Freeze–thaw treatment of RBC sludge from a remote mining exploration facility in subarctic Canada

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ABSTRACT

Freeze–thaw conditioning of RBC (Rotating Biological Contactor) sludge was tested using a pilot-scale freezing bed placed in a mobile freezer operated at −10 °C. Sludge samples from a remote mining exploration facility were flown in every 2 weeks, and added to the freezing bed in 8 layers of 10 cm thick. Approximately 4 months after the first layer of sludge was added, the pilot unit was removed from the freezer and thawed at ambient temperatures. After one day of thawing, the solids concentration increased from 2.6% to 16.2%. The final cake solids concentration was 21%. Melt water had increasing turbidity, COD, TSS, VSS, nitrogen and phosphorus concentrations during the thawing period. Freeze–thaw conditioning also decreased the initial densities of fecal coliforms and

Salmonella

in sludge. The results of this study showed that freeze-thaw technology successfully dewatered RBC sludge without the need for mechanical equipment, and is a sustainable option for sludge dewatering in cold and remote regions.

Key words | freeze-thaw, land application, RBC (Rotating Biological Contactor), sludge, treatment

INTRODUCTION

Sludge dewatering is one of the most challenging processes during sludge treatment. Particularly in cold climates, mechanical sludge dewatering becomes a major problem for treatment plants because the equipment is difficult to maintain and ices up frequently in subfreezing temperatures. In addition, supplying chemicals and dewatering aids can be expensive particularly for treatment plants in remote locations.

Attention has been placed on freeze-thaw technology in an attempt to solve the dewatering problem in cold regions. Freeze–thaw conditioning is a simple, effective, and low-cost technology when freezing is achieved naturally. Freeze–thaw technology works on the principal that ice crystals grow by incorporating water molecules only. Because the structure of ice crystal is highly organized and symmetrical, it cannot accommodate any other atoms or molecules. Each ice crystal continues to grow as long as water molecules are available. All other impurities and solids are forced to the boundaries of the ice crystal, where they become compressed or dehydrated (Chalmers 1959).

Hoekstra & Miller (1967) hypothesized that the layer of surface water surrounding the sludge particles allows them to move along the growing ice front. This means that smaller particles are more easily forced from the ice crystal, whereas larger particles are more likely to become entrapped in the ice crystal. Similarly, high freezing rates can reduce the effectiveness of freeze-thaw dewatering by entrapping particles within the ice front (Corte 1962). Therefore, freezing temperatures greater than −10 °C are generally used to generate slow-growing ice crystals, capable of moving sludge solids along the ice front. Slow growing ice crystals result in a network of continuous channels throughout the consolidated sludge particles (Hung et al. 1996). During thaw, the melt water drains freely throughout the network of channels, leaving a dewatered sludge.

Sludge characteristics play a role in determining the effectiveness of freeze-thaw conditioning. Freeze–thaw conditioning dramatically converts alum sludge from a fine particle suspension to a mixture of clear water and granular particles (Martel & Diener 1991). Presence of dissolved ions...
and extracellular polymers in activated sludge adversely affects the freezing process (Ormeci & Vesilind 2002; Ormeci 2004). Removal of these constituents from activated sludge substantially improves the effectiveness of freeze-thaw resulting in better dewaterability and melt water quality (Ormeci & Vesilind 2001).

Previous research has shown that freeze-thaw technology can be effective at reducing the quantity of pathogens and indicator bacteria in sludge (Sanin et al. 1994). Freezing temperature, storage time, and freeze-thaw cycles affected the survival of *Escherichia coli* and *Enterococcus faecalis*, and greater inactivation efficiencies were achieved under longer storage time and higher freezing temperatures (Gao et al. 2006, 2009). It was suggested that longer freezing times result in cell dehydration (Mazur 1965).

Sludge freezing beds together with a storage facility, such as a lagoon, tank, or digester to store the sludge in summer, can be used as the sole method of dewatering in cold regions. In temperate climates, freezing beds can be used in combination with drying beds to freeze the sludge in winter and dry it in summer. Most of the United States and all of Canada can potentially use freezing beds. Freeze–thaw technology is particularly a viable and sustainable option for facilities located in remote and cold regions.

The goal of this study was to evaluate the effectiveness of freeze-thaw treatment on RBC (rotating biological contactor) sludge generated at a remote mining exploration facility, and determine the improvements observed in physical, chemical and biological sludge characteristics after the freeze-thaw. The mining exploration facility is located in Matoush, which is located 950 km north of Montreal, Quebec in Canada. Freeze–thaw conditioning was considered as a low-cost and low-maintenance option that can solve the dewatering problem on site. The site is only accessible by air, and there is very limited opportunity for transportation both in summer and winter which limits the treatment options. The site has a subarctic climate with winter temperatures averaging −10 °C but ranging down to −40 °C. Summer temperatures are around 15 °C but can reach 30 °C, allowing the thawing of frozen sludge in summer.

