The Interaction of Newly Forming Frazil Ice and Sediments

by

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Abstract

In river freeze-up periods, small disc-shaped frazil ice forms during supercooling in turbulent river flow. Under continuous cooling, these particles collide and freeze to form frazil flocs and entrain suspended sediments. Sediment-laden flocs might rise to the surface and freeze into frazil pans, eventually becoming ice cover; or sinking to the bottom and forming anchor ice. Studies of the interaction between newly forming frazil ice and suspended sediments in northern rivers during the freeze-up period are limited. This study investigated how the suspended sediment concentration changes in the water column, which sediment sizes are more likely to get entrained in the frazil ice, and how organic content changes during the supercooling process. To study the sediment concentrations in natural frazil ice, samples were collected from the North Saskatchewan River during the freeze-up period of 2021. Laboratory experiments were done in a freshwater frazil tank in a cold room with three types of sediments (clay-silt, natural, and sand) under three initial concentrations. Samples, including the initial tank water, final tank water, interstitial water, and drained ice, were filtered to examine the sediment concentrations to study the sediment entrainment mechanism.

Results showed that when frazil ice formed in turbulent tank water, up to 75% of suspended sediments were removed from the water column, even though only 2~3% were entrained in the frazil ice. Based on observations, this is likely because sediment-laden frazil flocs can be shredded by propellers, releasing sediments close to the tank bottom. In addition, the sediment concentrations of the final tank water showed that coarser sediments were removed more efficiently than finer sediments, likely because finer sediments are easier to

suspend. Sediments were trapped inside the porous ice lattice of frazil flocs as sediment-laden water flowed through the flocs, like a sieving process. Coarser sediments were more easily entrained in frazil flocs, and finer sediments were more easily flushed out with water, as proven by the ratio of sediment concentrations in the drained ice versus interstitial water 0.7 for clay-silt, 2 for natural, and 3.3 for sand. Sediment concentrations in the field drained ice, and interstitial water samples ranged from 76.7 to 1244 mg/L and 15.1 to 48.9 mg/L. The field's drained ice versus interstitial water ratios (1.8~51) are much bigger than in the lab. Because sediments used in the lab were well-sorted in a specific range, field frazil can entrain small rocks that significantly increase the sediment mass in ice samples. The organic content in river water samples (0.18~0.6) was much higher than tank water samples (0.09~0.13); however, the organic content in drained ice samples from the river (0.05~0.14) and tank (0.1~0.17) was similar to each other, suggesting consistent organic harvesting ability of ice.

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1 Introduction

Frazil ice formation occurs in many northern rivers when turbulent open water and a sufficiently large heat loss result in supercooled water. Frazil ice crystals, typically in the shape of discs, are formed in the supercooled water, causing latent heat to be released into the water (Foulds and Wigle 1977; Martin 1981). Assuming that the air-water heat flux is constant, the formation of frazil and the associated release of latent heat slows down the supercooling process; at the same time, the frazil production rate increases because more ice nuclei are present to facilitate secondary nucleation (Ashton 1978; Hanley and Tsang 1984; Clark and Doering 2009). When the latent heat of fusion produced by ice formation equals the net heat loss to the environment, the water temperature reaches its lowest point, known as maximum supercooling. Once there are sufficient numbers of suspended frazil ice crystals, flocculation occurs, and frazil flocs are formed as crystals sinter together (Clark and Doering 2009; Schneck et al. 2019). This time the water temperature increases because the latent heat flux exceeds the net heat loss, and the water eventually reaches a constant residual supercooling temperature of ~0.01 °C.

Previous laboratory studies have shown that frazil ice and suspended sediments interact (Reimnitz et al. 1993; Ackermann et al. 1994; Kempema et al. 1993; Smedsrud 2001; Dethleff and Kempema 2007). In these flume and tank studies, suspended sediment was observed being entrained into frazil flocs. Sediment-laden frazil flocs may either adhere to the bed and create anchor ice (Qu and Doering 2007) or rise due to buoyancy and bring sediments to the surface. Sediment-laden floating frazil flocs may impact sediment transport, and if they become frozen into the ice cover may alter the surface energy balance.

Sediment frozen into the ice cover may substantially lower the albedo, significantly increasing the amount of absorbed solar radiation (Shapiro Ledley and Pfirman 1997). Studies of frazil ice interactions with suspended sediments are very limited, and additional research is needed to completely understand the importance of frazil-sediment interactions in rivers.

Reimnitz et al. (1993) conducted experiments in water columns. An insulated cylinder 1.82 m in height and 8 cm in diameter was placed in a 12 cm deep plastic pan; the pan was cooled with methanol and dry ice. The cylinder was filled with 9.3 L seawater with a salinity of around 32 ppt. A magnetic stirrer provided turbulence to up to 0.8 m depth. For better observation, a different apparatus was used in later experiments. A 13.75 L rectangular column tall 1.91 m that had sides of 12 cm. The column was placed on an aluminum base with cooling fins. A motor-driven propeller produced turbulence. The results showed that most frazil crystals were smaller than 1 to 2 cm in diameter. The porosity of flocs on the surface layer ranged from 68% to 85%. They stated that the salinities of drained ice ranged from 12 to 20 ppt. The salinity of interstitial water was slightly higher than the original tank water. Silty sand (53 to 833 μm), 1.6 to 2.4 g, was released at the water surface when frazil started rising. Drained frazil slush samples were observed to hold more sand than interstitial water samples. Twelve experiments using mud showed different results. Mud with concentrations ranging from 10 to 8000 mg/L was added to the cylindrical tank. Eight experiments showed that slush ice had higher sediment concentration than the underlying water. Two showed insignificant differences; slush ice had less sediment than underlying water in the other two samples. The mud particles were predominantly found in the interstitial water rather than drained ice. Their freshwater experiments showed no evidence that the ice had adhesive properties in supercooled water or that sediment particles became incorporated into the growing crystals. They also mentioned that ice formed in turbulent, supercooled salt water does not nucleate onto foreign particles and has no adhesive properties (Reimnitz et al. 1993).

Ackermann et al. (1994) conducted freshwater experiments in tall clear cylinders. The main part of the experimental apparatus was a clear plastic cylinder 1.15 m in height and 0.138 m in diameter. A propeller at the bottom created turbulence. Sediments were added to fresh water at 1% by weight. Experiments with fine silt (d_{50}=2x10^{-3} mm) showed that sediment concentrations in frazil ice slush were roughly 2/3 of that in the initial tank water. Experiments conducted with coarse silt (d_{50}=2x10^{-2} mm) found that the sediment concentrations in frazil slush were all lower than 0.1% by weight; hence they concluded that rising frazil could not permanently hold coarse silt. In experiments conducted with sand (d_{50}=0.12 mm), it was observed that the sediment-laden frazil contained so much sediment that it sank to the bottom. In half of the experiments, there was no frazil to collect at the surface. They stated that rising frazil scavenged suspended sand far more effectively than silt.

