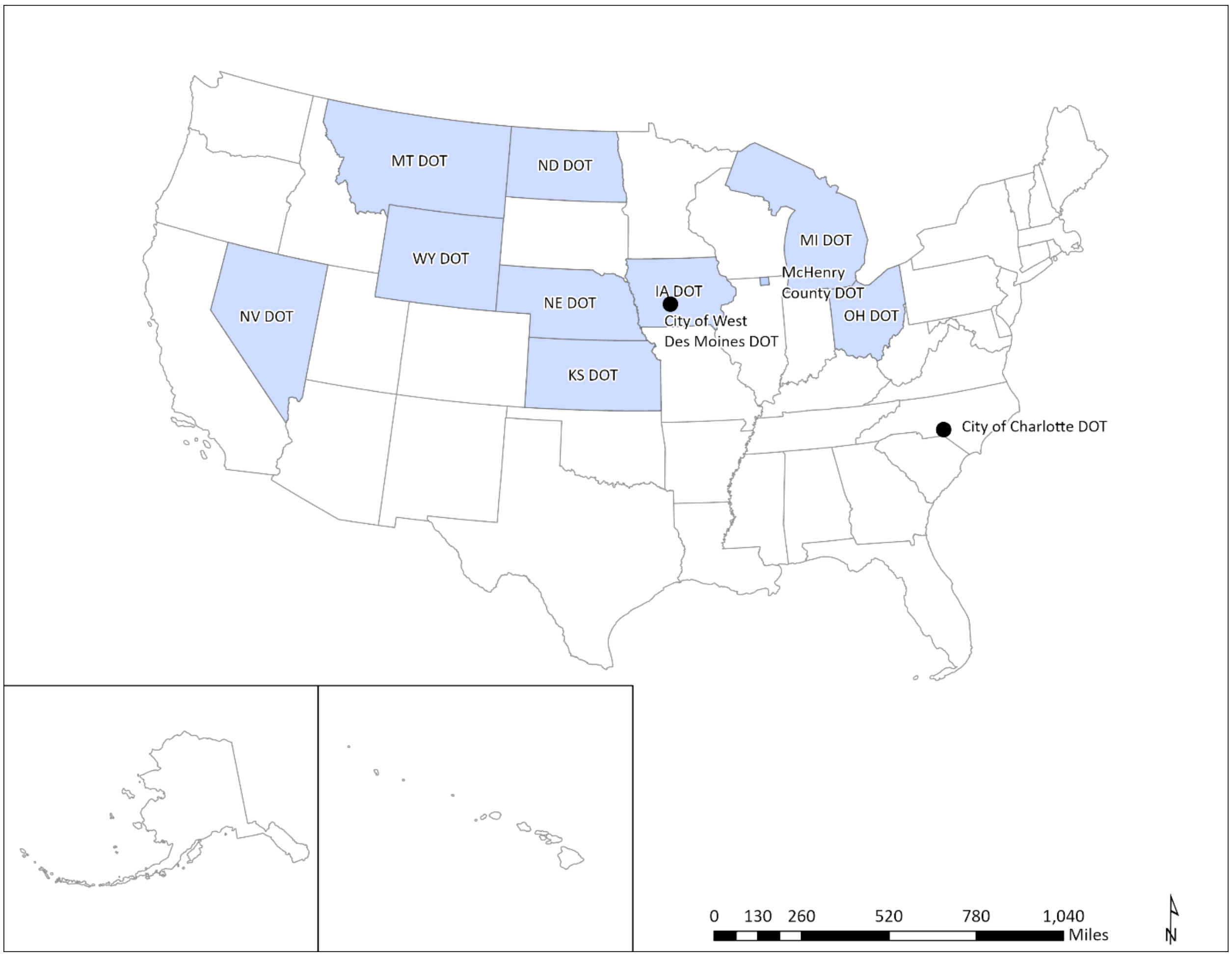


Figure 1. Respondents Who Use Non-Chloride Deicers

Table 2. Does your agency use non-chloride deicers (e.g., acetates, formates, agricultural-derived)?

Organization Name:	State	Does your agency use non-chloride deicers (e.g., acetates, formates, agricultural-derived)?
Alaska Department of Transportation and Public Facilities	Alaska	No
City of Charlotte Department of Transportation	North Carolina	Yes
City of West Des Moines Iowa	Iowa	Yes
Connecticut Department of Transportation	Connecticut	No
Delaware Department of Transportation	Delaware	No
Idaho Transportation Department	Idaho	No
Illinois Department of Transportation	Illinois	Yes
Iowa Department of Transportation	Iowa	No
Iowa Department of Transportation	Iowa	No
Kansas Department of Transportation	Kansas	Yes
Maryland Department of Transportation State Highway Administration	Maryland	No
Massachusetts Department of Transportation	Massachusetts	No
McHenry County Department of Transportation	Illinois	Yes
Michigan Department of Transportation	Michigan	Yes
Montana Department of Transportation	Montana	Yes
Nebraska Department of Transportation	Nebraska	Yes
Nevada Department of Transportation	Nevada	No
Nevada Department of Transportation	Nevada	Yes
North Dakota Department of Transportation	North Dakota	Yes
Ohio Department of Transportation	Ohio	Yes
Oregon Department of Transportation	Oregon	No
Road Commission for Oakland County	Michigan	No
Utah Department of Transportation	Utah	No
Utah Department of Transportation	Utah	No
Vermont Agency of Transportation	Vermont	No
Wyoming Department of Transportation	Wyoming	Yes

All respondents were then asked whether their agency used any heated pavements to aid in deicing. Just one respondent (Montana Department of Transportation) indicated that they were using heated pavements.

The remainder of this section discusses survey results from the 12 respondents who indicated that their transportation agency used a non-chloride deicer.

4.1.1 Non-Chloride Deicer Products Used

Respondents were asked to provide information on what non-chloride deicing products their agency used. Agriculturally derived (ag) products, primarily Beet 55 or beet juice, were the most commonly used, with 8 agencies using some form of ag-based deicer. [Note that agriculturally base additives, like beet products, are generally used as additives to chloride-based liquids and solids.] Other non-chloride deicing products used included Biomelt AG-64, Calcium Magnesium Acetate (CMA), Potassium Acetate (KAc), Sand, Sodium Formate, and SPC-5000. Detailed responses are provided in Appendix B - Detailed Responses.

4.1.1.1 Beet-Derived Products

Survey respondents indicated that their agency used the following beet-derived products, including Beet 55, Beet Heet Concentrate, Beet Heet Severe, Beet Juice, and GEOMELT. Agencies that chose beet-derived products used between 17,000 gallons (Nebraska DOT) and 500,000 gallons (North Dakota DOT) annually, with a cost ranging between $1.44 per gallon and $1.95 per gallon. The most common use of beet products was for pre-wetting, followed by anti-icing. Application rates ranged from 8 gallons per lane mile to 40 gallons per lane mile and were generally used for temperatures ranging from 0°F to 20°F. Nearly all respondents that used a beet-derived products were using it on all roadways. However, Wyoming DOT stated they only used Beet 55 in shady areas and Nebraska DOT stated they only used Beet 55 in the Omaha metropolitan area. For more information on those using beet-derived products, see Table 3.

Table 3. Survey Responses from Agencies using Beet Derived Products

Organization:	What non-chloride deicers does your agency use?	Quantity Used or Purchased Annually	Cost (per ton, per gallon, other)	Application Methods Used	Application Rate for Each Method	Temperature Range Used (°F)	Where is the product applied?	Storage/Handling Requirements
McHenry County DOT (Illinois)	Geo Melt (Beet Juice)	80,000 gallons	$1.95 per gallon	Anti-icing, Deicing, Prewet	40 gal/mile, 40-80 gal/mile, prewet - 8-20 gal/mile	0+	All locations	None
City of West Des Moines (Iowa)	Beet 55	20,000 gallons	$1.54 per gallon	Liquid Anti-Icing	40 gallons/ln mile	10-30, pavement temp	All City Streets	No
Kansas DOT	Beet 55	44,000 gallons	$1.73	Liquid Anti Icing	10-20% with NaCl Brine	0-20	All	Periodic Mixing
Nebraska DOT	Beet Juice	17,000 gallons	$1.44 per gallon	Liquid Deicing/Pretreatment		17 and dropping	Omaha metro area	No
North Dakota DOT	Ag Beet Liquid Deicer – mixed with brine at 20%	500,000 gallons	$1.50 per gallon	Liquid – Anti-Icing, Deicing, Pre-wetting	Varies – Don't directly apply, 20 gal (anti-icing) to 200 gal per lane mile (deicing)	10 and above	All roadways	None

Organization:	What non-chloride deicers does your agency use?	Quantity Used or Purchased Annually	Cost (per ton, per gallon, other)	Application Methods Used	Application Rate for Each Method	Temperature Range Used (°F)	Where is the product applied?	Storage/Handling Requirements
Ohio DOT	Beet Heet Concentrate	393,045 gallons	Between $1.65 to $2.42 per gallon. depending on delivery site and tanker size. We have additional drop fees as well.	Liquid/Deicing, Liquid/Anti-icing, Liquid/Prewet	10% mix with brine	Use blend when road temp is below 20.	All locations when warranted	We store all of our liquid deicers in single walled poly tanks with bollards around the tanks and no secondary containment
Ohio DOT	Beet Heet Severe	84,472 gallons	Between $1.45 and $2.22 per gallon depending on location and tanker size. We also have various drop fees.	Liquid/Deicing, Liquid/Anti-icing, Liquid/Prewet	10% mix with brine	Use blend when road temp is below 20	All locations when warranted	We store all of our liquid deicers in single walled poly tanks with bollards around the tanks and no secondary containment
Wyoming DOT	Beet55	17,418 gallons	$1.60 per gallon	Liquid/Prewet	30 gal/ LM	0 - 25	Shady areas	Tanks

4.1.1.2 Biomelt AG-64

Just one agency reported using Biomelt AG-64. Biomelt AG-64 is on the Clear Roads Qualified Product List and distributed by Evolution Liquids. Biomelt AG-64 is listed as a proprietary natural agricultural product blended with proprietary polyol used as an anti-icing and deicing liquid product.

Illinois uses Biomelt AG-64 for pre-wetting operations and the amount used annually varies from 160,000 to 257,000 gallons depending on need. Biomelt AG-64 costs $2.00 per gallon with shipping. Illinois uses Biomelt AG-64 for pre-wetting at 20 to 60 gallons per lane mile. The temperature range varied depending on the blend ratio, an 80/20 (by volume) blend was used between 15°F to 28°F and a 70/30 blend was used at 5°F to 15°F. No specific storage or handling requirements were mentioned. Illinois DOT mentioned that buy-in for the product varied throughout the state and that its use was determined by each district and team section.

- Biomelt AG-64 Product Data Sheet: https://www.evolutionliquids.com/_files/ugd/28cd8f_4227ab1aa27849d192c040ae131c60d3.pdf
- Biomelt AG-64 Safety Data Sheet: https://www.evolutionliquids.com/_files/ugd/28cd8f_3a977eb7e3b84820a8710dc619b1822e.pdf

4.1.1.3 Calcium Magnesium Acetate (CMA)

Michigan DOT is the only agency that reported using calcium magnesium acetate (CMA) in their winter maintenance operations. Michigan DOT reported that they use an estimated 100 metrics tons of CMA annually to treat the Zilwaukee Bridge, which cost an estimated $2,400 per ton.

4.1.1.4 Potassium Acetate (KAc)

Montana, Nebraska, and Nevada DOTs use potassium acetate (KAc) in their winter maintenance operations. Montana DOT reported using 12,253 gallons of KAc annually at a cost of $4.91 per gallon for deicing operations. Montana DOT used KAc at a temperature range of -20°F to 32°F on bridge decks. No specific storage or handling requirements were mentioned.

Nebraska DOT fluctuated the quantity of KAc used annually, with some years placing no orders, but the 5-year average was approximately 4700 gallons per year. The price depended on the quantity of material ordered, with an average price of $6.73 per gallon. NDOT only uses KAc on bridge decks.

Nevada DOT reported using 9,016 gallons of KAc annually at a cost of $6.96 per gallon including shipping. KAc is used for liquid anti-icing operations with a Boschung System. Application rates varied but Nevada DOT used approximately 0.002 gallons per square yard for a single application. KAc was used at a temperature range of -1°F to 32°F. KAc was used on structures along I-580: mile post (MP) 9.5 from Browns (where they applied 13 gallons per application seq.), to MP 10.5 Galena (40 gallons), to MP13.2

Steamboat (23 gallons), and to MP 14.3 Galena Forest (23 gallons). Nevada DOT reported using dedicated tanks for each structure.

4.1.1.5 Sand[1]

Wyoming DOT was the only respondent who reported using sand in their winter maintenance operations. Wyoming DOT reported using 180,460 tons of sand annually at a cost of $29.80 per ton. Sand was used at an application rate of 600 pounds per lane mile. Sand was reportedly used at all locations and used when temperatures drop below 32°F. Sand was stored under a covering.

4.1.1.6 Sodium Formate

The City of Charlotte DOT in North Carolina was the only respondent who reported using sodium formate in their winter maintenance operations. The City of Charlotte DOT used an estimated 2.5 tons of sodium formate annually at a cost of $1,850 per ton. Sodium formate was used for deicing at an application rate of 125 pounds per lane mile at a temperature range of 0°F to 32°F. The City of Charlotte DOT used sodium formate in chloride sensitive areas and specifically mentioned a 10-mile streetcar route. The City stored sodium formate in a low-moisture environment.

4.1.1.7 SPC-5000

Michigan DOT reported using SPC-5000 for winter maintenance operations on the Blue Water Bridge and Zilwaukee Bridge. No further information was provided.

4.1.2 Why Does Your Agency Use Non-Chloride Deicers?

The respondents were asked to provide information on why their agency used non-chloride deicer products (Figure 2). Most respondents (66.7%) indicated they used non-chloride deicers because they provided better performance and reduced impacts to infrastructure and equipment (Table 4). Three respondents (25.0%) indicated that they used non-chloride deicers because of environmental concerns. No respondents were using these products due to public pressure or concern. Five agencies responded with “other,” mentioning that non-chloride products helped reduce salt scatter, that their state had requirements not to use chlorides in certain areas, and that they worked better at lower temperatures than brine alone. The responses are provided in Table 5.

---

[1] It should be cautioned that sand does not truly fall in the category of deicer, because it provides a temporary friction layer on the pavement, rather than any function of deicing or anti-icing.

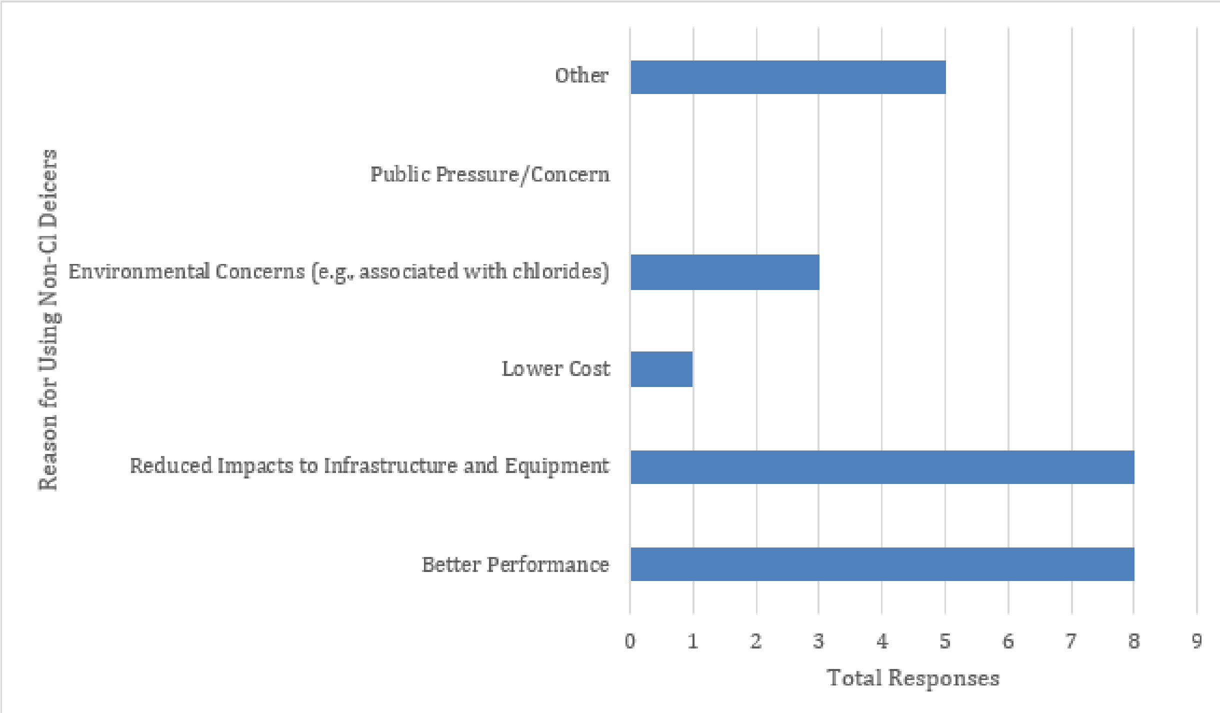


Figure 2: Why does your agency use non-chloride deicers?

Table 4. Why does your agency use non-chloride deicers? Agency Responses

Organization Name:	Better Performance	Reduced Impacts to Infrastructure and Equipment	Lower Cost	Environmental Concerns (e.g., associated with chlorides)	Public Pressure/Concern	Other
Illinois DOT	x	x				x
McHenry County DOT (Illinois)	x	x		x		x
Kansas DOT	x					
Michigan DOT		x				
Montana DOT	x	x				
Nebraska DOT						x
Nevada DOT		x				x

Organization Name:	Better Performance	Reduced Impacts to Infrastructure and Equipment	Lower Cost	Environmental Concerns (e.g., associated with chlorides)	Public Pressure/Concern	Other
City of Charlotte DOT (North Carolina)		x				
North Dakota DOT	x	x	x	x		
Ohio DOT	x			x		x
City of West Des Moines (Iowa)	x	x				
Wyoming DOT	x					

Table 5. Why does your agency use non-chloride deicers? Other Responses

Organization Name:	Why does your agency use non-chloride deicers? Other Responses
Illinois DOT	Buy-in and use varies statewide.
McHenry County DOT (Illinois)	Reduces salt scatter.
Nebraska DOT	In a metro it is a more forgiving product.
Nevada DOT	Declaration not to use chlorides on certain structures.
Ohio DOT	Work great at lower temperatures than brine alone.

4.1.3 Product Testing Results

The respondents were then asked if their agency had any testing results comparing the performance of non-chloride deicers with salt brine or rock salt. Most respondents (83.3%) did not have performance testing results. McHenry County DOT in Illinois responded that they did not have performance testing results but did mention that GEOMELT was mainly being used because it is “stickier” and that it helped to reduce salt scatter. Two respondents (16.7%) did have performance testing results. The City of West Des Moines in Iowa has completed field testing of Beet 55, which included photos. Ohio DOT included a link to *Evaluation and Analysis of Liquid Deicers for Winter Maintenance,* which was published in September 2017. This report examined the performance of eight liquid deicers in the field and in the lab. The report and a summary fact sheet on the effort can be found here: https://cdm16007.contentdm.oclc.org/digital/collection/p267401ccp2/id/15500

4.1.4 Success Stories

The survey respondents were asked to provide any success stories or lessons learned from the use of non-chloride deicers; seven respondents answered this question. The detailed responses are provided in Table 6. Successes included a 32% reduction in salt usage in McHenry County, Illinois where they had four liquid-only routes. Nevada DOT had seen benefits to preservation of structures by using KAc for anti-icing, relative to NaCl. Ohio DOT found that non-chloride products were less corrosive than chloride-containing products. The City of Charlotte DOT provided a lesson learned related to the storage of sodium formate. They originally ordered 60-lb bags, which were plastic, but the bags degraded. This resulted in material loss and difficulty with loading the product. They were planning to transition to 1-ton contractor bags for future orders.

Table 6. Success Stories or Lessons Learned

Organization Name:	Non-Chloride Products Used	Please share any success stories or lessons learned from the use of non-chloride deicers.
McHenry County DOT (Illinois)	GEOMELT (Beet Juice)	We run 4 liquid only routes. Data collected in house has shown a 32% savings in salt usage. These routes do contain salt brine though.
City of West Des Moines (Iowa)	Beet 55	Greater residual on road surfaces, lower working temperatures.
Nevada DOT	Potassium Acetate	We utilize potassium acetate to preserve the integrity of our structures. We certainly benefit from the real-time ability to apply anti-icing as needed, no lag or transport time. This has been a great benefit to safety of these structures but does require the use of non-chlorides.
City of Charlotte DOT (North Carolina)	Sodium Formate	Storage and handling is a challenge for us with Sodium Formate. Our original order for the material came on pallets. The pallets consisted of 1 ton of material in 60lb bags. The plastic bags have begun to degrade resulting in material spillage and difficulty loading during snow events. We plan to transition to 1 ton contractor bags for future orders and take extra precautions to ensure ambient air does not harden or degrade the material.
North Dakota DOT	Ag Beet Liquid Deicer	We use 20% in all out-salt brine. It works great. We have used it for 20+ years.
Ohio DOT	Beet Heet Concentrate, Beet Heet Severe	Basically, non-chloride deicers work and are less corrosive by nature than chloride products.
Wyoming DOT	Sand, Beet 55	Beet 55 is mainly an additive to our salt brine at 30%. That is not shown in the preceding questions. Direct application is only if they need the sand to stick more.

The transportation agency survey respondents identified 12 deicing products, see Table 7. However, it should be noted that agriculturally derived additives, such as beet-based products, are typically blended with a salt brine, instead of being used alone.

Table 7. Deicer Products Identified in Transportation Agency Survey

Product	Used By
Ag Beet Liquid Deicer	ND DOT
Beet 55	IA (City of West Des Moines), KS DOT, WY DOT
Beet Heet Concentrate	OH DOT
Beet Heet Severe	OH DOT
Beet Juice	NE DOT
Biomelt AG-64	IL DOT
Calcium Magnesium Acetate (CMA)	MI DOT
Geo Melt (Beet Juice)	McHenry County DOT (Illinois)
Potassium Acetate (KAc)	MT DOT, NV DOT
Sand	WY DOT
Sodium Formate	City of Charlotte DOT (North Carolina)
SPC-5000	MI DOT

4.2 Vendor Survey

A total of 8 organizations that made and/or sold non-chloride deicing products responded to the vendor survey, providing information on 20 deicer products, 5 of which were on the 2023 Clear Roads Qualified Products List (QPL) (Table 8). However, it should be noted that agriculturally derived additives, such as beet-based products, are typically blended with a salt brine.

Additional information on each product provided by vendors including product name, cost, environmental testing results, performance testing results, and any supplemental documents is provided in Appendix B Detailed Response – Vendor Survey.

Table 8. Deicer Products Identified in Vendor Survey

Product	Description	Vendor
Cryotech CF7	50% potassium acetate liquid deicer	Cryotech
Cryotech E36	50% potassium acetate liquid deicer	Cryotech
Cryotech LC17	potassium acetate hybrid liquid deicer	Cryotech
Cryotech NAAC	pelleted sodium acetate deicer	Cryotech
Cryotech CMA	pelleted calcium magnesium acetate deicer	Cryotech
Cryotech QS50	pelleted sodium acetate/formate deicer	Cryotech
Apogee	proprietary organic based components (not acetate-based)	Envirotech Services, Inc.
Safeway SF	sodium formate based solid deicer	Fyve Star
Aqua Hawk KA-50	liquid potassium acetate-based deicer	Hawkins, Inc.
Liquid Potassium Formate, 53%	53% potassium formate liquid deicer	Hawkins, Inc.
Alpine Ice Melt	50% potassium acetate liquid deicer	Nachurs Alpine Solutions, LLC
Alpine RF-11	50% potassium acetate liquid deicer	Nachurs Alpine Solutions, LLC
Alpine RF-14F	50% potassium formate liquid deicer	Nachurs Alpine Solutions, LLC
GEN3	hybrid, potassium acetate, 63% active ingredients liquid deicer	Nachurs Alpine Solutions, LLC
NASi-SF	solid sodium formate deicer	Nachurs Alpine Solutions, LLC
NEWDEAL Solid-Airfield Deicer	solid sodium acetate/formate blend deicer	New Deal Deicing
Isomex	aqueous solution of potassium acetate	OMEX
Isoway RTU	liquid anti-icer containing 25% potassium acetate (KAc)	OMEX
Isomelt	granular sodium formate-based deicer	OMEX
Beet 55	liquid organic additive derived from sugar beet molasses which is blended with salt brine	Smith Fertilizer and Grain

5 Evaluation of Clear Roads Qualified Product List (QPL) Specification Document

5.1 QPL Specification Document Evaluation

As shown in Table 9 and Table 10, the data required for approval on the QPL were consistent across all categories for non-chloride deicing products and non-chloride additives. A summary of available data for each QPL category is provided in Table 11, Table 12, and Table 13.

Table 9. Summary table of Clear Roads Qualified Product List (QPL) tests and limits for non-chloride deicers and non-chloride additives from Table 1 and Table 2 in the Specification Document.

Product Type	QPL Category 3 - Liquid Calcium Magnesium Acetate	QPL Category 7 - Solid Calcium Magnesium Acetate	QPL Category 12 - Other/Blended Acetates	QPL Category 13 - Liquid Products Greater than 30% Organics	QPL Category L - Experimental Category for Liquid Products	QPL Category S - Experimental Category for Solid Products	QPL Category A4 - Additive for Liquid Deicing Product and Pre-Wet Materials
Corrosion Rate	x	x	x	x	x	x	x
Phosphorus	x	x	x	x	x	x	x
Cyanide	x	x	x	x	x	x	x
Arsenic	x	x	x	x	x	x	x
Barium	x	x	x	x	x	x	x
Cadmium	x	x	x	x	x	x	x
Chromium	x	x	x	x	x	x	x
Copper	x	x	x	x	x	x	x
Lead	x	x	x	x	x	x	x
Selenium	x	x	x	x	x	x	x
Zinc	x	x	x	x	x	x	x
Mercury	x	x	x	x	x	x	x
pH	x, 8.0-10.0	x	x, 8.0-10.0	x, 6.0-9.0	x, 6.0-10.0	x, 6.0-10.0	x, 6.0-10.0
Toxicity	x	x	x	x	x	x	x
Ammonia -Nitrogen	x	x	x	x	x	x	x
TKN (Total Kjeldahl Nitrogen)	x	x	x	x	x	x	x

Product Type	QPL Category 3 - Liquid Calcium Magnesium Acetate	QPL Category 7 - Solid Calcium Magnesium Acetate	QPL Category 12 - Other/Blended Acetates	QPL Category 13 - Liquid Products Greater than 30% Organics	QPL Category L - Experimental Category for Liquid Products	QPL Category S - Experimental Category for Solid Products	QPL Category A4 - Additive for Liquid Deicing Product and Pre-Wet Materials
NO_3 & NO_2, as Nitrogen	x	x	x	x	x	x	x
Biological Oxygen Demand (BOD)	x	x	x	x	x	x	x
Chemical Oxygen Demand (COD)	x	x	x	x	x	x	x
Friction Analysis	x	x	x	x	x	x	x
Specific Gravity	x	x	x	x	x	x	x

Table 10. Continued from Table 1, Additional requirements from Clear Roads QPL Specification Document.

Product Type	QPL Category 3 - Liquid Calcium Magnesium Acetate	QPL Category 7 - Solid Calcium Magnesium Acetate	QPL Category 12 - Other/Blended Acetates	QPL Category 13 - Liquid Products Greater than 30% Organics	QPL Category L - Experimental Category for Liquid Products	QPL Category S - Experimental Category for Solid Products	QPL Category A4 - Additive for Liquid Deicing Product and Pre-Wet Materials
Additional Requirements	No less than 25% CMA, Weight per gallon, See pH, Total settable solids (TDS)/solids passing #10 sieve, storage temperature: 10°F ± 2°F	Only contain CMA, Mole ratio 3 to 7, Total settable solids (TDS)/solids passing #10 sieve (storage temperature: 10°F ± 2°F, total settleable solids (TSS) (v/v):4% max, passing solids (#10 sieve): 99% max), Moisture less than 10%, product attrition less than 2.5% with minimum dust generation on handling, residual base 0.30 milliequivalents base per gram of sample.	No less than 25% CMA, Weight per gallon, See pH, Total settable solids (TDS)/solids passing #10 sieve (storage temperature: 10°F ± 2°F, total settleable solids (TSS) (v/v):4% max, passing solids (#10 sieve): 99% max), storage temperature: 10°F ± 2°F, residual base 0.30 milliequivalents base per gram of sample.	Contain no less than 30% organics, weight per gallon, corrosion inhibitor (if applicable), See pH, Total settable solids (TDS)/solids passing #10 sieve (storage temperature: 0°F ± 2°F, total settleable solids (TSS) (v/v):4% max, passing solids (#10 sieve): 99% max). No chloride content requirement.	See pH Define active ingredients that can be measured, concentration range, and test methods to be used. Provide temperature for TSS % passing #10 sieve, provide sample for QA testing. Field trials should be conducted.	See pH Define active ingredients that can be measured, concentration range, and test methods to be used. Provide temperature for TSS % passing #10 sieve, provide sample for QA testing. Field trials should be conducted.	Provide active ingredient concentration and recommended dilution rate. Corrosion percent effectiveness rating of 30% or less. Finished product should have eutectic points equal to or lower than standard liquid deicing products without additive. Homogenously mix with liquid deicing product, not separation or settling. Additive in flowable and can fully mix at down to 15°F. Classification of storage based on temperature and separation/settling. Storage temperature: ±2°F, TSS (v/v): 1.0% max, solids passing #10 sieve: 99% min.

The following tables summarize the data provided by vendors and manufacturers for deicing products on the QPL for each category referred to in Table 10. Note that where data are not included in the summary tables, information was not provided by the vendor or manufacturer. Data submitted by vendors and manufacturers to Clear Roads for QPL approval were not available for use in this effort. To capture this information, the research team asked the vendors or manufacturers to share the data required for QPL evaluation, but the vendors or manufacturers were not required to do so.

Note that no information was provided by vendors or manufacturers of Category 3 Liquid Calcium Magnesium Acetate (CMA), Category L Experimental Category for Liquid Products, or Category A4 Additives for Liquid Deicing Products and Pre-wet Materials currently listed on the Clear Road QPL. At the time of this task effort, no products were listed on Clear Roads QPL for Category S Experimental Category for Solid Products.

Table 11 provides elemental, toxicity, and performance information for Category 7 Solid Calcium Magnesium Acetate (CMA) products on the QPL.

The relevant Standard Methods or Test Methods are provided in Table 11 only.

Table 11. Summary of the Data Collected for Clear Roads QPL Category 7 products.

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	Standard/Test Method	QPL Category 7 - CMA, Cryotech
Corrosion Rate	≥ 70 % corrosive than NaCl	NACE Standard TM0169-95 (1995 Revision)	-7
Phosphorus	≤ 2,500 ppm	APHA-AWWA-WPCF	14 (Total Phosphate)
Cyanide	≤ 0.20 ppm	APHA-AWWA-WPCF	< 0.05
Arsenic	≤ 5.0 ppm	APHA-AWWA-WPCF	< 1.0
Barium	≤ 100.0 ppm	APHA-AWWA-WPCF	< 0.5
Cadmium	≤ 0.20 ppm	APHA-AWWA-WPCF	< 0.05
Chromium	≤ 1.0 ppm	APHA-AWWA-WPCF	< 0.5
Copper	≤ 1.0 ppm	APHA-AWWA-WPCF	0.1
Lead	≤ 1.0 ppm	APHA-AWWA-WPCF	< 0.5
Selenium	≤ 5.0 ppm	APHA-AWWA-WPCF	< 1.0
Zinc	≤ 10.0 ppm	APHA-AWWA-WPCF	1.1
Mercury	≤ 0.05 ppm	APHA-AWWA-WPCF	< 0.02
pH	Varies	ASTM D 1293 except a dilution shall be made of 1 part chemical product to 4 parts distilled water	9.5
Toxicity		Short-term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Freshwater Organisms; 4th ed. October 2002, EPA821-R-02-013	
Ammonia -Nitrogen		APHA-AWWA-WPCF	< 1
TKN (Total Kjeldahl Nitrogen)		APHA-AWWA-WPCF	83
NO_3 & NO_2, as Nitrogen		APHA-AWWA-WPCF	< 2.0

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	Standard/Test Method	QPL Category 7 - CMA, Cryotech
Biological Oxygen Demand (BOD)		APHA-AWWA-WPCF	165,000 BOD_{20} (2°C): 0.40 g O_2/g BOD_{20} (10°C): 0.67 g O_2/g
Chemical Oxygen Demand (COD)		APHA-AWWA-WPCF	207,000 COD (TOD): 0.75 g O_2/g
Friction Analysis	Frictional analysis shall be conducted on products that have been applied at the prescribed application rate to a pavement surface within a sealed and controlled humidity chamber. The frictional coefficient shall be measured on pavement surface as the humidity in the chamber is lowered and raised over the course of time. The data shall show a plot of the humidity curve and a plot of the coefficient of friction curve over time. The device that measures the frictional coefficient shall be calibrated and certified prior to use on the sample analysis.		
Specific Gravity		ASTM D 1429, Test Method A Pycnometer at 20°C ± -1°C	

Table 12 provides elemental, toxicity, and performance information for Category 12 Other/Blended Acetates products on the QPL.

Table 12. Summary of the Data Collected for Clear Roads QPL Category 12 products.

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	CF-7, Cryotech (same product as E36)	Alpine Ice-Melt, Nachurs Alpine Sol. Ind.	Isoway, Omex Environmental
Corrosion Rate	> 70 % less corrosive than NaCl	AMS 4037 aluminum alloy (anodized as in AMS 2470): 0.01 AMS 4041 aluminum alloy: 0.05 AMS 4040 Aluminum Alloy: 0.01 AMS 4376 magnesium alloy (dichromate treated as in AMS 2475 (24 hrs)): 0.11 AMS 4911 titanium alloy: 0.01 AMS 5045 Carbon steel: 0.02 *Test method: ASTM F483, data reported as weight change in mg/cm^2/24 hrs	-5	-5
Phosphorus	≤ 2,500 ppm			
Cyanide	≤ 0.20 ppm			
Arsenic	≤ 5.0 ppm			
Barium	≤ 100.0 ppm			
Cadmium	≤ 0.20 ppm			
Chromium	≤ 1.0 ppm			
Copper	≤ 1.0 ppm			
Lead	≤ 1.0 ppm			
Selenium	≤ 5.0 ppm			
Zinc	≤ 10.0 ppm			
Mercury	≤ 0.05 ppm			
pH	8.0 - 10.0	10.5 - 11.5	9.5 - 10.5	7.13 - 8.5

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	CF-7, Cryotech (same product as E36)	Alpine Ice-Melt, Nachurs Alpine Sol. Ind.	Isoway, Omex Environmental
Toxicity		48-hr LC50 Daphnia magna: 2,175 mg/L, 48-hr LC50 Sheepshead Minnows: 6,300 mg/L, 96-hr LC50 Pimephales promelas: 3,000 mg/L, 48-hr LC50 Mysid: 1,400 mg/L	48 hr LC_{50}: 2,250 mg/L 96 hr LC50: 2,175 mg/L	
Ammonia -Nitrogen				
TKN (Total Kjeldahl Nitrogen)				
NO_3 & NO_2, as Nitrogen				
Biological Oxygen Demand (BOD)		BOD5 (20ºC): 0.25 g O_2/g	BOD (5-day): 0.25 kg O_2/kg	
Chemical Oxygen Demand (COD)		COD (TOD): 0.34 g O_2/g	TOD/COD (5-day): 0.33 kg O_2/kg	
Friction Analysis				
Specific Gravity		1.25 - 1.3 at 68°F (20°C)	1.27 - 1.3	1.24 - 1.28

Table 13 provides elemental, toxicity, and performance information for Category 13 Liquid products with greater than 30% organics on the QPL.

