A spray freeze field investigation for road salt recycling of contaminated melt water and sand wash water

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ABSTRACT
The natural separation of the salts from the snow at the City Edmonton Snow Storage Facility can be further enhanced physically by collecting the first portion (high concentration) of the snow melt and subsequently spraying it into the cold winter air (spray freezing). A field investigation was carried out using the sand recycling pond water. During the first and second pilot spray field studies 15% and 24% of the water froze, respectively. Through melting of the spray ice cores, up to 90% of the chlorides and sodium were released within the first 19% of the melt water.

RÉSUMÉ
La séparation naturelle des sels de la neige aux Installations d'entreposage de neiges usées de la ville d'Edmonton peut être améliorée en récoltant la première partie (forte concentration) des eaux de fonte et en la pulvérisant dans l'air froid d'hiver (congélation par pulvérisation). Une étude a été réalisée en utilisant l'eau des étangs de recyclage de sable. Au cours des première et deuxième études pilotes de pulvérisation, respectivement 15% et 24% de l'eau a gelé. Lors de la fonte de ces échantillons de glace, jusqu'à 90% des chlorures et du sodium ont été libérés dans les premiers 19% des eaux de fonte.

1 INTRODUCTION

To alleviate the hazardous winter driving conditions in Canada, a mixture of sand and road salts, usually sodium chloride, are spread over the roads. As traffic passes across roads, the snow and/or ice becomes bonded to the road surface; road salts are added to break this bond so that all material can be removed (TAC, 1999). To reduce the cost of trucking in aggregates, The City of Edmonton has undertaken a sand recycling program where sands are collect from the streets during the spring, washed and stockpiled at the sand recycling facility. The by-products of the sand recycling process are large volumes of (1400 m^3) salty water. Currently the City of Edmonton adds 2-6% salt to the road sand by weight and the salts from the snow dumps and the sands recycling facilities are diluted with snow melt water and discharged to the North Saskatchewan River. In order to ease the high salt load on the environment, freeze separation is being examined as a means of recycling a portion of the salt at municipal snow storage facilities, specifically the City of Edmonton Poundmaker facility. This paper briefly describes the effectiveness of spray freezing for further concentrating the melt water runoff and sand recycling wash water into reusable brine as a supplement to the crystal road salt. Two spray freezing field trials were conducted by the University of Alberta on January 15 and 16, 2008 and again on February 4, 2008. The results of these trials as well as a laboratory study of the spray ice mound ice cores are presented.

2 BACKGROUND

Freeze separation mechanisms have been used to desalinize sea water and brackish water as early as 1960 (Elmore, 1968; Fertuck, 1969). Several concepts of freeze separation; including spray freeze (Gao, 1998), trickle freeze (Beier, 2006; Otto, 2002), thin layer freezing (Willoughby, 2005) and freezing beds (Martel, 1993), have been proven to be effective on a variety of liquid industrial wastes.

The natural freezing process uses freeze separation to separate out contaminants through the formation of ice and snow. The crystal lattice in which water freezes is very selective and will not accept substitutes for the hydrogen and oxygen atoms, consequently if an aqueous salt solution is frozen extremely slowly, the foreign ions remain in the melt water and perfectly pure ice is formed (Pounder, 1965).

Impurities are further released during melting since the first portion of the melt water contains higher concentrations of impurities than the original bulk ice or snow; this phenomenon is called fractionation (Gao et al., 2004). Colbeck et al. (1981) found that soluble impurities contained in snow cover can be concentrated as much as five fold in the first fractions of the snowmelt. During winters with little or no snowmelt before spring, most of the pollutant load is retained in the snow pack and experiments have indicated that 50-80% of the pollutant load is released with the first 30% of the melt water (Johanessen & Henriksen, 1978). However, not all the solutes contained within the snow or ice are removed with the same efficiency (Brimblecombe et al., 1987).