A race-track flume 1.2 m in length, 0.21 m in width, and 0.32 m in depth was used to generate frazil and anchor ice by Kempema et al. (1993). The flume was insulated so that water was only cooled from the surface. The water depth was 17 cm, the total water volume was 110 L, and flow velocities varied from 30 to 70 cm/s. Freshwater experiments and saltwater experiments at salinities 29.2, 32, and 37 were conducted. The freshwater frazil crystals were mainly thin discs 1 to 5 mm in diameter, and flocs grew up to 8 cm in diameter. Saltwater frazil crystals were mainly thin discs 1 to 3 mm in diameter, and the crystals tended to be aligned along flat surfaces and formed into 1 cm thick small flocs. Sand with mean grain sizes of 0.25 mm or 0.3 mm was placed in the channel bed to a depth of 4 cm in different trials. Silt and clay at 60 g (0.55 g/L) were added to the water at the beginning of some trials. Kempema et al. (1993) reported that the maximum sediment concentration in ice was 88 g/L. Water sediment concentration averaged 0.42 g/L; the highest value was 1.5 g/L. They stated that frazil ice generally contained more sediment than underlying water (Kempema et al. 1993).

Four experiments were conducted by Smedsrud (2001) with saltwater (36 to 38 psu) circulated in a flume 20 m long, 6 m wide, and 1 m deep. Impellers were used to create a current of 10 to 30 cm/s. Air temperature at -15 °C and surface wind at 5 m/s provide upward heat flux of 140 to 260 Wm^{-2}. A wave machine generated waves with an amplitude of up to 10 cm. Frazil ice crystals were observed growing up to 2 cm in diameter, and the concentration of suspended frazil was approximately 1 g/L in the first three experiments, A, B, and C. In contrast, in the last experiment, D, it was 3 g/L. The surface slush layer grew up to 20 cm thick and had a water content of 60%. Silt and sand (63~250 µm) were added to the tank at concentrations of approximately 15 mg/L in experiments A, B, and C. Larger particles settled on the bed after a couple of hours. Clay and silt (median diameter 2.5 µm) were added to the tank at a concentration of 12 mg/L in experiment D; in this case, no sediment settled on the bed. The maximum sediment concentration in ice in experiment

A was 44.3 mg/L, and in C and D was 21 mg/L; however, it was very high in B, which reached 198.5 mg/L. After 5~8 hr, the sediment concentration in surface slush ice was similar to that of water. After 24 hr, the concentration in ice was 2~4 times higher than in water. Smedsrud (2001) concluded that frazil preferentially entrained smaller particles.

Natural sediment containing sand, silt, and clay with different initial sediment concentrations was used in shallow saltwater experiments performed by Dethleff and Kempema (2007). The insulated tank was 3.2 m in length, 0.5 m in width, and 0.12 m in depth. Wind of 5~7 m/s was used to generate surface waves and Langmuir circulations in the tank. Frazil crystals were observed to grow rapidly to 10 mm in diameter, and flocs grew up to 15 mm in diameter. Results showed that the sediment concentration in the underlying water, the interstitial water, and the ice was between 13.43 to 24.10 mg/L, 19.69 to 30.95 mg/L, and 20.93 to 36.78 mg/L, respectively. They stated that ice trapped more sediments than interstitial water and that both contained higher concentrations of sediments than the underlying water. They observed that higher initial sediment concentration led to more sediment entrainment. When the initial sediment concentration was relatively low, more sediments were frozen into ice rather than in interstitial water. However, when the initial sediment concentration was relatively high, the difference between the final concentration in ice and interstitial water was smaller. They found that the percentage of sand in frazil ice was lower than the underlying water column. Silt concentrations in frazil were similar to or higher; meanwhile, clay fraction ranged from 10% to 30% regardless.

Previous studies have provided valuable information about frazil ice properties and their interaction with sediments. Due to differences in tank/flume sizes, turbulence motion, sediment types, and sampling methods, researchers had similar or divergent observations. Most agree that ice and interstitial water contain more sediments than the underlying water (Dethleff and Kempema 2007; Ackermann et al. 1994). In flumes, researchers found that newly forming frazil ice had a preferential entrainment of finer particles (i.e., silt and clay) (Smedsrud 2001; Dethleff 2005; Dethleff and Kempema 2007). Field observations also showed that most sea ice sediments are fine-grained (Nürnberg et al. 1994). Dethleff and Kempema (2007) found that drained frazil trapped more sediments than interstitial water by conducting experiments with natural sediment. However, Reimnitz et al. (1993) concluded that sand tends to stay in drained frazil, and mud tends to stay in interstitial water.

In previous experiments, flumes provided enough space for particles to move freely under turbulence, and cylinders made observation easier. The apparatus used in this thesis was designed to simulate the natural environment and provide good circumstances for observation, measurement, and sampling. The objective of this research is to investigate sediment-frazil interactions in both laboratory and field experiments. Laboratory experiments were conducted using three types of sediments (clay-silt, natural, and sand) under three initial concentrations in a freshwater frazil tank in a cold room. Samples, including the initial tank water, final tank water, interstitial water, and drained ice, were filtered to measure sediment concentrations and study the sediment entrainment mechanism. To study the sediment concentrations in natural frazils ice, samples were collected from the North Saskatchewan River during the freeze-up period of 2021. This research focused on analyzing changes in suspended sediment concentration in the water column after ice formation, preferential entrainment of different-sized sediments, and changes in organic content during the supercooling process.

2 Methodology

2.1 Laboratory experimental setup

Frazil ice and sediment interaction laboratory experiments were performed using clay-silt, sand, and natural sediments in the University of Alberta's Cold Room Facility. The clay-silt sediment used in the experiments was Tile #6 Kaolin, supplied by the Plainsman Pottery Supply (Edmonton, Alberta). The sand used in the experiments was very fine sand, and it was sieved from Sil Industrial Minerals Inc - SIL 1. Natural sediments used in the experiments were collected from the riverbed of the North Saskatchewan River near Terwillegar Park (53°28'58.7" N, 113°36'20.8" W) in Edmonton, Alberta. With each type of sediments, experiments were done at three initial concentrations (series 1 at low concentration, series 2 at medium concentration, and series 3 at high concentration). Five repeatable runs were obtained under each experimental setup. The cold room air temperature was set to -10 ̊C when running experiments to provide continuous cooling. Chilled air blows horizontally into the cold room through two vents close to the ceiling. The frazil ice tank was placed in between the vents. The tank is constructed with a steel framework, stainless steel at the corners and bottom, the side walls are glass, and the top is open to the air. The tank is 1.2 m in length, 0.8 m in width, and 1.4 m in height. Figure 1 shows the tank setup. Heat transfer occurs through the water surface and the uninsulated bottom and walls.

