

## Deicing performance of common deicing agents for winter maintenance with and without corrosion-inhibiting substances

Michael R. Gruber<sup>a,\*</sup>, Bernhard Hofko<sup>a</sup>, Markus Hoffmann<sup>b</sup>, David Stinglmayr<sup>c</sup>, Teresa M. Seifried<sup>c</sup>, Hinrich Grothe<sup>c</sup>

<sup>a</sup> TU Wien, Institute of Transportation, Karlsplatz 13/E230-3, 1040 Vienna, Austria

<sup>b</sup> Hoffmann Consult e. U. & TU Wien, Institute of Transportation, Fürst-Liechtenstein-Str. 13, 1230 Vienna, Austria

<sup>c</sup> TU Wien, Institute of Materials Chemistry, Getreidemarkt 9/E165-01-5, 1060 Vienna, Austria

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### ABSTRACT

Sodium chloride (SC) is by far the most cost-effective deicing agent in winter road maintenance and therefore is used by road authorities worldwide. However, chloride ions foster high corrosivity, which significantly reduces the service lifetime of metals and reinforced concrete of transport infrastructures. Hence, a holistic evaluation with the main criteria of deicing performance and corrosion is demanded and, if possible, alternatives should be considered.

This paper focuses on the deicing performance of sodium chloride and other common acetate-, carbonate-, chloride- and formate-based deicing agents. A newly developed test method is presented, enabling high volume testing at good repeatability. From its results a nonlinear model is derived to predict deicing performance up to five hours after application. Subsequently, this model is compared with both existing empirical and theoretical approaches for evaluating the deicing performance. In addition, the impact of added corrosion-inhibiting substances like sugars on deicing performance is investigated. Finally, a comparison of all tested substances in terms of corrosivity and deicing performance is presented, with corrosion being investigated in detail in another paper.

### 1. Introduction

The availability and safety of transport infrastructures during the winter season is the main objective of winter maintenance, with the economic benefits far exceeding the costs. These objectives are primarily achieved through snow removal and the spreading of gritting materials or deicing agents during hoar frost, snowfall or freezing rain. As an efficient use of gritting materials is limited to sidewalks and roads with low traffic, the application of deicing agents has become a de facto standard in winter maintenance on all kinds of transport infrastructure (Hanke and Nutz, 2019).

Sodium chloride (SC; non-technical abbreviation to improve readability, especially for other substances, as will be shown later) is by far the most cost-effective deicing agent based on the criteria of availability, cost and deicing performance, and therefore the most commonly used deicing agent in industrialized countries with regular winter maintenance (PIARC, n.d.). However, since common deicing agents are highly corrosive and this being one of the main factors for reduced service life

of metal-based and reinforced transportation infrastructures (Shi et al., 2013; Shi et al., 2014; Koch et al., 2008; Shi et al., 2009), a significant reduction in corrosivity would lead to an increase in service life and substantial savings in infrastructure investment needs. In order to find alternatives to SC with lower corrosivity, a holistic evaluation of other deicing agents is needed, being based on the criteria deicing performance, application rates, costs, corrosion, impact on environment, and life cycle costs (Hoffmann et al., 2022).

This paper focuses on assessing the deicing performance of common deicing agents and, furthermore, on the influence of sugar-based corrosion-inhibiting substances added to SC. In the first part, an overview of the different theoretical and empirical approaches to evaluate deicing performance is presented, including a newly developed test method, allowing a more cost- and time efficient testing. For this method, a nonlinear regression model is derived, with confidence and prediction bands being calculated for SC and other common acetate-, carbonate-, chloride-, and formate-based deicing agents. The second part of the paper compares results obtained from the different models for

\* Corresponding author.

E-mail addresses: [michael.gruber@tuwien.ac.at](mailto:michael.gruber@tuwien.ac.at) (M.R. Gruber), [bernhard.hofko@tuwien.ac.at](mailto:bernhard.hofko@tuwien.ac.at) (B. Hofko).

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the maximum deicing performance of SC at  $-5\text{ }^{\circ}\text{C}$  and finally, a relation is established between all tested substances in terms of their corrosivity and deicing performance.

## 2. Deicing performance

All known deicing agents lower the thermodynamic freezing point of water, i.e. preventing the formation of snow and ice, according to their eutectic properties based on the phase diagram. In contrast, deicing performance determines the amount of ice or snow that can be thawed at a given temperature and in a given time and is largely based on the freezing curve. As the possible theoretical limit of deicing performance diminishes at lower temperatures, the deicing performance also decreases. For efficient winter maintenance, it is therefore crucial to determine the deicing performance of the respective deicing agents or products consisting of primary deicing agents, additives and impurities for the respective temperature range.

Basically, there are two approaches for the determination of freezing curves and deicing performance, i.e. empirical testing and calculation through freezing point depression (FPD). The latter is based on Raoult's idealized law (Albright, 2008), which can be seen in Eq. (1) and states that the partial pressure  $p_i$  of each component  $i$  of an ideal mixture of liquids (with mole fraction  $x_i$ ) is equal to the vapor pressure of the pure component  $p_i^*$ .

$$p_i = p_i^* \times x_i \quad (1)$$

Since the decrease in vapor pressure is associated with a decrease in freezing point, the latter can be calculated and results only from the molar mass of the solution (colligative properties) and the Van't Hoff factor (Tro, 2020) (dissociative properties of the solute) as shown in Eq. (2).

$$\Delta T_f = K_f \times i \times b \quad K_f \dots \text{cryoscopic constant of water} = -1.86 \left[ \frac{\text{kg K}}{\text{mol}} \right]$$

$\Delta T_f$  ... freezing point depression (FPD) [K]

$i$  ... Van't Hoff factor [-]

$$b \dots \text{molality} \left[ \frac{\text{mol}}{\text{kg}} \right] \quad (2)$$

The definition of molality can be seen in Eq. (3).

$$b = \frac{n_{\text{solute}}}{m_{\text{solvent}}} \quad n_{\text{solute}} \dots \text{mole of solute} [\text{mol}]$$

$$m_{\text{solvent}} \dots \text{mass of solvent} [\text{kg}] \quad (3)$$

Using Eq. (4), molality  $b$  can alternately be expressed by Eq. (5)

$$\text{for } 1 \text{ g: } n_{\text{solute}} = \frac{1}{M} \quad M \dots \text{molar mass} \left[ \frac{\text{g}}{\text{mol}} \right] \quad (4)$$

$$b = \frac{\frac{1}{M}}{m_{\text{solvent}}} = \frac{1}{M \times m_{\text{solvent}}} \quad (5)$$

With this expression, the freezing point depression in Eq. (6) is now in dependence of the molar mass instead of the molality.

$$\Delta T_f = (K_f \times 1000) \times i \times \frac{1}{M \times m_{\text{solvent}}} \quad (6)$$

Eq. (7) converts Eq. (6) to  $m_{\text{solvent}}$  as result, which is identical to the deicing performance seen in Eq. (8).

$$m_{\text{solvent}} = \frac{K_f \times i \times 1000}{M \times \Delta T_f} \quad (7)$$

$$\text{deicing performance} \left[ \frac{\text{g}}{\text{g}} \right] = \frac{K_f \times i \times 1000}{M \times \Delta T_f} \quad (8)$$

Thus, it is possible to determine the maximum deicing performance (= deicing capacity) at a certain temperature by converting the FPD for a certain concentration. For example: A FPD of 5 K with a mass concentration of 10m% SC (10m% SC, 90m% water) corresponds to SC thawing 9 times its own mass, which results to 9 g/g deicing capacity at infinite time. In contrast, a representation of deicing performance as a function of time is allowed by empirical test methods, such as the commonly used SHRP H-205.1 and H-205.2 (Chappelow et al., 1992) methods.

