Evaluating Snow and Ice Control Chemicals for Environmentally Sustainable Highway Maintenance Operations

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Case Study

Evaluating Snow and Ice Control Chemicals for Environmentally Sustainable Highway Maintenance Operations

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Abstract: The use of chemicals and abrasives for highway winter maintenance operations is an essential strategy for ensuring a reasonably high level of service, yet the performance of such materials has to be balanced with their potential negative impacts on motor vehicles, transportation infrastructure, and the natural environment. In this context, this work presents a comprehensive and quantitative evaluation of snow and ice control chemicals currently used by various Idaho Transportation Department districts for highway maintenance operations, including rock salts (mainly solid sodium chloride), IceSlicer products (solid sodium chloride with trace amounts of other chlorides), and salt brines. The analysis has been enabled by the utilization of existing lab and field test data along with reasonable assumptions, in the effort to identify environmentally sustainable materials for winter highway operations. Despite its caveats, this case study is the first attempt to incorporate the most up-to-date information into a multicriteria decision making framework for the data-driven, holistic examination of various snow and ice control chemicals used by a maintenance agency. **DOI:** 10.1061/(ASCE)TE.1943-5436.0000709.

Introduction

The use of chemicals and abrasives for highway winter maintenance operations is an essential strategy for ensuring a reasonably high level of service (Strong et al. 2010; Fay and Shi 2011), yet the performance of such materials has to be balanced with their potential negative impacts on transportation infrastructure (Shi et al. 2009a, 2010a, b, 2011, 2012; Pan et al. 2008), the natural environment (Levelton Consultants 2008; Fay and Shi 2012; Fay et al. 2013), and motor vehicles (Li et al. 2013; Shi et al. 2009b, 2013a). To promote sustainable highway winter service, it is crucial to "strike the right balance in meeting multiple goals of highway winter maintenance, including safety, mobility, environmental stewardship, infrastructure preservation, and economics" (Shi et al. 2013b).

Previous research (Shi and Akin 2012) demonstrated a framework to enable "a holistic approach to anti-icer procurement or design." In this Idaho Transportation Department (ITD) case study, this framework is further extended for the evaluation of products beyond anti-icers. Instead, chemicals in liquid or solid forms are assessed under the same framework. Other improvements have been made to advance the quantification of performance and risks of various products as well. For instance, friction coefficient measurements on the pavement before and after the anti-icing and deicing operations have been incorporated into the characterization of product performance. The corrosive effects of products to rebars and dowel bars have been incorporated into the characterization of risks, along with the damaging effects of products to asphalt (and concrete) pavements. Finally, for the first time, the environmental risks of various products have been quantified to the best possible extent, taking into account average lethal concentration (ALC) for aquatic species, chemical oxygen demand (COD), biochemical oxygen demand (BOD), emission factor for air quality impairment, and chloride emissions into the natural environment (soil, vegetation, surface water, groundwater, etc.). The laboratory tests employed in this study include differential scanning calorimetry (DSC) thermograms, ice melting test at −9.4°C (15°F), deicer corrosion to carbon steel, and freeze-thaw damage of portland cement concrete (PCC) in the presence of diluted deicers. These are further supplemented by data published elsewhere and by assumptions.

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Methodology

In this work, a total of 13 rock salts, three IceSlicer products (Redmond Minerals, Redmond, Utah), eight salt brines, and a corrosion-inhibited magnesium chloride brine were examined. These 25 products were samples provided by various ITD districts to the research team for laboratory testing. In addition, the rock salt sample from Boise, Idaho, was also made into a 23% by weight salt brine for some laboratory testing and thus included in the comprehensive evaluation. The following sections briefly describe the laboratory tests conducted on the select ITD materials for snow and ice control. For simplicity, the term *deicer* is used from this point on to refer to the 26 aforementioned products. Furthermore, the analysis has been enabled by the utilization of existing lab and field test data along with reasonable assumptions.

DSC Thermograms

The performance characteristics of the 29 ITD deicers were assessed by measuring their DSC thermogram with a Q200 apparatus (TA Instruments, Salt Lake City, Utah). As the DSC provides thermal information about melting characteristics of each individual deicer, the DSC thermograms were used as a tool to identify outliers in each category of deicers. Simply put, the DSC measures the amount of thermal energy that flows into a deicer sample during the solid/liquid phase transition. In light of the substantial similarities between most products, the number of products for in-depth investigation was limited to a few in each category (as detailed later). This approach offered the most flexibility and efficiency for comparing various properties of select deicers and allowed the analysis of numerous similar products within a short time frame. The use of DSC to quantify deicer or anti-icer performance is relatively new (Akin and Shi 2012) and all solid products were made into a liquid at 23% by weight. The thermograms were measured in the temperature range of 25 to −60°C (77 to −76°F) with a cooling/heating rate of 2°C (3.6°F) per minute. The liquid deicer was first diluted using the liquid deicer to deionized water volume ratio of 1:2. Subsequently, approximately 10-μL samples were pipetted into an aluminum sample pan and hermetically sealed for DSC measurements. At least three samples were run for each anti-icer to minimize data variability. The first peak at the warmer end of the heating cycle thermogram was used to derive the characteristic temperature of the liquid deicer tested (T_c), which basically indicates the *effective* temperature below which ice crystals start to form in the solution. The enthalpy of fusion (H_c, integrated surface area of the characteristic peak) and T_c can be used to predict the ice melting capacity (IMC) of the liquid deicer at 60 min of application under −1.1°C (30°F) (Akin and Shi 2012). In this study, the DSC data are used in a distinctly different manner. Specifically, the logarithm of ΔH_c (345.1 J/g, i.e., the tested enthalpy of fusion for water minus the tested H_c) was used as an indicator of how powerful the deicer chemicals are when tested in liquid form. In the case of solid salts, their ΔH_c was first divided by 23% to enable reasonable comparison between solids and liquids.