Table 13. Summary of the Data Collected for Clear Roads QPL Category 13 products.

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	Beet 55+, Smith Fertilizer and Grain
Corrosion Rate	≥ 70 % less corrosive than NaCl	13
Phosphorus	≤ 2,500 ppm	
Cyanide	≤ 0.20 ppm	
Arsenic	≤ 5.0 ppm	
Barium	≤ 100.0 ppm	
Cadmium	≤ 0.20 ppm	
Chromium	≤ 1.0 ppm	
Copper	≤ 1.0 ppm	
Lead	≤ 1.0 ppm	
Selenium	≤ 5.0 ppm	
Zinc	≤ 10.0 ppm	
Mercury	≤ 0.05 ppm	
pH	6.0 - 9.0	5 - 10
Toxicity		LCL50 (Rat) >5g/kg
Ammonia -Nitrogen		
TKN (Total Kjeldahl Nitrogen)		
NO_3 & NO_2, as Nitrogen		
Biological Oxygen Demand (BOD)		
Chemical Oxygen Demand (COD)		
Friction Analysis		Yes
Specific Gravity		1.275 - 1.34

Information was provided by vendors and manufacturers for the following deicing products, which are acetate based but are not on Clear Roads QPL (Table 14a and 14b).

Table 14a. Summary of the Data Collected for Acetate Based Deicing Products not on the Clear Roads QPL.

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	E36 (same material as CF7), Cryotech	LC17 Cyrotech	NAAC, Cryotech	Isomex, Omex	Aqua Hawk KA-50	Alpine RF-11, NASi	Gen3-64, NASi Acetate with glycerin)
Corrosion Rate	> 70 % less corrosive than NaCl			-4			AMS 4037 Al Alloy (anodized as in AMS 2470) - passed AMS 4041 Al Alloy - passed AMS 4049 Al Alloy - passed AMS 4376 Mg Alloy (dichromate treated per AMS 2475) - at limit AMS 4911 Ti Alloy - passed AMS 5045 Carbon Steel - passed	AMS 4037 Al Alloy (anodized as in AMS 2470) - passed AMS 4041 Al Alloy - passed AMS 4049 Al Alloy - passed AMS 4376 Mg Alloy (dichromate treated per AMS 2475) - passed AMS 4911 Ti Alloy - passed AMS 5045 Carbon Steel - passed
Phosphorus	≤ 2,500 ppm						1,236 mg/L (as phosphate)	2,134 mg/L (as phosphate)
Cyanide	≤ 0.20 ppm							
Arsenic	≤ 5.0 ppm							
Barium	≤ 100.0 ppm							
Cadmium	≤ 0.20 ppm						<1	<1
Chromium	≤ 1.0 ppm						<1	<1

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	E36 (same material as CF7), Cryotech	LC17 Cyrotech	NAAC, Cryotech	Isomex, Omex	Aqua Hawk KA-50	Alpine RF-11, NASi	Gen3-64, NASi Acetate with glycerin)
Copper	≤ 1.0 ppm							
Lead	≤ 1.0 ppm						<1	<1
Selenium	≤ 5.0 ppm							
Zinc	≤ 10.0 ppm							
Mercury	≤ 0.05 ppm						<1	<1
pH	varies		10.5 - 11.5	8 - 10.5 (15% solution)	10.8 - 11.2	8 - 11	9.5 - 10.5	10 - 11

Table 14b. Summary of the Data Collected for Acetate Based Deicing Products not on the Clear Roads QPL.

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	E36 (same material as CF7), Cryotech	LC17 Cyrotech	NAAC, Cryotech	Isomex, Omex	Aqua Hawk KA-50	Alpine RF-11, NASi	Gen3-64, NASi Acetate with glycerin)
Toxicity		48-hr LC50, sheepshead minnows: 6,300 mg/L 48-hr LC50, mysid: 1,400 mg/L	LD50 48 hr Daphnia Magna: 4,150 mg/L LC50 96 hr Pimephales Promelas: 4,225 mg/L	48-hr LC50, sheepshead minnows: > 8,000 mg/L 48-hr LC50, mysid: ~8,000 mg/L	LD_{50} oral (rat)>5,000 mg/L Microtox EC50: 0.3% solution (15 min)	Toxicity to Fish: 6,800 mg/L (LC50 96 hr semi-static-Oncorhynchus Mykiss) EPA 40 CFR 797.1400 96 hr LC50: 2,750 mg/L Rat LD50 (oral) 3,250 mg/kg Rabbit LD50 (dermal): >20,000 mg/kg	48 hr LC_{50}: 2,250 mg/L 96 hr LC50: 2,175 mg/L	48 hr LC50: 2,225 mg/L 96 hr LC50: 4,150 mg/l Glycerin Toxicity LD50 (Rat, oral) 12,600 mg/kg LD50 (Rabbit, dermal) > 10 g/kg LD50 (Rat, inhalation) >570 mg/m^3 LC50 (Oncorhynchus mykiss (fish)) 96 hr: 54,000 mg/L
Ammonia (N)								
TKN								
NO_3 & NO_2, (N)							NO_3: <2	NO_3: <2
BOD		BOD5 (20°C): 0.25 g O_2/g	BOD_5 (20°C): 0.24 kg O_2/kg	BOD_5 (20°C): 0.45 g O_2/g Deicer (450 mg O_2/Deicer)	BOD: 0.36 g O_2/g	BOD5-Day at 68°F: < 0.25 kg O_2/kg	BOD (5-day): 0.25 kg O2/kg	BOD (5-day): 0.24 kg O_2/kg

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	E36 (same material as CF7), Cryotech	LC17 Cyrotech	NAAC, Cryotech	Isomex, Omex	Aqua Hawk KA-50	Alpine RF-11, NASi	Gen3-64, NASi Acetate with glycerin)
COD		COD (TOD): 0.36 g O_2/g	COD: 0.68 kg O_2/kg	COD (TOD): 0.74 g O_2/g Deicer (740 mg O_2/g Deicer)	COD: 0.47 g O_2/g	COD (TOD5-Day) at 68ºF: < 0.36 kg O_2/kg	TOD/COD (5-day): 0.33 kg O_2/kg fluid	TOD/COD (5-day): 0.65 kg O_2/kg
Friction Analysis								
Specific Gravity			1.13 - 1.18 (68°F, 20°C)		1.26 (18°C)	1.287 - 1.294	1.27 - 1.3	1.24 - 1.27

Information was provided by vendors and manufacturers for the following deicing products, which are liquids with greater than 30% organics but are not on Clear Roads QPL (Table 15).

Table 15. Summary of the Data Collected for Liquids with Greater than 30% organics not on the Clear Roads QPL.

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	Apogee
Corrosion Rate	≥ 70 % less corrosive than NaCl	13.9
Phosphorus	≤ 2,500 ppm	
Cyanide	≤ 0.20 ppm	
Arsenic	≤ 5.0 ppm	
Barium	≤ 100.0 ppm	
Cadmium	≤ 0.20 ppm	
Chromium	≤ 1.0 ppm	
Copper	≤ 1.0 ppm	
Lead	≤ 1.0 ppm	
Selenium	≤ 5.0 ppm	
Zinc	≤ 10.0 ppm	
Mercury	≤ 0.05 ppm	
pH	varies	
Toxicity		Fathead minnow NOEC: 1.00 g/L *Ceriodaphnia dubia* NOEC: 1.00 g/L *Selenastrum* growth: 0.5 g/L
Ammonia -Nitrogen		
TKN (Total Kjeldahl Nitrogen)		0.5 mg/L
NO_3 & NO_2, as Nitrogen		NO_3: 100 mg/L, NO_2: 25 mg/L
Biological Oxygen Demand (BOD)		370 mg/L
Chemical Oxygen Demand (COD)		820,000 mg/L
Friction Analysis		
Specific Gravity		

Information was provided by vendors and manufacturers for the following deicing products, which are formate-based or blended with formate deicers that are not on Clear Roads QPL (Table 16).

Table 16a. Summary of the Data Collected for Formate based or Formate Blended Deicing Products not on the Clear Roads QPL.

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	QS50, Cryotech	Safeway SF (solid)	Liquid Potassium Formate	Alpine RF-14F, NASi	NASi-SF (Solid sodium formate)	New Deal (Solid Acetate/formate blend (~30/70))
Corrosion Rate	≥ 70 % less corrosive than NaCl		Transparent Plastic ASTM F 484 - passed Painted Surfaces ASTM F 502 - passed Unpainted Surfaces ASTM F 485 - passed Runway Concrete Scaling Resistance ASTM C 672 - passed Asphalt Concrete Degradation Resistance LFV Method 2-98 - passed Sandwich Corrosion ASTM F 1110 - passed Al Alloy - AMS 4037, 4041, 4049 - passed Mg Alloy, dichromate treated AMS 4367 - passed Ti Alloy AMS 4911 - passed Carbon Steel AMS 5045 - passed Low-Embrittling Cd Plate ASTM F 1111 - passed Hydrogen Embrittlement ASTM F 519 - passed Stress-Corrosion Resistance ASTM F 945 A - passed		AMS 4037 Al Alloy (anodized as in AMS 2470) - passed AMS 4041 Al Alloy - passed AMS 4049 Al Alloy - passed AMS 4376 Mg Alloy (dichromate treated per AMS 2475) - at limit AMS 4911 Ti Alloy - passed AMS 5045 Carbon Steel - passed	AMS 4037 Al Alloy (anodized as in AMS 2470) - passed AMS 4041 Al Alloy - passed AMS 4049 Al Alloy - passed AMS 4376 Mg Alloy (dichromate treated per AMS 2475) - passed AMS 4911 Ti Alloy - passed AMS 5045 Carbon Steel - passed	
Phosphorus	≤ 2,500 ppm				1,010 mg/L (as Phosphate)		
Cyanide	≤ 0.20 ppm						

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	QS50, Cryotech	Safeway SF (solid)	Liquid Potassium Formate	Alpine RF-14F, NASi	NASi-SF (Solid sodium formate)	New Deal (Solid Acetate/formate blend (~30/70))
Arsenic	≤ 5.0 ppm						
Barium	≤ 100 ppm						
Cadmium	≤ 0.20 ppm				<1		
Chromium	≤ 1.0 ppm				<1		
Copper	≤ 1.0 ppm						
Lead	≤ 1.0 ppm				<1		
Selenium	≤ 5.0 ppm						
Zinc	≤ 10.0 ppm						
Mercury	≤ 0.05 ppm				<1		
pH	varies	11 - 11.8 (15% solution)	11.5	7 - 8	9.5 - 10.5	10 - 12	9.5 - 11

Table 16b. Summary of the Data Collected for Formate based or Formate Blended Deicing Products not on the Clear Roads QPL.

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	QS50, Cryotech	Safeway SF (solid)	Liquid Potassium Formate	Alpine RF-14F, NASi	NASi-SF (Solid sodium formate)	New Deal (Solid Acetate/formate blend (~30/70))
Toxicity		Acute Fish Toxicity (Pimephales Promelas, Static System 96 hr LC50): 8,025 mg/L Acute Daphnid Toxicity (Daphnia Magna, Static System 48 hr LC50): 4,250 mg/L LD50 rat-oral: > 5 g/kg (sodium acetate); > 3 g/kg (sodium formate) LD50 mouse-oral: > 11 g/kg (sodium formate) LD50 rat-dermal: > 2 g/kg (sodium formate) LC50 rat-inhalation: > 0.67 mg/m3 (maximum attainable dust concentration of sodium formate) produced no signs of toxicity	Biodegradability (28 d, 20°C): 93% LC50 (Danio Rerio (Zebra Fish)), 96 hr: 8,226 mg/L Daphnia Magna (Water Flea), 48 hr: > 1,000 mg/L Pseudomonas Putida: 6,165 mg/L EC50 (Desmodesmus sub. (Algae)) 72 hr: >1,000 mg/L LD50 (Mouse): >2,000 mg/kg	LD50 (Mouse, oral) 5,000 mg/kg	48 hr LC_{50}: 550 mg/L 96 hr LC50: 2,075 mg/L LC50 (Rat, dermal) >2,000 mg/kg	Biological Elimination: >90% (Static Test, 7 Days) DIN 38 412-L25) Toxicity to Bacteria Eco: >10,000 (OECD 209, After 3 Hours) Daphnia Acute Toxicity Eco: 3.3 g/l (24h); 3.2 g/l (48h) EC50: 4.8 g/l (24h); 4.4 g/l (48h) Fish Toxicity LC50: 1000 m/l (96h, Zebra Fish, OECD 203) Acute oral toxicity LD50: >2,000 mg/kg (rats). Acute inhalation toxicity LC50: >680 mg/m^3 (dust, rats, 4 hrs.). LC0: >680 mg/m^3 (dust, rats, 4 hrs).	48 hr LC_{50}: 4,125 mg/l (Daphnia magna) 96 hr LC50: 8,050 mg/l (Pimephales promelas)
Ammonia (N)							

Tests Required for QPL (QPL Table 1 (pg.10) and Table 2 (pg. 11))	Specified Limits	QS50, Cryotech	Safeway SF (solid)	Liquid Potassium Formate	Alpine RF-14F, NASi	NASi-SF (Solid sodium formate)	New Deal (Solid Acetate/formate blend (~30/70))
TKN							□
NO_3 & NO_2, (N)			0		NO_3: <2		□
BOD		BOD5 (20°C): 0.05 kg O_2/kg Deicer	BOD5: 0.016 kg O_2/kg		BOD (5-day): 0.02 kg O_2/kg	BOD (5 day) 0.1-0.2 g O_2/g	BOD5 (20°C): 0.13 kg O_2/kg
COD		COD (TOD): 0.30 kg O_2/kg Deicer	0.240 kg O_2/kg		TOD/COD (5-day): 0.09 kg O_2/kg	COD: 0.25 - 0.35 g O2/g	TOD/COD: 0.42 kg O_2/kg
Friction Analysis							
Specific Gravity				1.37	1.34	900 - 950 kg/m^3	1.8

Based on the data provided by vendors and manufacturers, it could be observed that many data pieces were missing. Where a significant amount of data was provided, the vendors/manufacturers provided the data submitted to Clear Roads for QPL evaluation or for Federal Aviation Administration (FAA) approval. While this was a Clear Roads effort, the research team had to request data from product vendors/manufacturers directly. For this reason, not all products listed on the QPL have data provided for them.

While all of the data elements required in the QPL were important to determine a product's effectiveness and potential impacts, biolochemcial oxygen demand (BOD), chemical oxygen demand (COD), nitrogen- and phosphorus-based tests, cyanide, and ecological toxicity test results were of particular interest when considering non-chloride deicers. These are discussed in detail below.

5.2 Biological or Biochemical Oxygen Demand (BOD)

BOD is the amount of oxygen consumed by various microorganisms in water. The metabolism of microorganisms uses oxygen (USGS, 2018). If you introduce something to water that the microorganisms can consume as an energy source, such as acetate or formate deicers or agricultural additives, oxygen is used as they break down the food source. Typically, BOD is used to assess water quality, for example, the quality of effluent from water treatment facilities. Example BOD values are provided in Table 17. The World Health Organization set maximum BOD values at 100 mg/L and maximum COD values at 300 mg/L (Guideline for Discharge of Industrial Effluent Characteristics).

Table 17. BOD values as they relate to water quality (https://www.pharmaguideline.com/2013/06/determination-of-biological-oxygen.html) and wastewater (https://extension.uga.edu/publications/detail.html?number=C992).

Water Quality	BOD (mg/L, ppm, mg/kg)	Wastewater	BOD (mg/L)
Very good	1 -2	**Low**	110
Fair	3 - 5	**Medium**	190
Poor	6 - 9	**High**	350
Very Poor	100 or more		

The Standard Methods for the examination of Water and Wastewater (APHA-AWWA-WPCF) are listed as test method 19 (pg. 41) in the Clear Roads Snow and Ice Control Chemical Product Program *Guidance Document for Materials Qualified Product List, Specifications, Test Methods, and Product Purchasing* (2021)(https://clearroads.org/qualified-product-list/). This test method specifies BOD testing take place over a 5-day period at 68°F (20°C), which is the standard length of time and temperature used in most BOD test methods.

There is debate as to the relevance of BOD data as it pertains to deicers, because BOD is typically measured at warm temperatures (68°F). Microbial activity typically increases with an increase in temperatures; therefore, BOD is higher at warmer temperatures. Deicers are used at or below 32°F and, at these colder temperatures, microbial activity is suppressed or greatly reduced. Therefore, the BOD should be reduced as well. Work by Corsi et al. (2012) showed that when measured at 41°F (5°C), BOD values were, on average, over 60% less than when measured at 68°F (20°C). Corsi et al. (2012) also found that acetates had higher degradation rates than glycol-based deicers and they noted in the paper that traditional BOD testing was not well suited for "alternative" deicers because the microorganisms needed to adjust to the new food source. They found a lag in BOD and recommended a longer test period of 28 days, in place of the commonly used test period of 5 days.

Understanding BOD in the context of deicers and winter road maintenance (WRM) has been a challenge for a few reasons: a) BOD test results are temperature-dependent, b) BOD test are conducted over various lengths of time (5 days, 20 days, 28 days etc.), c) BOD is not reported in consistent units across different studies, d) BOD is most relevant for non-chloride deicers, which are not as commonly used as road salts (sodium chloride, magnesium chloride, and calcium chloride).

The following presents some terms and considerations associated with BOD testing.

- BOD5 – Biological Oxygen Demand testing occurring over 5 days
- BOD20 - Biological Oxygen Demand testing occurring over 20 days
- BOD testing can be completed at various temperatures, and these should be reported in the findings.
- BOD is reported in the following units in this report:
  - ppm – parts per million
  - mg/L – milligrams per liter
  - mg/kg – milligrams per kilograms
  - g O_2/g – grams of oxygen per gram
  - g/kg – grams per kilogram
  - kg/hectare – kilograms per hectare (A hectare is a measure of area equal to about 2.5 acres or 10,000 square meters)
  - mg/g – milligrams per gram
  - kg/kg – kilogram per kilogram
  - lb/lb – pound per pound
  - % BOD – percent BOD

Note that ppm, mg/L, and mg/kg are equivalent units.

Table 18, Table 19, Table 20, Table 21, Table 22, and Table 23 summarize BOD and COD data found on non-chloride deicers or additives. The references cited in these tables can be found in Appendix C - BOD COD References from tables.

Table 18. Summary table of BOD and COD values for chloride-based deicers.

Test (units)	Sodium Chloride	Magnesium Chloride	Magnesium Chloride with Additive	Calcium Chloride	Reference	Notes
BOD5 (ppm) or (mg/1000g)	<5	<200	34,000	16,000	8	23.3% salt brine; FreezeGard Zero with Shield LS, IceStop Cl; Caliber M1000; Liquidow Armor
BOD5 (ppm)			83,000		8	$MgCl_2$:IceBan M50 (50:50)
COD (ppm)			68,000		12	Caliber M1000
BOD (ppm)			34,000		12	Caliber M1000
COD (TOD) (g O_2/g)	0.75				27	NaCl:CMA (60:40)
BOD20 (2°C) (g O_2/g)	0.40				27	NaCl:CMA (60:40)
BOD20 (10°C) (g O_2/g)	0.67				27	NaCl:CMA (60:40)
COD/TOD (g O_2/g deicer)	0.74				28	NaCl:Sodium Acetate (60:40)
BOD5 (g O_2/g deicer)	0.45				28	NaCl:Sodium Acetate (60:40)

Table 19. Summary table of BOD and COD values for agriculturally derived deicing additives.

Test (units)	Grape extract	Beet Juice-Salt Brine	Dandelion Leaf extract	Coffee waste	Oxidized Starch	Steepwater (grain/legume)	Brewers Condensed Soluble	Cheese Whey	Reference
COD (mg/L)	135	278							2
BOD (mg/L)	0.77	25.82							2
COD (mg/L)			101.04 - 114.37	216					3
BOD (mg/L)			27.07 - 40.78	78					3
COD (g O_2/L)					340				5
COD (g O_2/g)					0.64				5
BOD5 (g O_2/L)					103				5
COD (mg/L)	135	278							9
BOD5 (mg/L)	0.77	25.82							9
BOD (lb O_2/lb)						0.13-0.26			13
BOD (lb O_2/lb)							0.13-0.32		14
BOD (lb O_2/lb)								0.23-0.24	15

Table 20. Summary table of BOD and COD values for formate-based deicers.

Test (units)	Potassium Formate	Sodium Formate	Reference
COD [g(O_2)/kg dry deicer]	190.00		1
COD (kg/10 hectare surface)	285.00		1
BOD_5 (mg O_2/g)	~100		1
COD (mg/L)		373,000	4
BOD5 (mg/L)	40,000		6
BOD5 (mg/g)		230	6
BOD (g O_2/g)	0.12		10
COD (TOD) kg O_2/kg		0.30	25
BOD5 (kg O_2/kg)		0.05	25
COD (mg/kg)		373,000	30
BOD5 (20°C) %		79.70	31
BOD5 (20°C) %		80.50	31
COD (kg/kg)		0.240	32
BOD (kg/kg)		0.016	32
COD (g O_2/g)	0.10		36
BOD5 (g O_2/g)	0.02		36
COD (mg O_2/g)		-211	37
COD (kg O_2/kg)		0.42	38
BOD5 (kg O_2/kg)		0.13	38
COD (kg/kg)	0.112		42
BOD (kg/kg)	0.008		42
COD (kg/kg)	0.129		43

Test (units)	Potassium Formate	Sodium Formate	Reference
BOD (kg/kg)	0.001		43
COD (kg O_2/kg)	0.10	0.20	48
COD (mg/kg)		242,000	52
BOD5 (mg/kg)		230,000	52
BOD5 (mg/L)	40.00		52

Table 20 Notes:

25 - Sodium acetate and sodium formate blend

31 - Sodium glycolate (33.1%), Sodium formate (31.8%), Sodium acetate (26.3%), Sodium maleate (6.4%), Sodium fumarate (1.4%) with small quantities of sodium lactate, sodium malate, sodium malonate, and sodium tartrate.

Table 21. Summary table of BOD and COD values for Acetate-based deicers.

Test (units)	Calcium Magnesium Acetate	Potassium Acetate	Sodium Acetate	Reference
COD [g(O_2)/kg dry deicer]		653		1
COD (kg/10 hectare surface)		1,134		1
BOD5 (mg O_2/g)		~300		1
COD (mg/L)		1,050,000	1,010,000	4
BOD5 (mg/L)		821,000	826,000	4
BOD28 modified (mg/kg) 20°C		970,000	981,000	4
BOD5 (mg/L)		180,000		6
BOD5 (mg/g)			410	6
BOD5 (gm O_2/gm)		0.27		7
BOD5 (ppm) or (mg/1000g)	114,000	148,000		8
BOD5 (ppm)	132,000	132,000		8
BOD20 (ppm)			580,000	8
COD (g O_2/g)		0.34		11
BOD5 (20°C) (g O_2/g)		0.25		11
COD (g O_2/g)		0.34		16
BOD5 (g O_2/g)		0.25		16
COD (TOD) g O_2/g			0.74	23
BOD5 g O_2/g			0.45	23
COD (kg O_2/kg)		0.68		24
BOD5 (kg O_2/kg)		0.24		24
COD (TOD) kg O_2/kg			0.30	25

Test (units)	Calcium Magnesium Acetate	Potassium Acetate	Sodium Acetate	Reference
BOD5 (kg O_2/kg)			0.05	25
COD(TOD) (g O_2/g)	0.75			26
BOD20 (2°C) (g O_2/g)	0.40			26
BOD20 (10°C) (g O_2/g)	0.67			26
COD(TOD) (g O_2/g)	0.75			27
BOD20 (2°C) (g O_2/g)	0.40			27
BOD20 (10°C) (g O_2/g)	0.67			27
COD (TOD (g O_2/g deicer)			0.74	28
BOD5 (g O_2/g deicer)			0.45	28
COD (g/kg)			747	29
BOD5 (g/kg)			552	29
COD (mg/kg)		1,050,000	1,010,000	30
BOD5 (mg/kg)		821,000	826,000	30
BOD5 (20°) %	69		80	31
COD (TOD5-day) (20°C) kg O_2/kg		<0.36		33
BOD5 (20 C) kg O_2/kg		<0.25		33
COD		0.35		34
BOD5 (g/g)		0.25		34
COD (g O_2/g)		0.35		35
BOD5 (g O_2/g)		0.25		35
COD (g O_2/g)		0.47		39

Test (units)	Calcium Magnesium Acetate	Potassium Acetate	Sodium Acetate	Reference
BOD5		0.36		39
COD		0.30		44
BOD (kg/kg)		0.15		44
COD (kg O_2/kg)		0.30	0.70	48
BOD5 (kg O_2/kg)		0.17		48
COD (mg/kg)		315,000	780,000	52
BOD5 (mg/kg)		140,000-300,000	580,000	52

Table 21 Notes:

8 – 25% CMA; 50% Potassium acetate; CMAK (CMA:Potassium acetate (50:50))

25 – Blend of Sodium acetate and sodium formate

27 – NaCl:Sodium acetate (60:40)

28 - NaCl:Sodium acetate (60:40)

31 - Sodium glycolate (33.1%), Sodium formate (31.8%), Sodium acetate (26.3%), Sodium maleate (6.4%), Sodium fumarate (1.4%) with small quantities of sodium lactate, sodium malate, sodium malonate, and sodium tartrate.

Table 22. Summary table of BOD and COD values for glycol-based deicers

Test (units)	EG Type I (ethylene glycol)	EG type IV (ethylene glycol)	PG Type I (propylene glycol)	PG Type IV (Propylene glycol)	Biodiesel	Reference
COD (mg/L)	1,280,000	1,290,000	1,610,000	1,680,000		4
BOD5 (mg/L)	535,000	517,000	1,130,000	1,080,000		4
BOD28 modified (mg/kg) 20°C	904,000	966,000	1,320,000	1,320,000		4
BOD5 (mg/L)	400,000			1,000,000		6
BOD5 (mg/L)	800,000					6
BOD5 (mg/L)	400,000			1,000,000		7
BOD5 (mg/L)	800,000					7
BOD5 (gm O_2/gm)				0.83		7
COD (g O_2/g)			1.61			17
BOD5 (g O_2/g)			0.57			17
COD (g O_2/g)			1.01			18
BOD5 (g O_2/g)			0.36			18
COD (g O_2/g)			0.89			19
BOD5 (g O_2/g)			0.31			19
COD (g O_2/g)			0.81			20
BOD5 (g O_2/g)			0.29			20
COD (g O_2/g)				0.82		21
BOD5 (g O_2/g)				0.40		21
COD (g O_2/g)				0.67		22
BOD5 (g O_2/g)				0.36		22
COD (g/kg)	1,500-1,610		1,860			29
BOD5 (g/kg)			1,580			29
COD (mg/kg)	1,280,000	1,290,000	1,610,000	1,680,000		30

Test (units)	EG Type I (ethylene glycol)	EG type IV (ethylene glycol)	PG Type I (propylene glycol)	PG Type IV (Propylene glycol)	Biodiesel	Reference
BOD5 (mg/kg)	535,000	517,000	1,130,000	821,000		30
COD (kg O_2/kg)			1.44			40
BOD5 (kg O_2/kg)			0.49			40
COD (kg O_2/kg)				0.85		41
BOD5 (kg O_2/kg)				0.34		41
COD (kg/kg)			1.38			45
BOD (kg/kg)			0.60			45
COD (kg/kg)			1.30			46
BOD (kg/kg)			0.66			46
COD (mg/g)	1.17					47
% BIODEG 21 days	90					47
COD (kg O_2/kg)			1.10	1.10	0.25-0.62	48
BOD5 (kg O_2/kg)					0.1-0.3	48
COD	0.57 - 1.14					49
BOD5 = (% Biodeg/100)*ThOD	0.39 - 0.79					49
COD (kg O_2/kg)		0.51				50
COD (kg O_2/kg)			1.38			51
BOD5 (kg O_2/kg fluid)			0.73			51

Table 22 Notes:

29 – Diethylene and triethylene glycol; Dipropylene glycol

48 – Did not specify type I or IV

Table 23. Summary table of BOD and COD values for urea, succinate-based, betaine deicers or deicing additives.

Test (units)	Urea	Disodium Succinate	Potassium Succinate	Betaine	Reference
COD [g(O_2)/kg dry deicer]	2,133				1
COD (kg/10 hectare surface)	5,365				1
BOD_5 (mg O_2/g)	~2,100			759	1
BOD5 (mg/g)	2,100				6
BOD (g O_2/g)			0.15		10
COD (g/kg)		684			29
BOD5 (g/kg)		481			29
COD (g/g)	1.87				30
COD (kg O_2/kg)	2.10				48

For these reasons noted previously, comparing BOD values reported in the various studies and reports was challenging. To address this, all BOD and COD values were converted into comparable units – ppm, mg/L, mg/kg.

When BOD5 (68°F) values from the literature were converted to similar units (ppm, mg/L, mg/kg), we saw some trends emerge. In Figure 3, three ranges in values appeared: above 2,000,000 Urea, 250,000 - 1,000,000 acetates and glycols, and below 250,000 chlorides, formates, and ag-based products.

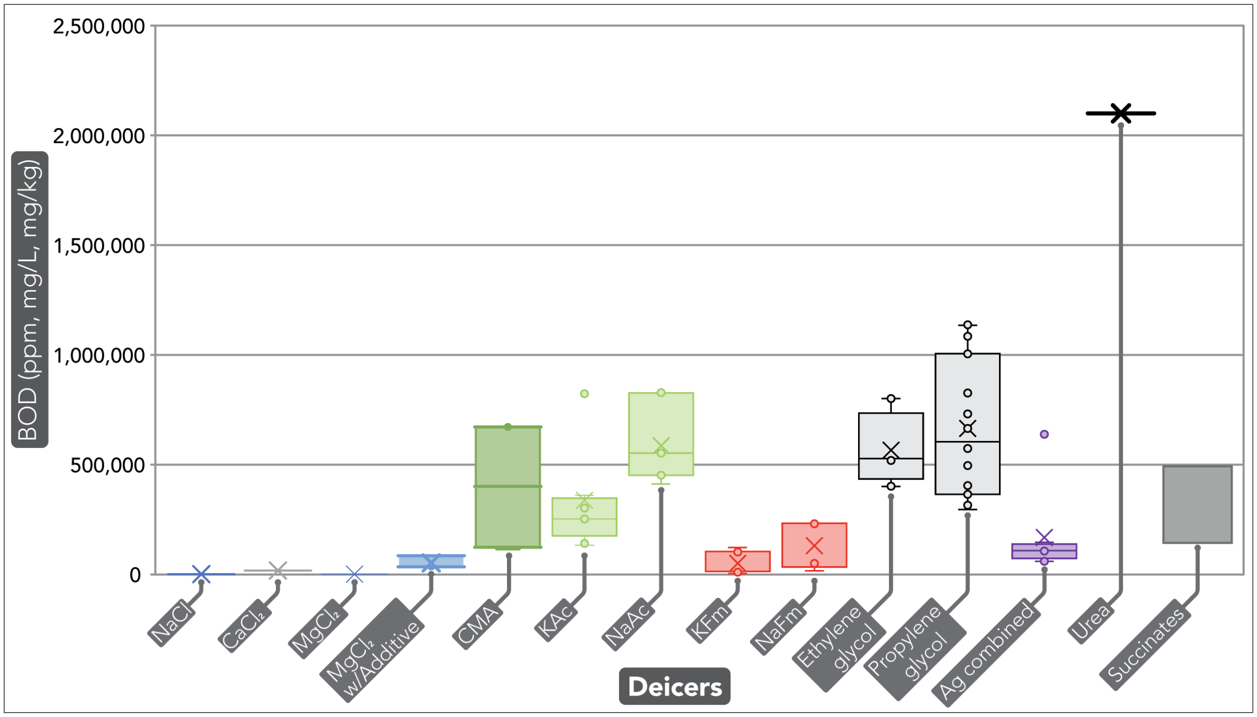


Figure 3. Graphical display of BOD5 (68°F) values reported in the literatures and shown in Tables 18-23 with units converted to be consistent for comparison.

BOD is typically used as the value to assess the impact of the non-chloride deicers on water quality. From this figure it can be clearly stated that Urea had the largest impact and most other non-chloride deicers had significant potential to impact dissolved oxygen levels in water. Overall, chlorides, formates, and agricultural additives showed the lowest potential to impact dissolved oxygen levels in water of the deicers considered.

5.3 Chemical Oxygen Demand (COD)

Chemical oxygen demand, COD, is a measure of the amount of oxygen necessary to break down organic substances in water (SciMed, 2023). When COD measurements from the literature were converted to similar units (ppm, mg/L, mg/kg), we saw some trends emerge in Figure 4, such as three major ranges in values: 2,000,000 for Urea, 1,000,000 – 2,000,000 for ethylene and propylene glycol, and/or less than 1,000,000 for chlorides, acetate, formates, ag-based, and succinates.

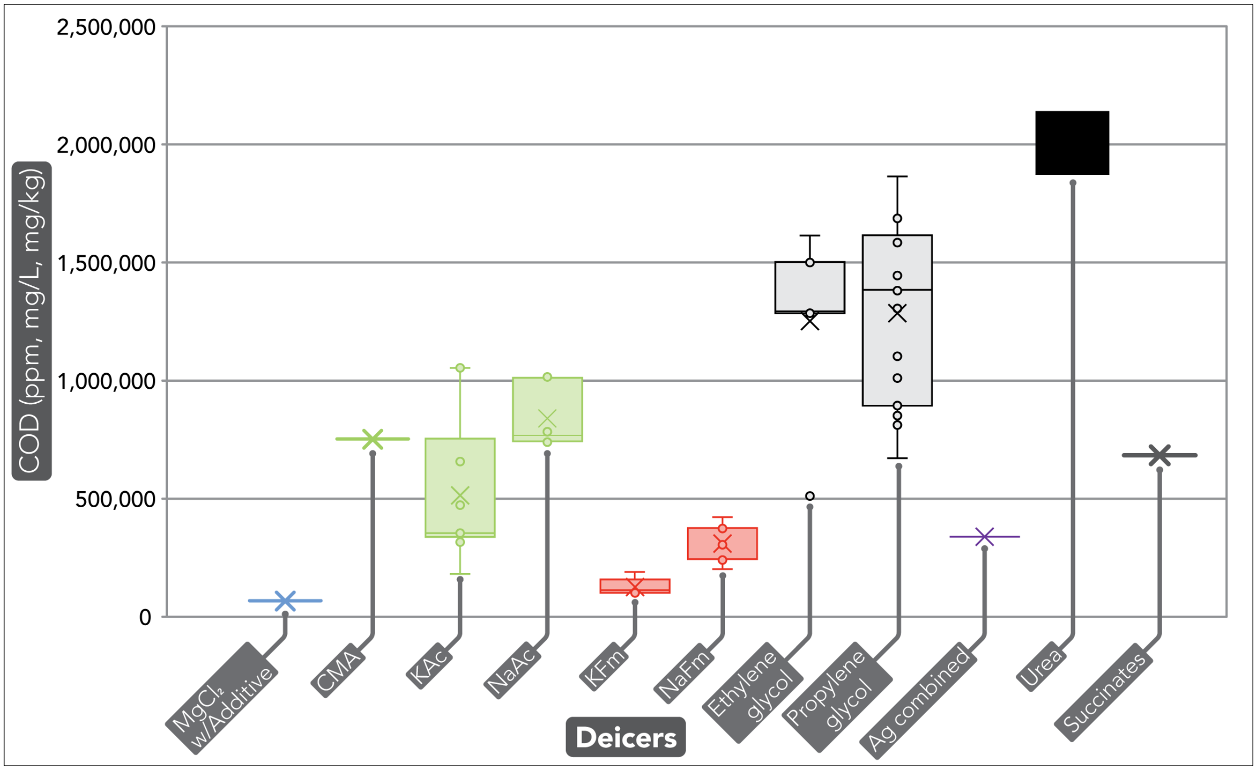


Figure 4. Graphical display of COD values reported in the literatures and shown in Tables 18-23 with units converted to be consistent for comparison.