**MATERIALS AND METHODS**

Wastewater collected from the living areas and eating facilities of the personnel is treated using a portable, containerized wastewater treatment system (Seprotech Systems Incorporated, Canada) which achieves primary and secondary treatment. RBCs (Rotating Biological Contactor) are used for biological treatment in the containerized unit. Figure 1a shows the remote site in Matoush where the facility is located.

Sludge samples from the RBC unit were flown in every two weeks during the summer months and added to a pilot-scale freezing bed. There were a total of 5 shipments of sludge. Figure 1b shows the pilot-scale freezing bed, which consists of a vertical freezing bed, a drainage system and underlying melt water collection basin. The freezing bed was made of stainless steel and had a plexiglass window to see the layers of frozen sludge. The pilot unit was kept in a mobile freezer at −10 °C throughout the freezing period. To prevent clogging, approximately 10 cm of medium-coarse sand and 10 L of water were added to the base of the drainage bed and frozen prior to sludge addition. Sludge was frozen in layers approximately 10 cm thick to ensure complete freezing. The thickness of each frozen sludge layer was measured through the plexiglass window. A total of 8 layers of sludge were added to the pilot unit over 3 months.

![Figure 1](https://iwaponline.com/wst/article-pdf/63/6/1309/445688/1309.pdf)

Figure 1 | (a) Remote mining exploration facility in Matoush, Quebec (Strateco Resources Inc.), (b) Pilot-scale freezing bed used for freeze-thaw conditioning of RBC sludge.
Approximately 4 months after the first layer of sludge was applied, the pilot unit was removed from the freezer and thawed at ambient temperatures varying from 17.5 to 26°C for 2 weeks. Melt water was analyzed for total suspended solids (TSS), volatile suspended solids (VSS), total dissolved solids (TDS), turbidity, pH, chemical oxygen demand (COD), nitrogen (total, nitrate and ammonia), phosphorus (total), fecal coliforms and Salmonella. Sludge cake samples were analyzed for total solids (TS), volatile solids (VS), COD, fecal coliforms and Salmonella.

The following methods were used to analyze the sludge feed and sludge cake: TS and VS using Standard Methods 2540 B and 2540 E (APHA 2005); COD using HACH method 8000 High Range Plus; and fecal coliforms and Salmonella using EPA methods 1681 and 1682 respectively (U.S. EPA 2005a, b). All measurements were carried out in triplicate.

Methods used to analyze the melt water were: TSS and VSS using Standard Methods 2540 D and 2540 E (APHA 2005); turbidity using HACH Chemical Model 2100AN turbidity meter; pH using a Thermo Orion 5-Star Benchtop Meter Kit and a Ross Ultra pH electrode; total nitrogen (TN), nitrate and ammonia using HACH methods 10072, 10020, and 10031 respectively, and total phosphorus (TP) using HACH method 10127. All measurements were carried out in triplicate.

RESULTS AND DISCUSSION

Initial TS of the five shipments of sludge samples from the site varied from 2 to 3% solids (average = 2.6%), initial fecal coliforms varied from 150 to 6250 MPN/g dry solids (average = 1816 MPN/g dry solids), and the initial Salmonella counts varied from 213 to 508 MPN/g dry solids (average = 242 MPN/g dry solids). It should be noted that the initial sludge bacteria numbers were lower than expected possibly due to the long transportation time (typically 3–5 days) of the samples from the remote site to our laboratory.

Overall, 290 L of liquid sludge was added to the freezing bed during the study. After 10 days of thawing period at ambient temperatures, 250 L of melt water was collected through simple drainage Figure 2 shows the cumulative volume of melt water collected and ambient temperature during the thawing period. During this time, the average total solids increased from 2.6% to 19%, and average volatile solids increased from 2.3% to 17.3%. Figure 3 shows TS and VS concentrations of the sludge before and during the thawing period. After an additional month, the cake solids content increased to 21%, and the final cake volume was approximately 35 L, which indicates that roughly 5 L of water evaporated.

The melt water collected periodically during the 2 week thawing period and was analyzed for several parameters. Figure 4 shows that TSS and VSS concentrations of the melt water gradually increased over time. This was expected since the first few melt water samples (thaw time = 1–2 days) contained some of the extra water which was added to the base of the freezing bed to prevent clogging, and secondly fines from upper sludge layers were displaced from the sludge cake by the draining melt water.

