Investigating Effectiveness of Different Salt Reagents (NaCl, CaCl₂, MgSO₄) On Solid Ice Cubes

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ABSTRACT: The goal for this experiment was to investigate which form of salt, calcium chloride (CaCl₂), sodium chloride (NaCl), and magnesium sulphate (MgSO₄), is most efficient for adequately deicing an ice cube (25.0cm³) by using freezing point depression and mass trials (with timings 5min, 15min, 30min, 45min, and 60min) when the mass of salts (5.0cm³) and the environment temperature (22°C) is maintained constant. The results that were yielded from the experiment was that calcium chloride (CaCl₂) is the most efficient salt reagent out of the three other tested reagents, sodium chloride (NaCl) and magnesium sulphate (MgSO₄).

KEYWORDS: Chemistry; Salts; Ice-cube; Deicing; Timing.

■ Introduction

From a young child, when immigrating from India to Canada, I was greeted by tons of snow and ice every year. During my life in India, I had always thought of salt as an additional seasoning to food to add an extra bit of flavor, but soon after moving to Canada, I learned of the possibilities and usefulness that salt has. I was fascinated by the fact of how even a small amount of salt could melt ice that was up to 5 or 10 times larger than the salt itself. In grade 8, our science class attempted a similar experiment with different procedures and variables. When doing the experiment, I understood that some salts would increase the rate of melting of the ice cube, but never quite understood the internal process of the reaction between the salt and ice cube. This process sparked an inspiration for this chemistry exploration, and lead me to the research question: Which form of salt, calcium chloride (CaCl₂), sodium chloride (NaCl), and magnesium sulphate (MgSO₄), is most efficient in adequately deicing an ice cube (25.0 cm³) by using freezing point depression and mass trials (with timings 5 min, 15 min, 30 min, 45 min, and 60 min) when the mass of salts (5.0 cm³) and the environment temperature (22°C) is maintained constant?

Background Information: This investigation was conducted as a percent-mass trial that will be analyzing the efficiency of each salt melting the ice cube when given a specific amount of time. To maximize the accuracy of the results yielded by the trials and ensure that truly efficient salt is found, we will use the freezing point depression equation. The freezing point depression equation has multiple components that will need to be reviewed and the experiment itself has some key information needed to be understood.

The experiment: This experiment consists of four solutions, and three of which will have a solvent and solute (the fourth solution will be the ice cube alone in the beaker that will melt at room temperature, also known as the control). The solvent will be H₂O and solute will be the salts (CaCl₂, NaCl,

MgSO₄). When our solute is added to the solvent, molecules of the solute will dissolve in the solvent. This is because the force of attraction between the solute and solvent molecules is greater than the force of attraction between the molecules only in the solute. H₂O is partially polarized because of the distribution of electrons caused by the partial positive charge at hydrogen ends, and the partial negative charge at the oxygen end. This disturbance makes H₂O a specifically better solvent, as it becomes possible for water molecules to shift around solute ions. Our salt solute can then lower the freezing point of the water. This is the basis of this investigation.¹

Freezing point depression: Freezing point depression is the decrease of the freezing point of a solvent which occurs when a non-volatile solute (a solute that has little tendency to escape the solution) is added. The solution thereby has its freezing point become lower than of the original solvent. Freezing point depression is a colligative property of matter. These properties do not depend on the specific type of compound or collective mass, but rather on the number of the particles present in the solvent. Other colligative properties include vapor pressure, boiling point elevation, and osmotic pressure. Applications of freezing point depression including removing ice from roads to prevent safety hazards. And this concept can be applied to create ice cream, as the salt helps keep the ice cream cold for long periods of time.²

Freezing point depression formula: The combination of two equations, the Clausius-Clapeyron equation, and Raoult's law, forms the freezing point depression formula:³

$$\text{Freezing Point}_{\text{total}} = \text{Freezing Points}_{\text{solvent}} - \Delta T_f,$$

$$\text{where } \Delta T_f = i * K_f * m$$

ΔT_f : ΔT_f is the change in temperature which will be measured in degrees Celsius (°C). This is essentially the value that is focused on because it will indicate which solute will have the highest change in freezing point for the solvent. This value will then be substituted in the total freezing point depression formula to calculate the final freezing point of the solution.²

van't Hoff factor (*i*): The van't Hoff factor or “*i*” is used to determine the number of molecules or ions the solute splits into when it dissolves in a solvent. This factor varies for different solutes depending on the form of electrolyte they are. The forms include strong, weak, and non-electrolytes. To identify if which group the solute is in, the conditions are provided:

strong electrolyte: strong acids, strong bases, and soluble ionic compounds (solute will dissociate ions in solution, $i > 1$)

weak electrolyte: weak acids, weak bases, and insoluble ionic compounds (solute will dissociate but only to a limited extent, $1 < i < 2$)

non-electrolyte: covalent compounds (solute will not dissociate in solution, $i = 1$)