5.3.1 Can we apply COD/BOD to deicers?

While COD is independent of BOD and typically results in higher values, the wastewater treatment industry found an empirical relationship between BOD and COD based on their ratio (University of Georgia, 2022). Because of this, once the necessary number of BOD and COD tests were run, an average ratio of COD/BOD could be established. This allows the much easier, less time-consuming, and less costly COD test be run in place of BOD in the future and, for this reason, we have provided COD/BOD ratios for various non-chloride deicers in Table 24. It is important to note the potassium acetate (KAc) (n=11) and propylene glycol type I (PG Type I) (n=10) had the largest quantity of published COD and BOD data, while sodium chloride (NaCl) (n=3), sodium acetate (NAAC) (n=5), potassium formate (KFm) (n=3), sodium formate (NaFm) (n=4), ethylene glycol type I (EG Type I) (n=3), propylene glycol type IV (PG Type IV) (n=4) had a moderate amount of published COD and COD values. For all other deicers, the average reported COD/BOD ratio values reported in Table 24 were based on only one or two published COD and COD values. Idaho DEQ required a COD/BOD ratio of 2:1 or better (Fair, 2005) for its application in wastewater treatment. Typically, the higher the COD/BOD ratio the more slowly biodegradable or non-biodegradable material was present (Woodward & Curran, Inc., 2006).

Table 24. Summary of average COD to BOD ratios for various deicers.

Deicer	Average COD:BOD
NaCl	1.55
$MgCl_2$ with ag-additive	2.00
$CaCl_2$	NA
KAc	1.65
NAAC	2.31
CMA	1.50
KFm	49.33
NaFm	6.32
EG Type I	1.76
EG Type IV	2.50
PG Type I	2.30
PG Type IV	1.99
Biodiesel	2.29
Ag - grape	175.00
Ag - beet	10.76
Ag - dandelion	3.17
Ag - coffee	2.76
Ag - starch	3.30
Succinate	1.42

By using the ratio to assess a deicer's potential impacts, we avoided the issue of inconsistent units across different publications, but one issue did still arise. An example was the agricultural product derived from grapes, which had a very low BOD value compared to the COD value. This created a misleadingly high COD/BOD ratio. If the COD/BOD ratio is going to be used (allowing for COD values to serve as proxy values for BOD), caution must be used in cases where the BOD value is very low.

5.4 Nitrogen

The following are various forms of nitrogen (N):

- Total Nitrogen – the amount of nitrogen that gives rise to NO_3 (nitrate) & NO_2 (nitrite) ions, including organic nitrogen and ammonia (NH_3).
- TKN – Total Kjeldahl Nitrogen is the sum of organic nitrogen and ammonia.

Nitrogen is a critically important element, but at excessive concentrations it can be harmful to water bodies. High nitrogen concentrations can stimulate growth of aquatic organisms, which in turn can use up available dissolved oxygen, among other issues (USGS, 2018a). The Environmental Protection Agency (EPA) limit for nitrate was 10 mg/L and nitrite was 1 mg/L in 2022 (both measured as nitrogen) (US EPA 2022). Clear Roads did not provide a limit for any form of nitrogen.

Identified sources of nitrogen in water bodies included fertilizers, atmospheric deposition, manure, nitrogen fixing crops, urban runoff, and wastewater treatment (USGS, 2018a). Nitrogen may be present in deicers. For example, nitrogen is the main component in Urea ($(NH_2)_2CO$), a deicer that is no longer in popular use. The concentrations of nitrogen and phosphorus in non-chloride deicers might be higher than those in traditional chloride-based deicers, and this may or may not translate to environmental risks to the quality of adjacent soils and receiving water bodies. Specific knowledge, however, was very limited in the published domain. Craig and Zhu (2018) investigated how nitrogen cycling was "impacted by the application of salt and nitrate to experimental plots in a field that [was] adjacent to Interstate 81, in Binghamton, NY". They found that the application of neither NaCl nor NO_3^- "discernibly affect[ed] the rates of [nitrogen] mineralization or nitrification".

5.5 Phosphorus

The following are various forms of phosphorus:

- Orthophosphate (PO_4)
- Total phosphorus

Phosphorus is a critically important element, but excessive concentrations can be harmful to water bodies. High phosphorus concentrations can lead to reduced dissolved oxygen in water bodies, among other issues (USGS, 2018b).

Sources of phosphorus included soil and rocks, wastewater treatment, fertilizers, septic systems, manure, runoff from disturbed land, and commercial cleaning (Litke, 1999; Tuser, 2022). High phosphate concentrations in water were typically associated with runoff events (Litke, 1999) and the 2023 limit for total phosphate on the Clear Roads QPL is ≤ 2500ppm. EPA recommended limits of 0.05 mg/L (or ppm) in streams entering lakes and 0.1 mg/L in flowing waters (US EPA, 1986).

Phosphorus from deicers typically entered the environment at concentrations ranging from 14–26 mg/L. At these concentrations, algae growth was stimulated, which then reduce the dissolved oxygen (DO) for other aquatic organisms (Fischel, 2001). The Colorado Department of Transportation (CDOT) followed the state water quality guideline, which was equal to or less than 25 mg/L for phosphorus (Fay et al., 2022). Because algal growth could be affected by very low concentrations of phosphorus (20 µg/L) (Staples et al., 2004), some states set their water quality standards below the 25 mg/L limit used by CDOT. For example, the State of Michigan set a phosphorus limit of 1 mg/L for point discharges (Public Sector Consultants, 1993).

Smith (2017) investigated the total phosphorus (TP) in the Cambridge, Massachusetts drinking-water source area using data from 10 continuous water-quality monitoring stations. They found that "concentrations of TP (range[d] from 0.008 to 0.69 mg/L in all subbasins) in tributary samples did not differ substantially between the Cambridge Reservoir and Stony Brook Reservoir Basins. About one-half of the concentrations of TP in samples collected during water years 2013–15 exceeded the EPA proposed reference concentration of 0.024 mg/L and between 57 and 92 percent of the annual load for TP was transported during stormflows".

Many agriculturally derived deicing additives had high phosphorus concentrations. Fay et al. (2022) found that waste cheese brine had a TP of 300-500 mg/L, but with treatment the TP was less than 25 mg/L. Unfortunately, with the removal of the phosphorus, common benefits associated with use of agriculturally derived additives were lost, such as an observed reduction in corrosion protection.

5.6 Cyanide

Cyanide as ferric ferrocyanide and sodium ferrocyanide compounds were commonly added to solid sodium chloride at very low concentrations as an anti-caking agent (Fu & Shi, 2018). This led to cyanide loading in the near-road environment and to leachate from storage facilities (Ramakrishna and Viraraghavan, 2005; Levelton Consultants et al., 2007). While this effort was focused on non-chloride products, it was common to blend these products with solid salt.

The EPA drinking water limit for cyanide was less than 0.004 mg/L in 2023, while the acute exposure limit for aquatic life was 0.22 mg/L and for chronic exposure was 0.005 mg/L (US EPA, 2022). The Clear Roads QPL cyanide limit was 0.2 mg/L.

Agriculturally derived additives may also have contained cyanide derived from apple seeds, apricot kernels (or seeds), or cassava (or yuca) (Ogbuagu et al., 2019). For this reason, understanding the source material of agricultural additives and monitoring cyanide concentration of each batch was important.

5.7 Toxicity

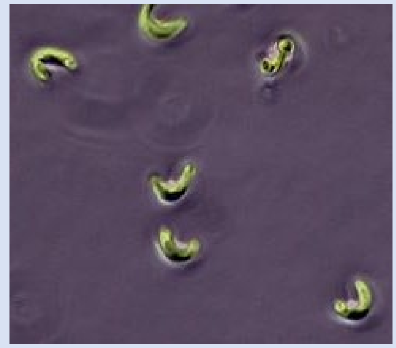
The Clear Roads QPL Specification Document relied on the EPA's *Short-term methods for estimating the chronic toxicity of effluents and receiving waters to freshwater organisms* (EPA, 2022a) document for guidance on assessing the toxicity of deicing materials. Test species referenced for use in the document are shown in Table 25. Sodium chloride, a common deicing material, was an acceptable reference toxicant for this test method. EPA toxicity limits for NaCl were 235, 250, 860 mg/L (EPA, 2022b), and are explained in more detail below.

- Chloride: 230 mg/L = Chronic, longer-term exposure at a lower dose, Freshwater National Recommended Aquatic Life Criteria
- Chloride: 250 mg/L = causes salty taste, Secondary Maximum Contaminant Level (EPA, 2023a)
- Chloride: 860 mg/L = Acute, one-time or shorter duration high exposure, Freshwater National Recommended Aquatic Life Criteria

These limits could be used to assess the relative toxicity of non-chloride deicing products. When reading toxicity data, the smaller the number the more toxic the substance.

Table 25. Common name, scientific name, and image of species used in toxicity testing (EPA, 2022a).

Common Name	Scientific Name	Image
Fathead minnow	Pimephales promelas	
Daphnid	Ceriodaphnia dubia	

Common Name	Scientific Name	Image
Green alga	Selenastrum capricornutum	

The following terms are commonly used when discussing toxicity testing results:

- LC – lethal concentration
- LC50 – lethal concentration of 50% of test population (test organisms), 48 or 96-hour test duration
- LD – lethal dose
- EC50 – median effective concentration which results in 50% reduction in algae growth or immobilization
- NOEC – no observed effect concentration, or highest concentration with no toxicity
- IC25 (7 days) – concentration at which there is a 25% reduction in young products, growth
- IC50 (7 days) – concentration at which there is a 50% reduction in young products, growth
- Acute – typically low concentration but longer exposure
- Chronic – typically higher concentration but short exposure time

Work by Fishel (2001), Nazari et al. (2021), and ACRP (2009) summarized toxicity results into data tables for various species, deicers, and test methods. A generalization of the data summarized in Nazari et al. (2021) is provided below for NaCl, $CaCl_2$, and Urea (Table 26).

Table 26. Summary of toxicity data for NaCl, $CaCl_2$, and urea from Nazari et al. (2015).

Deicer	Test Method	Species	Results (mg/L)
NaCl	LC50 48-hr	Various Species	1470 – 8900
NaCl	LC50 96-hr	Various Species	1720 – 21,450
$CaCl_2$	LC50 48-hr	Various Species	3540 – 20,730

Deicer	Test Method	Species	Results (mg/L)
Urea	LC50 48-hr	*Rana sylvatica* (amphibian)	14,370
Urea	LC50 96-hr	Various Species	14,290

A generalization of toxicity data summarized by Fischel (2001) for NaCl and CMA is provided below (Table 27).

Table 27. Summary of toxicity data for NaCl and CMA from Fischel (2001).

Deicer	Test Method	Species	Results (ppm)
NaCl	LC50 24-hr	Various Species	2724 – 14,000
NaCl	LC50 72-hr	Various Species	2308 – 11,112
NaCl	LC50 7-day	Various Species	1440 – 4040
CMA	LC50 48-hr	*Daphnia magna* (Daphnia)	>1000
CMA	LC50 96-hr	Various Species	2000 – 18,700

ACRP (2009) summarized toxicity data for commonly used airport deicers and additives using various test methods and species. The toxicity data was sourced from EPA ECOTOX database: https://cfpub.epa.gov/ecotox/ (EPA, 2023b). Below is summary of relevant toxicity data for non-chloride deicers commonly used at airports (Table 28).

Table 28. Summary of toxicity data for varying species and test methods for common airport deicers including propylene and ethylene glycols, glycerol, sodium acetate, sodium formate, and urea from ACRP (2009).

Deicer	Test Method	Species	Results (mg/L)
1, 2-Propylene glycol	LC50 96-hr	Fathead minnow	55,770
Propylene glycol, Type I	LC50 96-hr	Fathead minnow	6,250 – 52,000
Propylene glycol, Type I	LC50 48-hr	Fathead minnow	10,800
Propylene glycol, Type I	LC50 48-hr	*Ceriodaphnia dubia*	6,700 – 26,000
Propylene glycol, Type I	EC50 48-hr	*Ceriodaphnia dubia*	4,280

Deicer	Test Method	Species	Results (mg/L)
Propylene glycol, Type IV	LC50 96-hr	Fathead minnow	375 – 1,975
Ethylene glycol	LC50 96-hr	Rainbow trout	>18,500
Ethylene glycol, Type I	LC50 96-hr	Fathead minnow	16,300 – 30,900
Ethylene glycol, Type I	EC50 48-hr	*Ceriodaphnia dubia*	29,300 – 55,700
Ethylene glycol, Type IV	LC50 96-hr	Fathead minnow	370
Glycerol	LC50 96-hr	Rainbow trout	54
Sodium Acetate	LC50 120-hr	Fathead minnow	13,330
Sodium Formate	LC50 24-hr	Bluegill	5,000
Urea	LC50 96-hr	Guppy	17,500

Table 29. Recreated from Fishel (2001), Toxicity ranking of deicers for various species.

Ranking	Rainbow Trout	Water Fleas (Acute)	Water Fleas (Chronic)	Selenastrum
(Least toxic) 1	NaCl brine (23.3%)	NaCl brine (23.3%)	NaCl brine (23.3%)	NaCl brine (23.3%)
2	CMA	$MgCl_2$ + Caliber (M1000)	$CaCl_2$ (Liquidow Armor)	$MgCl_2$ (FreezGardZero, TEA)
3	$CaCl_2$ (Liquidow Armor)	CMA	$MgCl_2$ + Caliber (M1000)	$CaCl_2$ (Liquidow Armor)
4	CMAK	$CaCl_2$ (Liquidow Armor)	$MgCl_2$ (FreezGardZero, TEA)	IceBan: $MgCl_2$ (50:50)
5	$MgCl_2$ + Caliber (M1000)	$MgCl_2$ (FreezGardZero, TEA)	CMA	CMA
6	$MgCl_2$ (FreezGardZero, TEA)	NAAC	CMAK	$MgCl_2$ + Caliber (M1000)
7	NAAC	CMAK	KAc	CMAK
8	KAc	KAc	IceBan: $MgCl_2$ (50:50)	KAc
(Most toxic) 9	IceBan: $MgCl_2$ (50:50)	IceBan: $MgCl_2$ (50:50)	IceBan: $MgCl_2$ (50:50)	KAc

The range of LC50 values associated with each deicer varied significantly for each species. For example, work by Harless et al. (2011) found CMA and $CaCl_2$ were most toxic to amphibians, and others (Dougherty and Smith, 2006) found $MgCl_2$ caused decreased survival in frog tadpoles while NaCl did not. Fischel (2001) provided toxicity ranking for various deicers and species (Table 29). Fischel (2001) noted that, overall, IceBan M50 (IceBan: $MgCl_2$ (50:50)) was most toxic to fish and aquatic invertebrates, and that KAc, CMAK, and NAAC were more toxic to fish and water fleas than other deicers. Overall, sodium chloride brine had the lowest acute and chronic toxicity to fish and aquatic invertebrates.

Work for Clear Roads, as project CR 11-02 *Determining the Toxicity of Deicing Materials*, honed in on the nuances of aquatic toxicity of deicing materials and, overall, found NaCl to be least toxic and potassium acetate to be most toxic (Figure 5) (Pilgrim, 2013).

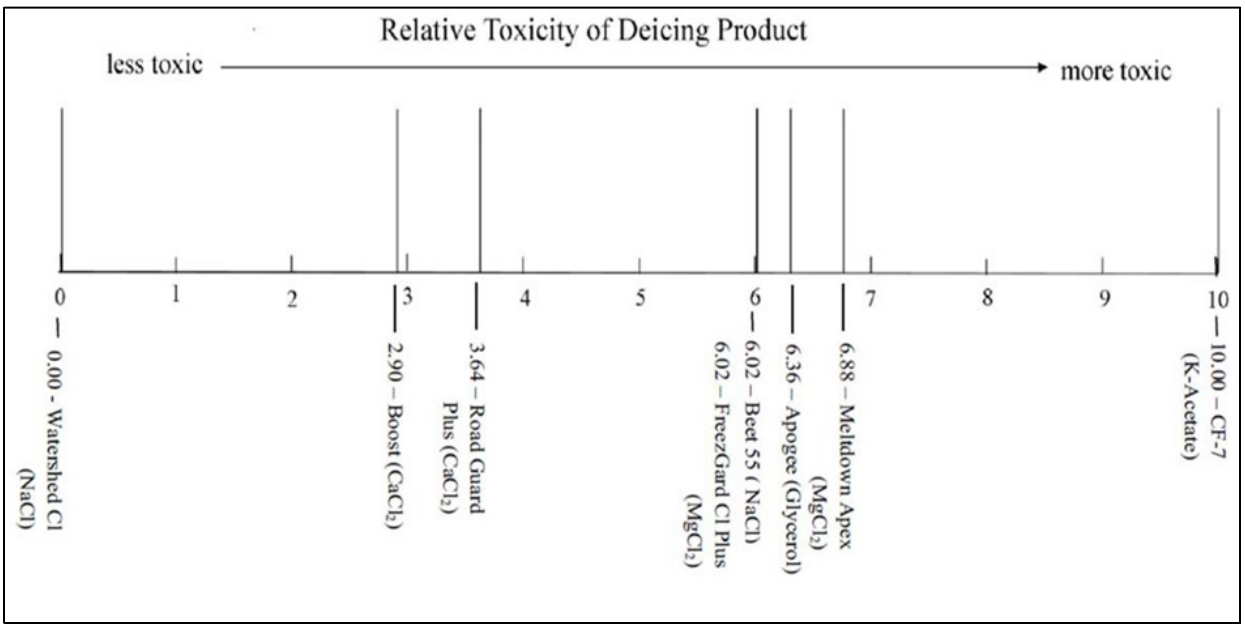


Figure 5. Graphic of relative toxicity of common deicers (copied from Pilgrim, 2013).

Pilgrim (2013) concluded the relative toxicity of deicers was as follows:

<u>Most to Least Toxic</u>

Potassium Acetate > $MgCl_2$ > $CaCl_2$ > NaCl

The results of Pilgrim (2013) deviated slightly from past results, which were generally similar, but found that $CaCl_2$ and NaCl were similarly toxic. This work also found the 96-hour acute test for Fathead Minnow (*Pimephales promelas*) was more sensitive than the 48-hour acute test for Daphnid (*Ceriodaphnia dubia*). For chronic testing, the 7-day Daphnid (*Ceriodaphnia dubia*) was significantly more sensitive than the 4-day Green Alga (*Selenastrum capricornutum*), which was more sensitive than the 7-day Fathead Minnow (*Pimephales promelas*) test.

Pilgrim (2013) noted that varying receiving water chemistry may produce different results and that some deicing products may be retained in the soil, both of which should be considered. Some of the data gaps identified included looking at the influence of colder temperatures on toxicity of deicers to organisms, the effects of longer-term loss of dissolve oxygen from deicers and how that loss could impact toxicity, investigating each deicing product's unique retention and decay in the near-road environment, and studying the effects of exposure periods representative of storm events.

Toxicity data was collected from the literature review, survey of vendors and manufacturers, and the published domain, and is reported in Table 30. Note that many different species were used in toxicity testing, outside of the species recommended for use in the QPL. Additionally, the data could be reported in many different ways, and had varying meanings.

In 2022, there was a wealth of reported (re: published) toxicity data available on many deicers, test methods, and species for comparison and future analysis. Variables to be aware of when using toxicity data or considering toxicity testing include the test method and the species used. For more information, a review by Nazari et al. (2021) summarized and organized existing data, including the latest findings about the adverse effects of deicers on surface water and groundwater, aquatic species, and human health, and identified future research priorities.

Table 30. Summary of toxicity data for various deicers, species, and test methods provided by vendors and manufacturers as part of this research effort.

Deicer	Toxicity Data for Species Approved in EPA (2002a) Test Method (mg/L) Fathead Minnow, *Pimephales promelas*	Toxicity Data for Species Approved in EPA (2002a) Test Method (mg/L) Daphnid, *Ceriodaphnia dubia*	Toxicity Data for Species Approved in EPA (2002a) Test Method (mg/L) Green Alga, *Selenastrum capricornutum*
NaCl	860 acute limit, 230 chronic limit		
CMA		4,670, 1,039	706
NaAC	3,750		
KAc	4,225		
Apogee	750	750	920
Beet-Based (Beet55+Salt)	1.7	4.26 (acute)	9.64
	6.24	7.69	
$MgCl_2$+Caliber		4,950	631
		2,150	
Corn Based (NaCl + Caliber (10%))		399	1,837
		538	2,721
$MgCl_2$+Ice Ban		1,530	1,090
		585	
		164	
$MgCl_2$ (80%) + IceBan (20%)		2,127	1,154
		644	
		1,004	
			4,144
$MgCl_2$ (50%) + IceBan (50%)		676	298
		86	
		164	1,090
NaCl (23%) + IceBan (20%)		585	1,483
		451	
		808	4,017
NaCl (50%) + IceBan (50%)		94	556
		142	876
Propylene Glycol	707 - 45,400	21,800	
Blend 88% Propylene Glycol	5,500		
Ethylene Glycol	50,000		
Blend 92% Ethylene Glycol	27,000		

Table Notes:

Table cell color indicates the test method used.

96-hr LC50
LC50 acute, chronic
IC50 (growth inhibition)
48-hr LC50
IC50 chronic
IC25

5.8 Corrosion

The Clear Roads QPL Specification Document required corrosion rate be reported using the NACE Standard TM0169-95 (1995 Revision) as modified by the Pacific Northwest Snowfighters, also known as the Dip Test. Values were reported as percent corrosion rate (PCR) and corrosion inhibited products were required to be 70% less corrosive than salt (NaCl) to pass. The corrosion rate was of particular importance for this effort as it was often one of the key reasons why a non-chloride deicer was chosen, such as for use at an airport.

PCR values were reported in the QPL (https://clearroads.org/qualified-product-list/). Table 31 summarizes general ranges of PCR values for common chloride, inhibited chloride, and non-chloride deicing products (Shi et al., 2009; Shi et al., 2011; Shi et al., 2013; Ye et al., 2013; Muthumani et al., 2015; Clear Roads, 2023).

Table 31. Summary table of general ranges of percent corrosion rate (pcr, %) values for deicers.

Deicer Type	Percent Corrosion Rate (%)
NaCl	99 – 100%
Corrosion inhibited NaCl	16 – 30%
Corrosion inhibited $MgCl_2$	8 – 29%
Corrosion inhibited $CaCl_2$	16 – 28%
Acetates	-3 to -11% (non-corrosive)

The Dip test method only required mild steel to be used. We knew from past work that acetates could be as corrosive as chloride salts when it came to corrosion of galvanized steel (Shi et al. 2014), but a recent survey for another Clear Roads project reported that metals most commonly found on State DOT fleet equipment included: i) steel (ii) stainless steel (iii) copper (iv) aluminum, and aluminum alloys (X. Shi, personal communication, August 4, 2023. Discussion of survey results collected for Clear Roads project CR 21-02 *Update to CR 13-04: Best Practices for Protecting DOT Equipment from the Corrosion Effects of Chemical Deicers*). Even though stainless steel showed passivity and formed a protective layer on its surface, it was still essential to test stainless steel for corrosion because it was susceptible to pitting in a salt-like humid environment. Pitting is a form of corrosion that can attack stainless steel, especially in salty conditions.

Regarding corrosion, the test method only required testing of mild steel. Additional metal types common on fleet equipment included stainless steel, copper, aluminum, and aluminum alloys. Given the prevalence of stainless steel in equipment and roadway infrastructure and its susceptibility to pitting corrosion, future testing should consider including stainless steel.

5.9 Performance testing

5.9.1 Friction Testing

The Clear Roads QPL required frictional analysis of liquid, or anti-icing products applied to pavement at prescribed application rates. The friction test was conducted in a sealed and controlled humidity chamber, and the coefficient of friction was measured as the humidity was lowered and raised over time in the chamber. This dataset provided evidence of whether a deicing product could create slippery road conditions as the ambient humidity changed.

Example friction test results are shown in Figure 6. When the liquid, anti-icing product was applied and as the humidity increased, the friction decreased, or became more slippery [1]. Then, as the humidity decreased, the product dried on the asphalt surface and friction increased [2]. Next, as the humidity increased (when it reached ~55%) a significant decrease in friction occurred as the product rehydrated [3]. The friction then increased with time as humidity slowly increased in a stepwise fashion [4].

To interpret friction values, we consider the range of friction coefficient (μ) values from 0.0 - 1.0. In the US, pavement friction values above 0.6 were considered good and safe (see green area in Figure 3) (Fay et al., 2022). Whereas pavement friction values from 0.4 – 0.6 may have triggered a watch or warning that the road was becoming more slippery (see orange area in Figure 6). Pavement friction values below 0.4 were considered slippery and typically resulted in winter maintenance operations occurring.

To assess how the product performed, you can see in Figure 6 that the lowest friction values of 0.57 occurred just after application of the liquid product and upon rehydration. Given that these values were very close to the "safe", or the green range, this product was unlikely to cause unsafe roadway friction, assuming it was applied at the same application rate as was used in this test (25 gal/l-m). Note that in this example, the test was run at 41°F. This test did not provide data as to whether the anti-icing or deicing products improved or reduced roadway friction during freezing, snowy or icy conditions.

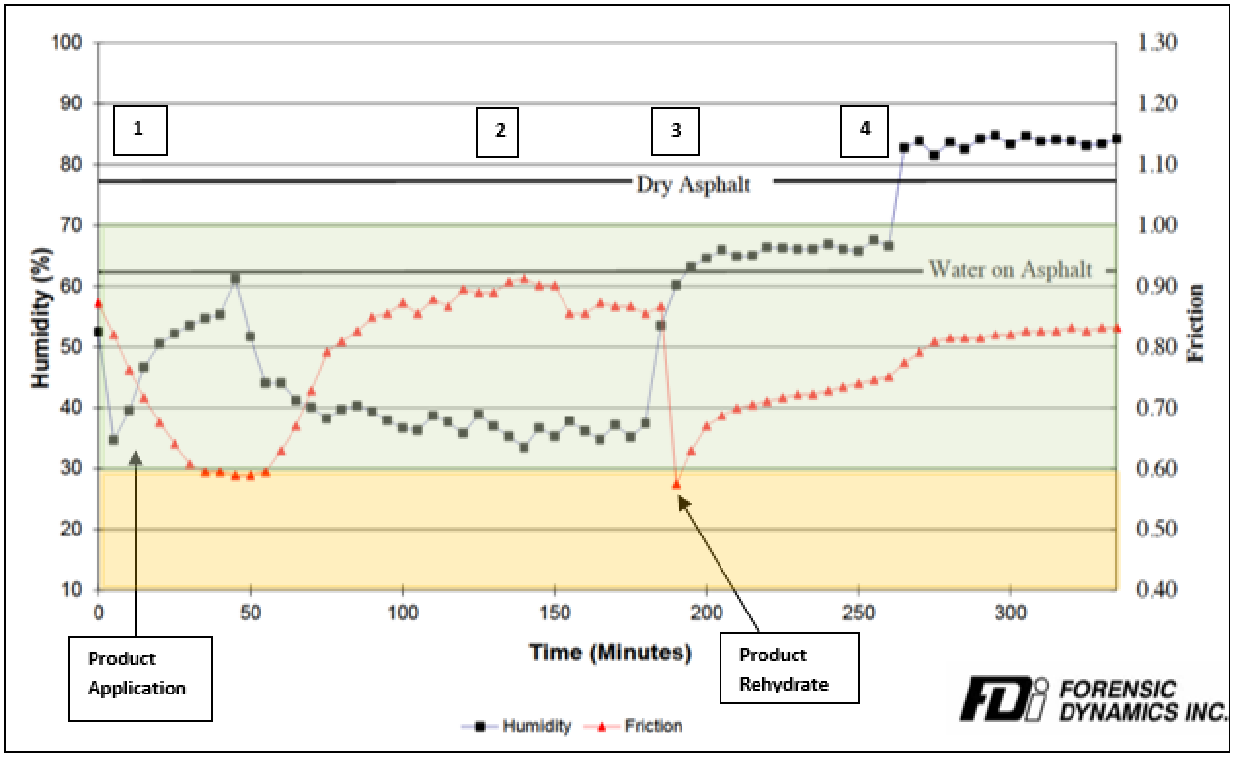


Figure 6: Graphical results of friction and humidity data required for Clear Roads QPL evaluation. Data provided by Clear Roads.

5.9.2 Ice Melting Capacity

No performance testing outside of the friction test was required by the Clear Roads QPL in 2023. Many agencies, vendors, and manufacturers conducted their own performance testing for various reasons – to understand how the product would perform relative to other products, to ensure the product meets performance spec, etc. Historically, performance testing included ice melting capacity, ice undercutting, and ice penetration using the SHRP 205.1-6 methods, eutectic temperature, or more recent techniques such as thermal analysis using differential scanning calorimetry (DSC) or a calorimeter, and the Mechanical Rocker Test developed by Gerbino-Bevins and Tuan (2011) and Tuan and Albers (2014). Recent work showed that the Mechanical Rocker Test provided the most accurate and precise ice melting capacity data for **liquid** deicers (Hansen & Halsey, 2019; Nazari et al., 2022). Future work will need to be done to assess the relative precision and accuracy of the mechanical rocker test method for solid and pre-wet deicers.

A summary of available Mechanical Rocker Test ice melting capacity (IMC) data is provided in Table 32. References used in this table can be found in Appendix C- References for 5.9.2 Ice melting Capacity, Table 32.

Table 32. Summary table of published ice melting capacity test results in g of ice melted per mL of deicer using the Mechanical Rocker Test.

Reference	Liquid Deicer Type	IMC range (g/mL)	IMC Reference Values (g/mL) 15°F	IMC Reference Values (g/mL) 0°F
1	23% NaCl (rg)	0.05 - 0.30	0.146	
1	NaCl + additive (c) (0°F, 15°F)	0.17 - 0.30		
1	29% $MgCl_2$ (rg)	0.29 - 0.48		0.384
1	$MgCl_2$ + additives (c) (0°F, 15°F)	0.45 - 0.52		
1	32% $CaCl_2$ (rg) (0°F, 15°F)	0.28 - 0.38		
1	$CaCl_2$ + additives (c) (0°F, 15°F)	0.39 - 0.48		
1	Potassium Acetate (c) (0°F, 15°F)	0.37 - 0.50		
2	$MgCl_2$ + additives (c) (0°F, 15°F)	0.4 - 0.57		
3	NaCl (10°F, 20°F)	0.3 - 0.59		
3	$MgCl_2$ + additives (rg & c) (0°F, 10°F, 20°F)	0.54 -1.06		
3	$CaCl_2$ + additives (c) (0°F, 10°F, 20°F)	0.70 - 1.05		
3	Potassium Acetate (c) (0°F, 10°F, 20°F)	0.65 - 1.40		
3	Beet juice (c) (10°F, 20°F)	0.32 - 0.65		
	Solid Deicer Type			
3	NaCl (c) (0°F - 20°F)	0.38 - 1.2		

Note: rg = reagent grade material, c = commercially available

The ice melting capacity results indicated that very consistent values could be obtained for liquid deicers, and that the mechanical rocker test method was good at detecting differences in ice melting capacity of deicing products with varying components and additives. Ice melting capacity data available in the published domain included those for salt brine (NaCl), magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), commercial variations of these, and potassium acetate. Given the focus of this effort was on non-chloride products, we suggested that the mechanical rocker test be used to provide ice melting capacity values for the following commonly used and commercially available deicing products – sodium acetate, calcium magnesium acetate, sodium formate, potassium formate, and ethylene and propylene glycol where feasible when these products are available in liquid form.

6 Educational Primers

Educational Primers, or 2-page fact sheets, were developed to provide high-level information on common categories of non-chloride deicing products so that they could be easily compared to salt, as rock salt or salt brine. Educational primers were developed for: acetates, including sodium acetate (NaAc), potassium acetate (KAc), and calcium magnesium acetate (CMA); formates, including sodium formate (NaFm) and potassium formate (KFm); glycols including propylene (PG) and ethylene glycol (EG); and agriculturally derived, or ag-based, deicing additives, which include but are not limited to beet juice, leaf extracts, and fruit pomaces. [Note that agriculturally base additives, like beet products, are generally used as additives to chloride-based liquids and solids.] The primers provide a general description of the products, pros and cons of their use, effective and eutectic temperatures, application rates for various application methods, cost information, impacts to the environment and infrastructure and equipment, and storage and handling considerations. Note that each primer includes information on salt, as rock salt or salt brine, for comparison purposes. The following pages provide examples of the Primers which can reviewed in full or downloaded on the Clear Roads project page for this study: https://clearroads.org/project/21-03/.

Non-Chloride Deicer Data Sheet

ACETATES

Description

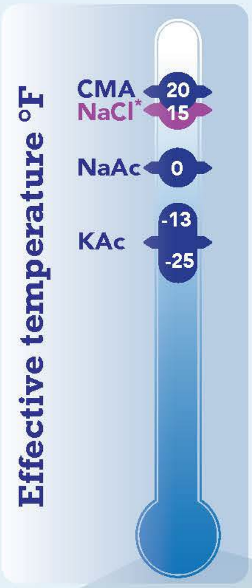
Acetate-based deicers including potassium acetate (KAc), calcium magnesium acetate (CMA), and sodium acetate (NaAc), can be an alternative to chloride-based deicers as they provide a low effective temperature, are less corrosive to metals, and have generally lower environmental impacts. Due to their higher cost, acetate-based deicers tend to be used as airport deicers and in areas where corrosion of metal is a concern.