SHRP Ice Melting Test at 15°F

Laboratory measurements of ice melting capacity of various deicers were conducted following the Strategic Highway Research Program (SHRP) H205.1 and H205.2 test methods (Chappelow et al. 1992). The SHRP H205.1 test measures the ice melting capacity of solid deicer pellets spread randomly across an ice surface of uniform thickness. The results of the test provide a measurement of the ice melting capacity of the deicer relative to the generated brine, or melted ice. The process was completed at −9.4°C (15°F). For liquid deicing solutions (SHRP H205.2), similar procedures were followed.

PNS/NACE Corrosion Test

Deicer products have been reported to pose a significant risk to bare metals used in vehicles and the transportation infrastructure new (Shi et al. 2009b). As such, the corrosive effects of various deicers to bare steel were tested following the National Association of Corrosion Engineers (NACE) standard TM0169-95 as modified by the Pacific Northwest Snowfighters (PNS). It measures the weight loss of carbon steel coupon samples that are cyclically immersed in deicer solutions and reports the percent corrosion rate (PCR) to indicate the corrosivity of the deicer solution relative to solid salt and deionized water. The metal coupons were purchased from Ad-Tek, and were 0.5-in. flat steel washers ($9.7 \times 14.2 \times 2.8$ mm, or $0.38 \times 0.56 \times 0.11$ in.) with an average density of 7.85 g/cm^3. The metal coupons were cleaned by placing in 1 + 1 hydrochloric acid for 2–3 min. The coupons were rinsed in tap water, then deionized water, then wiped dry and placed in chloroform. The coupons were then placed in the fume hood and were allowed to dry for 15 min. The coupons were then weighed and placed on the corrosion testing machine (Corrosion Testing Machine CTM10-10/50, Ad-Tek). The corrosion testing machine cyclically lowered the three metal coupons for 10 min into a 3% deicer solution and then raised the metal coupons into ambient air for 50 min. This cycle continued every hour for 72 h. The solid deicers were 3% weight-to-volume solutions were made and for liquid deicers were 3% volume-to-volume solutions. The final weight of the coupons was recorded after 72 h of cyclic testing and cleaning.

SHRP Test of Diluted Deicers on Freeze-Thaw Damage of PCC

Deicer products have been reported to pose a significant risk to PCC used in the transportation infrastructure (Shi et al. 2010a, 2011). The risks of diluted liquid deicers on concrete were assessed by conducting freeze-thaw tests of PCC samples in the presence of diluted deicers, following the SHRP H205.8 test method with minor modifications. The test evaluates the combined effects of liquid chemicals and freeze-thaw cycling on the structural integrity of specimens of non-air-entrained concrete. Concrete samples were made in 51 mm diameter × 102 mm length (2 in. × 4 in.) poly (vinyl chloride) piping with a volume of 206 cm^3. The concrete mix design had a water-to-cement ratio of 0.55, a slump of 25 mm (1 in.) and air content of 2.9% (with a commercial air entraining agent admixed at 0.006% by the mass of cement). Samples were cured in the mold in the first 24 h before being demolded and cured in open air for another 27 days with a relative humidity of 25 ± 5%, the average 28-day compressive strength of three test cylinders was 34 MPa (4,933 psi). The concrete sampled were then further cured in a water bath at 20°C for 7 days then at 60°C for 24 h. The average compressive strength increased to 51.5 MPa (7,474 psi). Before immersion in anti-icer solution, the concrete samples were cut to a final length of 76 mm (3 in.). The dry weight of each sample was recorded before placing it on a sponge inside a dish containing 310 mL of diluted (3%) anti-icer solution. The dish was covered in plastic wrap to press the concrete samples into the sponge. Three concrete specimens were tested in each anti-icer solution. There were two controls: (1) a 3% NaCl solution and (2) deionized water. A thermocouple was embedded in one of the control concrete samples to monitor temperatures during freeze-thaw cycling. The sealed dishes were placed in the freezer for 16 to 18 h at -17.8 ± 2.7°C (0 ± 4.9°F), then placed in the laboratory environment at 23.0 ± 1.7°C (73.4 ± 3°F) for 6 to 8 h. This cycle was repeated for 10 times. The test specimens were then removed from the dish and rinsed under running water to remove any scaled-off material. The specimens were air-dried overnight before the final weight of each was recorded.

Results and Discussion

The following sections will provide a detailed analysis of the 26 ITD deicers. The analysis will examine three aspects of using deicers, i.e., cost, performance (mainly for anti-icing and deicing), and risks. Subsequently, these data will be normalized between 0 and 100 and then used to calculate a *composite index* for each product. The value of this index will be very valuable for the comprehensive evaluation of available options in the snow and ice control materials and for the collaborative decision making by maintenance agencies such as ITD.