Spray freezing uses a concept similar to snow-making to pump and spray wastewater into the cold winter air. As the water is sprayed through a nozzle it is broken up into small droplets and as they solidify from the outside in they push the impurities to the centre of the drop. Droplet nucleation often takes longer than 10 seconds and therefore, commonly only a portion of each drop will freeze before it hits the ground (Gao, 1998). As the droplets hit the ground the frozen portion will create a spray ice mound of nearly pure water and the runoff will be a wastewater more concentrated than the source wastewater.

3 SITE DESCRIPTION

The subject Snow Storage and Sand Recycling Facility is located on 184 Street and 107 Avenue, in the west end of Edmonton, Alberta, Canada. The western portion of the site contains the Snow Storage Facility, a large region with a total drainage area of 7.31 hectares. The site is graded so that all overland flow from the snow pile flows into the Northwest corner of the melt water settling pond at a grade between 0.9 and 1.7%.

The Sand Recycling Facility is contained within the East portion of the site of which most of the area is occupied by the sand recycling equipment. All wash water from the sand recycling activities drain into the sand recycling pond located within the western portion of the site. This pond has an approximate volume of 4000 m^3.

4 SPRAY FREEZE PROGRAM

4.1 Methodology

Spray freezing was assessed as a method to further concentrate the melt water and sand recycling wash water. The snow storage settling pond was drained in the fall time due to sludge build-up and therefore the sand recycling settling pond was used for the spray freeze operation field experiments.

4.2 Spray Freeze Set-up

For both spray freeze experiments, two pumps in series were used with a total of approximately 370 metres of hose. During the second operation in February of 2008, less hose was run from the pump to the monitor in an attempt to minimize head loss and obtain more pressure at the nozzle. The spray runoff was allowed to trickle across the snow storage site to a small sump and low area. Figure 1 shows a site photograph of the spray freeze operation.

Figure 1. Spray freeze operation

4.3 Field Work Program #1

The first field work program took place on January 15, 2008. The hose used throughout majority of the system was 4" lay-flat hose designed for a maximum pressure of 1034 kPa (150 psi). The last 25 metres of hose near the fire fighting nozzle was standard 5.08 cm (2 inch) fire fighting hose. The nozzle was mounted on a steel frame fire fighting monitor that was pinned into the ground with steel pins. The vertical angle of the monitor was easily adjusted during spraying and the horizontal angle was adjusted and set for the prevailing Northwest winds prior to starting the pumps. The site was graded towards a small sump although no defined drainage path was constructed. The area available for spray freezing was more than 50 X 50 metres and the underlying clay liner along with the overlying ice and snow was considered adequate runoff control given the large available area.

Successful commencement of the spraying began at approximately 4:30 pm when the ambient air temperature was approximately -11 ℃. The air temperature was monitored continuously, and recorded every five minutes, with two thermistors hooked up to a data logger. A low freezing rate was observed during the initial 3 to 4 hours. Much of the water was running off the spray ice pile creating a large spread-out pool which slowly seeped across the site towards the sump area about 50 metres down from the spray ice mound. The height of the water jet was approximately 6 metres at its highest point, and more retention time was required for majority of the droplets to freeze at the ambient air temperatures (-10 ºC) during the course of the experiment. However, the greatest contributions to its growth were made during the night when the temperatures were coldest (-20 ºC). The ice mound was fairly yellowish in color at the beginning of the experiment but became whiter with time as it froze and the impurities continued to drain out.

Pumping continued until approximately 8:30 am on January 16, 2008 when the temperatures began to rise dramatically and unacceptably low freezing efficiency was being observed.

Electrical conductivity (EC) measurements of the runoff and the source water were made continuously throughout the experiment. The value of the EC is comparative to the concentration of dissolved ions (i.e. salts) in the water and therefore a good indication of the effectiveness of the freeze separation process taking place.

4.4 Field Work Program #2

The second field work program took place on February 4, 2008. For this trial, a different nozzle with adjustable flow rate settings was attached to the monitor. Three holes were drilled in the pond ice on February 1, 2008, prior to spraying, in order to estimate the remaining volume of water in the pond and hence the spraying time available. The depth of water in the pond had been reduced from 1 m to about 30 to 55 cm depending on location. Below the water was a 10 cm layer of sludge or suspended solids at the base of the pond which had to be avoided to prevent clogging of the nozzle.