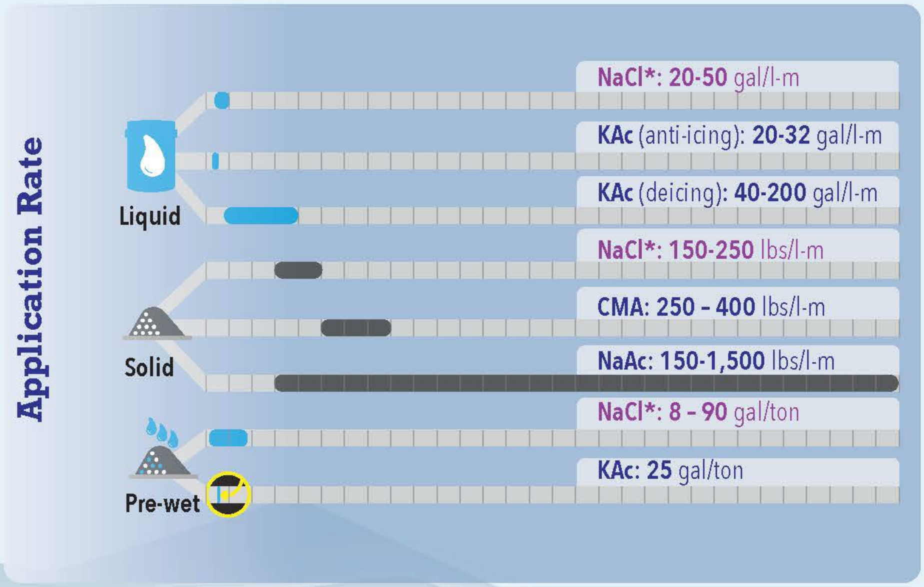
Pros

- Low effective temperature
- Non-corrosive to mild steel

Cons

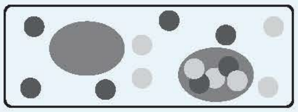
- Expensive
- Damaging impacts to pavements (concrete and asphalt)





Non-Chloride Deicer Data Sheet

ACETATES

	Impacts	NaCl*	CMA	NaAc	KAc
	BOD COD	Low	Moderate to High	Moderate to High	Moderate to High
	Ecological Toxicity	Low to Moderate	Low to Moderate	Low	Low to Moderate
	Asphalt Pavements	Low to Moderate	Moderate	Moderate	Moderate
	Concrete Pavements	High	Low	Moderate to High	High
	Mild Steel Corrosion	High	Low	Low	Low
	Galvanized Steel Corrosion	High	High	High	High

Storage and Handling

- All equipment surfaces that are frequently exposed to deicing products should be routinely rinsed with warm water to prevent accumulation.
- Keep containers tightly closed in a dry, cool and well-ventilated place.
- All liquids should be stored with secondary containment.
- All solids should be stored on non-permeable surfaces and covered from the elements.

* *NaCl* is included as a reference for comparison to the non-chloride deicers in this data sheet.

CLEAR ROADS research for winter highway maintenance
MONTANA STATE UNIVERSITY | Western Transportation Institute
mn DEPARTMENT OF TRANSPORTATION
September 2023

Non-Chloride Deicer Data Sheet

FORMATES

Description

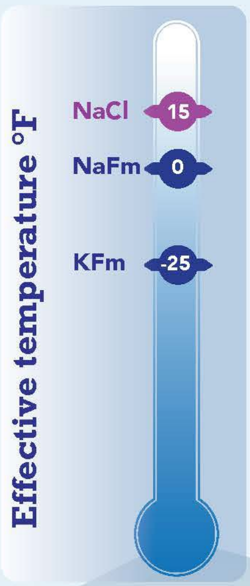
Common formate-based deicers include potassium formate (KFm) and sodium formate (NaFm). Formate-based deicers are similar to acetates and are commonly used at airports. Formate-based deicers are effective above temperatures of -25°F, however they can be costly.

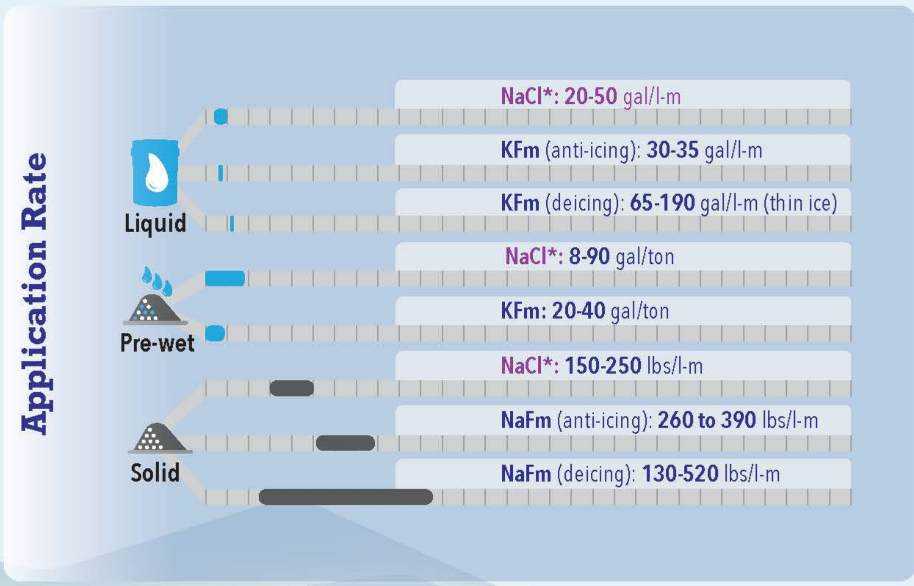
Pros

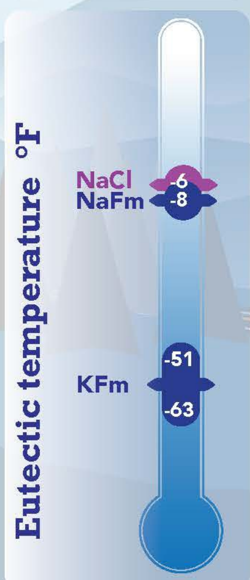
- Low effective temperature
- Fast acting

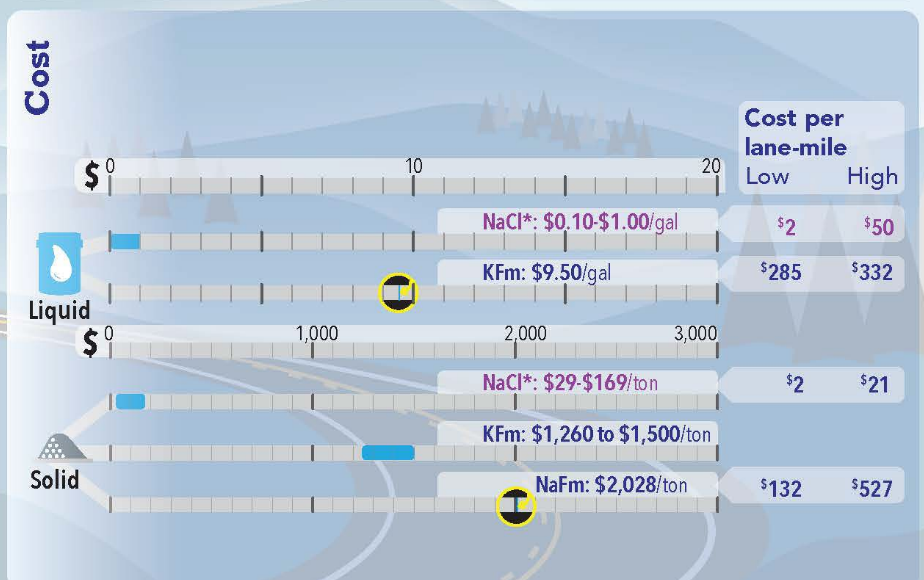
Cons

- Expensive
- Corrosive to galvanized steel









Non-Chloride Deicer Data Sheet

FORMATES

Impacts	NaCl*	KFm	NaFm
BOD COD	Low	Low to Moderate	Low to Moderate
Ecological Toxicity	Low to Moderate	Moderate	Moderate
Asphalt Pavements	Low to Moderate	Low to Moderate	Low to Moderate
Concrete Pavements	High	Moderate	Moderate
Mild Steel Corrosion	High	Low	Low
Galvanized Steel Corrosion	High	High	High

Storage and Handling

- All equipment surfaces that are frequently exposed to deicing products should be routinely rinsed with warm water to prevent accumulation.
- Keep containers tightly closed in a dry, cool and well-ventilated place.
- All liquids should be stored with secondary containment.
- All solids should be stored on non-permeable surfaces and covered from the elements.

** NaCl is included as a reference for comparison to the non-chloride deicers in this data sheet.*

CLEAR ROADS research for winter highway maintenance

MONTANA STATE UNIVERSITY Western Transportation Institute

DEPARTMENT OF TRANSPORTATION

September 2023

Non-Chloride Deicer Data Sheet

GLYCOLS

Description

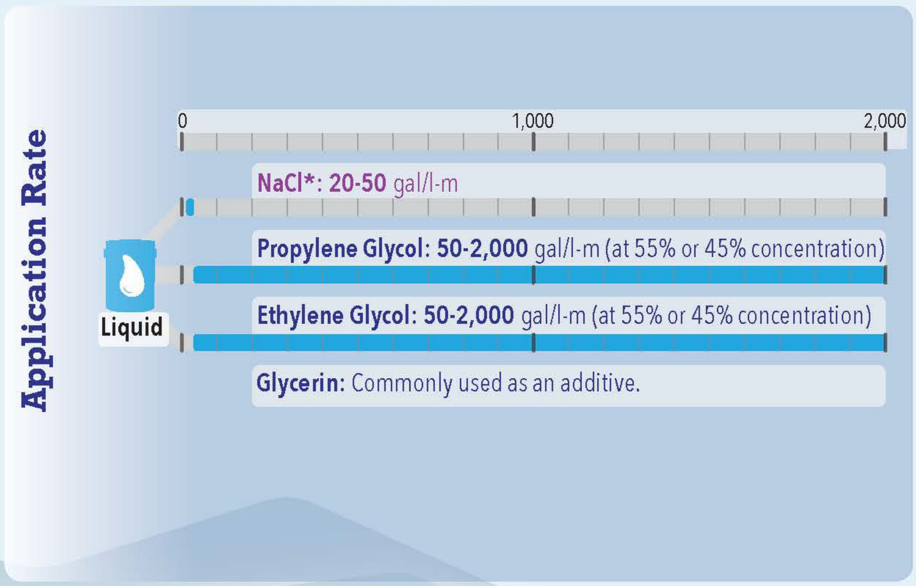
Glycol-based deicers are those that contain glycol, glycerol, and glycerin. Two common glycol-based deicers include propylene glycol and ethylene glycol, these can be an alternative to chloride-based deicers as they provide a very low freezing temperature and can act as an anti-caking agent to improve ice melting capability. Glycols can be sourced as a byproduct of biodiesel manufacturing. Generally glycol-based deicers are used at airports to deice aircraft.

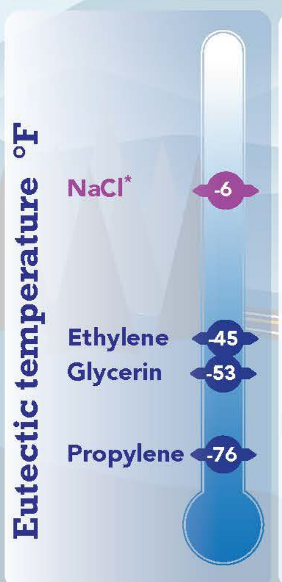
Pros

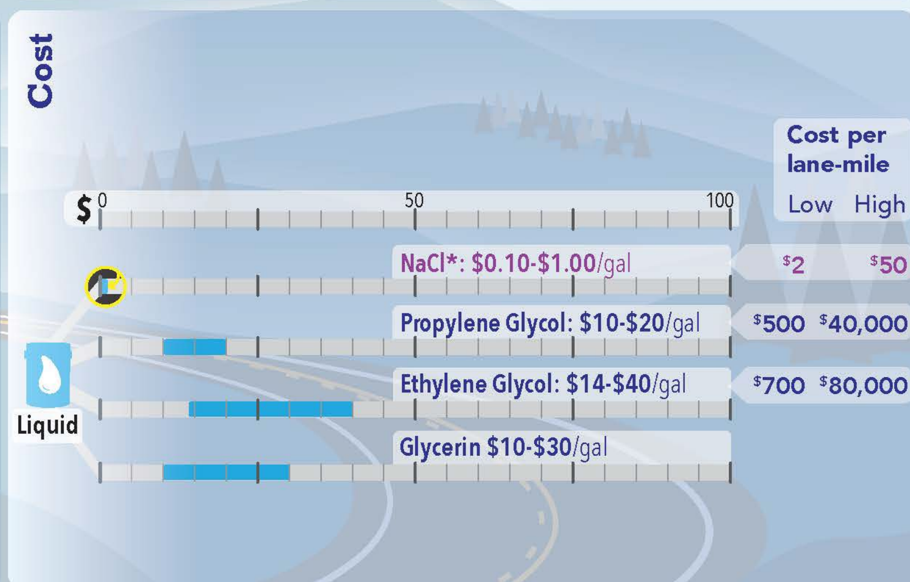
- Low Effective Temperature
- Non-Corrosive

Cons

- Glycols can negatively impact environment (increased BOD)
- Damaging impacts to concrete pavements

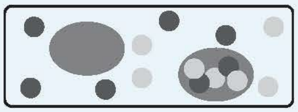






Non-Chloride Deicer Data Sheet

GLYCOLS

	Impacts	NaCl*	Propylene Glycol	Ethylene Glycol	Glycerin
	BOD COD	Low	High	High	High
	Ecological Toxicity	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
	Asphalt Pavements	Low to Moderate	Limited data available	Limited data available	Limited data available
	Concrete Pavements	High	High	High	High
	Mild Steel Corrosion	High	Non-corrosive	Non-corrosive	Non-corrosive
	Galvanized Steel Corrosion	High	Moderate	Moderate	Moderate (Based on glycol data)

Storage and Handling

- All equipment surfaces that are frequently exposed to deicing products should be routinely rinsed with warm water to prevent accumulation.
- Keep containers tightly closed in a dry, cool and well-ventilated place.
- For propylene glycol, store in tightly sealed original UV resistance containers, away from direct heat and strong oxidizing agents. Product should be stored in clear or semitransparent containers.
- For ethylene glycol, do not store with strong acids/bases. Containers may be hazardous when empty due to product residue.
- For glycerin, keep container closed when not in use, protect from freezing, store at temperatures below 120°F, water contamination should be avoided. Incompatible with oxidizers, boron trifluoride/calcium oxide.
- All liquids should be stored with secondary containment.
- All solids should be stored on non-permeable surfaces and covered from the elements.

** NaCl is included as a reference for comparison to the non-chloride deicers in this data sheet.*

CLEAR ROADS research for winter highway maintenance
MONTANA STATE UNIVERSITY Western Transportation Institute
mn DEPARTMENT OF TRANSPORTATION
September 2023

Non-Chloride Deicer Data Sheet AGRICULTURAL PRODUCTS

Description

Agricultural deicer products include those from various organic co- and by-products including beets, apple pulp, grapes, dandelions, sugar beets, foliage of these, and many others. These products are generally used as a deicer additive, allowing for a deicer to work at colder temperatures, remain on the pavement for longer periods of time, and provide varying levels of corrosion protection. The choice of ag products may vary based on local product availability.

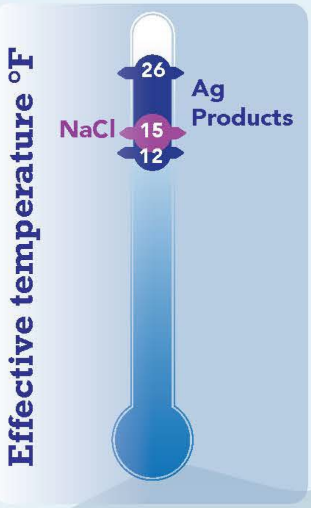
Pros

- Improved effectiveness of deicer products
- Reduces salt application rates (when used for pre-wet)
- Reduced corrosion

Cons

- Generally used as additive to deicers (not necessarily chloride-free)

Effective temperature °F



Application Rate

Generally used as an additive. Allow products to work at colder temperatures, but this will vary by product and concentration added. Note that these products help reduce the eutectic temperature, but do not necessarily improve ice melting ability.

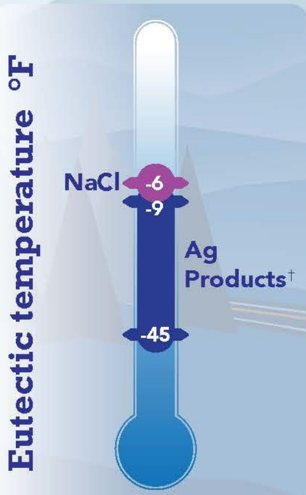
Ag products (anti-icing):

- Blended at 10 - 35 percent with salt brine and other chlorides.
- Apply at similar rates to other liquids.

Ag products (pre-wet):

- 5 - 15 gallons/ton.

Eutectic temperature °F



Cost

Cost per lane-mile	Low	High
NaCl* $0.10-$1.00/gal	$2	$50
Beet Based: $1.44 to $2.42/gal	$33	$148
Corn Based: $1.81 to $9.59/gal	$72	$575
Distiller By-product: $18.75/gal	$656	$844

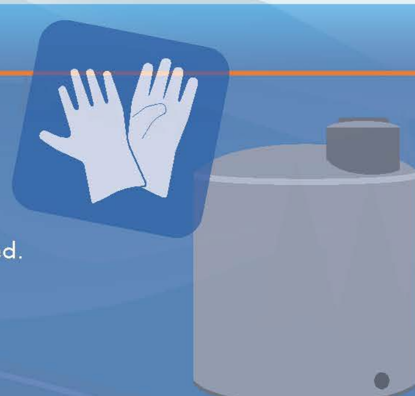
† The reduction in eutectic temperature from the addition of ag products can varying greatly depending on the product and concentration (Muthumani et al., 2015; Nazari et al., 2019).

Non-Chloride Deicer Data Sheet AGRICULTURAL PRODUCTS

Impacts	NaCl*	Ag Products
BOD COD	Low	Low to Moderate
Ecological Toxicity	Low to Moderate	Limited data available
Asphalt Pavements	Low to Moderate	Limited data available
Concrete Pavements	High	Limited data available
Mild Steel Corrosion	High	Limited data available
Galvanized Steel Corrosion	High	Limited data available

Storage and Handling

- Most Ag products are stable during storage for all seasons.
- Periodic recirculation of material in storage tanks may be suggested by the vendor.
- Store in a cool, dark location.
- Check periodically for biological growth, manage as is needed.
- All liquids should be stored with secondary containment.
- All solids should be stored on non-permeable surfaces and covered from the elements.



* *NaCl is included as a reference for comparison to the non-chloride deicers in this data sheet.*

CLEAR ROADS research for winter highway maintenance
MONTANA STATE UNIVERSITY Western Transportation Institute
DEPARTMENT OF TRANSPORTATION
September 2023

7 Conclusions & Recommendations

Non-chloride deicers are a viable option in winter roadway maintenance operations. This has been demonstrated in the significant number of publications and reports on their use on roadways and at airports. Additionally, many of the state and local transportation agencies across the country who participated in the survey reported successfully using these products.

A deeper evaluation of BOD, COD, nitrogen, phosphorus, cyanide, toxicity, and corrosion was completed because they are of particular interest when considering non-chloride deicers. Overall, BOD values for chlorides are the lowest, with formates and ag-based additives moderately higher, with acetates, succinates, and glycol much higher, and with BOD numbers the highest for urea. Generally, COD values follow a similar trend to BOD for the various deicer types. Nitrogen is an essential nutrient but at elevated concentrations can impact the near-road environment. Nitrogen is a primary component in urea and may be present in other deicing materials. Phosphorus is also an essential nutrient but at elevated concentrations can impact the near-road environment. Phosphorus can be present at elevated concentrations in deicers and ag-based additives. Cyanide can be present in anti-caking additives used in deicers and in ag-based additives, which can lead to cyanide loading around storage facilities and in the near-road environment. Toxicity of deicers is highly variable based on species and the components of the deicing material. Past work identified chlorides as the least toxic, followed by acetates as more toxic, in the following order: $NaCl < CaCl_2 < MgCl_2 <$ Acetates < Glycols < Formates. Corrosion of metals, or corrosion protection, is commonly associated with non-chloride deicers. Corrosion risk of deicing material varies greatly as a function of material type, pavement type, metal type, etc.

Performance testing of non-chloride deicers was evaluated and the influence of deicers on pavement friction was reviewed. In the U.S., pavement friction values (μ) above 0.6 are typically considered safe, friction values 0.6 – 0.4 may trigger a watch or warning that road condition is becoming more slippery, and friction values below 0.4 are considered slippery and often result in winter operations. This general guidance can be used by Clear Roads when reviewing friction data provided for QPL consideration. Ice melting capacity test methods were reviewed and of the methods available, the mechanical rocker test appears to provide the most accurate and precise results. However, limited data is available using this test method for many non-chloride deicing products.

Non-chloride deicers provide varying benefits depending on what they are made of, including performing at colder temperatures, higher corrosion protection, reduced (environmental) impacts, and residual (performance) benefits on the roadway. On the other hand, the same non-chloride deicers can have increased (detrimental) impacts relative to those of salt (rock salt or salt brine), such as with BOD, COD, and toxicity, and typically come at an increased cost. Because there is not a clear way to say one deicing product is better than another, each non-chloride deicing product should be evaluated individually based on an agency's needs and priorities.

7.1 Recommendations

A special group of Clear Roads members that works with the QPL may choose to consider the following:

1. Clear Roads requires a wealth of data be provided for QPL evaluation, however, clear guidance is needed on how these data are assessed, what guidelines are used, and required reporting (e.g., units).
2. Consider modifying the corrosion testing requirement to include galvanized steel and stainless steel.
3. Consider looking into the limits allowed for phosphorus, nitrogen, and cyanide.
4. Consider dilution in limits.

7.2 Future Research

Research needs identified in this work are detailed below, which could be addressed in the near future.

- Conduct ice melting capacity, as the Mechanical Rocker Test, for the non-chloride deicers sodium acetate, calcium magnesium acetate, sodium formate, potassium formate, and ethylene and propylene glycol in liquid form where feasible to serve as baseline values for these products. Additional work in this area would include establishing the Mechanical Rocker Test method for solid deicing products.
- Determine the best BOD test method for assessing the impacts of winter maintenance products on water quality. This could consider modifying existing BOD test methods to evaluate impacts at colder temperatures and/or for longer periods of time to more closely mimic winter conditions, and/or take dilution into account. Work by Corsi et al. (2012) showed that BOD testing conducted on non-chloride deicers should be modified to account for a lag in results and should be conducted at colder temperatures that better match winter conditions. Future research could investigate the fate and transport of non-chloride deicers following application on roadways.
- Additional work needs to be done to better understand the toxicity of all deicing products as it relates to dilution, species, water and soil chemistry, water temperature, and exposure duration.
- Friction testing is required in the Clear Roads QPL Specification Document as of 2023. This test is used to determine if a liquid anti-icing product will create slippery conditions as humidity changes. However, future research could also explore the use of friction, or grip, data to assess deicing product performance in winter conditions. Additionally, there is a lack of data and understanding on how blends and ag-based additives influence roadway friction. Future research could investigate the influence of ag-based additives, and blends of these with common chloride brines, on pavement friction using both the Clear Roads QPL Specification Document method and a method that incorporates freezing temperatures, and snowy and icy road conditions. Additionally, future research could investigate the influence of small organic

compounds, oligomers, bio-polymers, and other commonly used additives to liquid and solid deicing products on roadway friction, under typical road weather scenarios.

REFERENCES

Airport Cooperative Research Board (ACRP). (2009) Formulation for Aircraft and Airfield Deicing and Anti-icing: Aquatic Toxicity and Biochemical Oxygen Demand. Washington, D.C. The National Academies Press. http://doi.org/10.17226/23325

Akhmedov, M.E., Dadakhodzhaev, A.T., Guro, V.P. (2018). Anti-ice reagent on the basis of dolomite, nitrogen acid and carbamide. *International Journal of Engineering Technologies and Management Research*, *5*(10). https://doi.org/10.29121/ijetmr.v5.i10.2018.301

Al-Kheetan, M.J., Rahman, M.M., Ghaffar, S.H., Al-Tarawneh, M., Jweihan, S. (2020) Comprehensive investigation of long-term performance of internally integrated concrete pavement with sodium acetate. Results in Engineering, 6. https://doi.org/10.1016/j.rineng.2020.100110

Anastasio, S., Hoff, I., Thodesen, C. (2015) Influence of sodium chloride and potassium formate as deicing agents on asphalt mixture durability. Bituminous Mixtures and Pavements VI DOI: 10.1201/b18538-70

Blomqvist, S., Amiri, S., Rohdin, P., Ödlund, L. (2019) Analyzing the performance and control of a hydronic pavement system in a district heating network. Energies, 12(11). DOI:10.3390/en12112078

Caplan, D., Cohen, M. (1953) Accelerating effect of decreasing temperature on corrosion by glycol solutions. Corrosion, 9(8): 284-286. https://doi.org/10.5006/0010-9312-9.8.284

Clear Roads (2023) Qualified Products List, https://clearroads.org/qualified-product-list/

Corsi, S.R., Geis, S.W., Bowman, G., Failey, G.G., Rutter, T.D. (2009) Aquatic toxicity of airfield-pavement deicer materials and implications for airport runoff. Environ Sci Technol, 43(1): 40-46. DOI: 10.1021/es8017732

Corsi, S., Mericas, D., Bowman, G.T. (2012) Oxygen demand of aircraft and airfield pavement deicers and alternative freezing point depressants. Water, Air, and Soil Pollution 223:2447-2461

Craig, S., & Zhu, W. (2018). Impacts of deicing salt and nitrogen addition on soil nitrogen and carbon cycling in a roadside ecosystem. *Water, Air, & Soil Pollution*, *229*, 1-13.

Cuelho, E., Harwood, J., Akin, M., Adams, E. (2010). Establishing Best Practices for Removing Snow and Ice from California Roadways. California Department of Transportation.

Ding, L., Wang, X., Cui, X., Zhang, M., & Chen, B. (2021). Development and performance research of new sensitive materials for microwave deicing pavement at different frequencies. *Cold Regions Science and Technology*, *181*, 103176.

Doré, G., Konrad, J.- M., & Roy, M. (1997). Role of deicing salt in pavement deterioration by frost action. Transp. Res. Rec. J. Transp. Res. Board, 1596, pp. 70-75.

Dougherty, C., & Smith, G. (2006). Acute effects of road de-icers on the tadpoles of three anurans. *Applied Herpetology*, *3*(2), 87–93.

EPA (2022a) Short-term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Freshwater Organisms. Fourth Ed. EPA-821-R-02-013. Washington, D.C.

EPA (2022b) National Recommended Water Quality Criteria – Aquatic Life Criteria Table. https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table. Updated September 15, 2022, accessed August 7, 2023.

EPA (2023a) Secondary Drinking Water Standards: Guidance for Nuisance Chemicals. https://www.epa.gov/sdwa/secondary-drinking-water-standards-guidance-nuisance-chemicals. Updated February 14, 2023, accessed August 7, 2023.

EPA (2023b) ECOTOX Knowledgebase. https://cfpub.epa.gov/ecotox/. Updated June 15, 2023, accessed August 8, 2023.

Egüez Álava, H., De Belie, N., & De Schutter, G. (2016). Proposed mechanism for the formation of oxychloride crystals during sodium chloride application as a deicer salt in carbonated concrete. *Construction and Building Materials*, 109: 188–197.

Fair, C. (2005) BOD:COD Correlation provides operations, laboratory benefits. WaterWorld, May 31, 2005. https://www.waterworld.com/home/article/16190273/bodcod-correlation-provides-operations-laboratory-benefits

Fan, L., Li, Z., Du, S., Shi, X. (in press). Agro-based Additive in Chloride Brines Reduces the Damage of Portland Cement Concrete Exposed to Freeze/Thaw Cycles. *Journal of Materials in Civil Engineering*, 2023, in press.

Farnam, Y., Todak, H., Spragg, R., & Weiss, J. (2015a). Electrical response of mortar with different degrees of saturation and deicing salt solutions during freezing and thawing. *Cement and Concrete Composites*, 59: 49–59. https://doi.org/10.1016/j.cemconcomp.2015.03.003.

Farnam, Y., Wiese, A., Bentz, D., Davis, J., & Weiss, J. (2015b). Damage development in cementitious materials exposed to magnesium chloride deicing salt. *Construction and Building Materials*, 93: 384–392. https://doi.org/10.1016/j.conbuildmat.2015.06.004.

Farnam, Y., Villani, C., Washington, T., Spence, M., Jain, J., & Weiss, J. (2016). Performance of carbonated calcium silicate based cement pastes and mortars exposed to NaCl and MgCl2 deicing salt. *Construction and Building Materials*, 111: 63–71. https://doi.org/10.1016/j.conbuildmat.2016.02.098

Fay, L. and Akin, M. (2018) Investigation of alternative deicers for snow and ice control. Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC) University Transportation Center (UTC) and University of Alaska, Fairbanks. https://cesticc.uaf.edu/research/fay-alternativedeicers.aspx

Fay, L., Bell, M., Johnson, L., Clouser, K. (2022) Comparison of Ag[ro]-based deicing additives. Colorado DOT. CDOT-2022-06.

Fay, L., Clouser, C., Villwock-Witte, N. (2022) Assessing the Effectiveness of Friction as a Performance Management Tool in Colorado. Colorado Department of Transportation. CDOT-2022-08.

Fay, L., Honarvar Nazari, M., Jungwirth, S., Muthumani, A., Cui, N., Shi, X., et al. (2015) Manual of Environmental Best Practices for Snow and Ice Control. Clear Roads and MnDOT. https://clearroads.org/wp-content/uploads/dlm_uploads/Manual_ClearRoads_13-01_FINAL.pdf

Fay, L., Shi, X. (2012) Environmental Impacts of Chemicals for Snow and Ice Control: State of the Knowledge. Water Air Soil Pollution. Jun 1;223(5):2751–70.

Fischel, M. (2001) Evaluation of selected deicers based on a review of the literature. Colorado DOT. CDOT-2001-15.

Fu, L., & Shi, X. (2018) *Sustainable winter road operations* (L. Fu & X. Shi, Eds.). John Wiley & Sons.

Ganjyal, G., Fang, Q., Hanna, M.A. (2007). Freezing point and small-scale deicing testing for slats of levulinic acid made from grain sorghum. *Bioresource Technology, 98, 2814-2818.* doi:10.1016/j.biortech.2006.07.042

Gao, J., Guo, H., Wang, X., Wang, P., Wei, Y., Wang, Z., ... & Yang, B. (2019). Microwave deicing for asphalt mixture containing steel wool fibers. *Journal of Cleaner Production*, *206*, 1110-1122.

Gerbino-Bevins, B.M., Tuan, C.Y. (2011). "Performance Rating of Deicing Chemicals for Winter Operations". Nebraska Department of Roads, Materials & Research, SPR-P1(10)P328.

Han, S., Wei, H., Han, L., & Li, Q. (2019). Durability and electrical conductivity of carbon fiber cloth/ethylene propylene diene monomer rubber composite for active deicing and snow melting. *Polymers*, *11*(12), 2051.

Hansen, D., Halsey, L. (2019). "Validation of the Mechanical Rocker Test Method for Ice Melting Capacity (MRT-IMC)". Final report prepared for the Nebraska Department of Transportation, Lincoln, NE.

Harless, M.L., Huckins, C.J. Grant, J.B., Pypker, T.G. (2011) Effects of six chemical deicers on larval wood frogs (*Rana sylvatica*). *Env. Tox. Chem.* 30(7), 1637-1641.

Huang, H., & XU, J. Y. (2019, May). Effect of magnetite on concrete mechanics and microwave deicing performance. In *IOP Conference Series: Earth and Environmental Science* (Vol. 267, No. 4, p. 042019). IOP Publishing.

Jiao, W., Sha, A., Liu, Z., Li, W., Zhang, L., & Jiang, S. (2022). Optimization design and prediction of the snow-melting pavement based on electrical-thermal system. *Cold Regions Science and Technology*, *193*, 103406.

Jones, C., Ramanathan, S., Suraneni, P., & Hale, W.M. (2020). Calcium oxychloride: A critical review of the literature surrounding the formation, deterioration, testing procedures, and recommended mitigation techniques. *Cement and Concrete Composites*, 113: 103663. https://doi.org/10.1016/j.cemconcomp.2020.103663

Kim, H.S., Ban, H., Park, W-J. (2020) Deicing concrete pavements and road with carbon nanotubes (CNTs) as heating elements. Materials, 13. doi:10.3390/ma13112504

Lammers, E. (2021) Evaluation of Liquid Deicing Materials for Winter Maintenance Applications. Kentucky Transportation Cabinet. https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=2734&context=ktc_researchreports

LaPerriere, J.D., Rea, C.L. (1989) Effects of Calcium Magnesium Acetate Deicer on Small Ponds in Interior Alaska. Lake Reserv. Manag. Oct;5(2):49–57. https://doi.org/10.1080/07438148909354398

Levelton Consultants Limited (2007) Guidelines for the selection of snow and ice control materials to mitigate environmental impacts. NCHRP Report 5777. Washington, DC. AASHTO, FHWA.

Litke, D.W. (1999) Review of phosphorus control measures in the United States and their effects on water quality. USGS, Denver, Colorado. [https://pubs.usgs.gov/wri/wri994007/pdf/wri99-4007.pdf]

Liu, K., Fu, C., Xie, H., Wang, F., Wang, X., & Bai, H. (2019a). Design of electric heat pipe embedding schemes for snow-melting pavement based on mechanical properties in cold regions. *Cold regions science and technology*, *165*, 102806.

Liu, J. L., Xu, J. Y., Lu, S., & Chen, H. (2019b). Investigation on dielectric properties and microwave heating efficiencies of various concrete pavements during microwave deicing. *Construction and Building Materials*, *225*, 55-66.

Liu, J. L., Xu, J. Y., Huang, H., & Chen, H. (2020). Microwave deicing efficiency and dielectric property of road concrete modified using different wave absorbing material. *Cold Regions Science and Technology*, *174*, 103064.

Lu, S., Bai, E., Xu, J., & Chen, J. (2021). Research on electromagnetic properties and microwave deicing performance of carbon fiber modified concrete. *Construction and Building Materials*, *286*, 122868.

Ma, H., Yu, H., Cao, W., Bai, K., Zhou, P., Han, L. (2010) Freeze-thaw durability of Portland Cement Concrete subjected to aircraft deicer. Advanced Materials Research, 152-153: 1856-1861. https://www.scientific.net/AMR.152-153.1856

Malakooti, A., Sadati, S., Ceylan, H., Kim, S., Cetin, K.S., Taylor, P.C., Mina, M., Cetin, B., Theh, W.S. (2021) Self-heating electrically conductive concrete demonstration project. Intrans, Iowa Highway Research Board & Iowa DOT. https://intrans.iastate.edu/research/completed/self-heating-electrically-conductive-concrete-demonstration-project/

McCutchon, J.R., Joseph, A.P., Valkenburg, J.V. (1992). Assessment of the effect of urea deicing solution on asphaltic concrete pavements, Public Works Gov. Serv.

Mohammed, A. G., Ozgur, G., & Sevkat, E. (2019). Electrical resistance heating for deicing and snow melting applications: Experimental study. *Cold Regions Science and Technology*, *160*, 128-138.

Mundo, R.D., Labianca, C., Carbone, G., Notarnicola, M. (2020) Recent advances in hydrophobic and icephobic surface treatments of concrete. Coatings, 10(5). DOI:10.3390/coatings10050449

Muthumani, A., Fay, L., Akin, M., Wang, S., Gong, J., Shi, X. (2014). Correlating Lab and Field Tests for Evaluation of Deicing and Anti-icing Chemicals: A Review of Potential Approaches. *Cold Regions Science and Technology, 97(1): 21-32*. https://doi.org/10.1016/j.coldregions.2013.10.001

Muthumani, A., Fay, L., Shi, X., Bergner, D. (2015) Understanding the effectiveness of non-chloride liquid agricultural by-products and solid complex chloride/mineral products. Clear Roads and MnDOT.

National Academies of Sciences, Engineering, and Medicine. (2008) *Impact of airport pavement deicing products on aircraft and airfield infrastructure*. Washington, DC: The National Academies Press.