When the van't Hoff factor is found it can then be substituted into the freezing point depression equation.⁴

***K_f*:** The cryoscopic constant (*K_f*) can be defined as the molal depression constant and has units °C Kg mol⁻¹. This constant will vary for different solvents, but for this experiment, the solvent will be H₂O which has *K_f* = 1.86°C kg mol⁻¹.³

***m*:** The variable “*m*” in the freezing point depression formula, is defined as molality which is the concentration of moles of solute per kg of solvent, mol kg⁻¹. A value of 2 moles per kilogram can also be referred to as 2 molal.⁵

Table 1: A raw data table showing the relative performance ($\pm 0.01\%$) of the salt reagents, CaCl₂, NaCl, and MgSO₄ (5 cm³), to melt their specific distilled water ice cube (25cm³) in different trials with timings 5 min, 15 min, 30 min, 45 min, and 60 min at room temperature (22°C).

Reagents / Trial Number	Calcium chloride (CaCl ₂)	Sodium chloride (NaCl)	Magnesium sulfate (MgSO ₄)	Control ice cube
Trial 1 (5 mins)	11.2% $\pm$ 0.01%	10.3% $\pm$ 0.01%	9.6% $\pm$ 0.01%	5.2% $\pm$ 0.01%
Trial 2 (15 mins)	33.6% $\pm$ 0.01%	31.9% $\pm$ 0.01%	28.8% $\pm$ 0.01%	16.8% $\pm$ 0.01%
Trial 3 (30 mins)	67.3% $\pm$ 0.01%	62.6% $\pm$ 0.01%	57.5% $\pm$ 0.01%	32.5% $\pm$ 0.01%
Trial 4 (45 mins)	99.0% $\pm$ 0.01%	92.9% $\pm$ 0.01%	86.3% $\pm$ 0.01%	46.7% $\pm$ 0.01%
Trial 5 (60 mins)	100.0% $\pm$ 0.01%	99.6% $\pm$ 0.01%	93.5% $\pm$ 0.01%	72.3% $\pm$ 0.01%

■ Results

Qualitative observations: As time continued, the ice cube melted but also created holes where the salt particles were placed, thereby making it look as if shards were made in the cube. The smell of the salt was slowly decreasing and fading away as time continued, likely because the salt particles slowly mixed with the water and the smell reduces. For example, the MgSO₄ salt particles at first had a minty fresh smell, but as the time of the trials increased the smell dulled. The distilled water (which was frozen and taken out as an ice cube) was clear and opaque, but when the salt particles were reacted with the ice cube the water that melted was thick and viscous, and more faded. This is because the salt mixed in with the water combining and diluting the color of the water.

The results suggested that calcium chloride (CaCl₂) is the most efficient salt reagent out of the three other tested reagents, sodium chloride (NaCl) and magnesium sulfate (MgSO₄). This is shown through the experiment's line graph in Figure 1, which indicates the relative performance of each salt solute at experiment time trials of 5, 15, 30, 45, and 60 minutes. The blue line, representing calcium chloride, on the graph, shows

Figure 1: Line Graph Indicating the Relative Performance ($\pm 0.01\%$) of the Salt Reagents, CaCl₂, NaCl, and MgSO₄ (5 cm³), to Melt Ice cube (25cm³ of distilled water) in Different Timing Trials (5 min, 15 min, 30 min, 45 min, 60 min) at Room Temp (22°C).

ride consistently melts the ice cube the most in comparison to the other reagents and the control. The specific data results are shown in the Table 1. The line graph, on the other hand, depicts the pattern of the CaCl₂ being the fastest reagent. A close competitor to calcium chloride is sodium chloride solute.

■ Conclusion

In the first four trials, there is a visible gap in the relative percent mass, but at the last trial, which was 60 minutes, NaCl and CaCl₂'s difference in performance was very minuscule (0.37%) and almost negligible. The reason that CaCl₂ has a higher performance in deicing the ice cube may be due to the fact that when sodium chloride (NaCl) melts ice, the salt dissolves into separate sodium ions and chloride ions however calcium chloride (CaCl₂) is more effective at melting ice as it can break down into three ions, one calcium ion, and two chloride ions and as a result, the increase ions means that more ions are placing themselves in the rigid bonds of the ice cube. In addition to this, the calculations in section 6 also prove this is accurate but in the form of showing that CaCl₂ lowers the freezing point of the ice cube the most.