The second spray freeze experiment commenced at 2:00 pm on February 4, 2008. A lower ambient air temperature ranging between -16 and -22 ℃ was observed and the height of the water jet reached approximately 10 metres during the first portion of the experiment and was reduced to about 6 or 7 metres when ice and debris caused a decrease in flow rate. As the evening progressed, several issues such as an ice jam in one of the pumps as well as a plugged up nozzle required the spraying system to be shut down several times. A flow meter was used, with a data logger properly calibrated to read flow rates up to 108 m^3/hr. Spraying continued until about 11:50 pm on February 4, 2008 when frozen hoses and a lack of remaining pond water, required the experiment to be terminated early. EC measurements of the runoff and spray water were made as in the first experiment.

4.5 Spray Ice Sampling

On January 23, 2008, a core sample of the first spray ice mound was taken using a 1 metre long, 100 mm diameter, CRREL fibreglass core barrel. One vertical hole was drilled from the top of the ice mound. A total of approximately 2.15 metres of core were obtained. The cores were extruded, bagged and labelled and packed in a cooler with snow for safe transport back to the University of Alberta. The cores were stored in a cooler at -10 ℃. When core analysis could not be done shortly, within the following two days, the bagged core samples were surrounded by crushed ice and snow to minimize sublimation.

The second spray ice mound was sampled approximately one hour after the completion of spraying on February 5, 2008. The pile was cored until liquid was reached at the bottom of the pile and approximately 1.90 metres of core was obtained. The second spray ice pile was cored again on February 13, 2008 after sufficient drainage of the brine was allowed to take place within the pile. The pile was drilled to the very bottom and a total of 1.98 metres of core was obtained. The core obtained directly after spraying was yellowish in colour and contained more liquid than the core obtained a week after drilling. The core samples were dealt with in a similar manner as the ones obtained from the first spray ice mound.

5 RESULTS

5.1 Spraying Operation

During the first spray freeze operation on January 15 and 16, 2008, the pumps were run for approximately 16 hours and a total of approximately 800 m^3 of water was pumped. The flow rate was at or above 54 m^3/hr for the first 8 hours (the first half) of the experiment. The flow metre was not calibrated to read flows above 54 m^3/hr however it is not expected that the flow rate went significantly above this number and therefore, 54 m^3/hr was used as the maximum rate. During the final 8 hours, at around 12:00 am on January 16, 2008, the flow rate began to decrease as the nozzle became plugged with debris from the pond. The flow rate had decreased to about 38 m^3/hr when the system was shut off at around 8:00 am on January 16, 2008.

The University of Alberta Light Detection and Ranging (LIDAR) unit was used to scan the pile and obtain dimensions and overall pile volume. The overall pile volume was calculated using LIDAR software and found to be approximately 220 m^3 with a height of 2.5 metres. The average density of the spray ice was 0.57 g/cm^3. Therefore, approximately 125 m^3 of the 780 m^3 of water that was pumped had frozen, for a freezing efficiency of approximately 16%. Figure 2 shows a photo of the first spray ice mound.

Figure 2. Spray ice mound #1

The second spray freeze operation which took place on February 4, 2008 was notably more efficient than the first. Pumps ran for approximately 10 hours between 2:00 pm and midnight, with several shutdowns in between. A total of approximately 390 m^3 of water was pumped and the maximum flow rate reached was 49 m^3/hr. The adjustable nozzle used during the second field trial allowed for an increase in pressure at the nozzle resulting in a higher water jet which allowed for better retention time of the spray water droplets. As in the first spray freeze trial, peak freezing efficiency was not achieved until the system had been running for a few hours; results consistent with the trial done by Biggar et al., (2005).