Nazari, M.H., Havens, E.A., Muthumani, A., Shi, X. (2019) Effects of processed agro-residues on the performance of sodium chloride brine anti-icer. ACS Sustainable Chem. Eng. 7, pp. 13655-13667. DOI: 10.1021/acssuschemeng.8b06043

Nazari, M.H., Jamal, M., Green, D., Gonzalez, J., Beaurivage, S., Smith, H., Mislang, J., Potapova, A., Akin, M. (2022) Standardized Test Procedure for Ice Melting Capacity of Deicers, Task 1 & Task 2 Report. Clear Roads and Minnesota DOT.

Nazari, M.H., Mousavi, S.Z., Potapova, A., McIntyre, J., Shi, X. (2021) *Toxicological impacts of roadway deicers on aquatic resources and human health: A review*. Water, Environmental Research.

Nazari, M.H. & Shi, X. (2019) Developing renewable agro-based anti-icers for sustainable winter road maintenance operations. Journal of Materials in Civil Engineering, 31(12). DOI: 10.1061/(ASCE)MT.1943-5533.0002963

Nazari, M. H., Shi, X., Jackson, E., Zhang, Y., & Li, Y. (2017). Laboratory investigation of washing practices and bio-based additive for mitigating metallic corrosion by magnesium chloride deicer. *Journal of Materials in Civil Engineering*, *29*(1), 04016187.

Nazari, M. H., Yu, J., & Shi, X. (2020). Effect of Ferrous Alloy Type, Beetroot Juice, Deicer Type and Concentration on Early-Stage Corrosion Behavior of Buried Pipes. *Journal of Materials in Civil Engineering*, *32*(10), 04020281.

NCHRP 5777. Levelton Consultants. (2007) Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts. Transportation Research Board, Washington, D.C. https://www.trb.org/Publications/Blurbs/158876.aspx

Nilssen, K., Klein-Paste, A., Wåhlin, J. (2018). The Effect of Additives on the Low Temperature Ice-Melting capacity of NaCl. *Transportation Research Record: Journal of the Transportation Research Board, 2672(12).* https://doi.org/10.1177/0361198118767412

Nilsson, F. (2003). Durability problems on Nordic airfields- The influence of deicing agents on asphalt concrete, in: The XXIInd PIARC World Road Congress, 2003.

Ning, Y. P., Xu, J. Y., Huang, H., Wang, Z. H., & Yao, A. (2022). Effect of Carbon Fiber Admixture and Length on Microwave Deicing Efficiency of Airport Road Surface Concrete. *Advances in Materials Science and Engineering*, *2022*.

Ogbuagu, E. O., Airaodion, A. I., Okoroukwu, V. N., Ogbuagu, U., & Ekenjoku, J. A. (2019). Cyanide Toxicity: The Good, the Bad and the Ugly. *International Journal of Bio-Science and Bio-Technology*, *11*(9), 157-164.

Pan, T., He, X., Shi, X. (2008). Laboratory investigation of acetate-based deicing/anti-icing agents deteriorating airfield asphalt concrete. Asph. Paving Technol. -Proc., 77, pp. 773-793.

Pilgrim, K.M. (2013) Determining the Aquatic Toxicity of Deicing Materials. Clear Roads and Minnesota DOT. CR11-02.

Public Sector Consultants. (1993) The use of selected de-icing material on Michigan roads: Environmental and economic impacts. Michigan DOT.

Qiao, C., Chen, X., Suraneni, P., Weiss, J., & Rothstein, D. (2021a). Petrographic analysis of in-service cementitious mortar subject to freeze-thaw cycles and deicers. *Cement and Concrete Composites*, 122: 104112. https://doi.org/10.1016/j.cemconcomp.2021.104112.

Qiao, C., Hosseinzadeh, N., Suraneni, P., Wei, S., & Rothstein, D. (2021b). Petrographically quantifying the damage to field and lab-cast mortars subject to freeze-thaw cycles and deicer application. *Journal of Infrastructure Preservation and Resilience*, 2: 1-12.

Ramakrishna, D.M., Viraraghavan, T. (2005) Environmental Impact of Chemical Deicers – A Review. *Water Air & Soil Pollution* 166, 49–63

Sahaf, S.A. and Moradzadeh, B. (2015). Laboratory evaluation of CMA impact on the slipping resistance of the road surface. *Bulletin of Environment, Pharmacology and Life Sciences*, *4*(5), 9-18. https://profdoc.um.ac.ir/articles/a/1059713.pdf

SciMed. (2023) https://www.scimed.co.uk/education/what-is-chemical-oxygen-demand-cod/. Accessed March 14, 2023

Shen et al., (2020) Mechanically stable superhydrophobic surfaces on cement-based materials. Chemical Physics, 538. https://doi.org/10.1016/j.chemphys.2020.110912

Shi, X. (2008). *Impact of airport pavement deicing products on aircraft and airfield infrastructure* (Vol. 6). Transportation Research Board, Washington, D.C.

Eds. Shi, X., Fu, L. (2014) Sustainable Winter Road Operations. Wiley-Blackwell.

Shi, X., Akin, M., Pan, T., Fay, L., Liu, Y., Yang, Z. (2009) Deicer impacts on pavement materials: Introduction and recent developments. The Open Civil Engineering Journal, 3:16-27. https://doi.org/10.2174/1874149500903010016

Shi, X., Fay, L., Gallaway, C., Volkening, K., Peterson, M.M., Pan, T., Creighton, A., Lawlor, C., Mumma, S., Liu, Y., Nguyen, T.A. (2009) Evaluation of alternative anti-icing and deicing compounds using sodium chloride and magnesium chloride as baseline deicers. Colorado DOT, CDOT-2009-1

Shi, X., Fay, L., Fortune, K., Smithlin, R., Johnson, M., Peterson, M.M, Creighton, A., Yang, Z., Cross, D. (2011) Investing longevity of corrosion inhibitors and performance of deicer products under storage or after pavement application. Washington State DOT, PNA. WA-RD 759.1

Shi, X., Fortune, K., Smithlin, R., Akin, M., Fay, L. (2013) Exploring the performance and corrosivity of chloride deicers solutions: Laboratory investigation and quantitative modeling. Cold Regions Science and Technology 89(36-44) http://dx.doi.org/10.1016/j.coldregions.2012.10.011

Shi, X., Jungwirth, X, Akin, M., Wright, R., Fay, L., Veneziano, D., Zhang, Y., Gong, J., Ye, Z. (2014) Evaluating Snow and Ice Control Chemicals for Environmentally Sustainable Highway Maintenance Operations. Journal of Trans. Eng. (140).

Shi, X., Quilty, S.M., Long, T., Jayakaran, A., Fay, L., Xu, G. (2017) Managing airport stormwater containing deicers: challenges and opportunities. Frontiers of Structural and Civil Engineering, 11(1) pp. 35-46. DOI 10.1007/s11709-016-0366-6

Slick, D.S. (1988) Effects of Calcium Magnesium Acetate on Pavements and Motor Vehicles. Transportation Research Record, 1157: 27-30. https://onlinepubs.trb.org/Onlinepubs/trr/1988/1157/1157-004.pdf

Smith, K.P. (2017) Loads and yields of deicing compounds and total phosphorus in the Cambridge drinking-water source area, Massachusetts water years 2009-15. USGS. No. 2017-5047.

Song, J., Li, Y., Xu, W., Liu, H., Lu, Y. (2019) Inexpensive and non-fluorinated superhydrophobic concrete coating for anti-icing and anti-corrosion. Journal of Colloid and Interface Science, 541, pp. 86-92. https://doi.org/10.1016/j.jcis.2019.01.014

Sprinkel, M.M., Roosevelt, D.S., Flintsch, G.W., Izeppi, E. de L., Mokarem, D.W. (2009) Evaluation of the Cargill Safelane™ Surface Overlay. Virginia Transportation Research Council, Charlottesville, VA. https://vtechworks.lib.vt.edu/handle/10919/46665

Staples, J.M., Gamradt, L., Stein, O., Shi, X. (2004) Recommendations for winter traction materials management on roadways adjacent to bodies of water. Montana Department of Transportation. FHWA/MT-04-008/8117.

Taylor, P., Verkade, J., Gopalakrishnan, K., Wadhwa, K., Kim, S. (2010) Development of an improved agricultural-based deicing product. Iowa Highway Research Board. https://onlinepubs.trb.org/Onlinepubs/trr/1988/1157/1157-004.pdf

Taylor, P., Verkade, J.G., Gopalakrishnan, K., Wadhwa, K., Kim, S. (2014). Experimental Studies on Development of Sustainable Agricultural-Based Road Transport Deicing Applications. *International Journal for Traffic and Transport Engineering, 4(2).* 10.7708/ijtte.2014.4(2).01

Tazawa, E.I., Mizo-U-E, Y., Kojima, T. (1992) Interfacial debonding of ice–asphalt concrete. Journal of Japan Society of Civil Engineers, 453/VI-17, pp. 125-13 https://doi.org/10.2208/jscej.1992.453_125

Terry, L.G., Conaway, K., Rebar, J., Graettinger, A.J. (2020) Alternative deicers for winter road maintenance – a review. Water Air and Soil Pollution, 231:394 https://doi.org/10.1007/s11270-020-04773-x

Tiwari, A. (2020) A Study of Icephobic Coatings, Part 1. Paint & Coatings Industry. Jan. 15, 2020

TRS 1411. (2014) Chloride free snow and ice control material. Minnesota DOT and the Local Road Research Board. https://www.dot.state.mn.us/research/TRS/2014/TRS1411.pdf

TRS 1706. (2017). Field usage of alternative deicers for snow and ice control. Minnesota DOT and the Local Road Research Board. https://lrrb.org/media/reports/TRS1706.pdf

Tuan, C.Y. and Albers, T. (2014) Development of Shaker Test as a standardized test protocol for deicing chemicals evaluation. Mid-America Transportation Center, US DOT. MATC-UNL: 058

Tuser, C. (2022) What is Total Phosphorus? Wastewater Digest. March 21, 2022. https://www.wwdmag.com/editorial-topical/what-is-articles/article/10940686/kruger-veolia-water-technologies-what-is-total-phosphorus

University of Georgia. (2022) Understanding laboratory wastewater tests: 1. Organics (BOD, COD, TOC, O&G). https://extension.uga.edu/publications/detail.html?number=C992. Accessed March 16, 2023.

US EPA, National Recommended Water Quality Criteria. https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table. September 15, 2022. Accessed May 16, 2023.

US EPA. (1999) Review of phosphorus control measures in the United States and Their Effects on water quality. Denver, CO.

USGS, Water Science School. Biological Oxygen Demand (BOD) and Water. https://www.usgs.gov/special-topics/water-science-school/science/biological-oxygen-demand-bod-and-water. June 5, 2018. Accessed March 14, 2023.

USGS, Water Science School. Nitrogen and Water. https://www.usgs.gov/special-topics/water-science-school/science/nitrogen-and-water. May 21, 2018a. Accessed May 15, 2023.

USGS, Water Science School. Phosphorus and Water. https://www.usgs.gov/special-topics/water-science-school/science/phosphorus-and-water. June 5, 2018b. Accessed May 15, 2023.

USGS. (2000) The effect of calcium magnesium acetate (CMA) deicing material on the water quality of Bear Cree, Calckamas County, Oregon, 1999. US Geologic Survey, Portland, OR.

Wang, B., Yu, P., Yang, Q., Jing, Z., Wang, W., Li, P., Tong, X., Lin, F., Wang, D., Lio, G.E., Caputo, R., Ávalos-Ovando, O., Govorov, A.O., Xu, H., Wang, Z.M. (2022) Upcycling of biomass waste into photothermal superhydrophobic coating for efficient anti-icing and deicing. Materials Today Physics, 24. https://doi.org/10.1016/j.mtphys.2022.100683

Wei, H., Han, S., Han, L., & Li, Q. (2020). Mechanical and electrothermal properties of conductive ethylene–propylene–diene monomer rubber composite for active deicing and snow melting. *Journal of Materials in Civil Engineering*, *32*(8), 04020197.

WHO. Guideline for Discharge of Industrial Effluent Characteristics; World Health Organization (WHO): Geneva, Switzerland 3: 231−236

Woodward & Curran, Inc. (2006) Industrial Waste Treatment Handbook. Butterworth-Heinemann, Elsevier

Wright, M., Parry, T., Airey, G. (2016) Chemical pavement modifications to reduce ice adhesion. Proceedings of the Institute of Civil Engineers, Transport 169(TR2), pp. 76-87. http://dx.doi.org/10.1680/jtran.14.00053

Wu, J., Liu, J., & Yang, F. (2015). Three-phase composite conductive concrete for pavement deicing. *Construction and Building Materials*, *75*, 129-135.

Xie, N., Dang, Y., & Shi, X. (2019). "New insights into how $MgCl_2$ deteriorates Portland cement concrete." *Cement and Concrete Research*, 120: 244–255. https://doi.org/10.1016/j.cemconres.2019.03.026.

Xie, N., Shi, X., & Zhang, Y. (2017). "Impacts of Potassium Acetate and Sodium-Chloride Deicers on Concrete." *Journal of Materials in Civil Engineering*, 29 (3): 04016229. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001754.

Xu, G., & Shi, X. (2018). Impact of chemical deicers on roadway infrastructure: risks and best management practices. *Sustainable winter road operations*, 211-240.

Yan, Z., Liu, W., Chen, J., & Jin, D. (2021). Pavement conductive wearing surface with graphite heating film de-icing potential and performance experimental study. *International Journal of Pavement Research and Technology*, *14*(6), 688-696.

Yang, T., Yang, Z. J., Singla, M., Song, G., & Li, Q. (2012). Experimental study on carbon fiber tape–based deicing technology. *Journal of Cold Regions Engineering*, *26*(2), 55-70.

Yang, J., Zhu, X., Li, L., Ling, H., Zhou, P., Cheng, Z., ... & Du, Y. (2018). Prefabricated flexible conductive composite overlay for active deicing and snow melting. *Journal of Materials in Civil Engineering*, *30*(11), 04018283.

Yang, Z., Zhang, Y., & Shi, X. (2018). Impact of nanoclay and carbon microfiber in combating the deterioration of asphalt concrete by non-chloride deicers. *Construction and Building Materials*, *160*, 514-525.

Ye, Z., Shi, X., Veneziano, D., Fay, L. (2013) Evaluating the effectiveness of winter chemicals on reducing crashes in Idaho. Idaho Transportation Dept., RP 201

Zhang, Y., Liu, Z., & Shi, X. (2021). Development and use of salt-storage additives in asphalt pavement for anti-icing: Literature review. *Journal of Transportation Engineering, Part B: Pavements*, *147*(4), 03121002.

Zhang, Y., & Shi, X. (2021). Laboratory evaluation of a sustainable additive for anti-icing asphalt. *Cold regions science and technology*, *189*, 103338.

Zhang, Y., Deng, Y., & Shi, X. (2022). Model development and prediction of anti-icing longevity of asphalt pavement with salt-storage additive. *Journal of Infrastructure Preservation and Resilience*, *3*(1), 1.

APPENDIX A - Annotated Bibliography

Research on Non-Chloride Deicers

The following reports and journal papers were identified and provide information on non-chloride deicers. Key findings are summarized.

Title: Effects of Calcium Magnesium Acetate Deicer on Small Ponds in Interior Alaska
Authorship: LaPerriere and Rea, 1989
Products Investigated: calcium magnesium acetate (CMA)
Article/Report Summary: In this work, the results of a field investigation of the impacts of CMA on aquatic organisms in three ponds in interior Alaska are reported. The test ponds were dosed with CMA at concentrations expected after runoff from a typical roadway application. It was found that calcium did not persist and may have runoff with snowmelt. Acetate was rapidly used by organisms and cycled for several months reducing dissolved oxygen in the water. Bacteria and algae were stimulated by the CMA. The work suggests that salmonids may be stressed by the use of CMA because of the elevated BOD.
Citation: LaPerriere, J.D., Rea, C.L. (1989) Effects of Calcium Magnesium Acetate Deicer on Small Ponds in Interior Alaska. Lake Reserv Manag. Oct;5(2):49–57. https://doi.org/10.1080/07438148909354398

Title: The effect of calcium magnesium acetate (CMA) deicing material on the water quality of Bear Cree, Calckamas County, Oregon, 1999
Authorship: USGS, 2000
Products Investigated: calcium magnesium acetate (CMA)
Article/Report Summary: This report presents the results of a study by the U.S. Geological Survey and Oregon Department of Transportation (ODOT), which evaluated the effects of calcium magnesium acetate (CMA) deicer on the water quality of Bear Creek in the Cascade Range of Oregon. ODOT began using CMA (defined as an alternative deicer that has fewer adverse environmental effects than road salt) in the mid-1990s. This study was conducted to ensure that there were no unexpected effects on the water quality of Bear Creek. Streamflow, precipitation, dissolved oxygen, pH, specific conductance, and water temperature were measured continuously through the 1998–99 winter. No measurable effect of the application of CMA to Highway 26 on the biochemical oxygen demand (BOD), calcium concentration, or magnesium concentration of Bear Creek and its tributaries. BOD was small in all of the water samples, some of which were collected before CMA application, and some of which were collected after application. Five-day BOD values ranged from 0.1 milligrams per liter to 1.5 milligrams per liter, and 20-day BOD values ranged from 0.2 milligrams per liter to 2.0 milligrams per liter. Dissolved copper concentrations in a small tributary ditch on the north side of Highway 26 exceeded the U.S. EPA aquatic life criteria on three occasions, but these were probably not caused by the application of CMA.
Citation: USGS. (2000) The effect of calcium magnesium acetate (CMA) deicing material on the water quality of Bear Cree, Calckamas County, Oregon, 1999. US Geologic Survey, Portland, OR.

Title: Environmental impacts of chemical deicers – a review
Authorship: Ramakrishna and Viraraghavan, 2005
Products Investigated: sodium chloride, anti-caking agents, calcium magnesium acetate (CMA), urea, and glycols
Article/Report Summary: This overview paper summarizes work by others and provide details on the environmental impacts of roadway and airport deicers including sodium chloride or rock salt, anti-caking agents, CMA, urea, and glycols on surface waters, groundwater, and soil.
Citation: Ramakrishna, D.M, Viraraghavan, T. (2005) Environmental impacts of chemical deicers – a review. Water, Air, and Soil Pollution, 166(1-4), pp. 49-63 https://doi.org/10.1007/s11270-005-8265-9
Title: Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts
Authorship: NCHRP 5777, 2007
Products Investigated: chlorides, organics, abrasives
Article/Report Summary: This report presents guidelines for the selection of snow and ice control materials through an evaluation of their cost, performance, and impacts on the environment and infrastructure. Detailed information is summarized on performance and impacts of each deicer type.
Citation: NCHRP 5777. Levelton Consultants. (2007) Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts. Transportation Research Board, Washington, D.C. https://www.trb.org/Publications/Blurbs/158876.aspx

Title: Freezing point and small-scale deicing testing for slats of levulinic acid made from grain sorghum
Authorship: Ganjyal et al. 2007
Products Investigated: levulinic acid
Article/Report Summary: This laboratory study looked at levulinic acid produced using grain sorghum as a raw material for deicing. Freezing points of sodium levulinate, magnesium levulinate and calcium levulinate were determined ASTM D 1177-94 at 10, 20, 30 and 40 % w/w concentrations. Significant differences in the freezing points of the salts was found. Freezing points for rock salt, sodium levulinate, calcium levulinate and magnesium levulinate were in the ranges of −6.6 to −20.5 (21 to -5°F), −2.9 to −15.0 (27 to 5°F), −2.1 to −7.8 (28 to 18°F)and −1.5 to −6.5 °C (29 to 20°F), respectively. Effectiveness of the levulinic acid salt solutions as deicers at various concentrations (2%, 5% and 10%) was tested at −2.7 °C (27°F). Deicing capabilities of the three levulinic acid salts differed. Ice melting occurred for all three salts at −2.7 °C. Among the different levulinates studied sodium levulinate was the most effective deicing agent. These salts of levulinates could be a viable replacement for traditional deicers and could help in reducing the disadvantages of traditional deicers.
Citation: Ganjyal, G., Fang, Q., Hanna, M.A. (2007). Freezing point and small-scale deicing testing for slats of levulinic acid made from grain sorghum. *Bioresource Technology, 98, 2814-2818.* doi:10.1016/j.biortech.2006.07.042

Title: Aquatic toxicity of airfield-pavement deicer materials and implications for airport runoff
Authorship: Corsi et al. 2009
Products Investigated: potassium acetate, sodium formate

Article/Report Summary: This laboratory study quantified the toxicity of potassium acetate (K-Ac) and sodium formate (Na-For) on four aquatic species. They found toxicity is driven by the deicing material with the exception of Vibrio fisheri toxicity caused by additives. Acute toxicity end points for each species are provided. Water samples from GMIA airport in Milwaukee, WI found that 40% of samples had K-Ac concentration higher than the aquatic-life benchmark. Where urea was used, 41% of samples has ammonia concentration exceeding EPAs 1 hour water quality criterion. For chlorides this was exceeded 68% of the time when collected from a stream near the airport receiving urban runoff from road operations.
Citation: Corsi, S.R., Geis, S.W., Bowman, G., Failey, G.G., Rutter, T.D. (2009) Aquatic toxicity of airfield-pavement deicer materials and implications for airport runoff. Environ Sci Technol, 43(1): 40-46.
DOI: 10.1021/es8017732

Title: Evaluation of alternative anti-icing and deicing compounds using sodium chloride and magnesium chloride as baseline deicers
Authorship: Shi et al. 2009
Products Investigated: salts (sodium chloride, magnesium chloride), potassium acetate, sodium acetate, sodium acetate/sodium formate blends, potassium formate
Article/Report Summary: This report summarizes the evaluation of potassium acetate, sodium acetate, sodium acetate/sodium formate blends, potassium formate as alternative deicing options to traditional sodium chloride, magnesium chloride, and sand. The literature review found that deicers impart detrimental impacts to concrete and asphalt pavements and infrastructure, cause corrosion, and impact the environment. Laboratory testing measure ice melting, ice penetration, ice undercutting, differential scanning calorimetry (melting and cooling curves), and tribometer (friction) testing. Lab and field evaluation of impacts to metals and concrete was conducted. Chloride concentrations from three locations in Colorado were monitored over the course of the project. Results of all the lab and field testing can be found in the report.
Citation: Shi, X., Fay, L., Gallaway, C., Volkening, K., Peterson, M.M., Pan, T., Creighton, A., Lawlor, C., Mumma, S., Liu, Y., Nguyen, T.A. (2009) Evaluation of alternative anti-icing and deicing compounds using sodium chloride and magnesium chloride as baseline deicers. Colorado DOT, Denver, CO.

Title: Establishing Best Practices for Removing Snow and Ice from California Roadways
Authorship: Cuelho et al. 2010
Products Investigated: 23% NaCl brine, Calcium Chloride with Boost, FreezGard CI Plus, potassium acetate by Cryotech Deicing Technology, and ag-based Ice Clear RDF (derived from the processing of starches and sugars)
Article/Report Summary: This report looks at five typical anti-icing chemicals to examine the temperature at which snow-pavement bond fails, friction of the surface after snow removal, and snow-pavement bond strength. In the field tests, Agri often reduced bond strengths when compared to untreated sections. When anti-icers are applied, NaCl, KAce and $MgCl_2$ dried quickly, whereas $CaCl_2$ and Agri never dried. In the lab tests, Agri generally had a lower shearing temperature than NaCl on asphalt

and concrete samples, and this was more noticeable when a larger application rate (10 gal/lm) was applied, however, there was no statistical difference identified. Agri and KAce coefficients of friction were not statistically different from chloride-based deicers. Lastly, Agri had slightly lower bond strength between the snow and pavement when compared to NaCl, and especially no treatment.
Citation: Cuehlo, E., Harwood, J., Akin, M., Adams, E. (2010). Establishing Best Practices for Removing Snow and Ice from California Roadways. California Department of Transportation. Pdf download

Title: Environmental Impacts of Chemicals for Snow and Ice Control: State of the Knowledge
Authorship: Fay and Shi, 2012
Products Investigated: Deicers - abrasives, chlorides, acetates, formates, urea, glycols, and ag-based
Article/Report Summary: This literature review summarizes available information on chemicals used for snow and ice control of highway and airfield pavements or aircrafts and highlights recent finding on the detrimental impacts to the surrounding environment. Information is presented on environmental impacts deicers on surface, ground, and drinking waters; soil; flora; and fauna. Survey results of report on the impacts of abrasives, chlorides, acetates and formates, urea, glycols, and ag-based deicers. This paper provides a discussion of public perception of impacts and the role of best management practices (BMPs) to mitigate them.
Citation: Fay, L., Shi, X. (2012) Environmental Impacts of Chemicals for Snow and Ice Control: State of the Knowledge. Water Air Soil Pollution. Jun 1;223(5):2751–70.

Title: Oxygen demand of aircraft and airfield pavement deicers and alternative freezing point depressants
Authorship: Corsi et al. 2012
Article/Report Summary: In this study aircraft and airfield pavement deicing formulations and other potential freezing point depressants were tested for biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Propylene glycol-based aircraft deicers exhibited greater BOD5 than ethylene glycol-based aircraft deicers, and ethylene glycol-based products had lower degradation rates than propylene glycol-based products. Sodium formate pavement deicers had lower COD than acetate-based pavement deicers. The BOD and COD results for acetate-based pavement deicers (PDMs) were consistently lower than those for aircraft deicers, but degradation rates were greater in the acetate-based PDM than in aircraft deicers. In a 40-day testing of aircraft and pavement deicers, BOD results at 20°C (68°F)(standard) were consistently greater than the results from 5°C (41°F) (low) tests. The degree of difference between standard and low temperature BOD results varied among tested products. Freshwater BOD test results were not substantially different from marine water tests at 20°C, but glycols degraded slower in marine water than in fresh water for low temperature tests. Acetate-based products had greater percentage degradation than glycols at both temperatures. An additive component of the sodium formate pavement deicer exhibited toxicity to the microorganisms, so BOD testing did not work properly for this formulation. BOD testing of alternative freezing point depressants worked well for some, there was little response for some, and for others there was a lag in response while microorganisms acclimated to the freezing point depressant as a food source. Where the traditional

BOD5 test performed adequately, values ranged from 251 to 1,580 g/kg. Where the modified test performed adequately, values of BOD28 ranged from 242 to 1,540 g/kg.
Citation: Corsi, S.R., Mericas, D., Bowman, G.T. (2012) Oxygen demand of aircraft and airfield pavement deicers and alternative freezing point depressants. Water, Air, & Soil Pollution, 223(5), pp. 2447-2461. https://doi.org/10.1007/s11270-011-1036-x

Title: Determining the aquatic toxicity of deicing materials
Authorship: Pilgrim, 2013
Article/Report Summary: This study tested the acute and chronic toxicity of several deicing chemicals (sodium chloride, magnesium chloride, calcium chloride, potassium acetate and glycerol) using standard toxicity testing species. Two inhibitor products were identified and tested for sodium chloride, magnesium chloride, and calcium chloride while only one product was available for potassium acetate and one for glycerol. A ranking of the relative toxicity of the deicing materials was developed:

$$KAc > MgCl_2 > CaCl_2 > NaCl.$$

With KAc defined as most toxic and NaCl defined as least toxic. Acute and chronic toxicity endpoints are provided as part of the study report.
Citation: Pilgrim, K.M. (2013) Determining the aquatic toxicity of deicing materials. Clear Roads and Minnesota DOT. https://clearroads.org/project/11-02/

Title: Experimental Studies on Development of Sustainable Agricultural-Based Road Transport Deicing Applications
Authorship: Taylor et al. 2014
Products Investigated: Chloride-based, GEOMELT (sugar beet source), Ice B Gone (molasses, high-fructose corn syrup, carbohydrate based), BioOil (fast pyrolysis of forest and agricultural residues), E310 (corn-based ethanol, alkaline washed corn hull), and glycerol (by-product of fats, lipids, and biodiesel)
Article/Report Summary: This article focuses on by-products from agricultural processes that may be suitable for use in deicing applications. They mixed different concentrations of the selected products and determined freezing point, ice melting ability, skid resistance, and viscosity. Based on the variety of parameters tested, the combination of that shows the greatest promise is a combination of 80% glycerol with 20% NaCl. This solution, when diluted with water to a viscosity suitable for distribution equipment, shows promise as a deicing chemical based on agricultural by-products. The reduction in NaCl will reduce corrosive effects, and glycerol will not increase them. Also glycerol will have minimal effects on the environment.
Citation: Taylor, P., Verkade, J.G., Gopalakrishnan, K., Wadhwa, K., Kim, S. (2014). Experimental Studies on Development of Sustainable Agricultural-Based Road Transport Deicing Applications. *International Journal for Traffic and Transport Engineering, 4(2).* 10.7708/ijtte.2014.4(2).01

Title: Correlating Lab and Field Tests for Evaluation of Deicing and Anti-icing Chemicals: A Review of Potential Approaches
Authorship: Muthumani et al. 2014

Products Investigated: Report results from other on – Na, Mg, Ca-chlorides, ethylene glycol, urea, calcium magnesium acetate, potassium acetate, Ice Ban ultra, Caliber M-1000, sodium- calcium-magnesium-levulinate, sodium acetate, sodium formate, CF7, sodium acetate/sodium formate blend
Article/Report Summary: This study utilized a systematic laboratory investigation to better understand the chemical and/or physical processes by measuring the degree to which products 1) Lower the freezing point of water and improve the ice melting capacity, 2) Weaken the ice bond to pavement, 3) Improve product longevity on the road surface, 4) Prevent ice formation, 5) Influence absorbance of sunlight on performance, and 6) Corrosion to carbon steel. The study included a literature review, survey, and laboratory investigation. The laboratory investigation looked at two complex chloride/mineral based products (rock salts) and eight ag-based deicers - four of which were prepared by mixing with a 23.3 wt. % salt brine, at either 70:30 or 80:20 volume ratio, depending on the vendor specification, and the other four ag-based products were used, as received from the manufacturer for laboratory testing. Laboratory results found that CCM based deicers did not significantly reduce the freezing of water or melt more ice, except at 15°F. Whereas ag-products blended with salt brine significantly lowered the freezing point of water but did not more melt ice; and ag-based products from the vendor both lowered the freezing point of water and produced more ice melt. When looking at the effect of deicer type on ice bonding strength to the pavement, CCM products slightly reduced the bond strength, whereas ag-based products significantly reduced the bond strength. Ag-based products were found to have a larger percent remain on the pavement after traffic and plowing and were found to provide higher friction values on the pavement surface. When considering the role of UV absorption on deicer performance, the darker colored ag-based products had higher ice melting capacities. To support the application of this information in winter maintenance operations a best practices manual was also developed.
Citation: Muthumani, A., Fay, L., Akin, M., Wang, S., Gong, J., Shi, X. (214). Correlating Lab and Field Tests for Evaluation of Deicing and Anti-icing Chemicals: A Review of Potential Approaches. *Cold Regions Science and Technology, 97(1): 21-32*. https://doi.org/10.1016/j.coldregions.2013.10.001

Title: Chloride Free Snow and Ice Control Material
Authorship: Fortin Consulting, 2014
Products Investigated: chlorides, acetates, formates, urea, glycerol/glycol, succinate, ag-based additives, and abrasives
Article/Report Summary: This synthesis document summarizes the general categories of non-chloride deicers, the form they come in, performance by temperature, documents environmental impacts, cost, if the deicer is biodegradable and the exerted BOD/COD, pollutant removal feasibility from water, and corrosiveness. Information is provided on porous and permeable pavements, pavement type and various surface treatments. This work makes recommendations for future study on these topics.
Citation: TRS 1411. (2014) Chloride free snow and ice control material. Minnesota DOT and the Local Road Research Board. https://www.dot.state.mn.us/research/TRS/2014/TRS1411.pdf

Title: Manual of Environmental Best Practices for Snow and Ice Control

Authorship: Fay et al. 2015
Products Investigated: abrasives, chlorides, acetates, formates, glycols and glycerin, and ag-based additives
Article/Report Summary: A manual on environmental best management practices used for snow and ice control was developed using information gained from a literature review, survey, and follow-up interviews. The document presents information on commonly used snow and ice control products and their potential impacts, and pathways into the environment. Information is presented on material handling and storage, application techniques and equipment, advanced technology for decision making, environmental management tools, pre-storm to mid-storm practices, post storm clean-up, and training. The manual summarizes common areas for improvement in snow and ice control practices to realize material and cost saving, while reducing impacts to the environment. Information on each deicer type, application rates, application strategies, cost, performance, storage and handling, common issues and environmental impacts is summarized in tables.
Citation: Fay, L., Honarvar Nazari, M., Jungwirth, S., Muthumani, A., Cui, N., Shi, X., et al. (2015) Manual of Environmental Best Practices for Snow and Ice Control. Clear Roads and MnDOT.
https://clearroads.org/wp-content/uploads/dlm_uploads/Manual_ClearRoads_13-01_FINAL.pdf

Title: Laboratory Evaluation of CMA Impact on the Slipping Resistance of Road Surface
Authorship: Sahaf and Moradzadeh, 2015
Products Investigated: calcium magnesium acetate (CMA)
Article/Report Summary: This study examined the use of calcium magnesium acetate (CMA) as a substitute for salt in winter maintenance activities. Lab tests were completed using different samples of pavement. CMA was found to increase slip resistance on all types of pavements when compared to salt, the authors suggest the use of CMA to reduce crashes during the winter season. Initial lab tests show that CMA is harmless to plants and animals. Lab tests completed in this study found that CMA stuck to pavement samples better than salt.
Citation: Sahaf, S.A. and Moradzadeh, B. (2015). Laboratory evaluation of CMA impact on the slipping resistance of the road surface. *Bulletin of Environment, Pharmacology and Life Sciences*, *4*(5), 9-18.
https://profdoc.um.ac.ir/articles/a/1059713.pdf

Title: Field Usage of Alternative Deicers for Snow and Ice Control
Authorship: The Western Transportation Institute, 2017
Products Investigated: Deicers – chlorides, acetates, formates, glycols, succinates
Article/Report Summary: This synthesis document summarizes the use of acetates, formates, urea, and glycol use in winter maintenance operations, and identifies less commonly used options for future testing (succinates). Information is report on performance (functional temperature), cost, and impacts (BOD, corrosion, toxicity and other environmental impacts), and manufacturers of each product type.
Citation: TRS 1706. (2017). Field usage of alternative deicers for snow and ice control. Minnesota DOT and the Local Road Research Board. https://lrrb.org/media/reports/TRS1706.pdf

Title: Managing airport stormwater containing deicers: challenges and opportunities

Authorship: Shi et al. 2017

Products Investigated:
Article/Report Summary: This overview paper summarizes work by others on airport storm water impacts caused by deicer use, specifically the regulatory development of airport deicing stormwater management along with the milestone Airport Cooperative Research Program (ACRP) Report 14 publication. Stormwater runoff at airports is a significant and costly issue, especially for stormwater laden with deicing contaminants of high Biochemical Oxygen Demand (BOD) and aquatic toxicity. To reduce the loading of deicing constituents in stormwater and to manage the increasing pressure of tightening regulations, identifying fate and transport and evaluating environmental risks are of critical importance. Deicer usage and fugitive losses can be reduced, and the amount of deicer collected can be increased by having a better understanding of the fate and transport of deicing constituents in stormwater. To address this, an overview and evaluation of the constituents of concern in deicers is provided to support the assessment of environmental impacts and mitigation recommendations. The state of knowledge of airport deicing stormwater management is reviewed in the context of providing national guidance. Recommendations include the development of a guidebook and a decision tool for airports to aid in the adoption of specific practical stormwater management strategies while balancing their priorities in environmental, economic, and social values against operational constraints.
Citation: Shi, X., Quilty, S.M., Long, T., Jayakaran, A., Fay, L., Xu, G. (2017) Managing airport stormwater containing deicers: challenges and opportunities. Frontiers of Structural and Civil Engineering, 11(1) pp. 35-46. DOI 10.1007/s11709-016-0366-6