Based on the DSC measurements (parameters of T_c and H_c), four salts (AF, BLKFT, Firth, and Boise) were identified as outliers (T_c or H beyond the range of mean value $\pm$ standard deviation). The standard deviation was 0.4°F and 9.5 J/g for T_c and H_c, respectively. While all the solid salts were provided by various Idaho districts, their main ingredient is rock salt and the difference in performance may be attributed to the trace elements in them. The remaining 10 salts were considered *regular salt* (CW, Kiln salt Pocatello, Kiln salt Mn St., Road salt with anticaking, Road salt Bannock Cr, Road salt Pocatello, Downey, Malad, McCammon, and Boise). Three IceSlicer products were individually tested, i.e., AF slicer, IceSlicer BLKFT, and IceSlicer Malad, even though the last two showed similar DSC fingerprint. The DSC data also suggested two salt brines (BLKFT brine and Pocatello brine) as outliers whereas the remaining seven brines were considered *regular brine* (AF brine, Downey brine, Malad brine, McCammon brine, Tank 5, CW brine, and the 23% brine made from the Boise salt). For the regular brine samples, the standard deviation was 0.2° F and 10.4 J/g for T_c and H_c, respectively. A 30% by weight corrosion-inhibited magnesium chloride ($MgCl_2$) liquid deicer from Boise was also included in the testing program. As shown in Fig. 1, the two outlier brines and the $MgCl_2$ liquid deicer exhibited significantly different characteristic peak fingerprints (T_c and H_c) in their DSC thermograms, compared to the other brines.

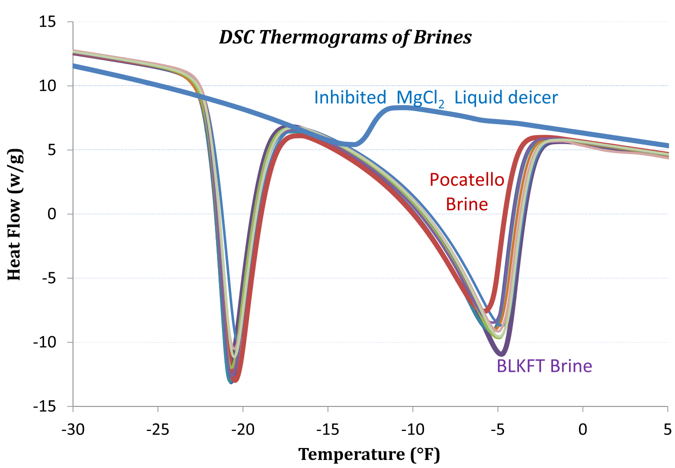

Fig. 1. DSC thermograms of brines, with the two outlier brines and the inhibited $MgCl_2$ liquid deicer highlighted; warming cycle, 2°C/min (3.6°F/min)

Relative Cost of ITD Deicers

The choice of using different deicer products for winter highway operations is expected to significantly affect the overall cost of such activities, assuming that different products were used to achieve a comparable level of service (LOS). It is well recognized that the direct costs include those in materials (storage cost, cost per ton, or per lane mile, or per storm), equipment (engine hours, fuel costs, etc.), and staffing (wages and benefits, overtime/standby time, training costs, etc.). In addition, the indirect costs of deicers mainly include those associated with negative impacts to motor vehicles, transportation infrastructure, and the natural environment.

Transportation agencies (including ITD) often do not have accurate or systematic records of the direct equipment and staffing cost items associated with specific winter maintenance products, let alone indirect costs. In this context, the cost of deicers examined will be presented by deicer category, instead of being product specific. Fitch et al. (2013) reported the cost of using chemicals for highway winter operations, with solid salts and salt brine at \$3,149 and \$3,343 per typical storm per 100 lane miles, respectively. This indicates an insignificant difference on a cost per storm basis. From the ITD survey results (Ye et al. 2013), the weighted average application rate for both the $MgCl_2$ liquid deicer and (23% NaCl) salt brines was approximately 28 gal. per lane mile and their average material cost can be estimated to be \$0.72/gal. and \$0.14/gal., respectively. This indicates considerable difference on a cost per gallon basis.

In this study, the cost of using various materials for highway snow and ice control was estimated by examining the documented labor, equipment, and materials expenditures for select study routes. The annual (direct) cost per lane mile was estimated to average \$123, \$121, and \$263 when using salt, salt brine, and corrosion-inhibited magnesium chloride ($MgCl_2$) liquid deicer on Idaho highways, respectively (Ye et al. 2013). Relative to salt, the use of salt brine was slightly more cost effective as a result of being a more proactive tool for maintaining the target LOS. The higher cost of using $MgCl_2$-based product is likely due to the inclusion of corrosion inhibitor in the product. Note that sand is a relatively inexpensive material but costs of environmental damage caused by repeated applications along with substantial cleanup costs can make it a less cost-effective alternative (Fay et al. 2010). Even after cleanup, 50 to 90% of the sand may remain in the environment (Parker 1999).