The LIDAR scan indicated that the second spray ice mound had a volume of 170 m^3 and a height of 1.7 metres at its highest point. The average drained density was 0.56 g/cm^3. Therefore approximately 95 m^3 of the pumped water had frozen representing a freezing efficiency of 24%, about 8% higher than the first trial. Figure 3 shows the LIDAR scan for the second spray ice mound.

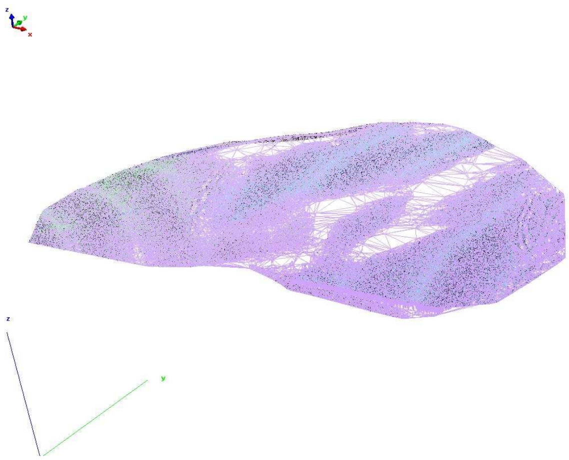

Figure 3. LIDAR scan – Spray ice mound #2

The electrical conductivity of the source water during the first spray freeze trial ranged between 6.8 and 7.1 mS/cm (3800 and 4000 mg/L) and the runoff concentrations were between 7.4 and 9.8 mS/cm (4100 and 5500 mg/L). The second spray freeze trial in February of 2008, had source water electrical conductivities (EC's) between 7.4 and 8.3 mS/cm (4100 and 4600 mg/L) and runoff EC's ranging between 9.0 and 12.1 mS/cm (5000 and 6900 mg/L). From these numbers it is evident that the second trial was more efficient in concentrating the source water than the first. Higher source water concentrations were observed during the second spray freezing trial due to the tendency of the denser more concentrated liquid to sink. The spray freeze process behaved as expected and further validated the results and expectations obtained by Biggar et al., (2005) and Gao (1998).

5.2 Ice core analysis

The ice core from the first spray ice pile, Core 1, had an average density of 0.56 g/cm^3, from a core taken 7 days after completion of spraying. The second spray ice pile had a similar density of 0.57 g/cm^3 from a core taken 8 days after spraying, Core 3. Core 2 was taken from the second spray ice mound approximately one hour after the completion of spraying. The characteristics of this core were much different than those of the cores taken several days after spraying. With an average density of 0.72 g/cm^3, it was evident that much of the liquid brine had not been drained from the pile when this core sample had been taken. Density readings were taken at various depths for each of the three core samples and there appeared to be no relationship between depth and density of the spray ice piles. Occasional dense lenses of more solidified brine liquid were visible in the cores. Figure 4 shows the density readings with depth taken for each of the 3 cores.

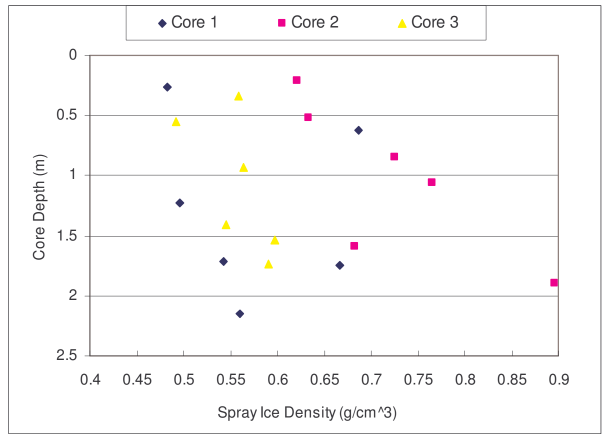

Figure 4. Spray ice density vs. depth

Electro-conductivity (EC) readings of the core samples were taken at various depths for each core. The EC readings as well as the concentrations of the major ions within the cores had no relation to depth. EC readings for the samples which were cored several days after spraying ranged between 0.28 and 0.54 mS/cm (140 and 260 mg/L). EC readings for the sample cored only one hour after spraying were much higher, ranging between 1.9 and 2.6 mS/cm (930 and 1300 mg/L), however these readings were still much lower than the source water.