In the following section, a new empirical method is presented and compared to also empirically determined results (SHRP test as well as from other literature (Melinder, 2007)), and to the maximum deicing performance derived from Raoult's law.

### 2.1. Standard SHRP test method

In the standard method for empirical testing SHRP H-205.1 (Chappelow et al., 1992) for solid and SHRP H-205.2 (Chappelow et al., 1992) for liquid deicing agents, deicing agents (4.17 g solid or 3.8 ml liquid) are applied onto an ice slab (130 ml of frozen water in a  $223 \times 3.2$  mm circular plastic dish) at a specific temperature. After a specific time period (10, 20, 30, 45 and 60 min) the melted ice and residual deicing agent are removed, the mass difference is weighed and divided by the mass of the initially applied deicing agent to obtain the deicing performance. Producing ice slabs, applying deicing agents, and measuring the weight loss is time-consuming. Additionally, the number of tests is limited by the size of the climate chamber and ice slabs. Furthermore, it is reported that the SHRP methods have low reproducibility and underestimate the deicing performance (Nilssen et al., 2016; Akin and Shi, 2012; Fay and Shi, 2011; Koefod et al., 2012). Therefore, a modified ice melting test evolved, using smaller circular petri dishes ( $100 \times 15$  mm), only applying 1 g solid or 0.9 ml liquid deicer (Akin and Shi, 2012).

Based on this idea, the authors tested deicing performance in a climate chamber, with extended time periods to account for typical deicer application cycles, according to national standards (FSV, 2010) (3 h for highways and 5 h for regional roads).

Therefore, measuring intervals are set to 5, 10, 30, 60, 120 and 240 min to plot a time-dependent deicing performance for a common winter reference temperature of  $-5 \pm 1\text{ }^{\circ}\text{C}$ .

The complete setup is shown in Fig. 1 and includes 8 specimens (250 g of frozen water in  $205 \times 15$  mm circular stainless-steel containers, 8 deicing agents (prepared samples of  $10 \pm 1$  g), a scale and a bucket for melted water. For temperature control, a dynamic climate chamber (Binder MKF-720) with arm inlets to allow handling the specimens from outside was used. Since temperature mapping shows a certain inhomogeneity of temperature inside the chamber, specific areas were assigned with weighting factors to normalize the results and produce comparable results. The weighting factors were chosen so that the deicing performance for the same time is equal for every position inside the climate chamber.

After all prepared specimens are frozen at  $-5\text{ }^{\circ}\text{C}$  overnight, the mass of the specimen and its container is weighed,  $10 \pm 1$  g of deicing agent is applied, weighed again and time of application is noted. After 5, 10, 30, 60, 120 and 240 min the specimen is weighed again (to identify possible sublimation or handling error), the brine and melted water is poured out, and the remaining specimen is weighed. The difference between deicing agent applied and melted ice divided by the amount of deicing agent applied is the deicing performance in dependency of time per gram of deicer.

To compare this SHRP-based test method with the newly developed test method, the deicing performance of SC was determined in the climate chamber at  $-5\text{ }^{\circ}\text{C}$  by conducting 20 tests.

### 2.2. Cryostat-based test method (CEDA)

To mitigate the problem of SHRP-based methods, which underestimate the deicing performance (Nilssen et al., 2016; Akin and Shi, 2012;



Fig. 1. Climate chamber for testing deicing performance according to SHRP H-205.1/2.

Fay and Shi, 2011; Koefod et al., 2012), a new test method (CEDA: Cryostat-based Evaluation of Deicing Agents) was developed at the Institute of Materials Chemistry, TU Wien. It accelerates the process and increases testing efficiency by using reaction plates (Bio Plas 80 Well Micro Tube Rack) instead of ice slabs and a cryostat (Huber ministat 240) instead of a climate chamber to maintain the desired temperature, allowing more tests in less time compared to the SHRP method (see Fig. 2).

Each well in the reaction plate is filled with 400  $\mu\text{l}$  (399.28  $\mu\text{g}$  at 20  $^{\circ}\text{C}$ ) of purified water using a micropipette, then covered to prevent evaporation/sublimation, and frozen at  $-20^{\circ}\text{C}$  overnight. Subsequently to the entire freezing, the reaction plate is placed inside the cryostat, and after reaching the target temperature of  $-5^{\circ}\text{C}$ , different masses of a deicing agent (30 to 500  $\mu\text{g}$ ) are put onto the frozen sample. The maximum amount of deicing agent was chosen to achieve results for exposure times of up to 300 min.

To determine how much time has passed until the ice is fully melted, a digital camera (Canon EOS 2000d) is used to take a picture every minute. Once all samples have been deiced, the images are manually reviewed, and as soon as a sample is visually classified as fully melted, the time is noted. The optical difference between a deiced and partly frozen state is displayed in Fig. 3, where, in contrast to the right wells (which are fully melted), in the left wells small formations of ice can still be detected by non-centered or multiple reflection of the light source above. The deicing performance at a specific time (here, the period from adding the deicing agent until the ice is fully melted) is then calculated by dividing the mass of the ice (which is constant) by the exact amount of deicing agent on each sample.

The size of the employed cryostat allows the number of samples to be 40 per test (compared to a maximum of 8 samples in the climate chamber when using the SHRP method). A manual visual classification of the sample's aggregate conditions may be slightly inaccurate. However, in comparison with the standard test method according to SHRP H-205.1/2 in a climate chamber, both the necessary effort and the deviation of this new method are significantly lower, as will be shown later.

### 2.3. Testing schedule

The deicing performance was tested for SC and other common acetate-, carbonate-, chloride- and formate-based deicing agents according to Table 1, which states the chemical formula and introduces a non-technical abbreviation (e.g., PA = Potassium acetate =  $\text{CH}_3\text{COOK}$ ) for improved readability, especially in figures. The other substances were tested as anhydrides except for calcium chloride (CC) and magnesium chloride (MC), which were only available as di- or hexahydrate. Inhibitory substances were added with 8m% of the mass of SC (e.g., 100  $\mu\text{g}$  SC + 8  $\mu\text{g}$  Glucose).

### 2.4. Calculated freezing point depression

As mentioned before, Raoult's idealized law (Albright, 2008) can be used to calculate the freezing point depression. It links the concentration of dissolved solute in an ideal solution (increased entropy, decreased chemical potential) to the changes in its vapor pressure. Since the decrease in vapor pressure is accompanied by an increase in boiling point and decrease in freezing point, the latter can be calculated and

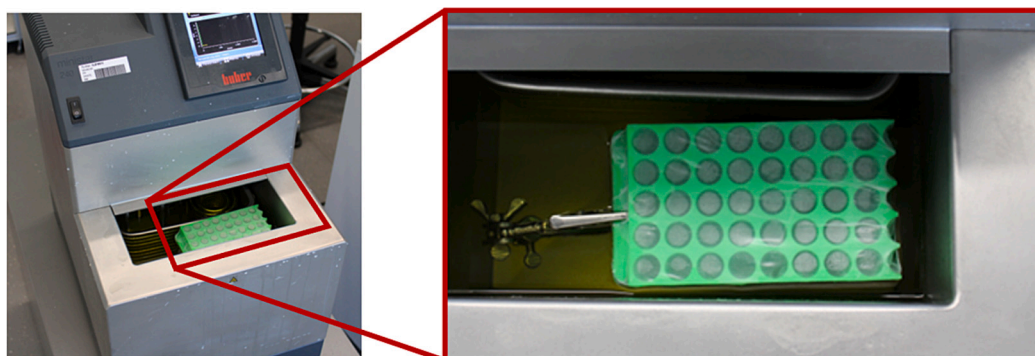


Fig. 2. CEDA: Cryostat (left) and reaction plate (right).