Performance Characteristics of ITD Deicers

This section is devoted to the quantitative analysis of performance characteristics of various ITD deicers, as characterized by the following four parameters: (1) effective temperature estimated from the eutectic curve of each product, T_e; (2) ice melting potential indicator, $\log(\Delta H_i)$, calculated from the DSC thermogram; (3) measured IMC, $\mathrm{IMC}_{15°\mathrm{F},60\ \mathrm{min}}$, as shown in Fig. 2; and (4) friction coefficient averaged from field measurements on the treated asphalt pavements, f_c (Akin et al. 2014). As indicated in Table 1, the data of most solid salts and most salt brines were grouped under *regular salt* and *regular brine* due to the great similarity in the DSC data within each group.

Fig. 2 illustrates the temporal evolution of ice melting capacity of various deicers (along with two ITD sand:salt mixtures) at −9.4°C (15°F). One sand-salt mixture exhibited little ice melting capacity, whereas the other one exhibited some ice melting capacity slightly higher than 1 mL/g deicer at 60 min. This inconsistency is mostly attributable to the difficulty in obtaining a representative sample from such solid mixtures, and the icemelt observed is a function of the salt content in the random sample. The 30%

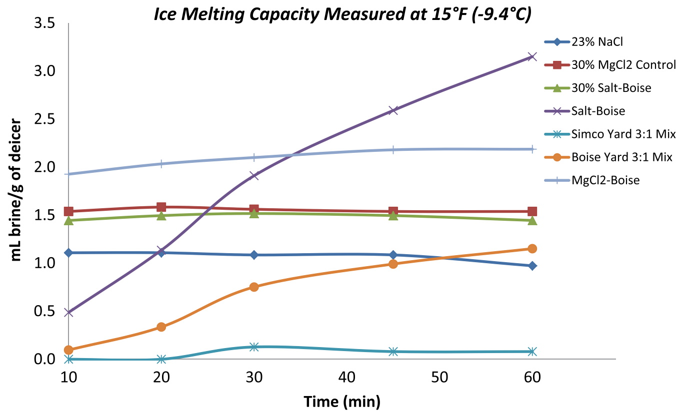

Fig. 2. Ice melting behavior of select ITD deicers at −9.4°C (15°F)

$MgCl_2$ control solution made from analytical-grade solid magnesium chloride hexahydrate exhibited ice melting behavior similar to that of supersaturated (30%) salt brine made from Boise rock salt. In contrast, the commercial 30% $MgCl_2$ liquid deicer from Boise exhibited significantly higher ice melting capacity, likely due to the additives in the latter. Finally, the solid rock salt from Boise produced considerably more ice melt than the liquid brines at 60 min of application. When solid NaCl is applied on ice, sufficient time (e.g., 60 min) should be allowed in order to achieve its full potential. This is consistent with the authors' previous study (Shi et al. 2013a).

The data shown in Table 1 illustrate the overall comparison in the performance of the select ITD deicers. The lower the T_e, the more likely the deicer would still work (instead of refreeze) under colder temperatures. The higher the $\log(\Delta H_c)$ and $\mathrm{IMC}_{15°\mathrm{F},60\ \mathrm{min}}$, the more powerful the deicer is. The higher the f_c value, the more friction benefits the deicers would bring to asphalt pavement surface during snowy weather. Table 1 reveals that among the ITD deicers, the $MgCl_2$ liquid deicer featured the lowest T_e value, whereas the solid salts featured the highest $\log(\Delta H_c)$, $\mathrm{IMC}_{15°\mathrm{F},60\ \mathrm{min}}$, and friction coefficient values.

For estimating the T_e from the eutectic curve of each product, the following equation was used to assume a weighted average of freezing point temperature from three possible dilution scenarios

$$T_e = (3 \times \mathrm{FP}_{25\%\mathrm{AAC}} + 2 \times \mathrm{FP}_{50\%\mathrm{AAC}} + \mathrm{FP}_{\mathrm{AAC}})/6 \quad (1)$$

Table 1. Performance Characteristics of the ITD Deicers

Deicer type	T_e from eutectic curve [°C (°F)]	Log (ΔH_c) (log, J/g)	$\mathrm{IMC}_{15°\mathrm{F},60\ \mathrm{min}}$ (mL/g, by as-received deicer)	Average friction coefficient, f_c
AF salt	−5.2 (22.7)	2.92	3.15	0.33
BLKFT salt	−5.2 (22.7)	2.92		
Firth salt	−5.2 (22.7)	2.85		
Boise salt	−5.2 (22.7)	2.92		
Regular salt	−5.2 (22.7)	2.88 ± 0.01		
AF slicer	−5.2 (22.7)	2.88	3.15	0.33
IceSlicer BLKFT	−5.2 (22.7)	2.78		
IceSlicer Malad	−5.2 (22.7)	2.77		
BLKFT brine	−7.7 (18.1)	2.22	1.10	0.32
Pocatello brine	−7.7 (18.1)	2.31		
Regular brine	−7.7 (18.1)	2.26 ± 0.02		
30% $MgCl_2$ Boise	−13.9 (7.0)	2.30	2.19	0.30

where T_e = average effective temperature estimated from the eutectic curve (°F); FP = freezing point temperature; and AAC = as-applied concentration.

