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Purity and mechanical strength of naturally frozen ice in wastewater basins

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A B S T R A C T

A fairly clean ice cover can form over a contaminated water pond when the air-cooled surface of water freezes and impurities are efficiently expelled to the remaining water underneath. Natural freeze crystallization has recently been studied as a potential wastewater purification method with aqueous solutions on a laboratory scale. The effect of impurity inclusions on ice strength has been researched in model ice basins over the past few decades. It is of interest to discover how efficiently natural freeze separation works under real weather conditions before freezing can be utilized for wastewater treatment application. Herein, understanding the mechanical strength properties of naturally frozen wastewater (ice) is important when planning ice breaking and harvesting devices.

This research implemented in-situ measurements of the flexural and compressive strength of ice in natural ice-covered environments of a freshwater lake, two peatlands and three mining site basins, and compares the determined strength with analyzed impurities of the ice. The results showed that despite varying ice growth conditions and initial water constituents, it was possible to deduce an evident yet simple relationship between mean ice strength and ice impurities: the more impure the ice is, the lower the value of strength is Based on this exploration, it was concluded that separation efficiencies, i.e. the impurity removal ratio between basin water and ice, from 65% up to 90% can be achieved by natural freezing.

1. Introduction

The major industries in raw material production and final product manufacturing produce large quantities of wastewaters, which also more often contain toxic heavy metals and other inorganic constituents in low concentrations. For instance, millions of cubic meters of water can be consumed annually in a mine during the extraction and processing of minerals. This is likely to pollute fresh water sources in the mine environment through acid mine drainage, leaks and the disposal of tailings (Akcil and Koldas, 2006; García et al., 2014). Thus, the large quantities of industrial wastewaters have generated a need to develop energy efficient wastewater treatment methods.

A naturally cold climate could be utilized as a sustainable cooling energy source to purify wastewaters in basins by means of freezing. Several studies have proved that the purification of aqueous solutions and wastewater by natural freezing is a simple, efficient and cost-effective method (Lorain et al., 2001; Hasan and Louhi-Kultanen, 2015; Shirai et al., 1998), which makes natural freezing a potential purification technique to treat huge volumes of wastewaters. The conventional industrial wastewater purification methods based on biological and physico-chemical treatment, such as adsorption, chemical precipitation, electrolytic treatment, flotation, ion exchange and membrane filtration, have some limitations (Fu and Wang, 2011; Kurniawan et al., 2006). In contrast, in wastewater freezing these can be turned to advantages:

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- Devoid of adding chemicals (Lorain et al., 2001),
- No waste product generation as in chemical precipitation and adsorption (Babel and Kurniawan, 2003),
- No high operational costs caused e.g. by fouling and cleaning of membrane filters or high energy consumption in electrodialysis (Kurniawan et al., 2006),
- High separation efficiency and non-selectivity in impurities are achievable, as ice is naturally highly intolerant to impurities (Bogdan et al., 2014; Lorain et al., 2001).

Sustainable wastewater management includes efficient water purification and provides the possibility for the recovery of valuable materials as well. Particularly with certain industrial wastewaters, natural freezing provides these both, as ice and salt can be crystallized simultaneously in eutectic condition (Hasan et al., 2017). Ice and salt can be separated due to gravity, when salt settles down and ice floats (Randall et al., 2011). If the purity of the ice layer is high, it could be recycled as process water or utilized further as a cold storing material for cold heat storage (Shirai et al., 1999).

Fig. 1 presents a conceptual design of wastewater freezing in a basin with downstream processing of the naturally frozen ice layer. At first, the surface of the wastewater is frozen naturally in the basin. This ice layer is broken into pieces, which could be collected and separated from the concentrated wastewater in the subsequent steps. For ice breaking device design and the optimization of the ice harvesting process, it is of great importance to have knowledge of the mechanical properties of the ice layer, such as bending and compressive strength, the influence of freezing conditions (consequently the purity of the ice) and wastewater composition. The ice strength, together with the ice thickness, determines the design requirements of the ice breaking device, i.e. the strength defines the force needed to break the ice. This research assays the variability on ice strength in the studied wastewaters and gives an overview of further device planning.