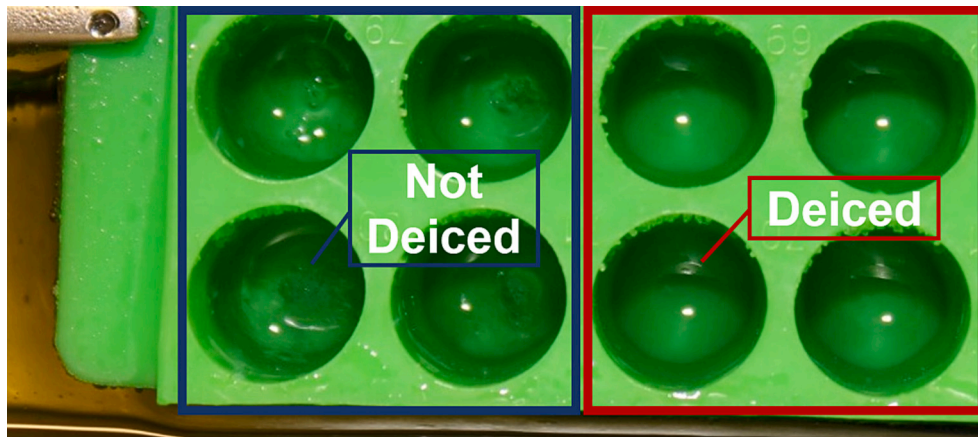


Fig. 3. Distinction of deiced state: Partly frozen (left) and deiced (right).

**Table 1**

Overview of the tested deicing agents including their abbreviations, formulas and number of studied samples.

Agent	Abbr.	Formula	Samples
Sodium chloride	SC	NaCl	25
Potassium carbonate	PC	K <sub>2</sub> CO <sub>3</sub>	14
Calcium chloride dihydrate	CC	CaCl <sub>2</sub> ·2H <sub>2</sub> O	14
Magnesium chloride hexahydrate	MC	MgCl <sub>2</sub> ·6H <sub>2</sub> O	14
Sodium acetate	SA	CH <sub>3</sub> COONa	20
Sodium formate	SF	HCOONa	24
Potassium acetate	PA	CH <sub>3</sub> COOK	26
Potassium formate	PF	HCOOK	14
Sodium chloride +8m% Arabinose	SC + Ara	NaCl + C <sub>5</sub> H <sub>10</sub> O <sub>5</sub>	28
Sodium chloride +8m% Glucose	SC + Glu	NaCl + C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	30
Sodium chloride +8m% Maltose monohydrate	SC + Mal	NaCl + C <sub>12</sub> H <sub>22</sub> O <sub>11</sub> ·H <sub>2</sub> O	28
Sodium chloride +8m% Mannose	SC + Man	NaCl + C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	25

results only from the amount of substance of the solute (colligative characteristics) and its Van't Hoff factor (Tro, 2020) (dissociative characteristics).

**Table 2**

Molar mass (M) and Van't Hoff factor (i) for all tested substances.

Substance	Abbr.	Formula	M g/mol	i
Sodium chloride	SC	NaCl	58.44	2
Magnesium chloride	MC	MgCl <sub>2</sub>	95.01	3
Magnesium chl. Hexahydr.	MC	MgCl <sub>2</sub> ·6H <sub>2</sub> O	203.01	3
Calcium chloride	CC	CaCl <sub>2</sub>	110.78	3
Calcium chloride dihydrate	CC	CaCl <sub>2</sub> ·2H <sub>2</sub> O	146.78	3
Potassium carbonate	PC	K <sub>2</sub> CO <sub>3</sub>	138.21	3
Glucose	Glu	C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	180.06	1
Arabinose	Ara	C <sub>5</sub> H <sub>10</sub> O <sub>5</sub>	150.05	1
Mannose	Man	C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	180.06	1
Maltose	Mal	C <sub>12</sub> H <sub>22</sub> O <sub>11</sub>	342.12	1
Maltose monohydrate	Mal	C <sub>12</sub> H <sub>22</sub> O <sub>11</sub> ·H <sub>2</sub> O	360.31	1
Sodium acetate	SA	CH <sub>3</sub> COONa	82.01	2
Potassium formate	PF	HCOOK	84.11	2
Sodium formate	SF	HCOONa	68.00	2
Potassium acetate	PA	CH <sub>3</sub> COOK	98.12	2
NaCl+8m%Glu	SC + Glu	NaCl+C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	58.44/180.06	2/1
NaCl+8m%Ara	SC + Ara	NaCl+C <sub>5</sub> H <sub>10</sub> O <sub>5</sub>	58.44/150.05	2/1
NaCl+8m%Man	SC + Man	NaCl+C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	58.44/180.06	2/1
NaCl+8m%Mal.H <sub>2</sub> O	SC + Mal	NaCl+C <sub>12</sub> H <sub>22</sub> O <sub>11</sub> ·H <sub>2</sub> O	58.44/360.31	2/1

To calculate the deicing performance or the factor of ice that can be melted at  $-5$  °C (which is a freezing point depression of 5 K), Eq. (8) can be used.

For example, the molar mass of SC (58.44 g/mol) is only a third of glucose (180.16 g/mol), so three times the mass of glucose is needed to achieve the same freezing point depression compared to SC. Furthermore, SC dissociates into Na<sup>+</sup> and Cl<sup>-</sup>, hence its Van't Hoff factor is twice the factor of the non-dissociating glucose (C<sub>6</sub>H<sub>12</sub>O<sub>6</sub>). Summarizing both characteristics results in only 1/6 of SC needed to achieve the same FPD as glucose. Table 2 shows the molar mass and Van't Hoff factor for every tested substance.

### 3. Results and comparison

#### 3.1. Calculated maximum deicing performance (Raoult's law)

As described in the previous section, the maximum deicing performance of all tested deicing agents was calculated according to Eq. (8) for  $-5$  °C and are given in Table 3.