The tank was filled with fresh tap water to a depth of 1.2 m in the clay and natural sediment experiments and 1.1 m in the sand experiments. Four propellers mounted at the bottom of the tank were driven by a single NEMA 34 DC variable speed electric motor (278 W, 1.514 N-m of torque, max speed 1750 rpm) connected to a drive belt to ensure that all four propellors rotated at the same speed. The propellers rotated counter-clockwise, creating water jets directed upward and a turbulent recirculating flow. The water temperature was measured every 4 seconds using a Sea-Bird SBE 39 temperature sensor (accuracy of ±0.002 ̊C), which was connected to a computer outside the cold room to enable real-time monitoring of supercooling events using Seaterm software. The temperature sensor was placed 13 cm below the water surface, approximately 10 cm from one wall. The air temperature in the cold room was recorded every 3 minutes using a Diver (accuracy of ±0.1 ̊C).

2.2 Laboratory experimental procedure

The frazil tank experiments were conducted using consistent procedures under stable and repeatable conditions. Three types of sediments: clay-silt, natural, and sand, were used in the experiments. Three series of experiments were conducted at low, medium, and high initial concentrations with each sediment type. Experiments using a particular sediment type and initial concentration were repeated five times to reduce the uncertainty and permit averaging of the results.

Before experiments, the tank was filled with fresh tap water, which was cooled to 2 ℃, and the propellers were set to rotate at 325 rpm. The propeller speed was checked periodically using a laser tachometer with an accuracy of ± 3 rpm. Schneck et al. (2019) conducted experiments studying frazil ice properties in the same tank. They confirmed that the tank was well mixed, and the water temperature was uniform to within 0.005 °C at a propeller speed of 325 rpm. The tank-averaged turbulent kinetic energy dissipation rate at 325 rpm is ~ 3.4 x 10^{-2} m^2s^{-3}, within the range of energy dissipation rates in Alberta rivers (McFarlane et al. 2015). At the beginning of each series of experiments, sediments were thoroughly mixed into a bucket of water by manually stirring and were then poured into the turbulent tank water. Although a propeller speed of 325 rpm does result in uniform water temperatures, it is not energetic enough to keep all the sediments suspended in the water column. Preliminary experiments showed the suspension rates of clay-silt, natural, and sand were approximately 80%, 25%, and 10% by weight, respectively. Preliminary experiments also demonstrated that it took some time for sediments to settle to the tank bottom and for the sediment concentration in the tank to reach a steady state. Therefore, sediments were added to the tank at least one day prior to the start of measurements to ensure that a steady state had been achieved.

At the beginning of each run, the cold room control temperature was set to -10 ̊C, and within ~10 minutes, the air temperature was observed to decrease to approximately -10 ̊C, as shown in Figure 2(a). At a constant air temperature of approximately -10 ̊C, the water temperature decreased at a constant rate, as shown in Figure 2(b), indicating that the air-water heat flux was constant. Samples of initial tank water (IT) were collected at depths of 10~30 cm using clean 1-L bottles before supercooling started. Typically, one to three 1-L samples were collected depending on the tank's sediment concentration to ensure sufficient volume for filtration. The filled bottles were sealed and stored in the cold room until filtration.

Shortly after supercooling started (i.e., $T_w < 0°C$), frazil ice crystals appeared in the tank, moving and coruscating in the turbulent flow. The number of frazil ice particles grew rapidly, and ~7 minutes after the start of supercooling, the water temperature reached a minimum value known as maximum supercooling ($T_w = T_m$). The number of particles in suspension reached a maximum shortly (one to two minutes) after maximum supercooling occurred, as shown in Figure 3 (Schneck et al. 2019). The number concentration of particles then started to decline as particles began flocculating, and flocs rose to the surface as the water approached the residual supercooling temperature ($T_w = T_r$) (McFarlane et al. 2015). As time progressed, frazil flocs rose and accumulated at the water surface, particularly along the walls and corners. Samples of final tank water (FT) were collected 25 mins after maximum supercooling using the same technique as for the initial tank water samples. The samples were collected from the center area of the tank, leaving the slush ice (along the walls) undisturbed, as shown in Figure 4.

Samples of interstitial water (IW) and drained ice (DI) were collected 30 mins after maximum supercooling using a metal strainer. The strainer was dipped underneath the slush floating on the water surface and then raised straight up into the air. The strainer was quickly placed over a bucket to collect the draining interstitial water. The strainer was shaken and gently tapped on the side of the bucket to ensure the slush was well drained, and the drained ice was poured into another bucket. After collecting several samples, the strainer was replaced with a clean one to prevent ice from clogging the mesh. This process was repeated five to seven times until sufficient sample volumes were collected. After sampling, the strainers were rinsed under tap water and air-dried to prepare for the next run. At the end of the run, the cold room temperature was set back to 2 ℃. The bucket containing drained ice was kept in the cold room to prevent the ice from melting, and to keep the entrained sediments evenly distributed. The bucket containing the interstitial water samples was stored at room temperature outside the cold room until filtration. Sample filtration was typically conducted within 30 minutes.

The tank was not emptied and refilled when repeating runs within the same series unless the gap between runs exceeds 3 days (five repeated runs were usually completed within one to two weeks). The water level in the tank was checked at the beginning of each run and maintained at the same level by adding water and corresponding amounts of sediments. When the next run was scheduled in one or two days, the propellers were kept running to help keep sediments suspended. After each run, the air temperature and water temperature time series were downloaded (Diver-Office and Seaterm software, respectively) and plotted (MATLAB) to check the repeatability.

2.3 Repeatability of laboratory experiments

Stable experimental conditions and repeatable procedures are required to ensure that frazil ice formation and sediment interactions are well controlled. Five repeated runs for three sediment types at three sediment concentrations were conducted for a total of 45 experiments.