Title: Investigation of alternative deicers for snow and ice control
Authorship: Fay and Akin, 2018
Products Investigated: potassium succinate (KSu)
Article/Report Summary: Building off of TRS 1706 (WTI, 2017) This effort report on the laboratory analysis of potassium succinate (KSu) as a roadway deicer. Laboratory tests used included the modified SHRP ice-melting testing, a differential scanning calorimetry (DSC) thermogram, and friction measurements to quantify performance. Overall results indicate that the performance of KSu is similar to that of NaCl at improving friction on roadways during snow and ice conditions. Thermal analysis of KSu shows it can be applied as a roadway deicer at -5°C (23°F) and above but does not function as a deicer at colder temperatures where salt brine will work. KSu has a slightly lower ice-melting rates than salt brine. Work by others shows KSu has reduced corrosion to metals, equipment, and pavements, and similar BOD to potassium acetates. KSu appears to be a viable option as a roadway deicer at temperatures at or above -5°C (23°F). Use of KSu as a roadway deicer may be focused in areas where there are concerns about impacts to infrastructure, equipment, or pavements, such as on bridges, elevated roadways, in parking garages, or on newer concrete pavements. Potential concerns with the use of KSu as a roadway deicer are its price, lack of full-scale manufacturing of KSu at this time, and the

BOD exerted by the product. Additional testing to fully quantify the environmental impacts of KSu on soil, water, flora, and fauna is recommended. If water quality and BOD are of concern, application of this product is not recommended in large quantities and during times of low water flow.
Citation: Fay, L. and Akin, M. (2018) Investigation of alternative deicers for snow and ice control. Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC) University Transportation Center (UTC) and University of Alaska, Fairbanks. https://cesticc.uaf.edu/research/fay-alternativedeicers.aspx

Title: Anti-ice reagent on the basis of dolomite, nitrogen acid and carbamide
Authorship: Akhmedov et al. 2018
Products Investigated: unbaked dolomite consisting of calcium, magnesium nitrates and carbamide
Article/Report Summary: This study examined the use of unbaked dolomite from Uzbekistan as an anti-icing reagent. Laboratory tests were conducted to determine optimal conditions to obtain anti-icing reagent, a solution of calcium and magnesium nitrates was obtained through decomposition of unbaked dolomite in a solution of nitric acid. This derivative is mixed with carbamide – with an ideal ratio of carbamide to the mixture of calcium nitrate and magnesium of 2.01:1. The resulting anti-icing reagent can be used to temperatures up to -25.6°F (-32°c) and is not corrosively aggressive.
Reagent has been tested on roads on the Kamchik Pass (Uzbekistan) and was recommended for production.
Citation: Akhmedov, M.E., Dadakhodzhaev, A.T., Guro, V.P. (2018). Anti-ice reagent on the basis of dolomite, nitrogen acid and carbamide. *International Journal of Engineering Technologies and Management Research*, *5*(10). https://doi.org/10.29121/ijetmr.v5.i10.2018.301

Title: The Effect of Additives on the Low Temperature Ice-Melting capacity of NaCl
Authorship: Nilssen et al. 2018
Products Investigated: Magnesium chloride, calcium chloride, potassium formate, calcium magnesium acetate, and sucrose sugar were added to NaCl at -18°C
Article/Report Summary: The results showed that solid chemicals had a far higher melting capacity than solutions. In a solid state NaCl had the highest ice-melting capacity, however, the results differed for solutions, where brine had the lowest. $CaCl_2$ had the highest ice-melting capacity of the solutions, melting 285% more than NaCl at −18.6°C. This was followed by $MgCl_2$, potassium formate, mix NaCl/$CaCl_2$, mix NaCl/CMA, CMA, and mix NaCl/$MgCl_2$. The improvements using chlorides ($MgCl_2$ and $CaCl_2$) depended on the amount of additive. Potassium formate had a destructive influence on melting capacity when mixed with NaCl, whereas mixing CMA with NaCl produced a higher melting capacity than the two components individually. Sugar froze at −18°C.
Citation: Nilssen, K., Klein-Paste, A., Wåhlin, J. (2018). The Effect of Additives on the Low Temperature Ice-Melting capacity of NaCl. *Transportation Research Record: Journal of the Transportation Research Board, 2672(12).* https://doi.org/10.1177/0361198118767412

Title: Developing renewable agro-based anti-icers for sustainable winter road maintenance operations

Authorship: Nazari and Shi, 2019

Products Investigated: Concord grape extract and glycerin, sodium chloride, sodium metasilicate, and sodium formate, chlorides, beet juice

Article/Report Summary: This work evaluated the performance and impacts of several agro-based anti-icers along with two traditional chloride-based anti-icers (23% by weight NaCl brine and its beet juice blend). A statistical design of experiments was employed to develop cost-competitive renewable agro-based anti-icing liquids consisting of Concord grape extract and glycerin; sodium chloride; sodium metasilicate; and sodium formate. Testing included ice-melting capacity at −3.9°C (25°F), splitting tensile strength of portland cement mortar samples after 10 freeze-thaw/deicer cycles, corrosion rate of C1010 carbon steel after 24-h immersion, and impact on low temperature performance of asphalt binder. The best performer was also tested for thermal properties by measuring its differential scanning calorimetry (DSC) thermograms and other properties (friction coefficient on anti-iced asphalt pavement, pH, oxygen demands). COD results for the best performer were 135 mg/L and BOD5 results for the best performer were 0.77 mg/L.

Citation: Nazari, M.H., Shi, X. (2019) Developing renewable agro-based anti-icers for sustainable winter road maintenance operations. Journal of Materials in Civil Engineering, 31(12). DOI: 10.1061/(ASCE)MT.1943-5533.0002963

Title: Effects of processed agro-residues on the performance of sodium chloride brine anti-icer

Authorship: Nazari et al. 2019

Products Investigated: dandelion leaf, sugar beet leaf

Article/Report Summary: A chemico-biological process was used to prepare liquid extracts from two agro-based feedstocks - dandelion leaf and sugar beet leaf. Laboratory analysis of these agro-based liquids assessed the ice-melting capacity at −3.9°C (25°F); mass loss and compressive strength of Portland cement mortar (PCM) samples after 10 rapid freeze−thaw cycles; corrosivity of C1010 carbon steel after 24-h immersion; and the impact on asphalt binder. For the best performer a freezing point depression phase diagram was developed, and the friction coefficient of asphalt pavement treated by anti-icing formulation was tested. The agro-based extracts improved the properties of the “green” anti-icer mixtures and the friction coefficient of treated pavement. The anti-icing formulation produced low COD (215 mg/L) and BOD (78 mg/L) values. The developed anti-icer contains less additive chemicals than traditional agro-based anti-icers, which likely helps to reduce their impacts on the environment.

Citation: Nazari, M.H., Havens, E.A., Muthumani, A., Shi, X. (2019) Effects of processed agro-residues on the performance of sodium chloride brine anti-icer. ACS Sustainable Chem. Eng. 7, pp. 13655-13667. DOI: 10.1021/acssuschemeng.8b06043

Title: Alternative deicers for winter road maintenance – a review

Authorship: Terry et al. 2020

Products Investigated: This paper provides a comprehensive review of the effectiveness and impacts of organic deicers including ag-based products, acetates, formates, glycols, and succinates. The benefits and negative impacts on the road, environment, and infrastructure are reviewed, as well as the

performance of each deicer for snow and ice control on roadways are reported based on others work. The environmental concerns of organic deicers are discussed, including the largest environmental concern: the increase in biological oxygen demand (BOD) to receiving water bodies. The impact of deicers on metals and infrastructure is presented as it varies considerably for each alternative deicer. Finally, opportunities and challenges to implementing alternative deicers in the field is discussed.
Citation: Terry, L.G., Conaway, K., Rebar, J., Graettinger, A.J. (2020) Alternative deicers for winter road maintenance – a review. Water Air and Soil Pollution, 231:394 https://doi.org/10.1007/s11270-020-04773-x

Title: Toxicological Impacts of Roadway Deicers on Aquatic Resources and Human Health: A Review
Authorship: Nazari et al. 2021
Products Investigated: sodium chloride (NaCl), magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), potassium chloride (KCl), sodium acetate (NaAc), potassium acetate (KAc), calcium magnesium acetate (CMA), sodium formate (NaFm), potassium formate (KFm), ethylene glycol ($C_2H_6O_2$), propylene glycol, and urea
Article/Report Summary: This work summarized and provides organized tables of existing data, including the adverse effects of deicers on surface water and groundwater, aquatic species, and human health, and identified future research priorities. Information is reported on deicer influence on roadway safety and mobility, and cost information, life cycle sustainability assessment is Data provided can be used to develop a framework for quantifying some of the variables that stakeholders and agencies use when preparing guidelines and standards for WRM programs.
Citation: Nazari, M.H., Mousavi, S.Z., Potapova, A., McIntyre, J., Shi, X. (2021) Toxicological Impacts of Roadway Deicers on Aquatic Resources and Human Health: A Review. *Water Environment Research*, 2021, DOI: 10.1002/wer.1581.

Title: Evaluation of Liquid Deicing Materials for Winter Maintenance Applications
Authorship: Lammers, 2021
Products Investigated: BioMelt AG64 (bio-based additive), FreezGard CI Plus ($MgCl_2$ with corrosion inhibitor), Ice-B'Gone Magic (bio-based:$MgCl_2$, 50:50), Ice Ban 305 (bio based additive and $MgCl_2$), calcium chloride ($CaCl_2$)
Article/Report Summary: The work evaluated the performance of deicing products BioMelt AG64, FreezGard CI Plus, Ice-B'Gone Magic, Ice Ban 305, and calcium chloride. To accomplish this an ice undercutting testing method was used to assess how well a deicer breaks the bond between pavement and ice. FreezGard CI Plus showed the largest average undercut area over the course of the experiment and at the 30 minutes end time (318 mm^2). All other products performed similarly with 201 to 218 mm^2 of undercut area. The report also provides information on each products cost (note prices will varying depending on deliver location): calcium chloride \$0.95 per gallon, FreezGard CI Plus \$1.29 per gallon, Ice Ban 305 \$1.81 per gallon, BioMelt AG64 \$2.10 per gallon, and IceB'Gone Magic \$3.00 per gallon. They note that the cost of salt brine in Kentucky is \$0.12 per gallon and provide information on costs when products are used as additives and cost per lane mile. The report provides information on storage and

handling of these products, and generally discusses the effects of each product on infrastructure and biosystems. Appendices provide detailed survey results provide information from some state DOTs (MT, ND, OH, TN, VA, WA, WI, West Des Moines, IA and Ontario, CA) and product information sheets for the products tested.
Citation: Lammers, E. (2021) Evaluation of Liquid Deicing Materials for Winter Maintenance Applications. Kentucky Transportation Cabinet.
https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=2734&context=ktc_researchreports

Heated Pavements Research

The following reports and journal papers were identified and provide information on a non-chloride deicing option of heating pavements. Key findings are summarized.

Title: Experimental Study on Carbon Fiber Tape–Based Deicing Technology
Authorship: Yang et al. 2012
Products Investigated: Carbon-fiber tape heating panels in concrete
Article/Report Summary: A new type of roadway deicing system based on commercially available carbon fiber tape is investigated. This paper presents the design of the heating panels used for this experiment and compares the results of the analysis to other deicing systems. Results show that the CFT-based deicing system performed satisfactorily during all deicing and anti-icing experiments. The deicing energy costs are sensitive to the ambient air and wind chill, with lower ambient air temperature and wind chill resulting in higher energy costs. However, snow density is shown to have little effect on the energy cost. Cost comparison analysis shows that the CFT-based deicing system demonstrates a higher energy efficiency and a lower installation cost among the systems compared. Applications of carbon-fiber tape heating panels could be used for sidewalks and parking lots in urban areas, bridge decks and road sections susceptible to icing, and street crossings and culverts that need to be operational at freezing temperatures in Alaska and other cold regions.
Citation: Yang, T., Yang, Z. J., Singla, M., Song, G., & Li, Q. (2012). Experimental study on carbon fiber tape–based deicing technology. *Journal of Cold Regions Engineering*, *26*(2), 55-70.

Title: Three-phase composite conductive concrete for pavement deicing
Authorship: Wu et al. 2014
Products Investigated: Steel, carbon, and graphite fiber conductive concrete
Article/Report Summary: Development of conductive fiber concretes were created and analyzed for deicing effectiveness. Conductivity factors and compressive strength of samples were analyzed. The composite ratio, preparation techniques and electrode layout mode of the three-phase composite conductive concrete are introduced and studied. The conductivity of concrete depends on the dosage of fibers in the concrete but also the uniformity of the fiber throughout. A sand ratio of 0.44 minimized voids and gaps that affect conductivity. The temperature tests show that the conductive concrete provide low resistivity and high power which has potential for snow melting and deicing.

Citation: Wu, J., Liu, J., & Yang, F. (2015). Three-phase composite conductive concrete for pavement deicing. *Construction and Building Materials*, *75*, 129-135.

Title: Pavement Treatments for Sustainable Winter Road Maintenance (Chapter 18 from Sustainable Winter Road Operations)
Authorship: Shi, Huang, and Yang (Shi and Fu, 2014)
Products Investigated:
Article/Report Summary: This chapter of *Sustainable Winter Roads Operations* provides an overview of pavement treatment options to support winter maintenance operations including high friction anti-icing polymer overlays (read: SafeLane), asphalt with anti-icing additives, ice-phobic pavements, thermochromic asphalt pavements, and heated pavement technologies. The chapter summaries work by others on the following heated pavement technologies by heating method – geothermal heating, electrical resistive heating, and external heating (wind, solar, microwave and infrared). Information on each heated pavement technology is provided on design, cost, effectiveness, etc. as is available.
Citation: Eds. Shi, X., Fu, L. (2014) Sustainable Winter Road Operations. Wiley-Blackwell.

Title: Experimental study on anti-icing and deicing performance of polyurethane concrete as road surface layer
Authorship: Chen et al. 2018
Products Investigated: Polyurethane asphalt (the asphalt binder is replaced with a polyurethane)
Article/Report Summary: The deicing and anti-icing performance was investigated for a polyurethane concrete (PC) and was compared to traditional asphalt concretes (AC) in the laboratory. The PC has a similar thermal conductivity (1.3 W/mK) but larger specific heat (AC=1.75 and PC=2.2 W/mK). Compared to the asphalt concrete, the polyurethane concrete can significantly increase the ice formation time. The pull-off strength was about 50% of AC (AC=110kPa, PC=60kPa) and interface shear strength at the interface of ice and PC is about 55% of those at the interface of ice and AC (AC=580-800kPa, PC=100-450kPa). The work to rupture or break ice layer bond on PC is about 50% (AC=42Nm, PC=20Nm) of the work required on AC with the same ice layer thickness.
Citation: Chen, J., Ma, X., Wang, H., Xie, P., & Huang, W. (2018). Experimental study on anti-icing and deicing performance of polyurethane concrete as road surface layer. *Construction and Building Materials*, *161*, 598-605.

Title: Prefabricated Flexible Conductive Composite Overlay for Active Deicing and Snow Melting
Authorship: Yang et al. 2018
Products Investigated: Conductive composite overlay
Article/Report Summary: This research investigates self-deicing technology. The prefabricated flexible conductive composite overlay is made of three layers: carbon-fiber heating wires that are distributed in a polyurethane rubber sheet, gravel bonded to the top surface with epoxy as a wear surface, and aluminum foil film on the bottom for adhesive and heat-insulating layer. Experiments were run to test the mechanical properties of the overlay and snow melting capabilities of the composite overlay. The

results show that at 16°C (60.8°F), the composite overlay melted 54.9% (620 g) more ice than the control group with no heating element. Similar to the ice melting, where the composite overlay melted 54% (900g) more frost compared to the control test (410g). The average heating rate of the composite overlay (0.137-0.381°C/min) is twice as much as the control group (0.063-0.175°C/min). The ultra-thin composite overlay has high electrothermal conversion efficiency and excellent flexibility. It also meets the mechanical requirements for friction and wear. The composite overlay is a viable option for accelerated construction methods for active snow melting.
Citation: Yang, J., Zhu, X., Li, L., Ling, H., Zhou, P., Cheng, Z., ... & Du, Y. (2018). Prefabricated flexible conductive composite overlay for active deicing and snow melting. *Journal of Materials in Civil Engineering*, *30*(11), 04018283.

Title: Analyzing the performance and control of a hydronic pavement system in a district heating network
Authorship: Blomqvist et al. 2019
Products Investigated: heated pavement, existing heating and cooling system
Article/Report Summary: This work analyzed the performance of a hydronic pavement system (HPS) heated using heat from a district heating and cooling (DHC) system. The study looked at energy performance of the HPS, and primary energy use, electricity production, and greenhouse gas (GHG) emissions from the DHC system. A simulation model was used to HPS using the DHC system. Three operational strategies were analyzed: A reference scenario based on the current control strategy, and scenarios where the HPS is shut down at temperatures below -10°C (14°F) and -5°C (23°F). The study found the DHC return temperature is suitable for use. It was found that use during peak demand in the DHC system can be avoided, resulting in reduced use of fossil fuel. The energy use of the HPS could be reduced by 10% and the local GHG emissions by 25%. The study emphasizes that the HPS may have positive effects on global GHG emissions, as it enables electricity production from renewable resources.
Citation: Blomqvist, S., Amiri, S., Rohdin, P., Ödlund, L. (2019) Analyzing the performance and control of a hydronic pavement system in a district heating network. Energies, 12(11). DOI:10.3390/en12112078

Title: Microwave deicing for asphalt mixture containing steel wool fibers
Authorship: Gao et al. 2019
Products Investigated: Steel wool additives in asphalt mixtures
Article/Report Summary: The microwave heating performance of asphalt mixtures with steel wool was tested. The effects of steel wool on air void content were studied and the fiber distribution was observed and tested at -5°C and -10°C. The heating uniformity of the asphalt samples and ice-thawing time and thickness was assessed. Results show that the optimal steel wool fiber contents for microwave heating of asphalt mixture are 0.3% of 000# (0.0015 in steel wool thickness/grade), 0.6% of 0# (0.002 in steel wool thickness/grade) sand 0.9%% of 2#, respectively. The ice-thawing time of the pavement with an initial temperature of -10°C is 9.3% (000#), 11.3% (0#) and 14.8% (2#) higher than that of -5°C. In addition, every 1 cm increase in ice layer thickness requires 5.9% (000#), 7.7% (0#) and 13.0% (2#) increase in thawing time. A larger diameter of the steel wool helps to improve the heating uniformity.

Citation: Gao, J., Guo, H., Wang, X., Wang, P., Wei, Y., Wang, Z., ... & Yang, B. (2019). Microwave deicing for asphalt mixture containing steel wool fibers. *Journal of Cleaner Production*, *206*, 1110-1122.

Title: Durability and Electrical Conductivity of Carbon Fiber Cloth/Ethylene Propylene Diene Monomer Rubber Composite for Active Deicing and Snow Melting
Authorship: Han et al. 2019

Products Investigated: Conductive ethylene propylene diene monomer (EPDM) rubber material with carbon fiber cloth as a heating layer and aluminum silicate fiber cloth for thermal insulation layer.

Article/Report Summary: The mechanical properties of EPDM rubber composites reinforced by carbon fiber cloth and the thermal behaviors of the composite material were investigated at 60°C and -20°C. The heat generation and transfer effect of the composite were analyzed by electrothermal tests. The results show that the conductive EPDM rubber composite material has good temperature durability, outstanding mechanical stability, and excellent uniform heat production capacity. The carbon fiber cloth improves the electrical conductivity and mechanical properties of the EPDM rubber. Although the feasibility of the material for active deicing and snow melting was verified, additional experiments and theoretical studies on actual deicing and snow melting need to be conducted.
Citation: Han, S., Wei, H., Han, L., & Li, Q. (2019). Durability and electrical conductivity of carbon fiber cloth/ethylene propylene diene monomer rubber composite for active deicing and snow melting. *Polymers*, *11*(12), 2051.

Title: Effect of magnetite on concrete mechanics and microwave deicing performance
Authorship: Huang and XU, 2019
Products Investigated: Magnetite additives in concrete for microwave deicing
Article/Report Summary: The mechanical properties, heat absorption, deicing efficiency, and frost resistance of magnetite aggregate concrete (MAC) was investigated. MAC with 0, 20%, 40%, 60%, 80%, and 100% magnetite content were created. The results show that the addition of magnetite aggregate can effectively improve the mechanical properties and deicing efficiency of concrete. With the increase of magnetite aggregate, the compressive strength and flexural strength increase gradually. The absorption and heating efficiency of magnetite aggregate concrete also increases gradually with the increase of magnetite aggregate. When the content of magnetite aggregate reached 100%, the efficiency of absorbing heat and deicing increased by 71.3% and 69.7% respectively. Magnetite aggregate can improve the microwave heating and electromagnetic loss performance of concrete.
Citation: Huang, H., & XU, J. Y. (2019, May). Effect of magnetite on concrete mechanics and microwave deicing performance. In *IOP Conference Series: Earth and Environmental Science* (Vol. 267, No. 4, p. 042019). IOP Publishing.

Title: Investigation on dielectric properties and microwave heating efficiencies of various concrete pavements during microwave deicing
Authorship: Liu et al. 2019

Products Investigated: Graphite-modified concrete

Article/Report Summary: In this study, different concrete mixes of water/cement and sand ratios were compared to concretes with the addition of graphite for heating efficiencies and microwave deicing capability. The addition of graphite led to an evident increase in the complex dielectric constant and microwave deicing efficiency of the graphite-modified concrete (GC). Graphite additives had the greatest influence to increase microwave heating, followed by sand ratio and then water/cement ratio. The cost time for deicing of GC-3 was reduced by 50% (90 seconds) in comparison with that of normal concrete (180 seconds). The variation of both the water/cement and sand ratios had a similar degree of influence—within 5%–10%—on the concrete strength and dielectric property. In comparison, the influence of graphite was in the high range from 149% to 254%. The addition of graphite materials had a more evident influence than changing the basic mix proportions of the concrete. When graphite additive was 15% of the cement mass, the microwave heating efficiency increased to 1.63 °C/s at a 20 mm microwave source height, where normal concrete was 0.65 °C/s.

Citation: Liu, J. L., Xu, J. Y., Lu, S., & Chen, H. (2019). Investigation on dielectric properties and microwave heating efficiencies of various concrete pavements during microwave deicing. *Construction and Building Materials*, *225*, 55-66.

Title: Design of electric heat pipe embedding schemes for snow-melting pavement based on mechanical properties in cold regions

Authorship: Liu et al. 2019

Products Investigated: Electric heat steel pipes embedded in concrete

Article/Report Summary: This paper investigates the feasibility of using electrified steel pipes embedded in concrete as a means for deicing roads in cold regions. It looks at the embedded depth and spacing of the steel pipes on the mechanical properties of concrete and develops a schema for use on roads. They took this design and did a field test on a road in Tibet. Based on the experiment and the simulated results, a design schema for electric heat pipe embedded concrete with 14-16 cm (5.5 – 6.3 inches) depth and 12-18 cm (4.7 – 7.5 inches) spacing is proposed. The field experiments showed that at -1^{o}C to -4^{o}C (30°F to 25°F), 5 cm (2 inches) of snow can be melted in 5 hours (70% of concrete slab completely dry surface) with a heating power of 533 Watts. In addition to melting accumulated snow, the field test showed snowflakes melted into water as soon as it fell on the heated concrete. These results help guide the design of electric heat pipe embedded concretes for deicing roads.

Citation: Liu, K., Fu, C., Xie, H., Wang, F., Wang, X., & Bai, H. (2019). Design of electric heat pipe embedding schemes for snow-melting pavement based on mechanical properties in cold regions. *Cold regions science and technology*, *165*, 102806.

Title: Electrical resistance heating for deicing and snow melting applications: Experimental study

Authorship: Mohammed et al. 2019

Products Investigated: Carbon-fiber heating elements in concrete

Article/Report Summary: In this report, three different forms of carbon fiber (e.g., cable filaments, woven and unidirectional fabrics) were embedded into concrete specimens to evaluate an electrical

resistance heating method for deicing and snow melting applications. Samples were tested at -5°C, -10°C, -20°C and -30°C. Experimental results showed that carbon fiber electrical heating is a viable solution for icing and snow accumulation problems. Using carbon fiber in cable form provides many advantages compared to using woven and unidirectional carbon fabrics. Quick temperature rise is possible by embedding heat panels close to the concrete surface but, long term reliance of the heat panels should not be jeopardized due to possible dynamic loads on the concrete. Compared to other heated pavement systems, it has relatively lower installment and material cost.
Citation: Mohammed, A. G., Ozgur, G., & Sevkat, E. (2019). Electrical resistance heating for deicing and snow melting applications: Experimental study. *Cold Regions Science and Technology*, *160*, 128-138.

Title: Mechanical and Electrothermal Properties of Conductive Ethylene–Propylene–Diene Monomer Rubber Composite for Active Deicing and Snow Melting
Authorship: Wei et al. 2020
Products Investigated: Conductive ethylene-propylene-diene monomer (EPDM) rubber composite embedded with graphite
Article/Report Summary: This research investigates a new type of active deicing material for roads to melt snow and ice. The composite material consists of a heat transfer layer with graphite embedded EPDM, a heat generation layer of carbon fiber cloth sandwiched between EPDM rubber, and an insulation layer made of aluminum silicate fiber cloth and EPDM rubber. Different graphite contents (0, 10, 20, 30, 40, and 50 parts) of EPDM were tested for mechanical properties, thermal conductivity, electric heating, and electrothermal properties. The tensile and tear strength was strongest at 40 parts graphite content and were 22.62% and 12%, respectively, stronger than the EPDM with no graphite embedded. The 50 parts graphite EPDM had a thermal conductivity 155% higher than the EPDM with no graphite. The mechanical properties of the EPDM material meet the requirements for road use and the composite material can heat up quickly. Further field tests are needed to prove the feasibility for road use proven in this study.
Citation: Wei, H., Han, S., Han, L., & Li, Q. (2020). Mechanical and electrothermal properties of conductive ethylene–propylene–diene monomer rubber composite for active deicing and snow melting. *Journal of Materials in Civil Engineering*, *32*(8), 04020197.

Title: Microwave deicing efficiency and dielectric property of road concrete modified using different wave absorbing material
Authorship: Liu et al. 2020
Products Investigated: Graphite concrete, iron black concrete, and silicon carbon concrete
Article/Report Summary: Graphite, iron black, and silicon carbon were added to road concrete to evaluate the microwave de-icing efficiency, heating efficiency, and temperature distribution of the samples. The addition of a wave absorbing material enhances the microwave de-icing efficiency of the concrete. When the addition of graphite reaches 15%, the microwave heating efficiency of the concrete increases by 0.98 °C/s, the relative dielectric constant increases by 3.5–4.7, and the de-icing area reaches 66.7 cm2, which is 5.1-times that of ordinary Portland cement (PC) concrete. Iron black also

enhances the microwave de-icing efficiency of the concrete, and the microwave heating efficiency increases by 0.35 °C/s and the effective de-icing area increases to 33.6 cm2 with the addition of 15% iron black. The enhancements of the three absorbing materials from high to low are from graphite, iron black, and silicon carbon.
Citation: Liu, J. L., Xu, J. Y., Huang, H., & Chen, H. (2020). Microwave deicing efficiency and dielectric property of road concrete modified using different wave absorbing material. *Cold Regions Science and Technology*, *174*, 103064.

Title: Deicing concrete pavements and road with carbon nanotubes (CNTs) as heating elements
Authorship: Kim et al. 2020
Products Investigated: carbon nano tubes as heating elements
Article/Report Summary: This study used laboratory and field tests and numerical analyses to examine the efficiency of deicing using carbon nanotubes (CNTs). In the lab, a CNT was inserted into the center of a concrete sample and then heated to 60°C (140°F) while maintaining the ambient and internal temperatures of the sample at -10°C (14°F) using a refrigeration chamber. Analysis of the thermal conductivity was then used to design the field test. Thermal conduction performance in the field was measured and results showed that the surface temperature between the heating elements exceeded 0°C (32°F). Additionally, the effective distance of the heating elements should be 20–30 cm (8-12 inches) for thermal overlap (based on lab testing). The numerical analysis indicated that the effective heating distance increased to 100 cm (40 inches) when the heating element temperature and experiment time were increased. Field test results showed that the heating elements spaced 100 cm (40 inches) apart could melt 62 cm- (42 inches)-deep snow, verifying the feasibility of use for deicing.
Citation: Kim, H.S., Ban, H., Park, W-J. (2020) Deicing concrete pavements and road with carbon nanotubes (CNTs) as heating elements. Materials, 13. doi:10.3390/ma13112504

Title: Research of properties on graphite conductive slag in asphalt concrete
Authorship: Sun et al. 2020
Products Investigated: graphite conductive slag
Article/Report Summary: Adding graphite to asphalt concrete can reduce the electrical resistivity to achieve the purpose of electrical conductivity. However, the aggregate electrical resistance in asphalt concrete is very large and does not play a conductive role. This work investigates the use steel slag as aggregate and graphite powder, both with good electrical conductivity, to prepare steel slag graphite conductive asphalt concrete (SGCAC). In this paper, the effects of steel slag and graphite on the conductive properties of SGCAC are separately explained. The ideal graphite content remains to be determined, to avoid damage to pavement performance. Repeated heating accelerated the aging of asphalt and shortened the service life. Overall, SGCAV is conductive but electrothermal conversion efficiency was found to be low. Additional work is recommended to improve this.
Citation: Sun, J., Bieliatynskyi, A., Krayushkina, K., Akmaldinova, O. (2020) Research of properties on graphite conductive slag in asphalt concrete. E3S Web of Conferences, 175, https://doi.org/1.1051/e2conf/202017511015

Title: Development and performance research of new sensitive materials for microwave deicing pavement at different frequencies
Authorship: Ding et al. 2021
Products Investigated: Ferric aluminum and hydroxy iron powder in asphalt mixtures for microwave deicing
Article/Report Summary: Microwave deicing has the advantages of high energy utilization rate, good deicing effect, environmental protection and economy. To improve the microwave deicing efficiency, a test was developed to test different ratios of ferric aluminum and hydroxy iron powder in asphalt mixtures. Considering factors such as cost and deicing efficiency, the most effective additive mass ratio of ferric aluminum is 1% at 2.45 GHz frequency, and 5% for hydroxy iron powder when microwave frequency is at 5.8 GHz. The microwave tests have determined that asphalt concrete with sensitive materials can improve absorbing ability as much as 2.3 times the original sample with no additives. Microwave sensitive materials in asphalt can improve the efficiency of microwave deicing. However, the deicing effect of the actual asphalt pavement with added sensitive materials, the durability of the mixture, and the comparison of other absorbing materials has not been tested. Further investigation is needed.
Citation: Ding, L., Wang, X., Cui, X., Zhang, M., & Chen, B. (2021). Development and performance research of new sensitive materials for microwave deicing pavement at different frequencies. *Cold Regions Science and Technology*, *181*, 103176.

Title: Research on electromagnetic properties and microwave deicing performance of carbon fiber modified concrete
Authorship: Lu et al. 2021
Products Investigated: Carbon-fiber modified concrete
Article/Report Summary: Carbon fiber was added to the concrete mixture to evaluate the microwave absorbing performance and road microwave deicing. When the microwave frequency is in the vicinity of 2.45 GHz, the permittivity of CFMC with a carbon fiber content of 1‰ (CFMC-1), 3‰ (CFMC-2) and 5‰ (CFMC-3) are 1.59 times, 1.69 times and 0.94 times of that of plain concrete (PC), respectively. The microwave deicing tests show that CFMC-3 has the fastest heating rate, which is 1.680 °C/s, 4.46 times that of PC. However, considering the mechanical properties, deicing effect and economic cost, CFMC-1 has the best application prospects, whose heating rate is 1.289 °C/s, 3.42 times that of PC. It is concluded that the efficiency of concrete road microwave deicing can be effectively improved by adding carbon fiber.
Citation: Lu, S., Bai, E., Xu, J., & Chen, J. (2021). Research on electromagnetic properties and microwave deicing performance of carbon fiber modified concrete. *Construction and Building Materials*, *286*, 122868.

Title: Pavement conductive wearing surface with graphite heating film de-icing potential and performance experimental study
Authorship: Yan et al. 2021

Products Investigated: Pavement conductive heating surface with graphite heating film

Article/Report Summary: This paper investigates the road performance (high-temperature, low-temperature, moisture susceptibility, friction-resistance) of pavement conductive wearing surface with graphite heating film (PCWSG) and then evaluates its deicing potential. Asphalt mixtures with PCWSG improve the high temperature (60°C or 140°F) performance by reducing the stress concentration from the wheel. The PCWSG increases the tensile strength of asphalt at low temperatures (-10°C or 14°F). The ice melting tests indicate that at 220 Volts, the asphalt mixture with pore heating film had the best performance and can heat the surface temperature from -10°C to 0°C (14°F to 32°F) in 20 minutes. This research shows that the ultra-thin PCWSG wear layer has lower heating and deicing costs, and better deicing effect than untreated asphalts.

Citation: Yan, Z., Liu, W., Chen, J., & Jin, D. (2021). Pavement conductive wearing surface with graphite heating film de-icing potential and performance experimental study. *International Journal of Pavement Research and Technology*, *14*(6), 688-696.

Title: Self-heating electrically conductive concrete demonstration project

Authorship: Malakooti et al., 2021

Products Investigated: electrically conductive heated concrete pavement

Article/Report Summary: This report summaries the results of a full-scale field implementation of electrically conductive heated concrete pavement testing 10 varying electrode and design configurations as an alternative to traditional snow removal operations. To support the field implementation, lab testing was conducted on the electrical components to determine thermal performance and geometries and conducted preliminary testing of electrodes in test slabs. Overall, flat bar and smaller diameter electrodes were found to be more cost-effective but larger sized electrodes increased energy efficiency. Field demonstration data was collected from 2018 to 2021 and found all test slab performed and required a power density range from 10.2 to 45.7 W/ft^2 (average 24.6 W/ft^2). The heated slabs were found to be stiffer with higher modulus than traditional pavement. Recommendations include heating pavement before snow events to melt snow and ice as it lands on the pavement, and implementation of this technology on bridge decks and at rest areas.