The eutectic curve of the 30% $MgCl_2$ liquid deicer was provided by ITD for analysis, whereas that of salt brines was adopted from a web source (Varitech Industries 2013). For solid salt, both $\mathrm{FP}_{50\%\mathrm{AAC}}$ and $\mathrm{FP}_{\mathrm{AAC}}$ was assumed to be 32°F since both concentrations exceeded the saturation point of NaCl brine, whereas $\mathrm{FP}_{25\%\mathrm{AAC}}$ (i.e., FP of 25% sodium chloride solution) was assumed to be 13.3°F. Finally, the f_c value of NaCl brines and 30% $MgCl_2$ liquid deicer was averaged from friction coefficient measurements on asphalt pavement during field operational tests conducted in Ohio in March 2013, with simulated traffic. Specifically, the f_c value of each was averaged between anti-icing (five measurements at 7 h after anti-icer application and then at 30 min after snow being trafficked) and deicing scenarios (five measurements at 30 min and then at 60 min after deicer application). The f_c value of solid salts, in contrast, was only averaged from friction coefficient measurements at the two stages of the deicer scenario.

Relative Risk of ITD Deicers on Infrastructures and Vehicles

This section is devoted to the quantitative analysis of how various ITD deicers affect the motor vehicles and transportation infrastructure, as characterized by the following five parameters: (1) corrosion to bare carbon steel, in terms of PCR measured by the PNS/NACE test; (2) average corrosion rate of rebar (steel bars in bridge or pavement concrete mixes) and dowel bar (MMFX and stainless steel tube in pavement concrete) after 254 days of continuous or cyclic immersion in deicers at 31% of as-applied concentration, i_{corr} (Shi et al. 2010b); (3) damage to half-air-entrained PCC by the combined action of 10 freeze-thaw cycles and diluted deicer (3% of as-applied concentration), in terms of weight loss, *WLd*, as illustrated in Fig. 3; (4) damage to air-entrained PCC concrete by the combined action of concentrated deicer (14% $MgCl_2$ and 18% NaCl) and 300 freeze-thaw cycles, in terms of loss in the dynamic modulus of elasticity, *MLc* (Sutter et al. 2008); and (5) loss in the Marshall stability of asphalt concrete in the presence of deicer solution, *MSL* (Özgan et al. 2013).

The data shown in Table 2 illustrate the overall risks to vehicles and infrastructure associated with the use of the select ITD deicers. The lower the PCR and i_{corr}, the less likely the deicer would cause corrosion to the bare steel or bars embedded in concrete. The lower the *WLd* and *MLc* values, the less negative impacts the deicer would likely cause to PCC, which is a crucial construction material for bridges and other infrastructure. The lower the *MSL* values, the less negative impacts the deicer would likely cause to asphalt concrete, which is the most common material used for pavement infrastructure. Table 2 reveals that among the ITD deicers, the $MgCl_2$ liquid deicer featured the lowest i_{corr}, PCR, *WLd*, and *MSL* values, whereas the salts and salt brines featured the lowest *MLc* values. The low *WLd* value associated with the diluted $MgCl_2$ deicer is consistent with previous studies (Fay and Shi 2011; Shi et al. 2010a), indicating the minimal role of such solution in aggravating the physical scaling of concrete. The high *MLc* value associated with the concentrated $MgCl_2$ deicer has also been confirmed in the authors' unpublished laboratory testing results, which is attributable to the chemical mechanism by which the magnesium chloride attacks the cementitious phases of the concrete (Shi et al. 2010a, 2011).

Note that for measuring the PCR, the solids (salts and IceSlicers) were made into a 3% weight-to-volume solution, whereas the liquid deicers were made into 3% volume-to-volume