After the cold room air temperature was set to -10 °C, the temperature decreased rapidly (cooling rate 1.26 ± 0.2 °C/minutes) and stabilized within ~10 minutes. The mean and the coefficient of variation (COV) of cold room air temperatures from 10 minutes before supercooling to 30 minutes after maximum supercooling (a total duration of approximately one hour) were calculated to determine their repeatability. The results are tabulated in Table 1 and show that the mean air temperature varied from -10.68 to -10.93 ℃ and the COV from 0.4 % to 2.1 %. These results demonstrate that the cold room air temperature was well-controlled, and the runs were repeatable.

Two time series plots of water temperatures from repeated runs are presented in Figure 5. The superimposed time series were created by aligning the maximum supercooling time during each run. The most and least repeatable time series are presented for comparison.

These plots indicate that the water temperature time series were repeatable and that experimental conditions were well controlled. This is confirmed in Table 1, where the average maximum supercooling temperatures, cooling rates, and corresponding COV are listed. The average maximum supercooling temperature ranged from -0.081 to -0.101 ℃, and the COV ranged from 1.2% to 3.8%. The average water temperature cooling rate, from the beginning of supercooling ($T_w = 0$ ℃) to maximum supercooling ($T_w = T_m$), varied from -0.011 to -0.012 ℃/min and the COV ranged from 1.7% to 6.3%. These results demonstrate that supercooling events were well-controlled and repeatable.

2.4 Field sampling

2.4.1 Study areas

Field observations and sampling of newly forming frazil ice were conducted during the freeze-up period, mid-November to mid-December, in 2021. Samples were collected from the North Saskatchewan River in Edmonton at the Quesnel Bridge (53°30'20.7" N 113°33'59.9" W) and the Laurier Park Boat Launch (53°30'37.1" N 113°32'47.3" W). A summary of relevant information for each trip is provided in Table 2.

The North Saskatchewan River (NSR) flows from the Canadian Rockies through the City of Edmonton and empties into Hudson Bay. The river is 1287 km long with an average annual discharge of over 200 m^3/s. The North Saskatchewan River Basin (NSRB) has a drainage area of 28,100 km^2 before Edmonton, with elevations varying from 611 to 3543 m. The average annual precipitation in the drainage region is 619.5 mm (1979~2016);

however, it varies significantly from around 475 mm in Edmonton to over 1000 mm in the Rocky Mountain ranges. The Cline, Brazeau, Ram, and Clearwater rivers provide 88 % of the total annual runoff for the NSR. Edmonton, Alberta's capital, is Canada's fifth most populated city, with 1.4 million citizens. The water provided by NSR to this urban area is regulated by the Bighorn Dam (52°18′31″N 116°19′47″W) and the Brazeau Dam (52°58′12″N 115°34′54″W) (Anis and Sauchyn 2021). The river valley inside Edmonton was formed after glaciation within a period of downcutting. After the river reached its base level, it started to migrate laterally, and the erosion of the low-lying river terraces became significant (Thomson and Townsend 1979). The average suspended sediment size indicated by the D_{10}, D_{50}, and D_{90} was 23, 90, and 262 µm, respectively (Stone and Collins, 2012). Historical data (1974~1983) from the Water Survey of Canada station (# 05DF001) on the NSR at Edmonton shows the sediment concentrations ranged from 3~2460 mg/L, with a mean and medium of 254 and 83 mg/L (Government of Canada, 2022).

2.4.2 Field sampling methodology

The goal of the field sampling component of this study was to collect samples of newly forming frazil ice that had interacted only with suspended sediment prior to arriving at the water surface. This meant that released anchor ice pans and frazil ice pans needed to be excluded when sampling because these are known to entrap sediments via other mechanisms. This was done visually by looking for loose agglomerations of frazil flocs and slush floating at the water surface while avoiding frazil ice pans with fully or partially frozen tops and anchor ice pans with entrained coarser sediments.

Frazil ice samples were collected by wading into the river to water depths < 1 m and using a net (hoop diameter = 40 cm, mesh opening = 4 mm) to scoop up the frazil slush as it flowed past. Frazil slush in the net was allowed to drain for a few seconds before quickly moving the draining sample above a clean 1-L sealable bottle to ensure interstitial water was collected rather than river water brought up by the net. The drained ice was then placed into a sealable 9-L plastic bag. The drained ice samples typically had a volume of ~5 L. Samples of river water (1-L) were also collected at depths of ~30 cm. One river water sample and fifteen frazil ice samples were collected during each trip. All samples were taken back to the University of Alberta to be analyzed for total solids concentrations and fixed solids concentrations. Ice samples were frozen in a freezer, and water samples were stored in the cold room at 2 ̊C until filtration.

2.5 Sample analysis

Samples collected during the laboratory experiments include initial tank water (IT), final tank water (FT), interstitial water (IW), and drained ice (DI). Samples collected from the river include water (RW), interstitial water (IT), and drained ice (DI). All samples were vacuum filtered using a 500 mL PALL 47 mm Magnetic Filter Funnel for gravimetric analysis according to the Standard Methods for the Examination of Water and Wastewater (American Public Health Association et al., 2018) to determine sediment concentrations (mg/L). Samples from the sand experiments were filtered using Whatman Glass Microfibre Filters (0.7 μm) - Grade 934-AH. All other samples were filtered using Millipore Sigma Glass Fiber Filters (0.49 μm). In preparation for filtration, all filter circles and aluminum dishes were pre-dried in an Isotemp Oven at 105 °C and pre-weighed on a Denver APX-200 Analytical and Precision Balance. After filtration, all filter circles were dried at 105 °C overnight to determine the total solids concentrations (TSC). Samples containing organic material (i.e., natural sediment laboratory samples and all field samples) were burned in an Isotemp Muffle Furnace at 550 °C for 30 minutes to obtain the fixed solids concentrations (FSC) and the volatile solids concentrations (VSC).

All DI samples were divided into 3~6 subsamples and transferred into beakers before melting to distribute sediments in subsamples evenly. The volume of the melted DI samples was measured using a graduated cylinder before filtering. Five subsamples taken from each water sample (RW, IT, FT, and IW) were transferred using a graduated cylinder or a wide-bore pipet into the funnel and filtered. Care was taken to carefully rinse the graduate cylinder or pipet to ensure all sediments in the sample were filtered. After filtering, filter circles were returned to their aluminum dish in preparation for drying, followed by burning in some cases.