5.3 Melting of the Ice Cores

The first ice core melting experiment was conducted on the ice core obtained from the first spray ice mound, Core 1. Approximately 1.1 metres of ice core was melted from 0 to 1.1 metres in depth. The ice core was placed on the melting apparatus from top down and was encased in latex membrane overlapping upwards to prevent leakage where overlapping occurred and to simulate the realistic through flow of the brine. A 60 Watt light bulb was placed approximately 80 to 150 mm away from the surface of the ice core in order to provide a sufficient amount of heat to melt the core at an adequate rate. The ice core was originally in 4 pieces which were held together in consecutive order with the latex membrane. A PVC pipe was split in half and used as additional support around the latex membrane.

The first core took approximately 6.5 days to completely melt. Samples were collected at approximately 12 hour intervals on average. The melting rate increased noticeably at first and then slowly decreased with time. For the first 12 hours no melting took place. The melt rate at its peak was approximately 31 mL/hour which took place approximately 48 hours into the melting process.

EC's of the collected melt water samples were also taken after the completion of the melt. The EC began at approximately 4.3 mS/cm (2300 mg/L) and then dropped dramatically to 1.6 mS/cm (780 mg/L) within approximately 12 hours. After about 60 hours or about 40% of the way through the melt, the EC remained low and did not change significantly. Similar results were observed for the melting of Core 2 and Core 3.

5.4 Chemical Removal Efficiency

The chemical removal efficiency was shown to be related to the overall freezing efficiency of the spray freeze operation, where better freezing resulted in higher concentrations in the spray freeze runoff. The second spray freeze trial in which a higher freezing efficiency was observed saw an average concentration factor between 1.3 and 1.4 for the majority of the major ions, while the first trial saw an average concentration factor of 1.1. Figure 5 shows a bar graph of the average concentration in the source water compared to the concentrations in the runoff for the major ions observed for the second spray freeze trial.

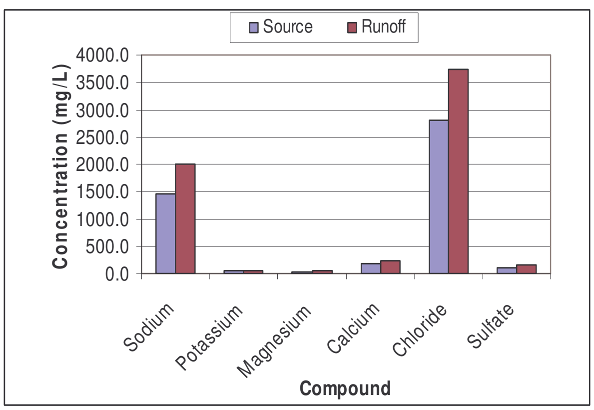

Figure 5. Major ion concentrations in supply & source water - Spray freeze trial #2

Supply water concentrations of Sodium ranged between 1240 to 1350 mg/L during the first spray freeze operation. Concentrations within Core 1, taken from the first spray ice mound showed that 70% of both the Sodium and Chloride was removed during the first 10% of the melt and 90% within the first 19%. During the final 70% of the melt, Sodium concentrations were below 72 mg/L and continued to fall to less than 8 mg/L during the last half of the melting process. For the second spray freeze operation Sodium concentrations ranged between 1450 to 1470 mg/L. The higher source water concentrations were again attributed to the fact that water was pumped closer to the bottom of the pond during the second spray freeze operation, where the denser brine was found in higher concentrations.