Using the freezing point depression equation CaCl₂, the theoretical freezing point that the ice cube can possess when in contact with CaCl₂ is -11.16 °C, NaCl is -11.09 °C and MgSO₄ is -6.20 °C. With this theoretical and experimental values as sufficient evidence to support calcium chloride (CaCl₂), I can conclude this investigation with the statement: calcium chloride (CaCl₂) is the most efficient salt reagent to deice an ice cube of distilled water when compared to sodium chloride (NaCl) and magnesium sulfate (MgSO₄) under the conditions of all salts having the mass 5cm³, ice cubes with masses 25cm³, and trials taking place at room temperature, 22 °C.

This chemistry investigation has limitations. The over-sanitation and artificiality of the lab can result in unnatural reactions that do not reflect real-life and have low ecological validity (the degree to which an investigation represents real-life experiences). These variables limit the accuracy of the experiment.⁷

Some improvements can be applied to this exploration as there are several weaknesses. One is the variance in the number of salt particles that come in contact with the ice cube. When the petri dish with the salt reagent is poured in the

beaker, not all the salt is in contact with the ice cube, and the results of the different trials may not be accurate.

Other experimental errors include impurities in the vessel that contained the reactants, inaccurate measurement readings from the scale, fluctuations in humidity, pressure, airflow, etc. Furthermore, another improvement for this experimentation is the number of trials, the experiment had 5 trials but with more time available the trials can go up to 7-8 trials so as to increase the number of data points on the graph so as to have more consistency. A final improvement is the website used to plot the data points in the Table 1. Google sheets was utilized for this experiment, but there is a limit to the detail of the value that the graph on sheets can examine. The more detail and separation in the reagent lines, the more detailed the analysis can be.⁷

■ Methods

This experiment requires multiple variables to identify the most efficient salt, while simultaneously keeping factors in the trials constant so as to keep them fair. The variables used in this experiment are listed and explained below.

Independent variables:

1. In each trial, the salt used includes calcium chloride (CaCl_2), sodium chloride (NaCl), and magnesium sulphate (MgSO_4). The different number of salts used shows the difference in the mass trial between the salts. The use of the different variables shows the increased reliability of the results as more data points on the graph creates visual patterns that can be analyzed.

2. In this experiment, we tried to minimize the number of pollutants, but there will always be the uncertainty of possible molecules on the solvent. They can possibly affect the rate at which the ice cube melts and as a result, will become an independent variable. But it is important to note that this is not a variable that was chosen on purpose, it is merely listed as a possibility for this experiment.

3. The amount of time allocated for each trial was varied where Trial 1 was given 5min, Trial 2 was 15min, Trial 3 was 30min, Trial 4 was 45min, and the last trial (5) was allocated 60minutes. These timings were varied with the purpose to show that one salt can consistently lower the freezing point of the ice cube the most and thereby melt the ice cube the most.

Dependent variables:

1. Amount of water melted from the ice cube: This is what will be calculated to see the percent mass of how much the ice cube has melted with the given amount of time. In the different trials, the reagent will result in different masses of the ice being melted at different times.

2. Reduction in the freezing point of the ice cube when in contact with the salts:

The different solutes reduce the freezing point of the ice cube by different values. This variable depends on the number of molecules dissolved in the solvent and as a result, becomes a dependent variable. Even though this variable is not a value this experiment itself will find, it still becomes a dependent variable part of the reaction.

Controlled variables:

1. Refrigerator temperature (-18°C) where the ice cubes were stored was kept constant: The storage where the ice cubes were stored is quite important as changing the location of ice cubes could alter the precision of the experiment, because some refrigerator-freezers may have their temperature changed.

2. Time ice cubes were left out before solutes were dissolved in them: Precisely 10 minutes after the ice cubes were taken out of the freezer, the salt solutes were placed in the beakers to keep the trials fair and constant. Keeping this a controlled variable was difficult, as I had to start a timer and quickly rush retrieving the ice cube tray, measure each ice cube and salt all within 10 minutes. I realized that I could have extended the time the ice cubes were left out, but also realized that the ice cubes could also start melting.

3. Masses of the solutes (CaCl_2 , NaCl , MgSO_4) and solvents (ice cubes) were kept constant as well: Each solute was measured with an electronic mass balance to be 5.0 cm^3 (Figure 2), and the solvents were measured to be 25.0 cm^3 . These masses were kept constant throughout the trials.

4. Location of the trials: The location of the trials is essential as different locations have different variables and factors that may affect the speed of the salt to lower the freezing point of the ice cube. This is why the location of the trials in this experiment was kept constant.