#### 3.2. Measured maximum deicing performance according to Melinder

Melinder (Melinder, 2007) empirically investigated the freezing point of different aqueous solutions as a function of concentration. His findings are shown in Table 4 and are displayed in Fig. 8 as the "Melinder Model". Based on his results, the maximum deicing performance (= deicing capacity) can be derived from the known

**Table 3**Calculated deicing performance of the tested substances for  $-5\text{ }^{\circ}\text{C}$ .

Substance	Abbr.	Formula	Calculated max. deicing perf. [g/g]
Sodium chloride	SC	NaCl	12.73
Magnesium chloride	MC	MgCl <sub>2</sub>	11.75
Calcium chloride	CC	CaCl <sub>2</sub>	10.07
Potassium carbonate	PC	K <sub>2</sub> CO <sub>3</sub>	8.07
Glucose	Glu	C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	2.07
Arabinose	Ara	C <sub>5</sub> H <sub>10</sub> O <sub>5</sub>	2.48
Mannose	Man	C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	2.07
Maltose	Mal	C <sub>12</sub> H <sub>22</sub> O <sub>11</sub>	1.09
Sodium acetate	SA	CH <sub>3</sub> COONa	9.07
Potassium formate	PF	HCOOK	8.85
Sodium formate	SF	HCOONa	10.94
Potassium acetate	PA	CH <sub>3</sub> COOK	7.58
NaCl+8m%Glu	SC + Glu	NaCl+C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	11.88
NaCl+8m%Ara	SC + Ara	NaCl+C <sub>5</sub> H <sub>10</sub> O <sub>5</sub>	11.91
NaCl+8m%Man	SC + Man	NaCl+C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	11.88
NaCl+8m%Mal. H <sub>2</sub> O	SC + Mal	NaCl+C <sub>12</sub> H <sub>22</sub> O <sub>11</sub> ·H <sub>2</sub> O	11.80
Magnesium chl. Hexahydr.	MC	MgCl <sub>2</sub> ·6H <sub>2</sub> O	5.50
Calcium chloride dihydrate	CC	CaCl <sub>2</sub> ·2H <sub>2</sub> O	7.60
Maltose monohydrate	Mal	C <sub>12</sub> H <sub>22</sub> O <sub>11</sub> ·H <sub>2</sub> O	1.03

**Table 4**

Concentration for FPD obtained from Melinder (Melinder, 2007) and derived deicing performance.

Agent	Formula	Abbr.	Concentration for FPD 5 K [m%]	Deicing Capacity [g/g]
Sodium chloride	NaCl	SC	7.89	11.67
Potassium carbonate	K <sub>2</sub> CO <sub>3</sub>	PC	13.66	6.32
Sodium formate	HCOONa	SF	10.12	8.88
Potassium formate	HCOOK	PF	16.67	6.32

concentration for an FPD and is calculated in the last column of Table 4. For example, a 7.89m% concentration consists of 7.89 g SC and 92.11 g water. The deicing capacity is then calculated dividing 92.11 by 7.89 = 11.67 g/g.

**Table 5**

Parameters of nonlinear regression model.

Agent	Abbr.	b <sub>0</sub>	b <sub>1</sub>
Sodium chloride	SC	12.74952	0.01806
Potassium carbonate	PC	6.73984	0.01927
Calcium chloride dihydrate	CC	8.28207	0.01341
Magnesium chloride hexahydrate	MC	6.82678	0.01708
Sodium acetate	SA	8.15554	0.00988
Sodium formate	SF	11.40702	0.01924
Potassium acetate	PA	10.59200	0.01800
Potassium formate	PF	6.38179	0.03885
Sodium chloride +8m% Arabinose	SC + Ara	11.63396	0.01679
Sodium chloride +8m% Glucose	SC + Glu	11.62069	0.02083
Sodium chloride +8m% Maltose monohydrate	SC + Mal	11.74680	0.01645
Sodium chloride +8m% Mannose	SC + Man	10.37474	0.02430

### 3.3. Measured deicing performance (CEDA)

The deicing performance is the amount of ice melted per mass of the deicing agent as a variable of time and temperature. The results were obtained from the CEDA test method as described in 2.2.

Statistical analysis was conducted using the programming language R; for determination of the nonlinear least-squares estimates of the parameter of a nonlinear regression model for the deicing performance, the nls-function was used with the formula provided in Eq. (9).

$$y(x) = b_0 \times (1 - e^{-b_1 \times x}) \quad (9)$$

For the calculation of the 95% confidence interval and the 95% prediction interval, the samples were bootstrapped (nlsBoot-function with 999 resamples) and calculated with the help of nlsBootPredict-function. The computed parameters  $b_0$  and  $b_1$  of the nonlinear regression model for each deicing agent are listed in Table 5. The entire program code is listed in the supplementary data section.

Fig. 4 shows the results and the regression model (incl. 95% confidence interval in red and 95% prediction interval in grey) of the time-dependent deicing performance at  $-5\text{ }^{\circ}\text{C}$  for sodium chloride (SC), potassium carbonate (PC), magnesium chloride hexahydrate (MC), and calcium chloride dihydrate (CC). It can be seen that SC shows the best deicing performance after 300 min with 12.7 g/g. The low ability to deice of MC with 6.8 g/g as well as of CC with 8.1 g/g is due to their hydrated form: with increasing amounts of water being solved or chemically bound, the deicing performance will decrease until an equilibrium with no further deicing capacity is reached. This equilibrium is determined by the concentration of the freezing curve for the given temperature.

As shown in Fig. 5, sodium formate (SF), and potassium acetate (PA) exhibit a similar deicing performance compared to SC, with 11.4 g/g and 10.5 g/g, respectively. Potassium formate (PF) and sodium acetate (SA) show significantly lower deicing performance with 6.4 g/g and 7.7 g/g respectively.

Since SC has the best deicing performance of the tested primary deicing agents with 12.7 g/g, another set of tests was conducted to examine the influence of a sugar-based inhibitors on the deicing performance of SC. Since sugars do not dissociate like SC (NaCl; into Na<sup>+</sup> and Cl<sup>-</sup>), a lower amount of melted ice can be expected. The results of the tests in Fig. 6 confirm this expectation. Except for Mannose, all added sugars show a reduced performance at around 11.6 g/g (which is 92% of SC's performance). Mannose-doped SC only deices 10.4 g/g.

### 3.4. Comparison of deicing performance CEDA and SHRP

Since it is reported that the SHRP test method underestimates the deicing performance (Nilssen et al., 2016; Akin and Shi, 2012; Fay and Shi, 2011; Koefod et al., 2012), a comparison between SHRP and the newly developed CEDA test method was conducted. For the results obtained from SHRP, a nonlinear regression model was derived from the data with the formula provided in Eq. (9), analogous to the previous section. The parameters for the nonlinear regression models are listed in Table 6.

Fig. 7 displays the results and the regression model (incl. 95% confidence interval in red and 95% prediction interval in grey) of the time-dependent deicing performance at  $-5\text{ }^{\circ}\text{C}$  for SC, clearly showing the underestimation of the deicing performance derived from the SHRP-based test method: At 300 min, only 9.5 g/g are deiced, which is 25% less than the result of the cryostat-based model (CEDA). Furthermore, the maximum deicing performance (= deicing capacity) of CEDA at 300 min is closer to the theoretical deicing capacity of 11.67 g/g (dashed line in Fig. 7) calculated from the FPD (Melinder, 2007).