The equations used for calculating the concentrations are as follows:

$$\text{TSC [mg/L]} = \frac{\text{B} - \text{A}}{\text{Sample Volume [L]}} \quad (1)$$

$$\text{FSC [mg/L]} = \frac{\text{C} - \text{A}}{\text{Sample Volume [L]}} \quad (2)$$

$$\text{VSC [mg/L]} = \frac{\text{B} - \text{C}}{\text{Sample Volume [L]}} \quad (3)$$

where, A is the initial weight of the aluminum dish and filter, and B and C are the final weights of the dish and filter following filtering and after drying and burning, respectively (all weights in mg). A total of 33 (out of 900) measured subsample concentrations from laboratory experiments were rejected based on Chauvenet's Method (Kennedy and Neville 1976). All subsamples from field experiments were included.

Suspended sediment size distributions were measured in initial tank water samples collected during the three series of laboratory experiments (i.e., clay-silt, sand, and natural sediment). The measurements were conducted by the Natural Resources Analytical Laboratory at the University of Alberta using a Beckman Coulter LS 13320 Laser Particle Size Analyzer following ISO 13320:2009, Particle size analysis — Laser diffraction methods. The suspended sediment size distribution of the clay-silt experiments was 37% clay (<5 μm), 60% silt (5~50 μm), and 3% sand (>50 μm), with D_{10}=1 μm, D_{50}=7 μm, and D_{90}=34 μm. The natural sediment experiments showed 5% clay, 30% silt, and 65% sand, with D_{10}=14 μm, D_{50}=73 μm, and D_{90}=171 μm. The sand experiments were 5% clay, 15% silt, and 80% sand, with D_{10}=12 μm, D_{50}=128 μm, and D_{90}=168 μm. Cumulative percentage graphs of grain size are presented in Figure 6.

3 Results

3.1 Lab results

The average total solids concentrations (TSC) of initial tank water (IT), final tank water (FT), interstitial water (IW), and drained ice (DI) samples from the clay-silt, sand, and natural sediment series are presented in Table 3. This data is also shown as bar graphs in Figure 7, and ratios of concentrations are tabulated in Table 4. Average TSC values were compared using the student t-test, and the variability in the measurements was quantified by computing the coefficient of variation (COV). This statistical analysis is presented in Table A.2 in Appendix A. The average COV of all samples was 0.05, 0.12, and 0.17 for the clay-silt, natural, and sand series, respectively; this shows that the variability in the experimental measurements was considerably lower for finer sediments. Summaries of sediment concentrations of all runs are presented in Table A.3, Table A.4, and Table A.5.

The clay-silt series results in Figure 7(a) show that the IT, FT, and DI concentrations were very similar, while the IW concentrations were considerably higher. Statistical analysis (see t-test results in Table A.1(a) in Appendix A) showed that only the average IW concentrations were statistically significantly different from the other values at the 5% level (i.e., α=0.05). This is confirmed by the ratios of IW/FT listed in Table 4, which are ~1.37. The FT/IT ratio was ~0.96, indicating that most clay-silt remained suspended after supercooling. The relatively high IW concentrations in Table 3 and the ratios DI/IW ranged from 0.75 to 0.85, indicating that considerably more clay-silt was entrained into the interstitial water than the drained ice.

The sand series results plotted in Figure 7(b) show that the DI concentrations were by far the highest, and FT concentrations were the lowest. The IT and IW concentrations were in between, with IT values slightly larger. All of the average concentration differences in the four sample types in the sand series were statistically different (see results in Table A.1(b) in Appendix A). The FT/IT ratios were ~0.25 (Table 4), indicating that three-quarters of the suspended sand was removed from the water column. The high DI concentrations in Table 3 and the DI/IW ratio was ~3.3, indicating that most sands were entrained into the drained ice.

The natural sediments contained finer and coarser sediments, but the pattern of the bar graph results in Figure 7(c) is quite similar to the sand series results in Figure 7(b). The only difference is that, unlike the sand series, the IW concentrations were slightly larger than the IT concentrations. Note that all of the average concentration differences in this series were also statistically different from each other (see results in Table A.1(c) in Appendix A). The FT/IT ratio was ~0.5 (Table 4), indicating that only half of the natural sediments remained suspended after supercooling. The ratio DI/IW was ~2, indicating that one-third of entrained natural sediments were in IW and two-thirds were in DI.

These results show that as the frazil ice formed in turbulent tank water, 5% to 75% of the suspended sediments were removed from the water column after a supercooling event. Coarser sediments were removed much more efficiently than finer sediments. In addition, a higher proportion of finer sediments were found in the interstitial water, whereas more coarse sediments were found in drained ice.

Average fixed solids concentrations (FSC) and volatile solids concentrations (VSC) of samples from the natural sediment series are presented in Table 5, and the organic content ratios (VSC/TSC) are tabulated in Table 6. The organic content in the IT samples was ~0.1 by weight. The organic content in the IW and DI were similar to each other and slightly higher than IT, with a mean of 0.128. The organic content of FT samples was statistically significantly higher than in the IT in all series (see results in Table A.1(d) in Appendix A), ranging from 0.12 to 0.26.

3.2 Field results

One river water sample and fifteen frazil ice samples were collected during each field trip. The filtration results for the river water samples are presented in Table 7. Averaged river water sediment concentrations were 42 mg/L and 9 mg/L at Quesnel Bridge and Laurier Park. The sediment concentrations in the interstitial water samples (IW) ranged from 26 to 153 mg/L at Quesnel Bridge and 5 to 43 mg/L at Laurier Park. The concentrations in the drained ice (DI) samples were considerably higher, ranging from 29 to 1311 mg/L at Quesnel Bridge and 126 to 3974 mg/L at Laurier Park.

The mean, standard deviation, and coefficient of variation (COV) of the sediment concentration measurements are presented in Table 8. The mean concentrations in the IW varied from 15.1 to 48.9 mg/L, while those in the DI from 76.7 to 1244 mg/L. The COV of the DI data was consistently higher compared to the IW data indicating greater variability in the DI concentrations. This is likely because some of the DI samples contained coarser sediments, even small rocks, that could not be flushed out as the ice sample drained, greatly increasing the sediment mass in the sample. Average ratios of DI to IW concentrations ranged from 1.67 to 51.4, as shown in Table 9. The DI samples always contained more sediments than the corresponding IW samples. Additionally, The DI/IW values increased monotonically and dramatically from the first trip on Nov. 18th to the fourth one on Dec. 12th, which may be related to the progression of the freeze-up.

The organic content (ratio of VSC to TSC) in the IW and DI samples are listed in Table 10, and for the river water samples in Table 7. The organic content in the IW samples was ~0.25 on three of the sampling days, but on Dec. 3rd, it was significantly higher at 0.48 with a standard deviation of 0.23 compared to ~0.06 on the other days. The organic content in the river water ranged from 0.18 to 0.6, with a mean value of 0.36, which is comparable to the IW. The organic content in the DI was much lower, ranging from 0.05 to 0.14.