5. The purity of the solutes and solvents: In each trial, the salt and ice cube had to be used in such a way to minimize the exposure to possible contaminants. This included using the same bottle of distilled water in which the ice cubes were frozen in and using clean apparatus (scoopulas, beakers, Petri dishes, etc.) to retrieve the salts from their jars. Even the jars from which the reagents were used were kept constant throughout the trials.

6. Size of salt particles: This may seem minuscule but has the possibility to greatly affect the rate at which the salt lowers the freezing point of the ice cube. The surface area that which the reagent covers is important, leaving the reagent in a more solid form can slow down the process of freezing point depression, which is why for this experiment I ground all the salts so as to keep the differences between the salts minimal.

Photograph of set-up:

Figure 2: Photograph of my experimental set-up, weighting out 5.0 grams of Calcium chloride reagent using a mass balance.

Experimental procedure: The procedure outlined by Science-Buddies.org with modifications to coincide with the different variables and factors in my experiment was utilized. The modified procedure is described in detail below.

100.0 cm³ of distilled water was collected from Glacéau Smartwater Vapour water bottle using the pipette and pipette pump, I then slowly and carefully poured 25.0 cm³ into 4 squares in the ice cube tray. Once again, 100.0 cm³ of distilled water was collected and poured into another 4 squares on the ice cube tray. Finally, this process was repeated until 20 ice cube squares in the ice cube tray were filled with distilled water. The ice cube tray was carefully transferred into a freezer and let sit overnight. The following day, I used a scoopula to transfer an eyeballed amount of calcium chloride in the mortar. I grounded the calcium chloride (CaCl₂) with the pestle to small particles. I repeated step 3 for sodium chloride (NaCl) and magnesium sulphate (MgSO₄), used different Petri dishes for the other salts. I retrieved ice cube tray from freezer and set a 10-minute timer, then placed 1 ice cube into each of the four 200.0 cm³ labelled glass beakers. Next, I placed the three salts on three ice cubes, but the last ice cube was the control. At the end of the 10 minutes, I started another timer for 5 min. I used a clean scoopula to try to place and shift as much of the salt on or near the ice cube and used Sony Xperia X Performance to take photos of the experiment. After the timer ended, I quickly used tweezers to retrieve the ice cubes from the four beakers and placed on new clean Petri dishes which were weighed (cm³) on the Acculab V 600 electronic mass balance, but not before the Petri dishes were zeroed out. In the four following days, the same experiment was conducted but with the timing in which the ice cubes were left in the beakers were changed to 15 min, 30 min, 45 min, and 60 min for the rest of the trials.

Calculation

Calculating freezing points: As stated earlier, the freezing point depression equation was used in addition to the experimentation as a safeguard to ensure that the results that I collected are accurate in the terms that the most effective salt will have the greatest change in the freezing point of the ice cube. The calculations of the values of the freezing point depression are shown below:

Calcium chloride (CaCl₂): To calculate the Freezing Point Depression³ for CaCl₂ the formula is $\text{Freezing Point}_{\text{total}} = \text{Freezing Point}_{\text{solvent}} - \Delta T_f$, where $\Delta T_f = i \cdot K_f \cdot m$. Here we are given the K_f of water which is 1.86 °C kg/molal and the freezing point of water is 0 °C. We require ΔT_f , van't Hoff factor (i), molality of solute (m), and $\text{Freezing Point}_{\text{total}}$.

Given the moles of CaCl₂ and volume of water in kg, we can calculate the molality of CaCl₂ which is 2.00 mol/kg. The next step is about the van 't Hoff factor "i". CaCl₂ is an ionic compound making it a strong electrolyte and therefore has "i" > 1. To determine the exact value of "i" we need to know the number of ions CaCl₂ that will dissociate in aqueous solution. The answer is 3 because there are 1 Ca⁺ ion and 2 Cl⁻ ions, totaling 3. Finally, since we have calculated the molality of CaCl₂, "i", and K_f, it can be calculated that the ΔT_f of CaCl₂ is 11.16 °C. By calculating the ΔT_f of CaCl₂ to be 11.16 °C, the $\text{Freezing Point}_{\text{total}}$ was -11.16 °C.

Using a method similar to CaCl₂, the $\text{Freezing Point}_{\text{total}}$ for NaCl was -11.09 °C and MgSO₄ was -6.10 °C.

Sample Calculation:

(for showing how relative performance was calculated):

Trial 1 for calcium chloride:

$$\begin{aligned}\text{Relative Performance} &= [(\text{original mass of ice cube} - \text{the new mass of ice cube}) / (\text{original mass of ice cube})] * 100\% \\ &= [(25\text{cm}^3 - 22.19\text{cm}^3) / (25\text{cm}^3)] * 100\% \\ &= 11.24\%\end{aligned}$$

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