Citation: Malakooti, A., Sadati, S., Ceylan, H., Kim, S., Cetin, K.S., Taylor, P.C., Mina, M., Cetin, B., Theh, W.S. (2021) Self-heating electrically conductive concrete demonstration project. Intrans, Iowa Highway Research Board & Iowa DOT. https://intrans.iastate.edu/research/completed/self-heating-electrically-conductive-concrete-demonstration-project/

Title: Optimization design and prediction of the snow-melting pavement based on electrical-thermal system

Authorship: Jiao et al. 2022

Products Investigated: Ordinary asphalt and asphalt with steel slag aggregate with 24 K Teflon-carbon fiber heating wire

Article/Report Summary: This paper investigates the design of a thermal conductive asphalt concrete (TCAC) and recommends the best system parameters based on the melting efficiency, energy costs, and

mechanical durability of the pavement. The results show that the 24 K Teflon-carbon fiber heating wire is suitable for a road heating system at -5ºC. It can provide a stable heat source and has the characteristics of high temperature/pressure resistance during the asphalt mixture molding and rolling process. The optimal heating wire spacing is 10 cm, set heating wire depth as 4 cm, besides, the heating wire power can be determined based on energy consumption, and actual environmental conditions. The ice-melting capability of the system was higher in the asphalt that had steel slag. The TCAC can reduce the snow melting time by 36-44 minutes compared to the ordinary asphalt slab and increase snow melting efficiency by 17.8-19.5%. This research supports the theory of thermodynamic structural design for snow melting pavement systems.
Citation: Jiao, W., Sha, A., Liu, Z., Li, W., Zhang, L., & Jiang, S. (2022). Optimization design and prediction of the snow-melting pavement based on electrical-thermal system. *Cold Regions Science and Technology*, *193*, 103406.

Title: Effect of Carbon Fiber Admixture and Length on Microwave Deicing Efficiency of Airport Road Surface Concrete
Authorship: Ning et al. 2022
Products Investigated: Carbon-fiber modified concrete
Article/Report Summary: This report looks at different doping amounts of carbon fibers and their lengths in concrete to evaluate microwave deicing efficiency of airport road surfaces. In the process of microwave deicing of concrete, changing the length of carbon fiber and the amount of doping will have a greater impact on the rate of temperature rise and deicing range. When the length of carbon fiber is short, it is not conducive to the absorption of microwave by concrete, and with the increase of fiber length and doping amount, the wave absorption performance of carbon fiber -modified concrete on the airport road surface is gradually improved; when the fiber length is 0.6 cm and the fiber mass ratio amount is 2‰, the wave absorption performance is the best, and the deicing rate is 1.82 times of ordinary concrete, and the deicing area is 1.2 times of ordinary concrete.

Citation: Ning, Y. P., Xu, J. Y., Huang, H., Wang, Z. H., & Yao, A. (2022). Effect of Carbon Fiber Admixture and Length on Microwave Deicing Efficiency of Airport Road Surface Concrete. *Advances in Materials Science and Engineering*, *2022*.

Anti-icing or Anti-Bonding/Water-Repellent Surface Treatments

Another category of non-chloride roadway deicing options are anti bonding surface treatments. These pavement treatments may be the application of a surface treatment on the pavement with a chemical and/or the blending of a chemical in the pavement mixing process. The success of these anti bonding strategies is marked by their ability to reduce the amount of plow force (ice adhesion) required to remove bonded snow and ice from pavement. Below is a summary of literature on this technology.

Title: Asphalt-ice interface adhesion reduction method

Authorship: Tazawa et al. 1992

Products Investigated: water repellents, rubber aggregate

Article/Report Summary: In order to clarify the nature of the bonding mechanism between ice and asphalt concrete and to develop new techniques to reduce debonding resistance, a series of experiments were conducted. Surface energy was varied by using various water repellents, and the stiffness of asphalt concrete was varied by mixing crushed rubber particles with the asphalt. Correlations between these variables were investigated and the following conclusion was obtained. Reducing surface energy and/ or increasing deformability of the asphalt concrete is an effective way to decrease interfacial bonding between ice and asphalt concrete. In this regard, use of water repellents or replacement of aggregate with rubber particles is a promising method to facilitate debonding of ice and asphalt concrete.

Citation: Tazawa, E.I., Mizo-U-E, Y., Kojima, T. (1992) Interfacial debonding of ice–asphalt concrete. Journal of Japan Society of Civil Engineers, 453/VI-17, pp. 125-13
https://doi.org/10.2208/jscej.1992.453_125

Title: Evaluation of the Cargill Safelane™ Surface Overlay

Authorship: Sprinkel et al. 2009

Products Investigated:

Article/Report Summary: This report details a study of Cargill's SafeLane™ surface overlay (SafeLane overlay) a 3/8-in-thick overlay constructed with epoxy and broadcast aggregates. SafeLane overlay is composed of a limestone aggregate designed to absorb and store liquid deicing chemicals that are applied to the surface of the roadway. This research compared SafeLane overlay, and the Virginia Department of Transportation (VDOT) modified EP-5 epoxy concrete overlay (VDOT modified EP-5 overlay) based construction, initial condition, and effectiveness in preventing frost, ice, and snow formation on the surface of the roadway. The comparison consisted of overlays placed on four bridges on I-81 in 2004 and 2005 (two SafeLane and two VDOT modified EP-5 overlays) and on four sections of continuously reinforced concrete pavement on the Virginia Smart Road in 2006. The evaluation with respect to the initial condition of the overlays on I-81 was based on a comparison of the as constructed properties, including aggregate properties, bond strength, permeability, skid resistance, and chloride content. The evaluation with respect to the initial condition of the overlays on the Smart Road was limited to skid resistance. The evaluation of the overlays with respect to their effectiveness in preventing frost, ice, and snow formation was based on visual observations and skid measurements of overlay surfaces under typical interstate winter conditions at the I-81 sites and under artificial snow and ice conditions at the Smart Road. In addition, the effectiveness of the overlays at the Smart Road in preventing frost, ice, and snow formation was compared with that of a bare-tined concrete surface. The evaluation indicated that the SafeLane overlay can provide a skid-resistant wearing and protective surface for bridge decks. The study was not able to determine the performance of the overlay with respect to providing a surface with less accumulation of ice and snow. Further, an insufficient amount of

time transpired to evaluate chloride penetration into the decks overlaid with SafeLane overlays in Virginia.
Citation: Sprinkel, M.M., Rossevelt, D.S., Flintsch, G.W., Izeppi, E. de L., Mokarem, D.W. (2009) Evaluation of the Cargill Safelane^{TM} Surface Overlay. Virginia Transportation Research Council, Charlottesville, VA. https://vtechworks.lib.vt.edu/handle/10919/46665

Title: Chemical pavement modifications to reduce ice adhesion
Authorship: Wright et al. 2016
Products Investigated: sodium formate, sodium silicate
Article/Report Summary: This work used scanning electron microscopy to examine the mechanism by which de-icing chemicals, added as a filler replacement to bituminous materials, transferred to the pavement surface. They found that sodium formate and sodium silicate can be transferred to the pavement surface by moisture absorption at relatively high humidity. Reduction in adhesion between ice and the pavement surface from the sodium formate and sodium silicate was found using an ice bond test and adhesion calculations based on surface energy parameters. The effect of the chemical modifications on pavement durability was assessed and sodium silicate was found to reduce durability of the pavement, while sodium formate showed no impact on durability.
Citation: Wright, M., Parry, T., Airey, G. (2016) Chemical pavement modifications to reduce ice adhesion. Proceedings of the Institute of Civil Engineers, Transport 169(TR2), pp. 76-87. http://dx.doi.org/10.1680/jtran.14.00053

Title: Inexpensive and non-fluorinated superhydrophobic concrete coating for anti-icing and anti-corrosion
Authorship: Song et al. 2019
Products Investigated: water-based stone protector (DC-30, containing silane and siloxane)
Article/Report Summary: This study reports on an inexpensive, non-fluorinated, and robust superhydrophobic concrete (S-concrete) coating with a contact angle of 160 ± 1° (low contact angle) and sliding angle of 6.5 ± 0.5°. This coating had a high surface mechanical strength and retained superhydrophobicity after blade scratches or sandpaper abrasion. The S-concrete coating had good anti-icing ability, a low ice adhesion (force to remove ice), and a high corrosion resistance.
Citation: Song, J., Li, Y., Xu, W., Liu, H., Lu, Y. (2019) Inexpensive and non-fluorinated superhydrophobic concrete coating for anti-icing and anti-corrosion. Journal of Colloid and Interface Science, 541, pp. 86-92. https://doi.org/10.1016/j.jcis.2019.01.014

Title: Mechanically stable superhydrophobic surfaces on cement-based materials
Authorship: Shen et al. 2020
Products Investigated: 1H,1H,2H,2H-Perfluorodecyl triethoxysilane (PFDTES, $C_{16}H_{19}F_{17}O_3Si$)
Article/Report Summary: In this study, a superhydrophobic surface was created on hardened cement pastes (HCP) without any additive. The surface microstructures and surface chemical composition of ordinary HCP (O-HCP) and superhydrophobic HCP (S-HCP) were characterized by SEM and FTIR. The

results of water absorption and anti-icing tests showed that the prepared S-HCP (1H,1H,2H,2H-Perfluorodecyl triethoxysilane (PFDTES, $C_{16}H_{19}F_{17}O_3Si$)) had lower water permeability, ice-adhesion strength and ice accumulation than O-HCP. Meanwhile, the surface of S-HCP remained superhydrophobic after a series of mechanical performance tests and weather resistance tests, which indicated that the SCM has application potential.
Citation: Shen et al., (2020) Mechanically stable superhydrophobic surfaces on cement-based materials. Chemical Physics, 538. https://doi.org/10.1016/j.chemphys.2020.110912

Title: A Study of Icephobic Coatings, Part 1
Authorship: Tiwari, 2020
Products Investigated: chlorides (calcium, magnesium, and sodium chloride), and chlorides mixed with sugars, lacquer formulations, sol-gels containing fluorinated compounds, viscoelastic rubber, icephobic treatments – epoxies, polyurethanes, silicones; synthetic polymers (e.g., Teflon); polycarbonate-based ice releasing block copolymer films; poly tetrafluoroethylene (PTFE) coatings; Braycoote, Rain-X, MP-55, UF-8TA.
Article/Report Summary: This overview article of icephobic coatings provides information on hydrophilic and hydrophobic coatings in multiple applications – air crafts and space shuttles, wind turbines, powerlines, roadways, etc. This article serves as a resource for additional source material and describes what icephobic coats are, how they work, and various physical properties – friction, water contact angle (lower contact angle is more hydrophobic), wettability, interfacial shear strength, etc. Noting that material, surface roughness and texture, air entrapment, permeability, absorption capacity, all influence ice adhesion.
This article also summarizes existing work and presents information on environmental and economic impacts on traditional chloride-based and CMA roadway deicers, as well as aircraft deicers (ethylene and propylene glycols).
Citation: Tiwari, A. (2020) A Study of Icephobic Coatings, Part 1. Paint & Coatings Industry. Jan. 15, 2020

Title: Comprehensive investigation of long-term performance of internally integrated concrete pavement with sodium acetate
Authorship: Al-Kheetan et al. 2020
Products Investigated: sodium acetate
Article/Report Summary: The work studied the efficacy of integrating sodium acetate with concrete with different water to cement ratios (w/c) as a protective material for concrete pavement. The results of freeze-thaw testing under water and increased humidity were compared. With 2% and 4% sodium acetate added, both freeze-thaw test produced destructive results, but the freeze-thaw cycling in water was more destructive. The distressed concrete was tested for water absorption and compressive strength after finishing six months of freeze-thaw testing. The samples with lower w/c ratios (0.32 and 0.37) were resistant to deterioration from freeze-thaw testing. The addition of sodium acetate further reduced deterioration, and increased dosages provided additional protection. But the addition of sodium acetate of high w/c sample exacerbated the deterioration and further increased with higher

dosages. Water absorption occurred in all samples, but least occurred in low w/c with 4% sodium acetate added. Additionally, the morphology of sodium acetate and its interaction with concrete were investigated by using Scanning Electron Microscope (SEM). Results demonstrated the effectiveness of sodium acetate in protecting concrete.

Citation: Al-Kheetan, M.J., Rahman, M.M., Ghaffar, S.H., Al-Tarawneh, M., Jweihan, S. (2020) Comprehensive investigation of long-term performance of internally integrated concrete pavement with sodium acetate. Results in Engineering, 6. https://doi.org/10.1016/j.rineng.2020.100110

Title: Recent advances in hydrophobic and icephobic surface treatments of concrete

Authorship: Mundo et al. 2020

Products Investigated: hydrophobic and icephobic

Article/Report Summary: This review paper presents information on hydrophobic surface treatment of concrete, distinguishing between coatings that cause pore blockage versus impregnation, compounds and formulations, performance, contact angle, water adsorption, chloride penetration, and anti-icing and icephobic properties. Findings include, coatings and impregnation using polyurethane and silane/siloxane appear more effective against water ingress creating hydrophobic to overhydrophic conditions. Embedding nano-powders in hydrophobic emulsions can create superhydrophobic coatings. These coatings have pronounced icephobic characteristics.

Citation: Mundo, R.D., Labianca, C., Carbone, G., Notarnicola, M. (2020) Recent advances in hydrophobic and icephobic surface treatments of concrete. Coatings, 10(5). DOI:10.3390/coatings10050449

Title: Upcycling of biomass waste into photothermal superhydrophobic coating for efficient anti-icing and deicing

Authorship: Wang et al. 2022

Products Investigated: biochar, titanium nitride nanoparticles

Article/Report Summary: This study proposes a facile method to fabricate superhydrophobic photothermal anti-icing coating using commercially available biochar (BC) and low-cost titanium nitride (TiN) nanoparticles. The coating displays superior photothermal conversion and anti-icing performance, benefiting from the micro-nano hierarchical structure's light trapping effect and high surface roughness. Meanwhile, the coating shows an extra-long anti-icing time of ~831s for water droplets, which is ~17 times longer than pure BC coating. The covering frost and ice can be melted into droplets under the illumination of sunlight and roll off rapidly, leaving a dry surface. Superhydrophobic photothermal coating may promote the development of anti-icing and deicing surfaces in outdoor applications.

Citation: Wang, B., Yu, P., Yang, Q., Jing, Z., Wang, W., Li, P., Tong, X., Lin, F., Wang, D., Lio, G.E., Caputo, R., Ávalos-Ovando, O., Govorov, A.O., Xu, H., Wang, Z.M. (2022) Upcycling of biomass waste into photothermal superhydrophobic coating for efficient anti-icing and deicing. Materials Today Physics, 24. https://doi.org/10.1016/j.mtphys.2022.100683

Appendix B – Survey Instruments & Detailed Results

Transportation Agency Survey

This survey has been created to help support Clear Roads project 21-03 Efficacy, Cost, and Impacts of Non-Chloride Deicers. The goal is to aid Clear Roads and its member states in their understanding of non-chloride deicers including their use, why they are being used, their performance, and lessons learned.

Information gathered in the survey will be used to inform other agencies on existing non-chloride deicers and their use. Some of the identified products will be developed into educational product information sheets which can be used by transportation agencies to compare between non-chloride products and sodium chloride (salt brine, rock salt).

This research study was reviewed by the Montana State University Institutional Review Board (irb@montana.edu). Participation in this survey is voluntary and you may skip any question you do not want to answer and/or you can stop at any time. Proceeding with this survey indicates your consent to participate. The survey should take about 5 minutes. Any questions or comments can be directed to Karalyn Clouser of WTI/MSU at karalyn.clouser@montana.edu or (406) 529-0654. Thank you for your time.

1. Organization Name:

2. Does your agency use non-chloride deicers (e.g., acetates, formates, agricultural-derived)? To clarify, we use the term "deicer" to refer to all products used for anti-icing, deicing, or pre-wetting operations.

☐ Yes
☐ No (Skip to Question 8, then end the survey.)

3. What non-chloride deicers does your agency use? (Please list the product at the top of the column and answer the following questions.)

Product	Product 1 Name:	Product 2 Name:	Product 3 Name:
Quantity Used or Purchased Annually – Please Specify			

Units (gal, lb, ton)			
Cost (per ton, per gallon, other) – Please Specify Whether the Cost Includes Shipping Fees			
Application Methods Used (Solid/Deicing, Liquid/Deicing, Liquid/Anti-Icing, Liquid/Prewet)			
Application Rate for Each Method			
Temperature Range Used (°F)			
Where is the product applied? (All Locations, Specific Locations (chloride sensitive areas, critical infrastructure, etc.), Other (please explain))			

Are there specific storage/handling requirements for this product? Please explain.			

4. Why does your agency use non-chloride deicers? (select all that apply)
☐ Better Performance
☐ Reduced Impacts to Infrastructure and Equipment
☐ Lower Cost
☐ Environmental Concerns (e.g., associated with chlorides)
☐ Public Pressure/Concern
☐ Other (please explain):

5. Does your agency have any testing results comparing the performance of non-chloride deicers with salt brine or rock salt?
☐ Yes
☐ No (Skip to Question 6)

6. Please explain any testing results comparing the performance of non-chloride deicers with salt brine or rock salt. Which testing methods were used to obtain results (laboratory testing vs. field testing)? If available, please provide titles or links to any reports or articles related to your testing of non-chloride deicers.

7. Please share any success stories or lessons learned from the use of non-chloride deicers.

8. Does your agency use any heated pavements to aid in deicing? (e.g., electrified concrete, heating mats, microwave additives)
☐ Yes
☐ No
☐ I Do Not Know

9. May we follow up via email or phone to learn more about your non-chloride deicer products?
☐ Yes

☐ No (Skip to End of Survey)

10. Please provide the following contact information.

Name: ____

Email Address: ____

Phone Number: ____

We thank you for your time spent taking this survey.

Detailed Responses – Transportation Agency Survey

Organization Name:	What non-chloride deicers does your agency use?	Cleaned Up	Quantity Used or Purchased Annually	Cost (per ton, per gallon, other)	Application Methods Used (Solid/Deicing, Liquid/Deicing, Liquid/Anti-Icing, Liquid/Prewet)	Application Rate for Each Method	Temperature Range Used	Where is the product applied? (All Locations, Specific Locations (chloride sensitive areas, critical infrastructure, etc.), Other (please explain))	Are there specific storage/handling requirements for this product? Please explain.
Illinois DOT	Biomelt AG-64	Biomelt AG-64	Varies - 160k to 257k last 3 years depending on need	approx. $2/gal w/ shipping	Liquid/Prewet	20 to 60 gal/ln mi	80/20 15-28; 70/30 5 - 15	Buy-in varies throughout the state. district and team section dependent.	No
McHenry County DOT (Illinois)	Geo Melt (Beet Juice)	Beet	80,000 gallons	$1.95/gallon	Anti-icing, Deicing, Prewet	40 gal/mile, 40-80 gal/mile, prewet - 8-20 gal/mile	0+	All locations	None

Organization Name:	What non-chloride deicers does your agency use?	Cleaned Up	Quantity Used or Purchased Annually	Cost (per ton, per gallon, other)	Application Methods Used (Solid/Deicing, Liquid/Deicing, Liquid/Anti-Icing, Liquid/Prewet)	Application Rate for Each Method	Temperature Range Used	Where is the product applied? (All Locations, Specific Locations (chloride sensitive areas, critical infrastructure, etc.), Other (please explain))	Are there specific storage/handling requirements for this product? Please explain.
City of West Des Moines (Iowa)	Beet 55	Beet	20,000 gallons	$1.54/gallon	Liquid Anti-Icing	40 gallons/ln mile	10-30 F. pavement temp	All City Streets	No
Kansas DOT	Beet 55	Beet	44,000 gallons	$1.73	Liquid Anti Icing	10-20% with NaCl Brine	0-20	All	Periodic Mixing
Michigan DOT	CMA	CMA	100 metric tons	$2,400				Zilwaukee Bridge	
Michigan DOT	SPC-5000	SPC-5000		maybe $.00 per gal				Blue water bridge and Zilwaukee Bridge	
Montana DOT	Potassium Acetate	KAc	12,253 gallons	$4.91	Deicing	Varies	-20F to 32F	Bridge Deck X2	No

Organization Name:	What non-chloride deicers does your agency use?	Cleaned Up	Quantity Used or Purchased Annually	Cost (per ton, per gallon, other)	Application Methods Used (Solid/Deicing, Liquid/Deicing, Liquid/Anti-Icing, Liquid/Prewet)	Application Rate for Each Method	Temperature Range Used	Where is the product applied? (All Locations, Specific Locations (chloride sensitive areas, critical infrastructure, etc.), Other (please explain))	Are there specific storage/handling requirements for this product? Please explain.
Nebraska DOT	Beet Juice KAc	Beet KAc	17,000 gallons 4,700 gallons annual 5 yr avg.	$1.44 gal $6.73 gal	Liquid Deicing/Pretreatment Only use on bridge decks	[NA] [NA]	17 degrees and dropping [NA]	Omaha metro area Bridge decks	No

Organization Name:	What non-chloride deicers does your agency use?	Cleaned Up	Quantity Used or Purchased Annually	Cost (per ton, per gallon, other)	Application Methods Used (Solid/Deicing, Liquid/Deicing, Liquid/Anti-Icing, Liquid/Prewet)	Application Rate for Each Method	Temperature Range Used	Where is the product applied? (All Locations, Specific Locations (chloride sensitive areas, critical infrastructure, etc.), Other (please explain))	Are there specific storage/handling requirements for this product? Please explain.
Nevada DOT	Potassium Acetate	KAc	9,016 gallons	$6.96/gal. Incl shipping	Boschung System, Liquid Anti-icing	Variable, but approx. 0.002 gal/sq yd for single application	-1 to 32F	On structures all I580: MP 9.5 Browns (13 gals per app seq.), MP 10.5 Galena (40 gal), MP 13.2 Steamboat (23 gals), MP 14.3 Galena Forest (23 gals)	Dedicated tanks for each str.

Organization Name:	What non-chloride deicers does your agency use?	Cleaned Up	Quantity Used or Purchased Annually	Cost (per ton, per gallon, other)	Application Methods Used (Solid/Deicing, Liquid/Deicing, Liquid/Anti-Icing, Liquid/Prewet)	Application Rate for Each Method	Temperature Range Used	Where is the product applied? (All Locations, Specific Locations (chloride sensitive areas, critical infrastructure, etc.), Other (please explain))	Are there specific storage/handling requirements for this product? Please explain.
City of Charlotte DOT (North Carolina)	Sodium Formate	Sodium Formate	2.5 tons	$1,850 per ton	Solid/Deicing	125 lbs per mile	0-32 F	chloride sensitive areas, specifically 10-mile streetcar route	Low moisture environment
North Dakota DOT	Ag Beet Liquid Deicer	Beet	500,000 gallons	$1.50/gallon	Liquid - Anti-Icing, Deicing, Pre-wetting	Varies - Don't directly apply, 20 gal to 200 gal per lane mile	10° and above	All roadways	None

Organization Name:	What non-chloride deicers does your agency use?	Cleaned Up	Quantity Used or Purchased Annually	Cost (per ton, per gallon, other)	Application Methods Used (Solid/Deicing, Liquid/Deicing, Liquid/Anti-Icing, Liquid/Prewet)	Application Rate for Each Method	Temperature Range Used	Where is the product applied? (All Locations, Specific Locations (chloride sensitive areas, critical infrastructure, etc.), Other (please explain))	Are there specific storage/handling requirements for this product? Please explain.
Ohio DOT	Beet Heet Concentrate	Beet	393,045 gallons	Between $1.65 to $2.42 per gal. depending on delivery site and tanker size. We have additional drop fees as well.	Liquid/Deicing, Liquid/Anti-icing, Liquid/Prewet	10% mix with brine	Use blend with road temp is below 20 degrees F.	All locations when warranted	We store all of our liquid deicers in single walled poly tanks with bollards around the tanks and no secondary containment, w

Organization Name:	What non-chloride deicers does your agency use?	Cleaned Up	Quantity Used or Purchased Annually	Cost (per ton, per gallon, other)	Application Methods Used (Solid/Deicing, Liquid/Deicing, Liquid/Anti-Icing, Liquid/Prewet)	Application Rate for Each Method	Temperature Range Used	Where is the product applied? (All Locations, Specific Locations (chloride sensitive areas, critical infrastructure, etc.), Other (please explain))	Are there specific storage/handling requirements for this product? Please explain.
Ohio DOT	Beet Heet Severe	Beet	84,472 gallons	Between $1.45 and $2.22 per gallon depending on location and tanker size. We also have various drop fees.	Liquid/Deicing, Liquid/Anti-icing, Liquid/Prewet	10% mix with brine	Use blend with road temp is below 20 degrees F	All locations when warranted	We store all of our liquid deicers in single walled poly tanks with bollards around the tanks and no secondary containment
Wyoming DOT	Beat55	Beet	17,418 gallons	$1.60 per gal	Liquid/Prewet	30 gal/ LM	0°F - 25°F	Shady areas	Tanks
Wyoming DOT	Sand	Sand	180,460 tons	$29.80 per ton	Solid/Deicing	600 #/ LM	below 32°F	All locations	Under cover

Vendor Survey

This survey has been created to help support Clear Roads project 21-03 Efficacy, Cost, and Impacts of Non-Chloride Deicers. The goal is to aid Clear Roads and its member states in their understanding of non-chloride deicers including their use, why they are being used, their performance, and lessons learned.

Information gathered in the survey will be used to inform other agencies on existing non-chloride deicers and their use. Some of the identified products will be developed into educational product information sheets which can be used by transportation agencies to compare between non-chloride products and sodium chloride (salt brine, rock salt).

This research study was reviewed by the Montana State University Institutional Review Board (irb@montana.edu). Participation in this survey is voluntary and you may skip any question you do not want to answer and/or you can stop at any time. Proceeding with this survey indicates your consent to participate. The survey should take about 5 minutes. Any questions or comments can be directed to Karalyn Clouser of WTI/MSU at karalyn.clouser@montana.edu or (406) 529-0654. Thank you for your time.

1. Vendor Name: ____

2. Please list any deicer products or additives your company produces/sells that do not contain chlorides.

3. Please provide links or Safety Data Sheets on each product.

4. Please provide any additional information on each product.
5. Please provide the cost per gallon/ton.

6. Please provide any environmental test results – toxicity, BOD, etc.

7. Please provide any performance test results – corrosion testing, ice melting, ice undercutting, ice penetration, friction/grip, etc.

8. May we follow up via email or phone to learn more about your non-chloride deicer products?
   - ☐ Yes
   - ☐ No (Skip to End of Survey)

9. Please provide the following contact information.

Name: ____

Email Address: ____

Phone Number: ____

We thank you for your time spent taking this survey.

Detailed Response – Vendor Survey

Cryotech (https://www.cryotech.com/)

Product Name:	**Cryotech CF7 (https://www.cryotech.com/products/cf7-liquid-deicer?app=pavement)**
Vendor:	Cryotech Deicing Technology (https://www.cryotech.com/)
Description:	Cryotech CF7 is a 50% potassium acetate liquid deicer.
Average Cost:	Pricing depends on volume, negotiated discounts, and freight costs. The average cost for Cryotech CF7 is \$6 to \$7 per gallon for bulk truckloads.
Environmental Test Results:	From Safety Data Sheet: • Ecotoxicity (Aquatic and Terrestrial): Not expected to cause long-term adverse effects in the aquatic or terrestrial environments. • Persistence and Degradability: Readily Biodegradable ○ COD (TOD): 0.34 g O_2/g Deicer ○ BOD5 (20°C): 0.25 g O_2/g Deicer • Bioaccumulative Potential: Bioaccumulation is not expected. • Mobility in Soil: Adverse effects not expected. • Other Adverse Effects: None expected. Cryotech E36 meets the US Fish and Wildlife Toxicity rating of "relatively harmless" (acute toxicity results are above 1000 milligrams per liter (mg/L).

	• 48-hr LC50, sheepshead minnows: 6300 mg/L • 48-hr LC50, mysid: 1400 mg/L
Performance Test Results:	• Cryotech CF7 is on the Clear Roads Qualified Products List. • Cryotech CF7 has a low freeze point of -76°F and is effective to -25°F.
Documents Provided:	• Cryotech CF7 Fact Sheet • Cryotech CF7 Safety Data Sheet • Toxicity of Acetate-Based Deicers in Marine (Saltwater) Environments

Product Name:	**Cryotech E36 (https://www.cryotech.com/products/e36-liquid-runway-deicer)**
Vendor:	Cryotech Deicing Technology (https://www.cryotech.com/)
Description:	Cryotech E36 is a 50% potassium acetate liquid deicer.
Average Cost:	Pricing depends on volume, negotiated discounts, and freight costs. The average cost for Cryotech E36 is $6 to $7 per gallon for bulk truckloads.

Environmental Test Results:	From Safety Data Sheet:
	• Ecotoxicity (Aquatic and Terrestrial): Not expected to cause long-term adverse effects in the aquatic or terrestrial environments.
	• Persistence and Degradability: Readily Biodegradable
	  ○ COD (TOD): 0.36 g O_2/g Deicer
	  ○ BOD5 (20°C): 0.25 g O_2/g Deicer
	• Bioaccumulative Potential: Bioaccumulation is not expected.
	• Mobility in Soil: Adverse effects not expected.
	• Other Adverse Effects: None expected.
	Cryotech E36 meets the US Fish and Wildlife Toxicity rating of "relatively harmless" (acute toxicity results are above 1000 milligrams per liter (mg/L).
	• 48-hr LC50, sheepshead minnows: 6300 mg/L
	• 48-hr LC50, mysid: 1400 mg/L

Performance Test Results:	• Cryotech E36 has a low freeze point at -76°F and is effective to -25°F.

Ice Melting Results at 28.4°F (-2°C)

Deicer	Refractive Index at 68°F (20°C)	Time Interval (minutes)	Amount of Ice Melted (Avg of 3 Tests) (g)
Cryotech E36	1.3946	5	6.49 ± 0.42
		10	7.96 ± 0.41
		30	13.19 ± 0.40

Ice Melting Results at 14°F (-10°C)

Deicer	Refractive Index at 68°F (20°C)	Time Interval (minutes)	Amount of Ice Melted (Avg of 3 Tests) (g)
Cryotech E36	1.3946	5	3.83 ± 0.37
		10	4.40 ± 0.34
		30	6.55 ± 0.04

Ice Undercutting Results at 28.4°F (-2°C)

Deicer	Refractive Index at 68°F (20°C)	Time Interval (minutes)	Ice Undercutting (mm^2)
Cryotech E36	1.3946	5	54.8 ± 5.4
		10	96.9 ± 11.6
		30	139.3 ± 17.9

Ice Undercutting Results at 14°F (-10°C)

Deicer	Refractive Index at 68°F (20°C)	Time Interval (minutes)	Ice Undercutting (mm^2)

	Cryotech E36	1.3946	5	24.6 ± 5.4
			10	34.9 ± 3.1
			30	53.0 ± 3.7

Ice Penetration Results at 14°F (-10°C)

Deicer	Refractive Index at 68°F (20°C)	Time Interval (minutes)	Penetration (Avg of 4 Cavities) (mm)
Cryotech E36	1.3946	5	0.9 ± 0.3
		10	1.3 ± 0.3
		30	1.5 ± 0.0

Documents Provided:

- Cryotech E36 Fact Sheet
- Cryotech E36 Safety Data Sheet
- Toxicity of Acetate-Based Deicers in Marine (Saltwater) Environments
- E36 AIR6170 AMIL – FM – Ice Melting
- E36 AIR6172 AMIL – FM – Ice Undercutting
- E36 AIR6211 AMIL – FM – Ice Penetration

Product Name:	**Cryotech LC17 (https://www.cryotech.com/products/lc17-liquid-runway-deicer)**
Vendor:	Cryotech Deicing Technology (https://www.cryotech.com/)
Description:	Cryotech LC17 is a potassium acetate hybrid liquid deicer.
Average Cost:	Pricing depends on volume, negotiated discounts, and freight costs. The average cost for Cryotech LC17 is \$11 to \$13 per gallon.

Environmental Test Results:	From Safety Data Sheet:
	• Ecotoxicity (Aquatic and Terrestrial): Not expected to cause long-term adverse effects in the aquatic or terrestrial environments.
	  ○ LD50 48 hr Daphnia Magna: 4150 mg/L
	  ○ LC50 96 hr Pimephales Promelas: 4225 mg/L
	• Persistence and Degradability: Biodegradable

	○ BOD5 (20°C): 0.24 kg O_2/kg fluid ○ COD: 0.68 kg O_2/kg fluid • Bioaccumulative Potential: Bioaccumulation is not expected. • Mobility in Soil: Adverse effects not expected. • Other Adverse Effects: None expected.
Performance Test Results:	• Cryotech LC17 is effective to -20°F.
Documents Provided:	• Cryotech LC17 Fact Sheet • Cryotech LC17 Safety Data Sheet

Product Name:	**Cryotech NAAC (https://www.cryotech.com/products/naac-solid-deicer?app=pavement)**
Vendor:	Cryotech Deicing Technology (https://www.cryotech.com/)
Description:	Cryotech NAAC is a pelleted sodium acetate deicer.
Average Cost:	Pricing depends on volume, negotiated discounts, and freight costs. The average cost for Cryotech NAAC is \$2,000 to \$3,000 per ton.
Environmental Test Results:	From Safety Data Sheet: • Ecotoxicity (Aquatic and Terrestrial): Not expected to cause long-term adverse effects in the aquatic or terrestrial environments. • Persistence and Degradability: Readily Biodegradable ○ COD (TOD): 0.74 g O_2/g Deicer (740 mg O_2/g Deicer) ○ BOD5 (20°C): 0.45 g O_2/g Deicer (450 mg O_2/Deicer) • Bioaccumulative Potential: Bioaccumulation is not expected. • Mobility in Soil: Adverse effects not expected. • Other Adverse Effects: None expected. Cryotech NAAC meets the US Fish and Wildlife Toxicity rating of “relatively harmless” (acute toxicity results are above 1000 milligrams per liter (mg/L). • 48-hr LC50, sheepshead minnows: > 8000 mg/L • 48-hr LC50, mysid: ~8000 mg/L

Performance Test Results:	• Cryotech NAAC is effective to low temperatures (0^oF).

Ice Melting Results at 28.4^oF (-2^oC)

Deicer	Refractive Index at 68^oF (20^oC)	Time Interval (minutes)	Amount of Ice Melted (Avg of 3 Tests) (g)
Cryotech NAAC Lot# CDTN1C 25% w/w	1.3666	5	3.10 ± 0.28
		10	4.43 ± 0.27
		30	7.44 ± 0.09

Ice Melting Results at 14^oF (-10^oC)

Deicer	Refractive Index at 68^oF (20^oC)	Time Interval (minutes)	Amount of Ice Melted (Avg of 3 Tests) (g)
Cryotech NAAC Lot# CDTN1C 25% w/w	1.3666	5	0.65 ± 0.04
		10	0.78 ± 0.11
		30	1.27 ± 0.17

Ice Undercutting Results at 28.4^oF (-2^oC)

Deicer	Refractive Index at 68^oF (20^oC)	Time Interval (minutes)	Ice Undercutting (mm^2)
Cryotech NAAC Lot# CDTN1C 25% w/w	1.3666	5	24.6 ± 3.0
		10	51.1 ± 8.4
		30	68.0 ± 9.4

Ice Undercutting Results at 14^oF (-10^oC)

	<table><tr><td>Deicer</td><td>Refractive Index at 68°F (20°C)</td><td>Time Interval (minutes)</td><td>Ice Undercutting (mm²)</td></tr><tr><td rowspan="3">Cryotech NAAC Lot# CDTN1C 25% w/w</td><td rowspan="3">1.3666</td><td>5</td><td>6.4 ± 0.6</td></tr><tr><td>10</td><td>6.9 ± 0.6</td></tr><tr><td>30</td><td>11.0 ± 1.6</td></tr></table> Ice Penetration Results at 14°F (-10°C) <table><tr><td>Deicer</td><td>Refractive Index at 68°F (20°C)</td><td>Time Interval (minutes)</td><td>Penetration (Avg of 4 Cavities) (mm)</td></tr><tr><td rowspan="3">Cryotech NAAC Lot# CDTN1C 25% w/w</td><td rowspan="3">1.3666</td><td>5</td><td>0.5 ± 0.0</td></tr><tr><td>10</td><td>0.6 ± 0.3</td></tr><tr><td>30</td><td>0.6 ± 0.3</td></tr></table>
Documents Provided:	• Cryotech NAAC Fact Sheet • Cryotech NAAC Safety Data Sheet • Toxicity of Acetate-Based Deicers in Marine (Saltwater) Environments • NAAC AIR6170 AMIL – FM – Ice Melting • NAAC AIR6172 AMIL – FM – Ice Undercutting • NAAC AIR6211 AMIL – FM – Ice Penetration

Product Name:	**Cryotech CMA (https://www.cryotech.com/products/cma-solid-deicer?app=pavement)**
Vendor:	Cryotech Deicing Technology (https://www.cryotech.com/)
Description:	Cryotech CMA is a pelleted calcium magnesium acetate deicer.
Average Cost:	Pricing depends on volume, negotiated discounts, and freight costs. The average cost for Cryotech CMA is $2,000 to $3,000 per ton.
Environmental Test Results:	From Safety Data Sheet:

	• Ecotoxicity (Aquatic and Terrestrial): Not expected to cause long-term adverse effects in the aquatic or terrestrial environments.
	• Persistence and Degradability: Readily Biodegradable
	  ○ COD (TOD): 0.75 g O_2/g Deicer
	  ○ BOD20 (2°C): 0.40 g O_2/g Deicer
	  ○ BOD20 (10°C): 0.67
	• Bioaccumulative Potential: Bioaccumulation is not expected.
	• Mobility in Soil: Adverse effects not expected.
	• Other Adverse Effects: None expected.