A similar trend can be seen with the removal of Chlorides. The supply water concentration for Chlorides during the first spray freeze operation was 2620 to 2890 mg/L and between 3080 and 4390 mg/L during the second spray freeze trial. During the melting of the core taken from the first spray freeze trial, it was observed that Chloride concentrations lower than 121 mg/L remained in the remaining 81% of the core. Although there was no available Canadian guideline for Chloride concentrations, the US EPA recommends that concentrations not exceed 860 mg/L for the protection of aquatic life (Alberta Environment, 1999). The concentrations observed during the last 80% of the core melt were well below this guideline. Slightly lower chemical removal efficiencies were observed for the second and third spray ice cores.

5.5 Mass Balance

A mass balance was preformed to ensure the freezing efficiency obtained as well as the concentrations in the runoff, spray ice and source water, were accurate. The mass balance was done by using the flow rate obtained during spraying to estimate the total volume of water that was pumped. By subtracting the total volume of water pumped from the volume of water frozen within the spray ice mound, the total volume of runoff was obtained. Masses for each of the chemical constituents were obtained by multiplying the average concentrations by the total volume of water within each of the spray realms including the runoff, spray ice and source water pumped. If the data obtained was reasonably accurate then the total mass of the each chemical constituent within the runoff plus the spray ice should be reasonably close to the mass within the supply water. Table 1 shows the mass balance done for Core 1, for the first spray freeze field trial. The masses of each of the constituents seem to be within reasonable limits. The greatest discrepancies appear to be within the constituents with the smallest overall concentrations. This is likely due to the compounded imprecision resulting from the small errors in the concentrations leading to greater inaccuracy in the mass balance.

Table 1. Mass balance – Spray Ice Mound #

Ion	in ice (g)	in runoff (g)	Ice+runoff (g)	In supply (g)	(+/-)
Na^{+}	8475	1029805	1038280	1034022	-0.4%
K^{+}	439	32214	32653	32631	-0.1%
Mg^{+2}	685	19053	19737	21361	7.6%
Ca^{+2}	1585	133821	135406	119573	-13.2%
Cl^{-}	20018	1742058	1762076	1742384	-1.1%
SO_4^{-2}	1016	94477	95493	83821	-13.9%

6 DISCUSSION

From the melting of the spray ice cores, it is apparent that melting is far more efficient in separating out contaminants than freeze separation. Fractionation of the contaminants and release of the majority of the salts during the first portion of the spray ice runoff is highly visible. It is recommended that further research be done in the area of decontamination of road salt by spray freezing with the following additional items taken into special consideration:

- Spraying water during the winter involves many complications and it is therefore imperative that the distance from the source to the spray area be kept to a minimum to reduce risk of ice jams in the hoses and pumps.
- The spray nozzle should be checked frequently for clogging and a proper screen should be placed at the suction end of the hose to prevent particles from reaching the nozzle.
- An engineered drainage system with an adequately sized collection pond for the runoff should be constructed so that re-spraying of the runoff can occur.
- Ambient air temperatures should not be warmer than -20 ºC in order to maintain adequate freezing efficiencies.
- Droplet size and retention time of the spray droplets play an important role in the spray freezing process. Adequate velocities are required at the nozzles to produce sufficient air retention times for partial freezing/super cooling of the droplets.

If extremely high freezing efficiencies can be obtained then greater contaminant removal can be accomplished through the collection of the first portions of the melt water from the spray ice mound.

7 CONCLUSIONS

The pilot spray freeze field study had only 15% and 24% of the water freeze during the first and second spray freeze trials, respectively. However, freezing efficiency is expected to increase with a higher pressure system allowing more retention time for the spray droplets and with colder ambient air temperatures.

During melting of the spray ice cores it was found that up to 90% of the Chlorides and Sodium were released within the first 19% of the melt water.

The use of spray freeze technology to concentrate salts at city snow dumps seems feasible, but for optimal success it is recommended that the first portions of the snow melt water be collected from the snow pile in a separate holding pond which can then be re-sprayed to further increase salt concentrations. Construction of a well designed drainage system will further increase the viability of the spray freeze system by allowing the runoff to be re-sprayed. Successful reuse of this brine could prevent large amounts of salts from being released into local waterways.

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