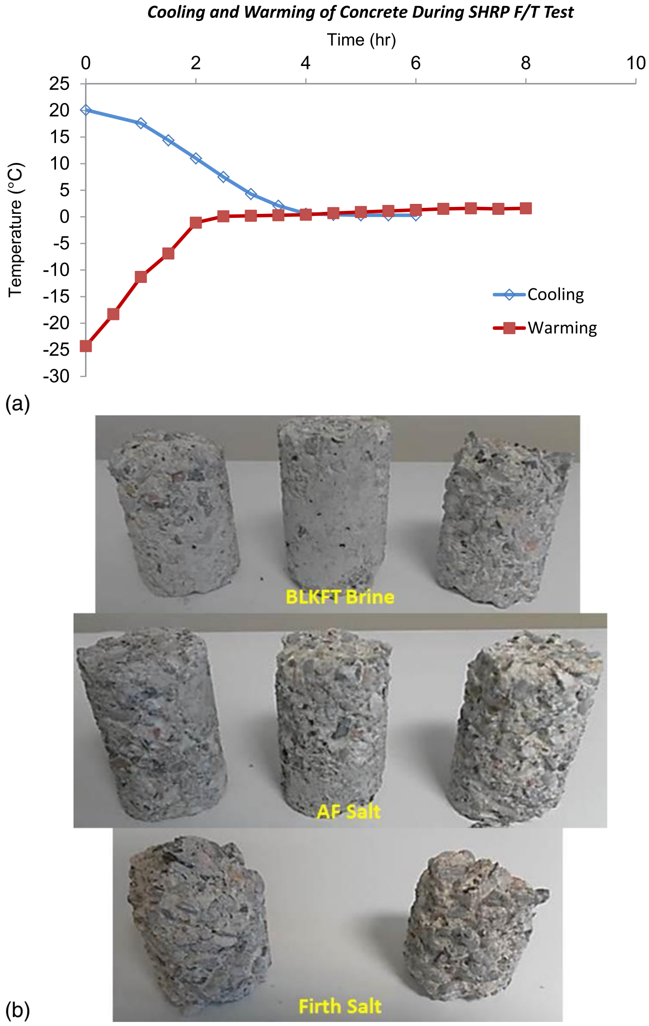

Fig. 3. SHRP H205.8 test: (a) cooling and warming rates during each cycle inside the concrete specimens; (b) select photos of concrete specimens after the testing of 10 cycles

solutions. In light of the lack of available data, the *MLc* value of all solid salts and salt brines were assumed to be equal to that of 18% NaCl, whereas the *MLc* value of the 30% $MgCl_2$ liquid deicer was assumed to be equal to that of 14% $MgCl_2$ (Sutter et al. 2008). Finally, the *MSL* value of salt brines and solid salts was assumed to equal to that of 1M NaCl and 4M NaCl solutions, respectively, whereas the *MSL* value of the 30% $MgCl_2$ liquid deicer was assumed to be that of 1M calcium chloride solution (Özgan et al. 2013).

Table 3. Risk of ITD Deicers on the Natural Environment

Deicer type	ALC (g/L)	COD (mg/L)	BOD (mg/L)	Air quality (emission factor, mg/km)	Cl^- emissions (kg, per lane mile)
All salts	3.04	6,209	1,085	26.4	204
All IceSlicers	3.04	6,209	1,085	26.4	204
All 23% salt brines	13.22	3,725	651	6.1	130
30% $MgCl_2$ Boise	2.58	27,800	4,860	7.9	208

Relative Risk of ITD Deicers on the Natural Environment

This section is devoted to the quantitative analysis of how various ITD deicers affect the natural environment, as characterized by the following five parameters: (1) average lethal concentration (ALC) for aquatic species; (2) chemical oxygen demand (COD); (3) biochemical oxygen demand (BOD); (4) risk to air quality, in terms of average aggregate emission factor or EF_a, where EF was "calculated by dividing the total flux of particulate matter (PM) perpendicular to the road by the number of vehicles passing the (sampling) tower" (Gertler et al. 2006); and (5) chloride anion emission, *ClE*, which was estimated for the amount released per lane mile "during a typical storm in the piedmont region of Virginia" (Fitch et al. 2013). Note that chloride anions are not degradable in the environment and their accumulation over time thus poses a significant risk not only to vehicles and infrastructure but also to soil, vegetation, wildlife habitat, and possibly human health.

The data shown in Table 3 illustrate the overall risks to the natural environment associated with the use of the select ITD deicers. The higher the ALC, the less likely the deicer would pose toxicological effects to aquatic species. The lower the COD and BOD, the less likely the deicer would lead to significant reduction in the concentration of dissolved oxygen in the surrounding environment such as receiving soil and water bodies. Finally, the EF and *ClE* indicate the air quality risk and the amount of chloride emission into the environment, respectively, and lower values are desirable.

Table 2. Vehicle and Infrastructure Implications of the ITD Deicers

Deicer type	Corrosion to bare steel, *PCR*	Corrosion rate of rebar or dowel bar, i_{corr} ($\mu A/cm^2$)	Damage to concrete, *WLd* (percentage)	Damage to concrete, *MLc* (percentage)	Effect on asphalt pavement, *MSL* (percentage)
AF salt	81.8	2.09	10.4	5	13.7
BLKFT salt	70.7		21.1		
Firth salt	73.6		39.4		
Boise salt	86.3		34.2		
Regular salt	95.9		20.0		
AF slicer	72.6	2.09	35.4	5	13.7
IceSlicer BLKFT	78.3		19.5		
IceSlicer Malad	76.5		37.3		
BLKFT brine	84.6	2.01	15.7	5	10.3
Pocatello brine	85.8		18.2		
Regular brine	85.8		18.2		
30% $MgCl_2$ Boise	16	0.95	0.2	50	1.4

Table 4. Normalized Assessment of ITD Deicers by the Cost, Performance, and Infrastructure Risk Parameters

Normalized data	Low cost per storm per 100 lane miles	Low T_e	High log (ΔH_c, J/g)	High IMC15°F, 60 min	High average friction	Low corrosion to steel	Low corrosion of bars	Low damage to concrete (diluted)	Low damage to concrete (concentrated)	Low risk to asphalt concrete
AF salt	100	33	87	100	58	54	63	80	100	0
BLKFT salt			83			62		58		
Boise salt			83			51		32		
Regular salt			61 ± 9			45		60		
AF slicer			61			61		29		
IceSlicer BLKFT			2			57		61		
IceSlicer Malad			0			58		26		
BLKFT brine	96	47	48	0	56	52	65	69	100	25
Pocatello brine			100			52		64		
Regular brine			77 ± 7			52		64		
30% $MgCl_2$ Boise	0	79	63	53	50	100	100	100	18	90
Max	\$ 7,960	1.1°C (34°F)	2.94	5 mL/g	0.5	160	4 $\mu A/cm^2$	50%	60%	13.7%
Min	\$ 3,149	−17.8°C (0°F)	2.77	0 mL/g	0.1	16	0 $\mu A/cm^2$	0%	0%	0%

Table 3 shows that among the ITD deicers, the salt brines featured the lowest COD, BOD, EF, and *ClE* values as well as the highest ALC values.