4 Discussion

Three series of experiments (clay-silt-1, natural-2, and sand-3) were conducted with similar initial sediment concentrations (80~100 mg/L). The concentration ratios for these experiments are compared in Figure 8. Firstly, the ratios of FT/IT are all smaller than one, indicating that the concentration of suspended sediments in the water column decreased after ice formation. Furthermore, the ratio decreases as sediment size increases, indicating that coarser sediments are more likely to settle during ice formation than finer sediments. Secondly, ratios of IW/FT are always greater than one and increase with sediment size, which is consistent with sediments being trapped inside the porous ice lattice of frazil flocs as sediment-laden water flows through flocs. Thirdly, the ratios of IW/FT, DI/FT, and DI/IW increase with increasing sediment size. This indicates that coarser sediments were more easily trapped in frazil flocs, and finer sediments were more easily trapped and flushed out of flocs as the sampled ice drained.

Sediment mass balance calculations were carried out, and they produced some surprising results. For example, during the lowest concentration natural sediment series (Natural-1), the tank contained 1152 liters of water, and a typical supercooling event generated approximately 18 liters of ice. The average initial amount of suspended sediment in the tank was 36 g. At the end of a supercooling experiment, the average mass of sediments in the tank water and frazil slush was 14 g and 0.7 g, respectively. The 14.7 g only accounts for 41% of the total mass of suspended sediment initially in the tank, meaning that 59% of the suspended sediment was unaccounted for or missing (i.e., not in the water or ice) at the end of each supercooling event. Similar calculations were performed for all series, and the average percentage of missing sediments after a supercooling event was 2%, 47%, and 73% in the clay-silt, natural, and sand series, respectively. A description of the mass balance calculations and a summary of the results can be found in Appendix B.

The most logical explanation for the missing sediment is that it was deposited on the tank bottom during the supercooling event. In that case, the frazil ice formation in the tank must have initiated a mechanism promoting sediment deposition. It was observed during the sand experiments that frazil flocs were advected by the turbulent circulating flow close to the bottom and then shredded by the propellers. Entrapped sediments were released and deposited on the bottom and formed sand ripples. This proposed mechanism appears more effective at depositing coarser sediment since only 2% of the fine clay-silt sediment was deposited compared to 73% of the sand. This is likely because finer sediments would be more easily resuspended after flocs were shredded, while the coarser sediments would settle to the bottom. This proposed mechanism could, in theory, also occur in rivers when flocs are swept downward into the shear layer at the bottom and shredded due to the large shear strain rates present in the flow region. If anchor ice is present, the sediment released by the shredded flocs could become entrapped or adhere to the anchor ice surface, especially when the frazil is still 'active' during supercooling. This would then cause a temporary decrease in the suspended sediment concentration, similar to an observation reported by McFarlane et al. (2019). Times series analysis of FrazilCam images showed decreased sediment particles per image as the water was supercooled. Interestingly, sediment particles increased as the water temperature rose above 0°C. In this research, the cold room temperature was set to 2°C after each experiment so that all the ice could melt overnight. A comparison of the initial sediment concentrations (IT) at the start of successive runs in the same experimental series found that, on average, the concentration at the start of the second run was ~95% of the value at the start of the previous run. With clay-silt, natural, and sand, the variation was -7% to +4%, -15% to +3%, and -27% to +14%. This shows that once the ice had melted, sediments previously entrained in the ice were released, and sediments previously deposited on the bottom were resuspended. The reasons why the deposited sediments would remain on the tank bottom during supercooling and then be resuspended after the ice had melted are unclear. It may be that the viscosity of the ice-water mixture changes, which affects the turbulent flow field in the tank, causing enhanced settling of suspended sediments.

When water runs through the high-porosity open framework of ice flocs, suspended sediments can be left trapped in the crystal structure, like a sieving process. Results of this research consistently demonstrated higher sediment concentrations in IW compared to FT, knowing that FT was sampled only 5 mins earlier than IW, and they are both sampled from the upper layer of the tank. Moreover, the ratio of IW/FT increased with increasing sediment size, indicating coarser sediments are easier to be trapped and finer sediments are easier to flow through the framework and escape. In this research, sampling was done by a strainer, and interstitial water was let drain by gravity. The ratios of DI/IW were 3.3 and 2 in the sand and natural series; however, they ranged from 0.5~0.7 in the clay-silt series. Coarser sediments were more found in drained ice, while finer sediments were more found in interstitial water. Reimnitz et al. (1993) conducted sediments frazil interaction experiments and reported values of DI/IW of 0.57 and ~10 for mud and sand, respectively. These results are consistent with this study, and the ratio discrepancy might be due to differences in the experimental setup and procedures. In addition, Ackermann et al. (1994) found that sand particles were entrained into frazil ice far more efficiently than silt in their experiments.

The goal of the field component of this study was to collect samples of newly forming frazil slush comparable to the frazil slush generated in the laboratory tank. To ensure this, care was taken to avoid collecting ice samples from older frazil pans that had already frozen tops and released anchor ice containing aquatic plant material, pebbles, or stones. This selective sampling method significantly improves the likelihood that the field samples were newly formed frazil slush. Evidence to support this argument is provided by comparing the sediment concentrations measured in the field against results from the laboratory and a previous study of sediment concentrations in released anchor ice pans. The field samples' IW and DI sediment concentrations ranged from 15 to 50 mg/L and 76 to 1244 mg/L, while the concentrations in the natural sediment laboratory samples IW and DI ranged from 36 to 326 mg/L and 80 to 683 mg/L, respectively. Sediment concentrations in released anchor ice pans reported by Kalke et al. (2017) had mean values ranging from 12000 to 38000 mg/L, which is several orders of magnitude higher than the frazil ice sampled in this research. Significantly, the IW and DI concentrations measured in the field samples are closer to the ranges measured in the laboratory. Therefore, it is reasonable to conclude that the ice samples collected in the field were likely newly forming frazil ice. However, the ratio of DI/IW in the field samples was higher than the laboratory results. The ratios of DI/IW in natural sediment laboratory samples were ~2. In field samples, the ratio varied wildly from 1.7 to 51. This difference may be attributed to sediments dispersed in the lab being well sorted within a specific size range. In contrast, sediments in the river environment were more varied. Note that small rocks significantly increased the sediment weight in some DI samples as they were too large to be flushed out as the ice drained.