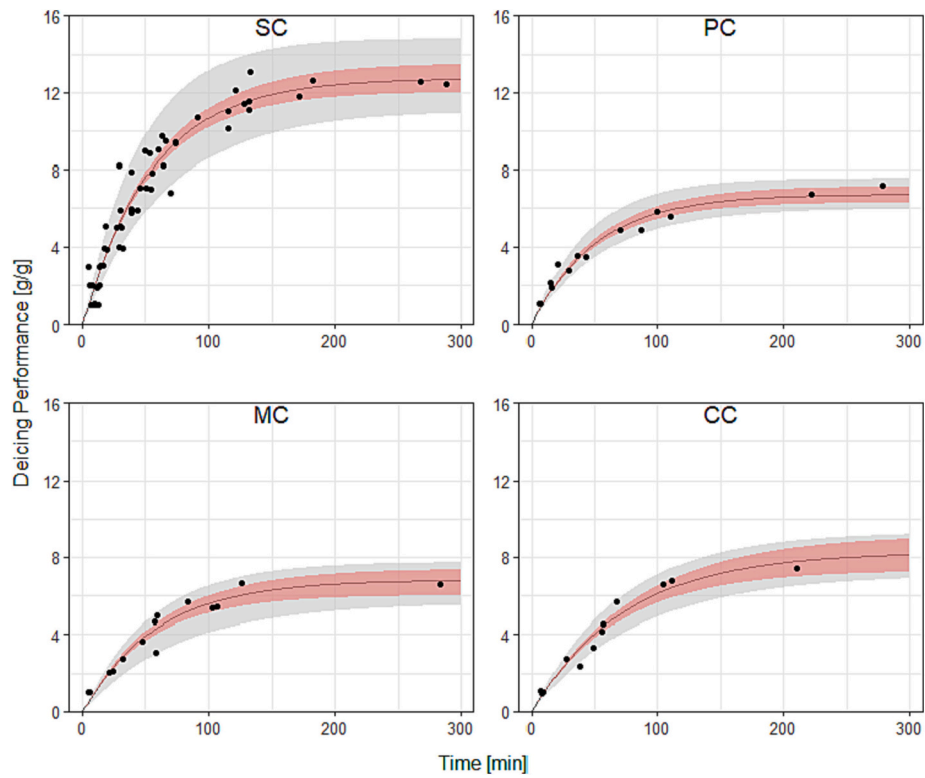


Fig. 4. Deicing performance of sodium chloride (SC), potassium carbonate (PC), magnesium chloride hexahydrate (MC) and calcium chloride dihydrate (CC).

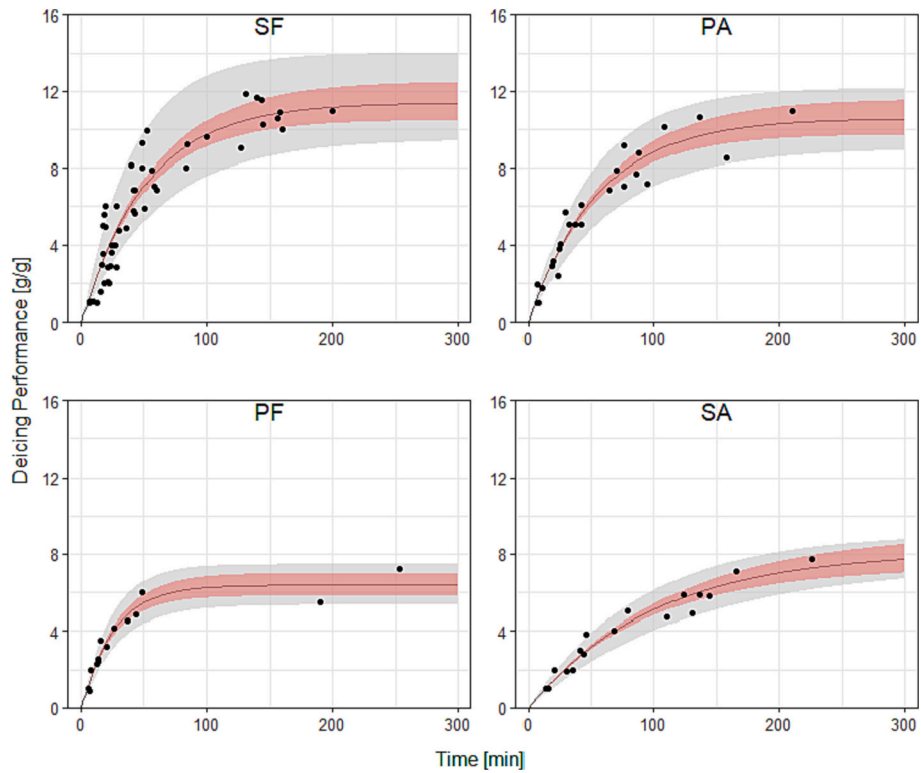


Fig. 5. Deicing performance of sodium formate (SF), potassium acetate (PA), potassium formate (PF) and sodium acetate (SA).

### 3.5. Comparison calculated and measured FPD

Fig. 8 compares the calculated (Raoult's law - 3.1) and measured (Melinder - 3.2) FPD with the solution's concentration. Additionally, the

95% confidence interval of the concentration needed for achieving an FPD of 5 K (to  $-5^{\circ}\text{C}$ ) is displayed, which was converted (deicing performance at 300 min converted back to get the concentration) from the deicing performance tests (CEDA) at  $-5^{\circ}\text{C}$  presented in 3.3. Thus, the

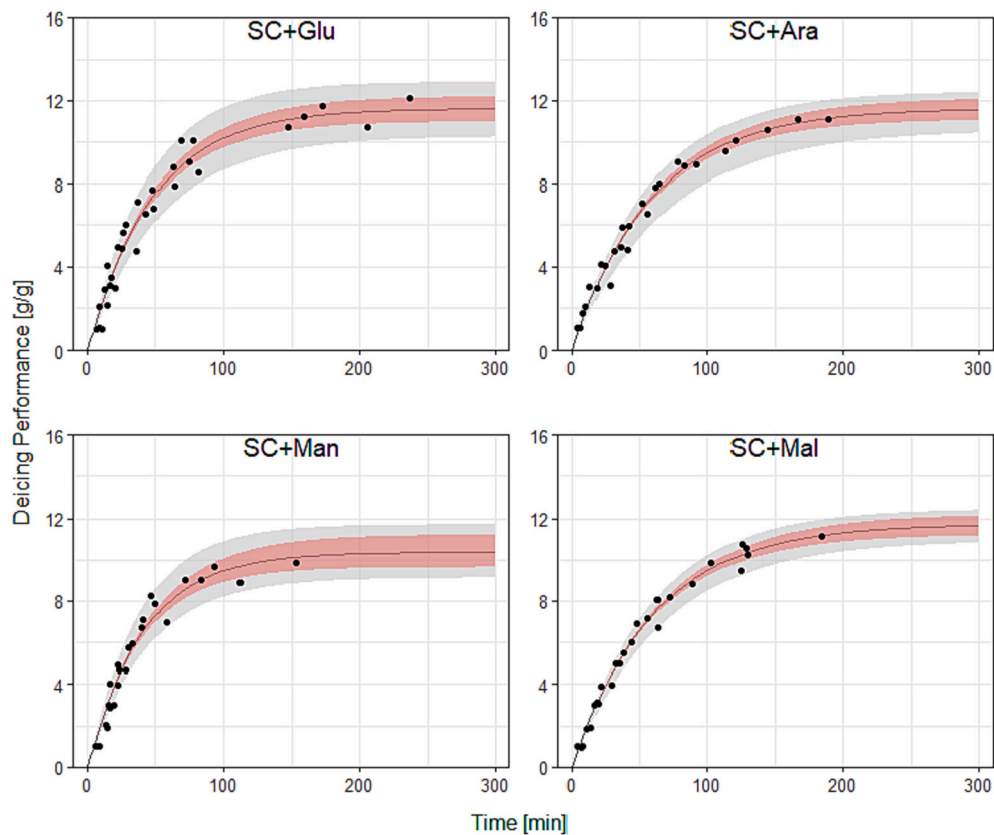


Fig. 6. Deicing performance of sodium chloride (SC) with 8% Glucose (Glu), 8% Arabinose (Ara), 8% Mannose (Man), and 8% Maltose Monohydrate (Mal).