Note that for estimating the ALC, the following five parameters were averaged for each deicer: LC_{50} (96 h, *trout*), IC_{25} (7 days, *Ceriodaphnia*), IC_{50} (7 days, *Ceriodaphnia*), IC_{25} (7 days, *Selanastrum*), and IC_{50} (7 days, *Selanastrum*). These aquatic toxicity data for solid salts and the 30% corrosion-inhibited $MgCl_2$ liquid deicer were provided by the ITD. For the 23% salt brine, its ALC was estimated by dividing that of solid salt by its NaCl weight concentration. The BOD and COD data for the 30% corrosion-inhibited $MgCl_2$ liquid deicer were provided by the ITD. For simplicity, the BOD data recently reported by Fitch et al. (2013) were adopted for solid salts and salt brines, and their missing COD data were infilled assuming that their COD to BOD ratio follows that of the $MgCl_2$ liquid deicer. Note that typical winter traction sand contains only trace amounts of toxic substances, yet a high sand content in the spring stormwater runoff may cause toxic effects to aquatic species, since abrasives can reduce oxygen in streambeds and cause increased turbidity (Staples et al. 2004; Fay and Shi 2012).

For estimating the EF_a from the PM_{10} and $PM_{2.5}$ data, the following equation was developed to assume a weighted average of EF from these two groups of particulate matters

$$EF_a = [(EF_{2.5} - 76) \times (1/6.25) + (EF_{10} - 229) \times (1/100)]/(1/6.25 + 1/100) \quad (2)$$

where EF_a = average emission factor (mg/km); EF_{10} and $EF_{2.5}$ = emission factor of PM_{10} and $PM_{2.5}$ particles after the deicer application, with their baseline concentration before any deicer application being 229 and 76 mg/km, respectively; and 1/6.25 and 1/100 = decision weights of the two types of particles based on their relative exposed surface area, with smaller particles posing bigger risk to air quality.

The baseline concentrations and EF data of solid salts were obtained from a case study reported by Gertler et al. (2006). For simplicity, the EF_a value of the 23% salt brine and the 30% $MgCl_2$ liquid deicer was estimated by multiplying that of solid salt by their weight concentration, respectively. The *ClE* data of solid salts and 23% salt brines were adopted from those recently reported by Fitch et al. (2013), whereas the *ClE* value of the 30% $MgCl_2$ liquid deicer was derived from its relative Cl^- loading relative to that of 23% NaCl.

Collaborative Decision Making for Deicer Selection

This section is devoted to the comprehensive assessment of the deicer performance and risks by normalizing the aforementioned data on the selected 16 parameters (as shown in Tables 4 and 5) and then integrating them into a single composite index (as shown in Table 6). This approach enables collaborative decision making for deicer selection as the normalized data present a holistic overview on the multiple dimensions of this crosscutting issue. Different from the authors' previous studies (Shi and Akin 2012; Fay and Shi 2012), this study assumes equal user priority within each deicer dimension and between the four select dimensions (Table 6). This is based on the general observation obtained from the results of surveying the ITD district highway winter maintenance practitioners, in which the economics, performance (safety and mobility), infrastructure preservation, and environmental stewardship were considered equally important. In other words, if an ITD district or maintenance shed would consider a different set of assumptions and user priorities for its specific region or road segments, the calculation of the values in all the tables (including the composite index) would change accordingly. Furthermore, *what-if* analysis can be conducted to demonstrate how the deicer selection can be change as a function of assumptions and/or user priorities.

Four different methods were utilized for the normalization of the experimental or estimated data for each deicer, using the

Table 5. Normalized Assessment of ITD Deicers by the Select Environmental Risk Parameters

Normalized data	High ALC	Low COD	Low BOD	Low air risk	Low Cl^- emissions
AF salt	43	45	47	0	2
BLKFT salt					
Boise salt					
Regular salt					
AF slicer					
IceSlicer BLKFT					
IceSlicer Malad					
BLKFT brine	100	60	63	80	38
Pocatello brine					
Regular brine					
30% $MgCl_2$ Boise	37	0	0	73	0
Max	50 g/L	100 g/L	10 g/L	79 mg/km	208 kg/l-mi
Min	1 g/L	1 g/L	0.2 g/L	1 mg/km	1 kg/l-mi

Table 6. Normalized Assessment of ITD Deicers by the Select Four Dimensions and the Composite Indices Calculated from Them