Figure 5 shows the COD concentrations in the melt water. The average COD concentration was calculated as 3,100 mg/L. Similar to the TSS concentrations, the COD of the melt water increased during the first 4 days of the thawing period. After the first day of thawing, 50 L of melt water was collected with an average COD of 1300 mg/L. The following day, another 15 L of melt water was collected with a COD around 3000 mg/L. Peak COD concentrations in the melt water occurred after 2–3 days of thawing, and were around 5000 mg/L. In the following days, the melt water COD concentrations decreased, and after 8–9 days of thawing, the COD of the melt water was around 2000 mg/L. In
addition to the melt water CODs, the total COD of the feed sludge and the total COD of the cake were also measured (1.84 and 1.76 g/g TS respectively), and showed that majority of the organic substances remained in the cake during thawing and did not pass into the melt water.

Figure 6 shows the measured TP, TN, nitrate and ammonia concentrations of the melt water collected during the thawing period. TP, TN and ammonia concentrations increased in the first week but then levelled off or slightly decreased in the following days. As expected, majority of the total nitrogen was contributed by ammonia, and the nitrate concentrations were close to zero. The highest TP concentration was 90 mg/L and the highest TN concentration was 465 mg/L.

Figure 7 shows the turbidity and pH of the melt water during the thawing period. Turbidity measurements on the melt water samples collected during the first day were all less than 30 NTU. After 2 days, the turbidity increased slightly to 40 NTU and after 3 days the turbidity was around 60 NTU. After 4 days however, the turbidity of the melt water increased to 125 NTU, and eventually reached a maximum of 340 NTU after 8 days of thawing. The gradual increase in turbidity is due to fines being washed down with the melt water, with microbial growth also potentially playing a role. The average pH of the melt water collected during the first week of thawing was 5.7, and 6.5 during the second week. The standard deviation for each pH measurement was less than 0.3.

A decrease was also measured in the fecal coliform and *Salmonella* counts in sludge after the freeze-thaw treatment. The fecal coliforms decreased from 1816 MPN/g dry solids to 102 MPN/g dry solids, and the *Salmonella* decreased from 242 MPN/4 g dry solids to 14 MPN/4 g dry solids. Ice crystals that form inside and outside the cells can rupture the cell membrane and cause significant injury or death to the cells. In this study, approximately 1-log reduction was observed in fecal coliform and *Salmonella* counts. It should again be noted that the initial sludge bacteria numbers were lower than expected possibly due to long transportation times. The findings of this research are in agreement with previously reported decreases in sludge microbial densities after freeze-thaw treatment (*Sanin et al.* 1994; *Chu et al.* 1999; *Gao et al.* 2009). Sludge characteristics, freezing and storage temperatures, and number of freeze-thaw cycles are expected to affect
the inactivation rates of microorganisms during freeze-thaw treatment.

The results of this study show that freeze-thaw treatment achieves excellent dewatering and major sludge volume reduction in a simple and cost-effective way. The results also show that melt water has high COD, nitrogen and phosphorus concentrations, and therefore require treatment before disposal. This can be achieved on-site by simply circulating the melt water to the beginning of the RBC treatment system, preferably over a number of days to avoid shock organic loadings from the return melt water.

Odor generation during thawing is another potential problem that might be encountered in the field. In this study, all of the melt water was collected within a week and odors were not detected until day 3 when sludge was still partially frozen. Unless sludge is stored for extended times after thawing, odor generation is not expected to be a significant problem especially in remote regions.

CONCLUSIONS

Freeze–thaw conditioning successfully dewatered RBC sludge and increased the solids content from 2.6% to 21% when sludge was frozen at –10 °C. Melt water quickly drained after thawing, and the solids concentration increased to 16.2% after only one day of thawing. Increases in TSS, VSS, COD, turbidity, TN, TP and ammonia were observed in the melt water during the thawing period. Overall, the melt water had high concentrations of COD, nitrogen and phosphorus and required treatment which can be achieved on site by circulating the drainage waters back to the wastewater treatment system. Freeze–thaw conditioning also decreased the densities of fecal coliforms and Salmonella in sludge by 1-log. The results of this study indicate that freeze-thaw technology is an effective, low-cost and low-tech method of sludge treatment, which is ideal for small treatment facilities located in cold and remote regions.

ACKNOWLEDGEMENTS

This work was funded by Natural Sciences and Engineering Research Council of Canada (NSERC) under the Discovery program. The authors would like to thank Stratco Resources Inc. personnel for collecting and shipping the sludge samples to our laboratory, and Seprotech Systems Inc. for providing the pilot scale freezing bed.

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