Natural ice consists of ice crystals whose orientation, shape and size determine the structural characteristics of the ice as well as impurity inclusions due to the formation of aqueous solution pockets and veins and gas bubble voids in the ice cover. Ice properties such as temperature and structure are considered to affect the physical and mechanical properties of the ice (Light et al., 2003; Timco and Weeks, 2010). Bogdan and Molina (2010, 2017) investigated the impacts of a freeze-concentrated solution on complex phase transformations (such as ice crystallization) during the cooling and warming of bulk solution droplets in emulsions in a highly controlled manner in a temperature range between 133 K and 278 K. They evidenced that the processes yielded mixed-phase particles formed of an ice core with a freeze-concentrated solution coating. The effects of impurities on sea ice in the form of brine (salt) have been studied to a great extent in the past. The studies have shown that increasing the brine content in ice weakens the ice significantly; see Timco and Weeks (2010) for a review study.

The effects of chemicals on the mechanical properties of ice have been studied to some extent already decades ago. These studies have focused on scaling down the mechanical properties of the ice to a suitable strength for model testing in ice basins by weakening the ice (Borland, 1988). Hirayama (1983a) showed a clear decreasing trend in the ice flexural strength and elastic modulus with increased urea concentration; the top layer of the urea doped is thicker than what is observed in sea ice (Hirayama, 1983b). Timco (1981) tested various salts, alcohols, acetates, amides and sugar and came to similar conclusions regarding the reduction in flexural strength with increasing impurities. Timco (1981) reported that the lower the molecular weight of the doped substance is, the lower the concentration required to reduce ice strength is. The same applies for the saturation point, i.e. the point whereafter the ice strength does not decrease (Timco, 1981). Some interaction between various chemicals that intensify the weakening of the ice has also been postulated between aliphatic detergent and ethylene glycol (Lehmus, 1988).

However, studies focusing on purification by freezing have not clearly addressed the effect of impurities on the mechanical properties of ice. Studies focusing on the effect of doped substances on the mechanical properties have considered the concentration of the initial solution, but the purification has not been studied precisely. Furthermore, studies on purification by freezing have been conducted in laboratory conditions where the environment and the initial impurities have been controlled. In contrast, real wastewater is a complicated mixture of various impurities, as it contains constituents that the water accumulates through different processes. When the wastewater is exposed to the open environment conditions, the freezing process is hardly controlled. To use natural freezing for wastewater purification in practice and to be able to break and harvest the purified ice, a few issues need to be clarified: 1) how efficiently the natural freezing purifies the wastewater in the open environment; 2) what the mechanical properties of the ice are; 3) how impurities affect the mechanical properties of ice and 4) how the purity and strength of ice could be assessed.

In this study, the flexural and compressive strength tests for ice were carried out and ice and water samples were collected for chemical impurity analyses from several locations in different types of natural water and wastewater environments. As a result, the effects of impurities on the mechanical properties of ice were

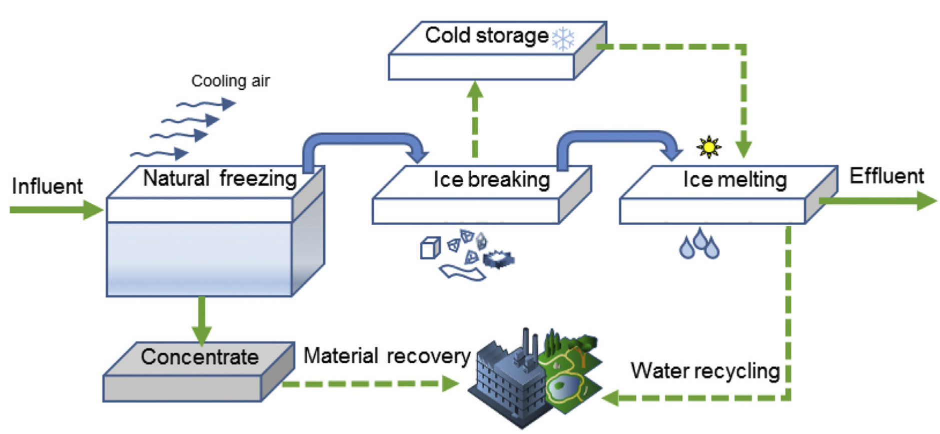

Fig. 1. Principled process of water purification by natural freezing.