Normalized data	Cost per lane mile	Average performance	Infrastructure/vehicle Impacts	Environmental impacts	Composite index
AF salt	100	73	59	27	65
BLKFT salt		86	57	27	55
Firth salt		83	49	27	53
Boise salt		86	49	27	54
Regular salt		73 ± 3	53	43	51 ± 1
AF slicer		84	50	27	54
IceSlicer BLKFT		79	56	27	54
IceSlicer Malad		79	49	27	52
BLKFT brine	96	26	62	68	63
Pocatello brine		6	60	68	45
Regular brine		11 ± 13	60	68	50 ± 10
30% $MgCl_2$ Boise	0	61	82	22	41
Max	100	86	82	68	65
Min	0	2	49	22	41

maximum and minimum values shown in Tables 4 and 5 for each select parameter. The ultimate goal is ensure that a deicer with a desirable attribute (e.g., low effective temperature) would have a reasonably high score and a deicer with an undesirable attribute (e.g., high corrosivity) would have a reasonably low score on the specific parameter of interest. First, the $\log(\Delta H_c)$, $IMC_{15°F,60\ min}$, and f_c values were normalized via $X_{normalized} = [(X - X_{min})/(X_{max} - X_{min})] \times 100$ as the higher values are desirable. Second, the COD and BOD values were normalized via $X_{normalized} = 100 - [(\lg X - \lg X_{min})/(\lg X_{max} - \lg X_{min})] \times 100$. Third, the ALC values were normalized via $X_{normalized} = [(\lg X - \lg X_{min})/(\lg X_{max} - \lg X_{min})] \times 100$. Finally, all the other values were normalized via $X_{normalized} = 100 - [(X - X_{min})/(X_{max} - X_{min})] \times 100$ as the lower values are desirable.

Table 6 presents the final results of the quantitative analysis. One caveat is that in the absence of sensitivity analysis, it is unclear how the error in the raw data would propagate through the calculation of composite index. In other words, it is uncertain whether the differences in rankings are statistically significant or not. Under the established evaluation framework, one can conclude that AF salt featured the highest composite index of 65 and thus should be considered a best practice where the road weather scenario allows its effective use. Some salt brines also featured relatively high composite indices. The inhibited $MgCl_2$ liquid deicer featured the lowest composite index of 41 among the investigated chemicals.

Arguably, brines, solid salts, and sand-salt mixtures are integral components of the highway winter maintenance toolbox and they are best suitable for different application scenarios. For instance, for anti-icing on relatively warm pavement, NaCl brine is likely the best product to use; yet $MgCl_2$ brine would be a better choice to use for cold pavements, such as −12.2°C (10°F) or lower. For deicing, the choice between brines, solid salts, and sand-salt mixtures will hinge on how quickly one has to achieve a relatively bare pavement under the existing amount of snow accumulation and whether or not a temporary traction layer is needed on the pavement. Thus, it would be beneficial to establish separate models for different road weather scenarios, instead of relying on a single generalized model to make decisions on deicer selection. To this end, more laboratory and (ideally) field testing would be required.

Concluding Remarks

Currently, there are considerable data gaps when it comes to the quantification of deicer performance and impacts and their comprehensive assessment for decision making. Nonetheless, this work is an important step towards the right direction, aimed to enable maintenance agencies to make informed and defensible decisions following an established methodology to balance the multiple dimensions of using chemicals and abrasives for winter highway operations. Note that the quantitative evaluation of various materials were made possible by adopting data either from laboratory testing or field testing conducted by the authors' group at the Western Transportation Institute, or from our survey of the ITD practitioners, or from recently published literature, among other sources. Furthermore, whenever necessary, reasonable assumptions were made in order to bridge the data gaps that currently exist in certain aspects related to the performance or risks of the select snow and ice control materials.

There are caveats in the quantitative analysis in light of discrepancies inherent in extending data from the laboratory testing or from field studies in other regions to the State of Idaho road weather scenarios. There is still a lack of reliable correlation between data from current laboratory methods employed to assess deicer performance and field performance data of deicer products. In other words, the performance parameters used in Table 1 summarize the current approach to predicting actual field performance in light of various aspects of deicer performance, yet there is a need for experimental validation of their predictive strength. Current methods employed to assess the environmental risks (e.g., aquatic toxicity) do not adequately reflect field exposure scenarios. For instance, stormwater discharge from winter chemical use is largely a seasonal event, i.e., late winter and early spring when various biota are in low metabolic resting phase. Yet current EPA toxicity testing assumes full metabolic incorporation of potential pollutants. In addition, it is known that the performance and impacts of snow and ice control products tend to be site specific and can vary as a function of the localized pavement conditions, the prevailing climatic conditions, the receiving water body, the traffic volume, the nearby infrastructure, among other site characteristics. Finally, additional data would be desirable to enable sensitivity analysis and to validate the calculation of composite index for each product of interest.

In light of the data gaps identified through this work, additional research is much needed for better quantification of cost effectiveness, performance (friction behavior at different times of anti-icing, deicing, and sanding practices as a function of pavement type and deicer type, deicer longevity on the pavement, etc.), infrastructure impacts (e.g., field risk to bare metals, rebars, dowel bars as a function of deicer type), and environmental impacts (e.g., aquatic toxicity and air quality risks by deicer type and deicer longevity on the road surface, and dilution dynamics). In addition to composite index, other approaches, such as an analytical hierarchy process (Subramanian and Ramanathan 2012), may be adopted to facilitate the multicriteria decision analysis pertinent to this crosscutting issue.

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