Initial tank water samples (IT) collected during the natural sediment series had an organic content (VSC/TSC ratio) ranging from 0.09 to 0.13. The organic content in IW and DI varied from 0.09 to 0.18 and 0.10 to 0.17, respectively. The organic content in field water samples was higher than in lab samples and comes with more significant variability, with river water and river IW ranging from 0.18 to 0.6 and 0.25 to 0.48, respectively. The organic content in river DI samples ranged from 0.05 to 0.14, similar to that in lab ice samples. This may be due to the consistent organic-harvesting ability of ice.

Frazil ice can ultimately become a part of ice cover. Sediments entrained in the ice may reduce surface albedo when the ice cover is not covered with snow, leading to increased absorbed solar energy. This process affects ice thickness, extent, air temperature, and surface energy balance (Shapiro Ledley and Pfirman 1997). Even seemingly clean ice containing 5~10 mg/L of particles can reduce the albedo by 5~10% in the visible spectrum (Light et al. 1998). Field samples from this study reveal that IW and DI can contain up to 50 mg/L and 1244 mg/L of sediments on average, which may significantly reduce the albedo.

The impact of sediment-frazil interactions on the sediment transport budget of rivers is uncertain. Sediments entrained into frazil ice may be released back into the water column quickly if supercooling ends, or it may become trapped in the ice cover and immobilized until spring breakup. Kalke et al. (2017) showed that the instantaneous sediment mass flux by released anchor ice pans could be approximately 25% of the average suspended sediment mass flux on the Peace River. However, sediment concentrations in the field samples of frazil slush collected on the NSR were several hundred times smaller compared to released anchor ice pans. This leads to the conclusion that it is unlikely that sediment transportation by frazil slush is a significant factor in the sediment budget. However, additional field measurements of sediment concentrations in frazil slush, frazil ice pans, and ice covers might be helpful.

5 Conclusion

To study sediment entrainment during the supercooling period, 45 experiments were conducted in a freshwater frazil tank using three types of sediments (clay-silt, natural, and sand) at three initial sediment concentrations. The sediment concentrations in the interstitial water, drained ice, and the water column before and after a supercooling event were examined. Filtration was performed according to the Standard Methods for the Examination of Water and Wastewater (American Public Health Association et al., 2018). Laboratory experiments showed that when frazil ice formed in turbulent tank water, 5%, 50%, and 75% of the suspended sediments were removed from the water column for clay-silt, natural, and sand, respectively. However, only 3%, 3%, and 2% of the sediments were entrained into the frazil ice. A proposed mechanism suggested that entrained sediments were released and deposited on the bottom as frazil flocs were advected by turbulent flow and shredded by propellers. Coarser sediments were removed more efficiently than finer sediments, likely because finer sediments are easier to suspend.

Sediments were trapped inside the porous ice lattice of frazil flocs as sediment-laden water flowed through the flocs, similar to a sieving process. Coarser sediments were more easily trapped in frazil flocs, and finer sediments were more easily flushed out as the ice sample drained. The ratios of DI/IW varied in different sediment series, which was 0.7, 2, and 3.3 for clay-silt, natural, and sand series, respectively.

Field sampling was conducted on the North Saskatchewan River to study sediment concentrations in newly forming frazil ice. One river water sample and fifteen frazil ice samples were collected during each field trip. Mean concentrations in the IW varied from 15.1 to 48.9 mg/L, while those in the DI ranged from 76.7 to 1244 mg/L. Average ratios of DI/IW concentrations ranged from 1.67 to 51.4. The presence of small rocks significantly increased the sediment weight in some of the river DI samples. The organic content (i.e., VSC/FSC) in river water samples (0.18 to 0.6) was much higher than in the tank water samples (0.09 to 0.13). However, the organic content in DI samples collected in the field (0.05 to 0.14) and frazil tank (0.1 to 0.17) were similar, suggesting consistent organic harvesting ability of ice.

To summarize, the results of the laboratory experiments shed light on the interaction mechanism between frazil and sediment, providing insights into what occurs in natural rivers during freeze-up periods. The sediment concentration data can be used to estimate how entrained sediments reduce surface albedo, affecting various aspects of the environment, such as ice thickness, extent, air temperature, and surface energy balance. To comprehensively study annual sediment transportation, it is necessary to consider the sediments trapped in frazil ice. Although frazil ice can only carry a limited amount of sediments compared to anchor ice, the sediments entrained in frazil ice undergo delayed transportation until spring breakup. Moreover, the significant drop in suspended sediment in the water column during supercooling is an interesting fact that can be utilized in planning water intake and managing ecosystems in natural rivers.