Table 6  
Parameters of the nonlinear regression model for CEDA and SHRP.

Agent	Test Method	Abbr.	$b_0$	$b_1$
Sodium chloride	CEDA	SC - CEDA	12.74952	0.01806
Sodium chloride	SHRP	SC - SHRP	9.48086	0.01506

data given in Fig. 8 allow for comparison of all investigated methods.

For SC, a comparison of the Raoult's and Melinder's model shows accordance until a FPD of 15 K (to  $-15\text{ }^\circ\text{C}$ ) and concentrations up to 20m %. At higher concentrations, the FPD diverges. The measured model (converted from the deicing performance of the cryostat-based method CEDA) matches both calculated and Melinder's model at a temperature of  $-5\text{ }^\circ\text{C}$ . For all other compared deicing agents (SF, PC, and PF), the cryostat-based FPD is more likely to line up with the measured results

obtained from Melinder, while the calculated (Raoult's law) FPD model indicates a better deicing performance. As the measured results exhibit some deviations, but a high repeatability and are independently acquired, there is a high probability that Raoult's law is of limited use for accurate calculations and predictions on the behavior of other substances.

#### 4. Comparison deicing performance and corrosion

The primary purpose of deicing in winter maintenance is to provide a sufficient level of skid resistance by avoiding freezing due to preventive spreading or by removing residual snow and ice after plowing by applying necessary amounts of deicing agent. With a focus beyond winter maintenance and highly expensive transport infrastructure consisting of metals and reinforced concrete (e.g. train stations, bridges,

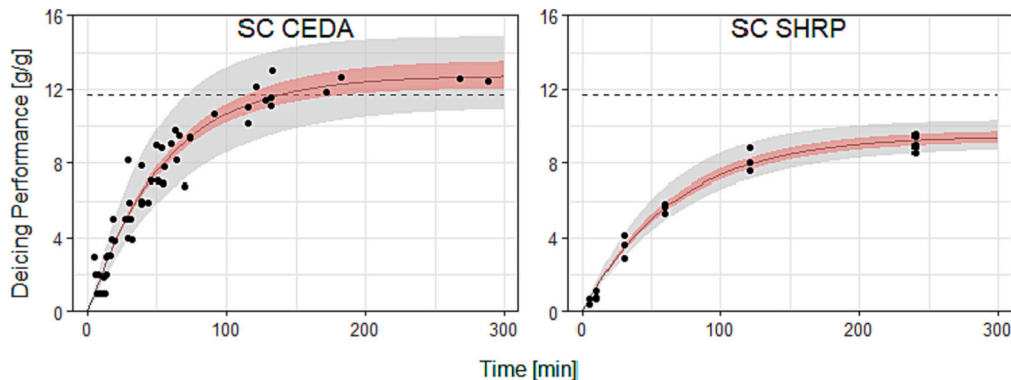


Fig. 7. Deicing performance of sodium chloride (SC) obtained with the CEDA (left) and with SHRP H-205.1 (right) – dashed line represents the theoretical deicing capacity (11.67 g/g).

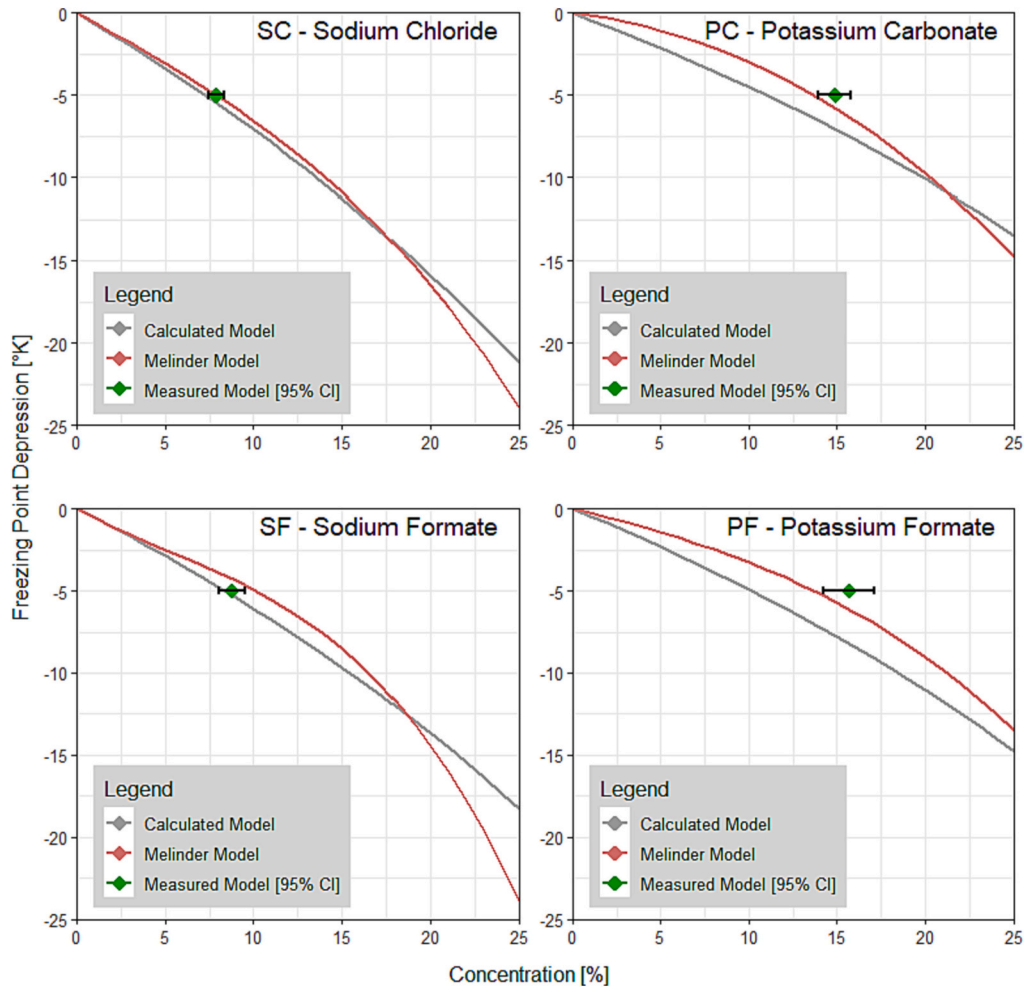


Fig. 8. Comparison of the FPD in dependence of the concentration [m%] of all models.