Performance Test Results:	• Cryotech CMA is on the Clear Roads Qualified Products List. • Cryotech CMA works best above 20°F.
Documents Provided:	• Cryotech CMA Fact Sheet • Cryotech CMA Safety Data Sheet • CMA PNS Analytical Labs Report

Product Name:	**Cryotech QS50 (https://www.cryotech.com/products/qs50-solid-deicer)**
Vendor:	Cryotech Deicing Technology (https://www.cryotech.com/)
Description:	Cryotech QS50 is a pelleted sodium acetate/formate deicer.
Average Cost:	Pricing depends on volume, negotiated discounts, and freight costs. The average cost for Cryotech QS50 is $2,000 to $3,000 per ton.

Environmental Test Results:	From Safety Data Sheet:
	• Ecotoxicity (Aquatic and Terrestrial)
	  ○ Acute Fish Toxicity (Pimephales Promelas, Static System 96 hr LC50): 8025 mg/L
	  ○ Acute Daphnid Toxicity (Daphnia Magna, Static System 48 hr LC50): 4250 mg/L
	• Persistence and Degradability: Biodegradable
	  ○ COD (TOD): 0.30 kg O_2/kg Deicer
	  ○ BOD5 (20°C): 0.05 kg O_2/kg Deicer
	• Bioaccumulative Potential: Bioaccumulation is not expected.
	• Mobility in Soil: Adverse effects not expected.
	• Other Adverse Effects: None expected.

Performance Test Results:	• Cryotech QS50 is effective to low temperatures (0°F).
Documents Provided:	• Cryotech QS50 Fact Sheet • Cryotech QS50 Safety Data Sheet • QS50 AIR6170A AMIL – FM – Ice Melting (graphical display of results) • QS50 AIR6172A AMIL – FM – Ice Undercutting (graphical display of results) • QS50 AIR6211A AMIL – FM – Ice Penetration (graphical display of results)

EnviroTech Services, Inc. (https://envirotechservices.com/)

Product Name:	**Apogee (https://envirotechservices.com/products/anti-icing-deicing/ultra-low-based-products/)**
Vendor:	EnviroTech Services, Inc. (https://envirotechservices.com/)
Description:	Apogee is a non-chloride liquid deicer and anti-icer. Apogee is made up of proprietary organic based components, however, is not acetate-based.
Average Cost:	$2.21 per gallon
Environmental Test Results:	

Parameter	Method	Results	Units	Reporting Limit	Date Analyzed
Chemical Oxygen Demand	EPA 410.4	820,000	mg/L	50,000	7/23/2012
Nitrate Nitrogen	EPA 300.0	100	mg/L	100	7/18/2012
Nitrite Nitrogen	EPA 300.0	25	mg/L	25	7/18/2012
Biochemical Oxygen Demand	SM 52 JOB	370	mg/L	6	7/19/2012
Total Kjeldahl Nitrogen	EPA35l.2	0.5	mg/L	0.5	7/24/2012

	From Safety Data Sheet:
	
	• Ecotoxicity: Product:
	  ○ Fathead minnow NOEC: 1.00 g/L
	  ○ Ceriodaphnia dubia NOEC: 1.00 g/L
	  ○ Selenastrum growth: 0.5 g/L
	• Persistence and Degradability: No data available.
	• Bioaccumulative Potential: No data available
	• Mobility in Soil: No data available
	• Other Adverse Effects: None known

Performance Test Results:	• Corrosion score of 13.9 percent, test method: NACE Standard TM0169-95 (1995 Revision) as modified by PNS[2].
Documents Provided:	• Apogee Safety Data Sheet: https://envirotechservices.com/wp-content/uploads/apogee-ghs-sds.pdf • 2006 Apogee Toxicity Testing

Fyve Star (https://www.fyvestar.com/)

Product Name:	**Safeway SF**
Vendor:	Fyve Star (https://www.fyvestar.com/)
Description:	Safeway SF is a sodium formate based solid deicer.
Average Cost:	Cost information not provided.
Environmental Test Results:	From Safety Data Sheet: • Ecotoxicity ○ Toxicity to Fish: LC50 (Danio Rerio (Zebra Fish)): 8,226 mg/l, Exposure Time: 96 hr, Method: OECD Test Guideline 203

[2] Source: USDA BioPreferred program catalog. Accessed November 28, 2022. https://www.biopreferred.gov/BioPreferred/faces/catalog/Catalog.xhtml

	◦ Toxicity to Daphnia and Other Aquatic Invertebrates: Daphnia Magna (Water Flea): > 1,000 mg/l, Exposure Time: 48 hr, Method: OECD Test Guideline 202 ◦ Toxicity to Algae: Desmodesmus Subspicatus (Green Algae): >1,000 mg/l, Exposure Time: 72 hr, Method: OECD Test Guideline 201 ◦ Toxicity to Microorganisms: Pseudomonas Putida: 6,165 mg/l, Method: ISO/DIS 10712.2 (Ref 3) • Biodegradability (28 d, 20°C): 93% • COD: 0.240 kg O_2/kg • BOD_5: 0.016 kg O_2/kg
Performance Test Results:	• Safeway SF conforms to SAE AMS 1431 specifications.
Documents Provided:	• Safeway SF Product Sheet • Safeway SF Safety Data Sheet

Hawkins Inc. (https://www.hawkinsinc.com/)

Product Name:	**Aqua Hawk KA-50 Deicer (https://www.hawkinsinc.com/groups/oil-field-chemicals/potassium-acetate-deicer-supplier/)**
Vendor:	Hawkins Inc. (https://www.hawkinsinc.com/)
Description:	Aqua Hawk KA-50 is a liquid potassium acetate based deicer.
Average Cost:	All pricing is volume-based, and a specific quote is required. $0.55 per pound (Bulk Pricing) or $0.66 per pound Totes, FOB
Environmental Test Results:	• KA-50 is readily biodegradable and does not contain chlorides or nitrogen. From Safety Data Sheet: • Potassium Acetate 127-08-2, Toxicity to Fish: 6800 mg/L (LC50 96 hr semi-static-Oncorhynchus Mykiss)

	From Technical Data Sheet: • BOD5-Day at 68°F: < 0.25 kg O_2/kg KA-50 • COD (TOD5-Day) at 68°F: < 0.36 kg O_2/kg KA-50
Performance Test Results:	• Aqua Hawk KA-50 has a freezing point of -75°F.
Documents Provided:	• Aqua Hawk KA-50 Technical Data Sheet • Aqua Hawk KA-50 Safety Data Sheet • Aqua Hawk KA-50 Product Data Sheet

Product Name:	**Liquid Potassium Formate, 53% (https://www.hawkinsinc.com/groups/oil-field-chemicals/liquid-potassium-formate-53/)**
Vendor:	Hawkins Inc. (https://www.hawkinsinc.com/)
Description:	Liquid Potassium Formate is a liquid deicer used in a variety of industries including use for deicing, it is available in bulk quantities.
Average Cost:	All pricing is volume-based, and a specific quote is required. $0.63 per pound (Bulk Pricing) or $0.75 per found Totes, FOB
Environmental Test Results:	From Safety Data Sheet: • Ecotoxicity: The environmental impact of this product has not been fully investigated.
Performance Test Results:	• None provided
Documents Provided:	• Potassium Formate 53% Safety Data Sheet • Potassium Formate 53% Product Data Sheet

Nachurs Alpine Solutions, LLC (https://www.nasi-tm.com/)

Product Name:	**Alpine Ice Melt (https://www.nasi-tm.com/alpine-ice-melt)**
Vendor:	Nachurs Alpine Solutions, LLC (https://www.nasi-tm.com/)
Description:	Alpine Ice Melt is a 50% potassium acetate liquid deicer. ***Alpine Ice Melt is the same product as Alpine RF-11 without the blue dye.***
Average Cost:	$7.00 per gallon
Environmental Test Results:	• BOD (5-day): 0.25 kg O_2/kg fluid • TOD/COD (5-day): 0.33 kg O_2/kg fluid • Aquatic Toxicity ○ 48 hr LC_{50}: 2,250 mg/l ○ 96 hr LC_{50}: 2,175 mg/l
Performance Test Results:	• Alpine Ice Melt is on the Clear Roads Qualified Product List. • Alpine Ice Melt has a freeze point of -76°F.
Documents Provided:	• Alpine Ice Melt Safety Data Sheet: https://bit.ly/3XZKHd0 • Alpine Ice Melt Technical Data Sheet: https://irp-cdn.multiscreensite.com/27e0cdf5/files/uploaded/ALPINE%20Ice-Melt%20T%26M%20TDS.pdf

Product Name:	**Alpine RF-11 (https://www.nasi-tm.com/alpine-rf-11)**
Vendor:	Nachurs Alpine Solutions, LLC (https://www.nasi-tm.com/)
Description:	Alpine RF-11 is a 50% potassium acetate liquid deicer.
Average Cost:	$7.05 per gallon
Environmental Test Results:	• BOD (5-day): 0.25 kg O_2/kg fluid • TOD/COD (5-day): 0.33 kg O_2/kg fluid • Aquatic Toxicity ○ 48 hr LC_{50}: 2,250 mg/l ○ 96 hr LC_{50}: 2,175 mg/l

Performance Test Results:	• Alpine RF-11 has a freeze point of -76°F.

Ice Melting Results at 28.4°F (-2°C)

Deicer	Time Interval (minutes)	Ice Melting Capacity (Mim/Md)
Alpine RF-11, 50% w/w	5	1.79
	10	1.93
	30	2.41

Ice Melting Results at 14°F (-10°C)

Deicer	Time Interval (minutes)	Ice Melting Capacity (Mim/Md)
Alpine RF-11, 50% w/w	5	1.02
	10	1.08
	30	1.53

Ice Undercutting Results at 28.4°F (-2°C)

Deicer	Time Interval (minutes)	Ice Undercutting (mm^2)	Added Ice	Added Ice
Alpine RF-11, 50% w/w	5	74.60	0.116	0.341
	10	108.62	0.168	0.410
	30	129.29	0.200	0.472

Ice Undercutting Results at 14°F (-10°C)

Deicer	Time Interval (minutes)	Ice Undercutting (mm^2)	Added Ice	Added Ice
	5	26.51	0.014	0.118

Alpine RF-11, 50% w/w	10	36.71	0.062	0.249
	30	57.94	0.900	0.949

Ice Penetration Results at 28.4°F (-2°C)

Deicer	Time Interval (minutes)	Avg Penetration Depth	Added Avg
Alpine RF-11, 50% w/w	5	4.00	0.157
	10	6.00	0.236
	30	8.00	0.138

Ice Penetration Results at 14°F (-10°C)

Deicer	Time Interval (minutes)	Avg Penetration Depth	Added Avg
Alpine RF-11, 50% w/w	5	2.00	0.079
	10	3..50	0.138
	30	4.00	0.157

3.2.5.2 Total Immersion Corrosion: The product, tested in accordance with ASTM F483 (except the panels of AMS4376 that shall be tested for 24 hours), shall neither show evidence of corrosion of panels, nor cause a weight change of any test panel greater than shown in Table 1.

TEST PANEL	WEIGHT CHANGE ($mg/cm^2/24hrs$)	
	ALLOWABLE	RESULTS
AMS 4037 aluminum alloy, anodized as in AMS 2470	0.3	**< 0.01**
AMS 4041 aluminum alloy	0.3	**+ 0.02**
AMS 4049 aluminum alloy	0.3	**0.02**
AMS 4376 magnesium alloy, dichromate treated per AMS 2475	0.2	**+ 0.04**
AMS 4911 titanium alloy	0.1	**< 0.01**
AMS 5045 carbon steel	0.8	**0.02**

"+" indicates weight gain

Result Conforms

Documents Provided:	• Alpine RF-11 Safety Data Sheet: https://irp.cdn-website.com/27e0cdf5/files/uploaded/Alpine%20RF-11%20SDS%20NA12062021F%20%28EN%29.pdf • Alpine RF-11 Technical Data Sheet: https://irp-cdn.multiscreensite.com/27e0cdf5/files/uploaded/ALPINE%20RF-11%20T%26M%20TDS.pdf

Product Name:	**Alpine RF-14F (https://www.nasi-tm.com/alpine-rf-14)**
Vendor:	Nachurs Alpine Solutions, LLC (https://www.nasi-tm.com/)
Description:	Alpine RF-14F is a 50% potassium formate liquid deicer.
Average Cost:	$9.50 per gallon

Environmental Test Results:	• BOD (5-day): 0.02 kg O_2/kg fluid
	• TOD/COD (5-day): 0.09 kg O_2/kg fluid
	• Aquatic Toxicity
	  ○ 48 hr LC_{50}: 550 mg/l
	  ○ 96 hr LC_{50}: 2,075 mg/l

Performance Test Results:	• Alpine RF-14F meets FAA requirements of the latest edition SAE AMS1435C specifications. • Alpine RF-14F has a freeze point of -63°F.

Ice Melting Results at 28.4°F (-2°C)

Deicer	Time Interval (minutes)	Ice Melting Capacity (Mim/Md)
Alpine RF-14F, 50% w/w	5	1.30
	10	1.60
	30	1.80

Ice Melting Results at 14°F (-10°C)

Deicer	Time Interval (minutes)	Ice Melting Capacity (Mim/Md)
	5	1.10

Alpine RF-14F, 50% w/w	10	1.30
	30	1.60

Ice Undercutting Results at 28.4°F (-2°C)

Deicer	Time Interval (minutes)	Ice Undercutting (mm^2)	Added Ice	Added Ice
Alpine RF-14F, 50% w/w	5	68.30	0.106	0.326
	10	86.20	0.134	0.366
	30	107.80	0.167	0.409

Ice Undercutting Results at 14°F (-10°C)

Deicer	Time Interval (minutes)	Ice Undercutting (mm^2)	Added Ice	Added Ice
Alpine RF-14F, 50% w/w	5	38.30	0.059	0.768
	10	48.30	0.075	0.274
	30	57.90	0.090	0.300

Ice Penetration Results at 28.4°F (-2°C)

Deicer	Time Interval (minutes)	Avg Penetration Depth	Added Avg
Alpine RF-14F, 50% w/w	5	4.00	0.157
	10	4.50	0.177
	30	6.00	0.236

Ice Penetration Results at 14°F (-10°C)

Deicer	Time Interval (minutes)	Avg Penetration Depth	Added Avg

Alpine RF-14F, 50% w/w	5	2.00	0.079
	10	3.50	0.138
	30	3.50	0.138

3.2.5.2 Total Immersion Corrosion: The fluid, tested in accordance with ASTM F 483 except that panels of AMS 4376 shall be tested for 24 hours, shall neither show evidence of corrosion of panels nor cause a weight change of any test panel greater than shown in Table 1:

TEST PANEL	WEIGHT CHANGE (mg/cm²/24hrs)	
	ALLOWABLE	RESULTS
AMS 4037 Aluminum Alloy, anodized as in AMS 2470	0.3	< 0.01
AMS 4041 Aluminum Alloy	0.3	< 0.01*
AMS 4049 Aluminum Alloy	0.3	< 0.01*
AMS 4376 Mg Alloy, dichromate treated as in AMS 2475	0.2	+ 0.02
AMS 4911 or MAM 4911 Titanium Alloy	0.1	+ 0.01
AMS 5045 Carbon Steel	0.8	0.01

Dulled / discolored

Result Conforms

Documents Provided:	• Alpine RF-14F Safety Data Sheet: https://irp-cdn.multiscreensite.com/27e0cdf5/files/uploaded/Alpine%20RF-14F%20SDS%20%28Blue%29%20REVUS012318F3.pdf • Alpine RF-14F Technical Data Sheet: https://irp-cdn.multiscreensite.com/27e0cdf5/files/uploaded/ALPINE%20RF-14F%20T%26M%20TDS.pdf

Product Name:	**GEN3 (https://www.nasi-tm.com/gen3-64)**
Vendor:	Nachurs Alpine Solutions, LLC (https://www.nasi-tm.com/)
Description:	GEN3 is a hybrid, potassium acetate, 63% active ingredients liquid deicer.
Average Cost:	$9.50 per gallon

Environmental Test Results:	• BOD (5-day): 0.24 kg O_2/kg fluid
	• TOD/COD (5-day): 0.65 kg O_2/kg fluid
	• Aquatic Toxicity
	    ○ 48 hr LC_{50}: 2,225 mg/l
	    ○ 96 hr LC_{50}: 4,150 mg/l

Performance Test Results:	• GEN3 meets FAA's AMS1435D specifications. • GEN3 has a freeze point of -54ºF.

Ice Melting Results at 28.4ºF (-2ºC)

Deicer	Time Interval (minutes)	Ice Melting Capacity (Mim/Md)
GEN3	5	1.24
	10	1.57
	30	2.02

Ice Melting Results at 14ºF (-10ºC)

Deicer	Time Interval (minutes)	Ice Melting Capacity (Mim/Md)
GEN3	5	0.81
	10	1.04
	30	1.44

Ice Undercutting Results at 28.4ºF (-2ºC)

Deicer	Time Interval (minutes)	Ice Undercutting (mm^2)	Added Ice	Added Ice
GEN3	5	48.30	0.073	0.270
	10	74.60	0.116	0.341
	30	98.50	0.153	0.391

Ice Undercutting Results at 14°F (-10°C)

Deicer	Time Interval (minutes)	Ice Undercutting (mm^2)	Added Ice	Added Ice
GEN3	5	17.50	0.027	0.164
	10	38.20	0.059	0.243
	30	56.50	0.088	0.297

Ice Penetration Results at 28.4°F (-2°C)

Deicer	Time Interval (minutes)	Avg Penetration Depth	Added Avg
GEN3	5	2.00	0.079
	10	3.50	0.138
	30	8.00	0.138

Ice Penetration Results at 14°F (-10°C)

Deicer	Time Interval (minutes)	Avg Penetration Depth	Added Avg
GEN3	5	2.00	0.079
	10	2.50	0.098
	30	3.50	0.138

AMS 1435D Periodic Tests Page 3 of 5

3.2.5.2 Total Immersion Corrosion: The product, tested in accordance with ASTM F483 (except the panels of AMS4376 that shall be tested for 24 hours), shall neither show evidence of corrosion of panels, nor cause a weight change of any test panel greater than shown in Table 1.

TEST PANEL	WEIGHT CHANGE ($mg/cm^2/24hrs$)	
	ALLOWABLE	RESULTS
AMS 4037 aluminum alloy, anodized as in AMS 2470	0.3	**0.04**
AMS 4041 aluminum alloy	0.3	**0.04**
AMS 4049 aluminum alloy	0.3	**0.04**
AMS 4376 magnesium alloy, dichromate treated per AMS 2475	0.2	**0.15**
AMS 4911 titanium alloy	0.1	**0.01**
AMS 5045 carbon steel	0.8	**0.04**

Result Conforms

Documents Provided:	• GEN3 Safety Data Sheet: https://bit.ly/3FfGWJ1 • GEN3 Technical Data Sheet: https://irp-cdn.multiscreensite.com/27e0cdf5/files/uploaded/Gen3%206-4%20T%26M%20TDS.pdf

Product Name:	**NASi-SF (https://www.nasi-tm.com/nasi-sf-dot)**
Vendor:	Nachurs Alpine Solutions, LLC (https://www.nasi-tm.com/)
Description:	NASi-SF is a solid sodium formate deicer.
Average Cost:	$2,235 per metric ton
Environmental Test Results:	From Safety Data Sheet: • Biological Elimination: >90% (Static Test, 7 Days) DIN 38 412-L25) Toxicity to Bacteria Eco: >10000 (OECD 209, After 3 Hours) • Daphnia Acute Toxicity Eco: 3.3 g/l (24h); 3.2 g/l (48h) • EC50: 4.8 g/l (24h); 4.4 g/l (48h) • Fish Toxicity LC50: 1000 m/l (96h, Zebra Fish, OECD 203) • BOD (5-day): 0.1 – 0.2 g O_2/g fluid

	• TOD/COD (5-day): 0.25 – 0.35 g O_2/g fluid
Performance Test Results:	• NASi-SF meets SAE AMS1431E specifications. • NASi-SF has a freeze point of -8°F.

3.2.9.2 Total Immersion Corrosion: The product, tested in accordance with ASTM F483, except that panels shall be AMS4376 tested for 24 hours, shall neither cause corrosion of test panels nor a weight change of any test panel greater than shown in Table I.

ALLOY	WEIGHT LOSS $mg/cm^2/24hrs$		
	Allowed	5 %	15 %
AMS 4037 Aluminum anodized per AMS 2470	0.3	0.01	0.02
AMS 4041 Aluminum	0.3	0.01	0.02
AMS 4049 Aluminum	0.3	0.01	0.02
AMS 4376 Magnesium, dichromate (AMS 2475)	0.2	0.11	0.13
AMS 4911 Titanium	0.1	0.04	0.03
AMS 5045 Carbon Steel	0.8	0.12*	< 0.01

"+" indicates weight gain
**Discoloration*

Result Conforms

Documents Provided:	• NASi-SF Safety Data Sheet: https://bit.ly/3gUgfAb • NASi-SF Technical Data Sheet: https://irp-cdn.multiscreensite.com/27e0cdf5/files/uploaded/NASi%20SF%20-%20DOT%20-%20T%26M%20TDS.pdf

New Deal Deicing (www.newdealdeicing.com)

Product Name:	**NEWDEAL Solid-Airfield Deicer (https://newdealdeicing.com/products/)**
Vendor:	New Deal Deicing (www.newdealdeicing.com)
Description:	NEWDEAL Solid-Airfield Deicer is a solid sodium acetate/formate blend deicer.

Average Cost:	$2,500 per ton

Environmental Test Results:	From Safety Data Sheet:
	
	• Degradability: Readily biodegradable
	• BOD5 (20°C): 0.13 kg O_2/kg solid
	• TOD/COD: 0.42 kg O_2/kg solid
	• Aquatic Toxicity:
	  ○ 48 hr LC_{50}: 4,125 mg/l (Daphnia magna)
	  ○ 96 hr LC_{50}: 8,050 mg/l (Pimephales promelas)

Performance Test Results:	• None Provided
Documents Provided:	• NEWDEAL Solid-Airfield Deicer Safety Data Sheet: https://newdealdeicing.com/wp-content/uploads/2020/09/NEWDEAL-SDS-OFFICIAL-COPY-9-23-20-compressed.pdf

OMEX (https://omexenvironmental.com/deicers)

Product Name:	**Isomex (https://omexcanada.com/products/specialty-products/47-isomex)**
Vendor:	OMEX (https://omexenvironmental.com/deicers)
Description:	Isomex is an aqueous solution of potassium acetate.
Average Cost:	$17 to $18 per gallon
Environmental Test Results:	From Safety Data Sheet: • Biochemical Oxygen Demand (BOD): 0.36 g O_2/g • Chemical Oxygen Demand (COD): 0.47 g O_2/g • Acute Toxicity: LD_{50} oral (rat)>5000 mg/l • Microtox EC_{50}: 0.3% solution (15 minutes) • Local Effects: Not classified as harmful if swallowed. Irritating to eyes but does not injure eye tissue. • Carcinogen Risk: No evidence.

Performance Test Results:	• None provided.
Documents Provided:	• Isomex Safety Data Sheet

Product Name:	**Isoway RTU (https://omexcanada.com/products/specialty-products/46-isoway)**
Vendor:	OMEX (https://omexenvironmental.com/deicers)
Description:	Isoway RTU is a liquid anti-icer containing 25% potassium acetate (KAc). Isoway RTU is generally used on sidewalks and footpaths or areas where ice buildup can create safety issues for pedestrians and users.
Average Cost:	$12 to $13 per gallon
Environmental Test Results:	None Provided
Performance Test Results:	• Isoway RTU is effective to temperatures as low as -13°F.
Documents Provided:	• Isoway Product Information Sheet

Product Name:	**Isomelt**
Vendor:	OMEX (https://omexenvironmental.com/deicers)
Description:	Isomelt is a granular sodium formate based deicer.

Average Cost:	$4.55 per kilogram
Environmental Test Results:	• None provided.
Performance Test Results:	• Isomelt is on the Clear Roads Qualified Products List.
Documents Provided:	• Isomelt Product Information Sheet: https://www.omex.com/wp-content/uploads/2019/05/Isomelt.pdf

Smith Fertilizer and Grain (https://sfgroadmaintenance.com/)

Product Name:	**Beet 55 (https://www.sfgroadmaintenance.com/products/beet-55/)**
Vendor:	Smith Fertilizer and Grain (https://sfgroadmaintenance.com/)
Description:	Beet 55 is a liquid organic additive derived from sugar beet molasses which is blended with salt brine.
Average Cost:	$1.65 per gallon
Environmental Test Results:	• None Provided.
Performance Test Results:	• Beet 55 is on the Clear Roads Qualified Products List. • Beet 55 can reduce salt application rates by 30 percent.
Documents Provided:	• Beet 55 Product Safety Data Sheet: https://www.sfgroadmaintenance.com/upl/downloads/products/sds-sheet.pdf • Beet 55 Product Fact Sheet: https://www.sfgroadmaintenance.com/upl/downloads/products/pds-sheet.pdf

	• Beet 55 Brochure: https://www.sfgroadmaintenance.com/upl/downloads/library/sfg-brochurespreads-102620.pdf

APPENDIX C – Additional References

BOD COD References from tables

1. National Academies of Sciences, Engineering, and Medicine. (2008) *Impact of airport pavement deicing products on aircraft and airfield infrastructure*. Washington, DC: The National Academies Press.
2. Nazari, M.H., Mousavi, S.Z., Potapova, A., McIntyre, J., Shi, X. (2021) Toxicological impacts of roadway deicers on aquatic resources and human health: A review. Water, Environmental Research. DOI: 10.1002/wer.1551
3. Nazari, M.H., Haves, E.A., Muthumani, A., Shi, X. (2019) Effects of processed agro-residues on the performance of sodium chloride brine anti-icer. ACS Sustainable Chemistry & Engineering, 7: 13655-13667.
4. Corsi, S.R., Mericas, D., Bowman, G.T. (2012) Oxygen demand of aircraft and airfield pavement deicers and alternative freezing point depressants. Water, Air, and Soil Pollution 223: 2447-2461
5. Plahuta, J.M., Teel, A.L., Ahmad, M., Beutel, M.W., Rentz, J.A., Watts, R.J., (2011) Oxidized Starch Solutions for Environmentally Friendly Aircraft Deicers
6. Switzenbaum, M.S., Veltman, S., Mericas, D., Wagoner. B., Schoenberg, T. (2001) Best management practices for airport deicing stormwater
7. Gibbs, D.P, Willing, B.L., (1992) Master's Thesis: A Study in Use and Management of De/Anti-Icing Constituents with Regard to New Storm Water Legislation
8. Fischel, M. (2001) Evaluation of selected deicers based on a review of the literature. Colorado DOT.
9. Nazari, M.H., and Shi, X. (2019) Developing Renewable Agro-Based Anti-Icers for Sustainable Winter Road Maintenance Operations
10. BioAmber Green Technologies (2011) Next Generation Deicing Solutions: Succinate Based Road and Runway Deicers Fact Sheet, https://paperzz.com/doc/8803811/succinate-based-road-and-runway-deicers
11. Cryotech (2021) E36 Liquid Runway Deicer Safety Data Fact Sheet https://www.cryotech.com/products/e36-liquid-runway-deicer
12. Taylor Development of an Improved Agricultural-Based Deicing Product
13. Janke et al. (1999) Deicing Composition and Method, U.S. Patent 5965058, Ice Ban USA, Inc.
14. Janke et al. (1999) Deicing Composition and Method, U.S. Patent 5922240, Ice Ban USA, Inc.
15. Janke et al. (1999) Deicing Composition and Method, U.S. Patent 5919394, Ice Ban USA, Inc.
16. Cryotech (2023) CF7 Liquid Commercial Deicer Safety Data Fact Sheet https://www.cryotech.com/images/docs/products/commercial/MKT302-CF7-SDS-2023.pdf
17. Cryotech (2021) Polar Plus LT Concentrate Safety Data Sheet https://www.cryotech.com/products/polar-plus-lt
18. Cryotech (2021) Polar Plus LT 63/37 Dilute Safety Data Sheet https://www.cryotech.com/products/polar-plus-lt
19. Cryotech (2021) Polar Plus LT 55/45 Dilute Safety Data Sheet https://www.cryotech.com/products/polar-plus-lt
20. Cryotech (2021) Polar Plus LT 50/50 Dilute Safety Data Sheet https://www.cryotech.com/products/polar-plus-lt
21. Cryotech (2022) Polar Guard Advance Safety Data Sheet https://www.cryotech.com/products/polar-guard-advance

22. Cryotech (2022) Polar Guard Xtend Safety Data Sheet https://www.cryotech.com/products/polar-guard-xtend
23. Cryotech (2023) NAAC Solid Deicer Safety Data Sheet https://www.cryotech.com/products/naac-solid-deicer?app=runway
24. Cryotech (2021) LC17 Safety Data Sheet
25. Cryotech (2021) QS50 Safety Data Sheet https://www.cryotech.com/products/qs50-solid-deicer
26. Cryotech (2023) CMA Safety Data Sheet https://www.cryotech.com/products/cma-solid-deicer?app=pavement
27. Cryotech (2023) CMA40 Safety Data Sheet https://www.cryotech.com/products/cma40-solid-commercial-deicer
28. Cryotech (2022) NAAC40 Safety Data Sheet https://www.cryotech.com/products/naac40-solid-deicer
29. Natil Academies (2010) ACRP Web-Only Document 8 : Alternative Aircraft Anti-icing Formulations with Reduced Aquatic Toxicity and Biochemical Oxygen Demand
30. Natil Academies (2010) ACRP Web-Only Document 3 : Formulations for Aircraft and Airfield Deicing and Anti-Icing
31. Bang, S.S. and Johnston, D. (1998) Environmental Effects of Sodium Acetate/Formate Deicer, Ice Shear
32. Clariant Corp (2018) Safeway SF Runway Deicer Safety Data Sheet
33. Hawkins (2021) Aqua Hawk KA-50 Pamphlet
34. Harmoney Deicing Liquid Potassium Acetate Runway Deicer webpage https://www.harmoneydeicing.com/runway-deicers
35. "NASi (2019) Alpine Ice-Melt Brochure https://irp.cdn-website.com/27e0cdf5/files/uploaded/Alpine%20Ice%20Melt%20SDS%20NA12062021F%20%28EN%29.pdf, RF-11 Brochure https://irp-cdn.multiscreensite.com/27e0cdf5/files/uploaded/ALPINE%20RF-11%20T%26M%20TDS.pdf"
36. NASi (2019) Alpine RF-14F Deicer Technical Data Sheet https://irp-cdn.multiscreensite.com/27e0cdf5/files/uploaded/ALPINE%20RF-14F%20T%26M%20TDS.pdf
37. NASi (2016) SF Safety Data Sheet https://irp-cdn.multiscreensite.com/27e0cdf5/files/uploaded/NASi%20SF%20Solid%20Sodium%20Formate%20SDS%20REV%2005272016.pdf
38. NEWDEAL (2020) Blend Solid Airfield Deicer Safety Data Sheet
39. OMEX_2000 Isomex 1 Safety Data Sheet
40. Clariant Corp (2019) Safewing MP I LFD 88 Safety Data Sheet https://www.fyvestar.com/faa-approved-deicers/
41. Clariant Corp (2016) Safewing MP IV LAUNCH Safety Data Sheet https://www.fyvestar.com/faa-approved-deicers/
42. Clariant Corp (2022) Safeway KF Hot Safety Data Sheet
43. Clariant Corp (2022) Safeway KF Safety Data Sheet
44. Clariant Corp (2022) Safeway KA Hot Safety Data Sheet
45. Clariant Corp (2021) Safewing MP I 1938 ECO (80)
46. Clariant Corp (2021) Safewing MP I ECO PLUS (80)

47. Clariant Corp (2021) Safewing EG I 1996 (80)
48. SERDP (2009) Final Report: Development of Environmentally Benign and Reduced Corrosion Runway Deicing Fluid
49. UCAR Aircraft Deicing Fluids for Safe Winter Operations https://www.dow.com/content/dam/dcc/documents/en-us/app-tech-guide/183/183-00021-01-ucar-aircraft-deicing-fluids-for-safe-winter-operations.pdf?iframe=true
50. UCAR Endurance EG106 Product Guide https://www.dow.com/documents/en-us/app-tech-guide/183/183-00101-01-ucar-endurance-aircraft-deicingantiicing-fluid-application-guide.pdf
51. UCAR PG Aircraft Deicing Fluids for Safe Winter Operations https://www.dow.com/content/dam/dcc/documents/en-us/app-tech-guide/183/183-00024-01-ucar-pg-aircraft-deicing-fluids-for-safe-winter-operations.pdf?iframe=true
52. Sulej (2012) Pollutants in Airport Runoff Water and EPA (2000) Preliminary Data Summary, Airport Deicing Operations (Revised) https://www.epa.gov/sites/default/files/2015-06/documents/airport-deicing-pds-2000.pdf

References for 5.9.2 Ice melting Capacity, Table 32

1. Nazari, M.H., Jamal, M., Green, D., Gonzalez, J., Beaurivage, S., Smith, H., Mislang, J., Potapova, A., Akin, M. (2022) Standardized Test Procedure for Ice Melting Capacity of Deicers, Task 1 & Task 2 Report. Clear Roads and Minnesota DOT.
2. Hansen, D., Halsey, L. (2019). “Validation of the Mechanical Rocker Test Method for Ice Melting Capacity (MRT-IMC)”. Final report prepared for the Nebraska Department of Transportation, Lincoln, NE.
3. Gerbino-Bevins, B.M., Tuan, C.Y. (2011). “Performance Rating of Deicing Chemicals for Winter Operations”. Nebraska Department of Roads, Materials & Research, SPR-P1(10)P

CLEAR ROADS
research for winter highway maintenance

Lead state:
Minnesota Department of Transportation
Research Services
395 John Ireland Blvd.
St. Paul, MN 55155