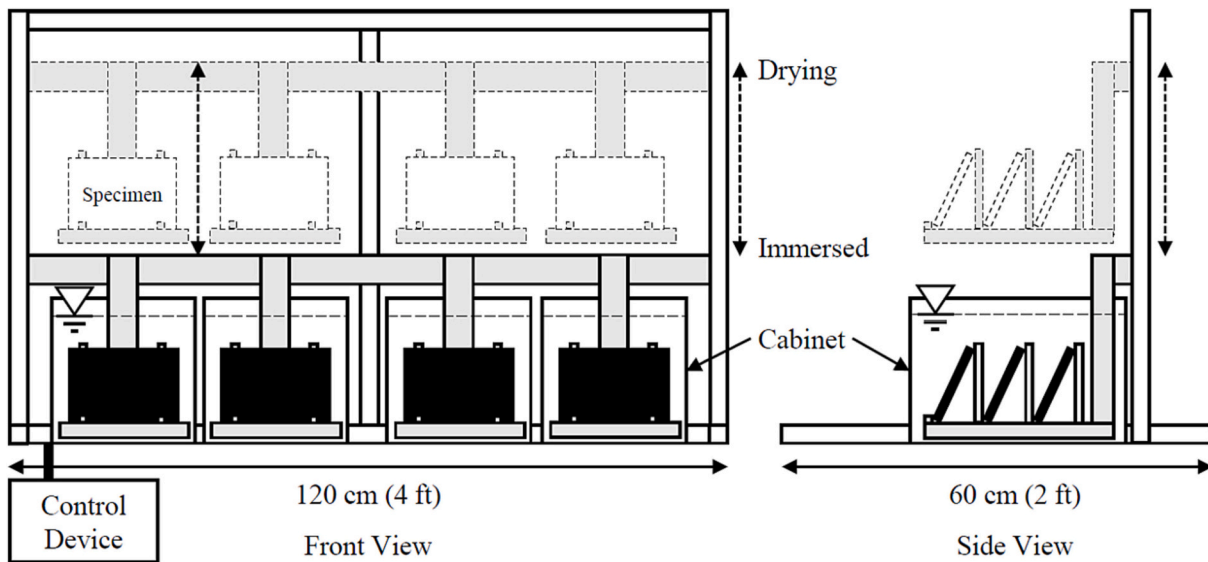


Fig. 9. Testing device for alternate immersion (AI) test (Gruber et al., 2023).

airports), corrosion will be an additional and decisive factor from a life cycle perspective for any infrastructure operator or owner.

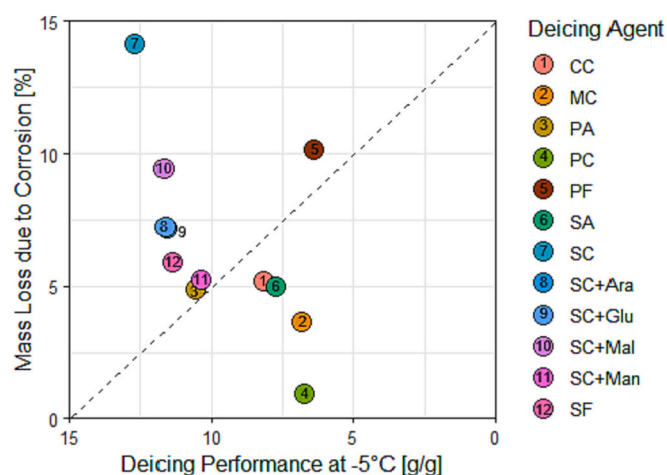
Data for mass loss due to corrosion are extracted from (Gruber et al., 2023). In this paper, corrosion was produced with help of the alternate

immersion test method based on the standard ISO 11130 (ISO, 2017): At a surrounding temperature of 35 °C, metal plates (unalloyed steel EN 10025 S235JR (Austrian Standards, 2004), dimensions 150 × 100 × 1 mm) are submerged into a 5m% solution of the deicing agent for 10 min,



**Table 7**  
Median of relative mass loss due to corrosion at 35 °C (Gruber et al., 2023).

Agent	Abbr.	Specimens	Median relative mass loss [m%]
Sodium chloride	SC	38	14.16
Potassium carbonate	PC	6	0.96
Calcium chloride	CC	6	5.21
Magnesium chloride	MC	6	3.63
Sodium acetate	SA	6	4.97
Sodium formate	SF	6	5.93
Potassium acetate	PA	6	4.87
Potassium formate	PF	6	10.18
Sodium chloride +8m% Arabinose	SC + Ara	6	7.17
Sodium chloride +8m% Glucose	SC + Glu	6	7.23
Sodium chloride +8m% Maltose	SC + Mal	6	9.45
Sodium chloride +8m% Mannose	SC + Man	6	5.23



**Fig. 10.** Comparison of mass loss due to corrosion (Gruber et al., 2023) and deicing performance.

then dried for 50 min. This cycle is repeated, and after 21 days, the metal plates are cleaned until mass constancy (ISO 8407 – Corrosion of metals and alloys – Removal of corrosion products) (ISO, 2021) in an ultrasonic bath with a 20m% diammonium hydrogen citrate solution. Relative mass loss is then calculated by dividing the total mass loss by the initial mass before the test. A scheme of the testing device for alternate immersion can be seen in Fig. 9.

The median of relative mass loss due to corrosion produced by alternate immersion is presented in Table 7. All agents were tested as 5m% solution, except SC with an added inhibitory substance, which was tested as 5m% solution plus 8m% inhibitor (8m% based on dry mass of deicing agent). That means to a 1000 g of 5m% sodium chloride solution, consisting of 50 g SC and 950 g water, 8 m% inhibitor (8m% of 50 g = 4 g) was added. Results show that SC has the highest (14.2m%) and PC (1m%) the lowest mass loss due to corrosion. In addition, the inhibitory substances are proven to be able to reduce corrosion by up to 60% compared to SC.

Fig. 10 provides a comparison of all tested deicing agents with and without inhibitory substances regarding relative mass loss due to corrosion (vertical axis) and deicing performance at  $-5^{\circ}\text{C}$  (horizontal axis) derived from the measured CEDA model in 3.3. The figure is structured in a way that the best performing deicing agents are at the bottom left. Potassium carbonate (PC, color: green, No: 4) has the same deicing performance as potassium formate (PF, color: burgundy, No: 5), but has only one-tenth of the corrosion.

## 5. Conclusions and outlook

Deicing agents in winter road maintenance are critical in providing safe roads at all times by guaranteeing an adequate level of skid resistance. Even though sodium chloride (SC) is the most cost-effective deicing agent, it is highly corrosive and significantly shortens the service life of transport infrastructures. Therefore, efficient alternatives or ways to reduce corrosion effects without diminishing the road safety are key to saving billions of transport infrastructure investments every year on a world-wide scale. This paper presents the results of extensive research and analysis of the essential criterion of deicing agents: deicing performance. Additionally, a possible reduction due to corrosion-inhibiting additives is presented. Finally, a comparison of deicing performance and corrosion is provided.

A new method (CEDA) for an efficient and repeatable evaluation of deicing performance with increased testing capacity compared to standard procedures was introduced. The test schedule based on this procedure included SC as well as other common acetate-, carbonate-, chloride- and formate-based deicing agents. Furthermore, the addition of sugar-based corrosion-inhibiting substances to SC was investigated, exhibiting minimal decrease in deicing performance (11.6 g/g) to SC (12.7 g/g). Based on the obtained results, a nonlinear model was derived clearly showing the time and temperature dependency of the deicing performance allowing for reliable predictions of the necessary amounts of deicers for any given situation. The comparison with other empirical models in the literature are consistent for different deicing agents in contrast to theoretical approaches (e.g. Raoult's law). Utilizing the colligative characteristics of the solution and the dissociative characteristics of the solute to calculate the freezing point depression and in further consequence the deicing performance, exhibits a much lower predictive accuracy compared to the empiric results with high repeatability.

Additionally, the relative mass loss of unalloyed steel due to corrosion is compared to deicing performance for different deicing agents. This allows a purposive decision for different areas of application, especially when the service life of metal-based transport infrastructure needs to be considered. It is shown that with minimal sacrifice in deicing performance, a significant reduction of up to 60% in corrosion on unalloyed steel can be achieved by the addition of inhibitors such as sugar. Less corrosion at the expense of lower deicing performance can be achieved with other deicing agents. For instance, potassium carbonate (PC) produces only 1m% of relative mass loss compared to 14m% mass loss of SC, but has only half of the deicing performance at  $-5^{\circ}\text{C}$ .

In summary, the research has shown that the developed cryostat-based test method CEDA is not only suitable, but highly efficient for determining deicing performance, helping to decide which deicing agent to prefer in areas with costly transport infrastructure. Although literature (Klein-Paste and Wählin, 2013) indicates a much lower amount of deicing agents needed due to the ability of traffic to weaken ice or to prevent its formation altogether, this study is based on the freezing point depression theory and suggests amounts of deicing agents without considering these effects. There are also ongoing efforts (Klein-Paste and Wählin, 2017) to represent the deicing process by deicing rate (g/h), rather than by deicing capacity (g/g), as it should give more detailed results, especially for the initial deicing process. However, this study focuses on the most used method, displaying the deicing performance respectively deicing capacity. Nevertheless, the next step is to identify and test additional inhibitors with respect to corrosion and deicing performance (also at lower temperatures).

Overall, the methods and results in this paper provide concise answers and a clear path for future research towards cost-effective deicing agents with significantly lower corrosion compared to SC. Thus, extending the service life of transport infrastructures at reasonable additional costs has become a feasible option.

## CRedit authorship contribution statement

**Michael R. Gruber:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Bernhard Hofko:** Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Markus Hoffmann:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing – review & editing, Supervision, Funding acquisition. **David Stinglmayr:** Investigation, Resources, Data curation, Writing – review & editing. **Teresa M. Seifried:** Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing. **Hinrich Grothe:** Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Michael R. Gruber reports article publishing charges was provided by TU Wien. Markus Hoffmann reports financial support was provided by Austrian Research Promotion Agency.

## Data availability

Data will be made available on request.

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## References

Akin, M., Shi, X., 2012. Development of standard laboratory testing procedures to evaluate the performance of deicers. *J. Test. Eval.* 40 (6), 1015–1026. <https://doi.org/10.1520/JTE103615>.

- Albright, L., 2008. *Albright's Chemical Engineering Handbook*, 325. CRC Press. ISBN 978-0-8247-5362-7.
- Austrian Standards, 2004. OENORM EN 10025–1:2004. Hot Rolled Products of Structural Steels - Part 1: General Technical Delivery Conditions. Wien. [www.austrian-standards.at](http://www.austrian-standards.at).
- Chappelow, C.C., McElroy, A.D., Darwin, D., et al., 1992. *Handbook of Test Methods for Evaluating Chemical Deicers*. National Academy of Sciences: Strategic Highway Research Program. Volume SHRP-H-332. Washington DC.
- Fay, L., Shi, X., 2011. Laboratory Investigation of Performance and Impacts of Snow and Ice Control Chemicals for Winter Road Service. [https://doi.org/10.1061/\(ASCE\)CR.1943-5495.0000025](https://doi.org/10.1061/(ASCE)CR.1943-5495.0000025).
- FSV, 2010. RVS 12.04.12: Winter Maintenance – Organization and Performance. Wien [www.fsv.at](http://www.fsv.at).
- Gruber, M.R., Hofko, B., Hoffmann, M., Stinglmayr, D., Grothe, H., 2023. Cost-Efficient and Low-Corrosion Deicing Agents for Winter Maintenance. *Corrosion Engineering, Science and Technology*.
- Hanke, H., Nutz, P., 2019. *International Development of Application Methods of De-Icing Chemicals-State of the Art and Best Practice*, pp. 4–9. ISBN: 978-2-84060-514-0.
- Hoffmann, M., Gruber, M.R., Hofko, B., 2022. Winterlife: effective, sustainable and non-corrosive deicing agents in winter maintenance. In: PIARC - XVI World Winter Service and Road Resilience Congress, 2022.
- ISO, 2017. ISO 11130:2017. Corrosion of metals and alloys — Alternate immersion test in salt solution. International Organization for Standardization. [www.iso.org](http://www.iso.org).
- ISO, 2021. ISO 8407:2021. Corrosion of Metals and Alloys — Removal of Corrosion Products from Corrosion Test Specimens. International Organization for Standardization. [www.iso.org](http://www.iso.org).
- Klein-Paste, A., Wählin, J., 2013. Wet Pavement Anti-icing — A Physical Mechanism, *Cold Regions Science and Technology*, 96, pp. 1–7. S. <https://doi.org/10.1016/j.coldregions.2013.09.002>.
- Klein-Paste, A., Wählin, J., 2017. The effect of mass diffusion on the rate of chemical ice melting using aqueous solutions. In: *Cold Regions Science and Technology*, vol. 139, pp. 11–21. ISSN 0165-232X. <https://doi.org/10.1016/j.coldregions.2017.04.001>.
- Koch, G.H., Brongers, M., Thompson, N.G., et al., 2008. *Handbook of Environmental Degradation of Materials*. <https://doi.org/10.1016/B978-081551500-5.50003-3>.
- Koefod, S., Adkins, J., Akin, M., 2012. *Alternative Approaches to Measuring Deicer Ice-Melting Capacity*, Transportation Research Circular E-C162, pp. 432–442. ISSN 0097-8515.
- Melinder, A., 2007. *Thermophysical Properties of Aqueous Solutions Used as Secondary Working Fluids*. Doctoral dissertation.. Royal Institute of Technology KTH. Stockholm.
- Nilssen, K., Klein-Paste, A., Wählin, J., 2016. Accuracy of ice melting capacity tests: review of melting data for sodium chloride. *Transp. Res. Rec.* 2551 (1), 1–9. <https://doi.org/10.3141/2551-01>.
- PIARC; Snow and Ice Databook 2018 - SIDB 2018EN. PIARC Technical Committee B.2 Winter Service, La Défense. [www.piarc.org](http://www.piarc.org).
- Shi, X., Fay, L., Yang, Z., et al., 2009. Corrosion of deicers to metals in transportation infrastructure: introduction and recent developments. *Corros. Rev.* 27 (1–2), 23–52. <https://doi.org/10.1515/CORRREV.2009.27.1-2.23>.
- Shi, X., Veneziano, D., Xie, N., Gong, J., 2013. Use of chloride-based ice control products for sustainable winter maintenance: a balanced perspective. *Cold Reg. Sci. Technol.* 86, 104–112. ISSN 0165-232. <https://doi.org/10.1016/j.coldregions.2012.11.001>.
- Shi, X., Jungwirth, S., Akin, M., et al., 2014. Evaluating snow and ice control chemicals for environmentally sustainable highway maintenance operations. *J. Transp. Eng.* 140 (11) [https://doi.org/10.1061/\(ASCE\)TE.1943-5436.0000709](https://doi.org/10.1061/(ASCE)TE.1943-5436.0000709), 5014005.
- Tro, Nivaldo J., 2020. *Chemistry: A Molecular Approach*, Fifth ed. Person Education, Hoboken. NJ. ISBN 978-0-1349-8889-4.