Figures

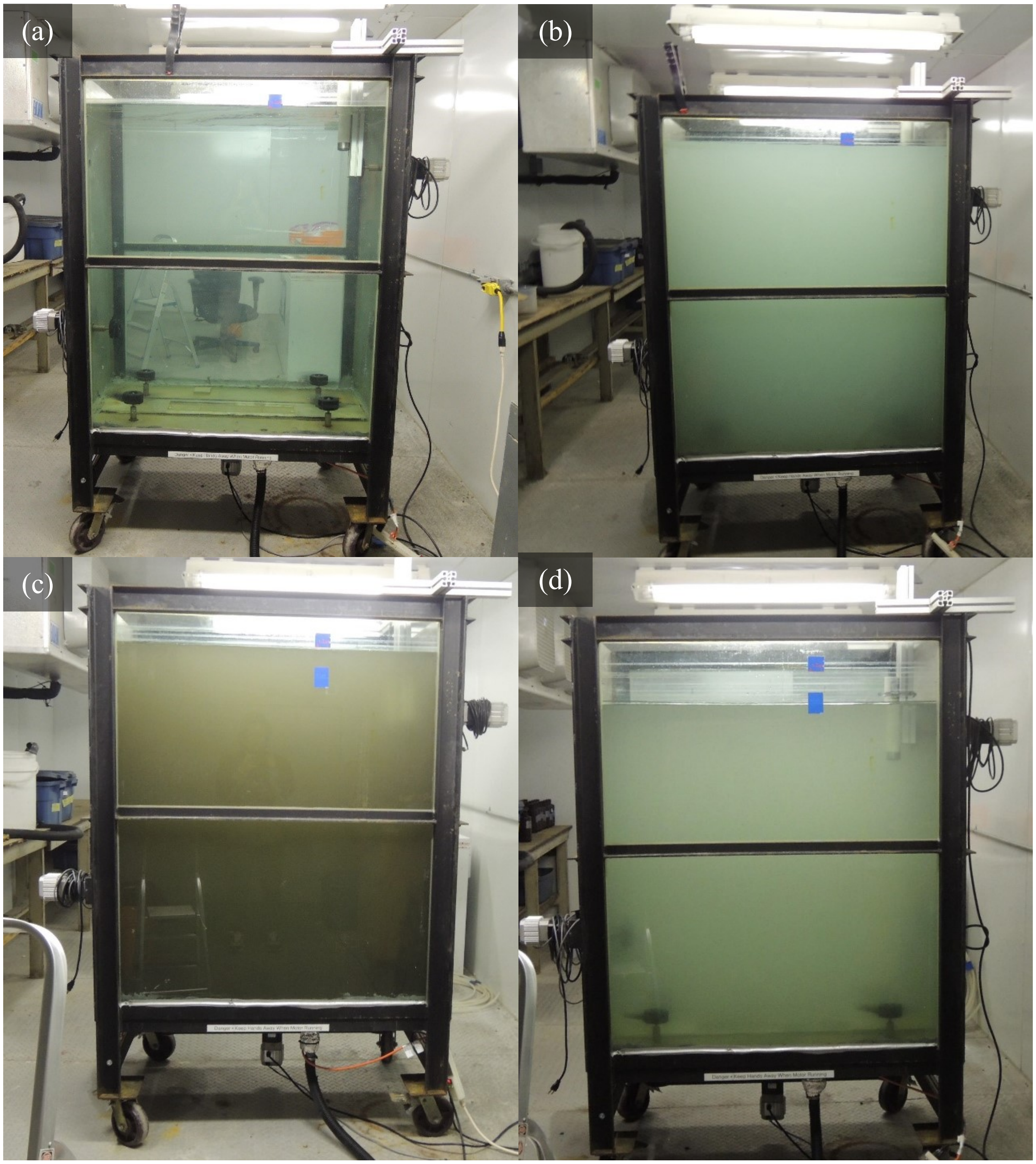

Figure 1: Photos show the frazil ice tank setup under various experimental conditions. (a) clear tap water with no sediments, (b) clay-water mixture, (c) natural sediment-water mixture, and (d) sand-water mixture.

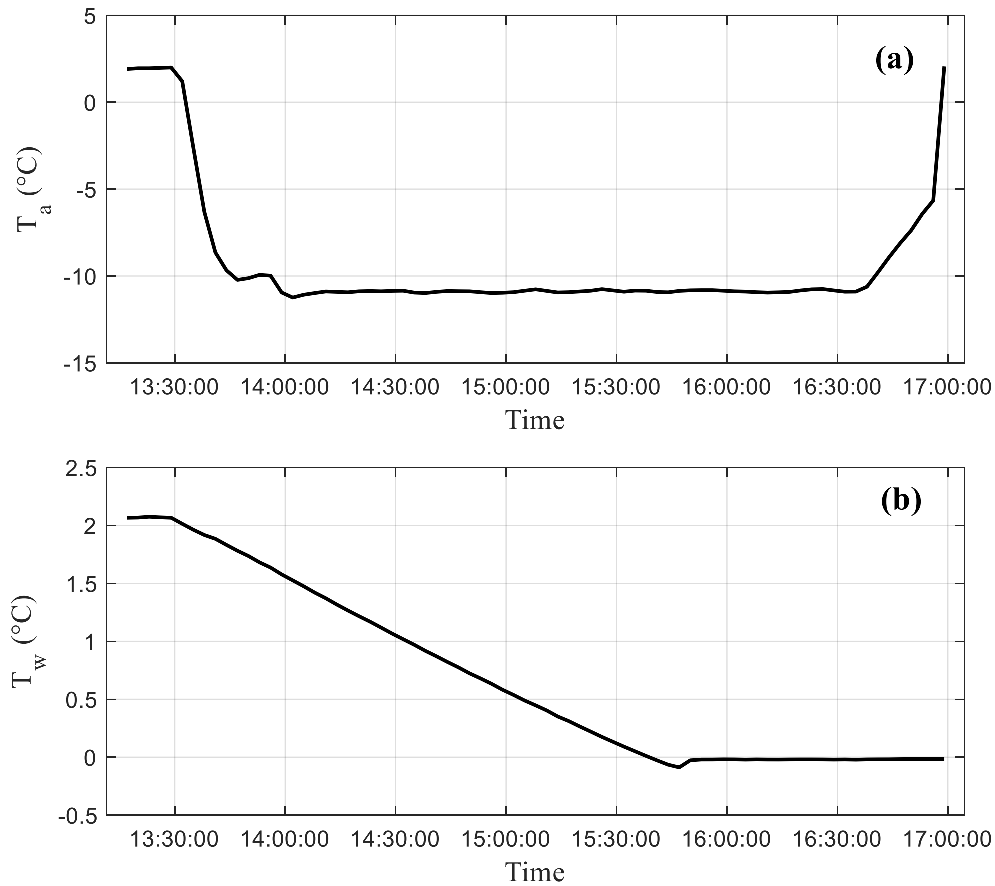

Figure 2: Time series plots of (a) air temperature Ta and (b) water temperature Tw during a typical experiment.

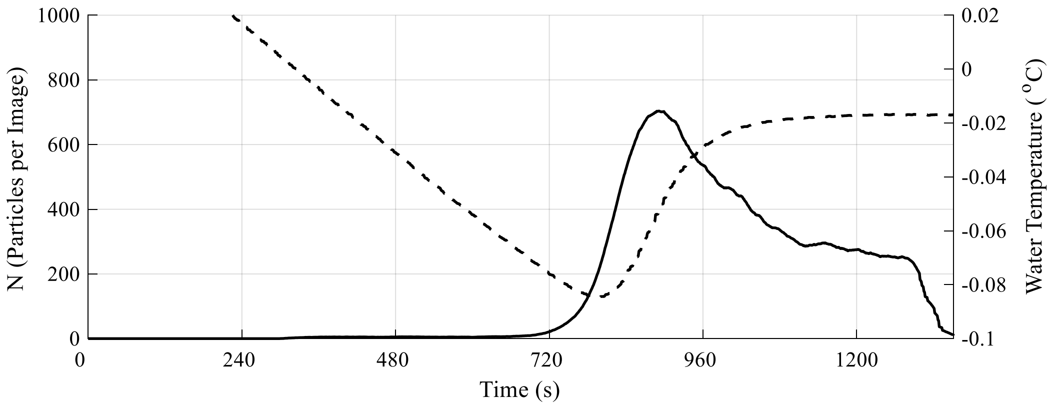

Figure 3: Time series plot showing the number of frazil ice particles per image (N, solid line) and the water temperature (Tw, dashed line) during a typical supercooling event (adapted from Schneck 2018).

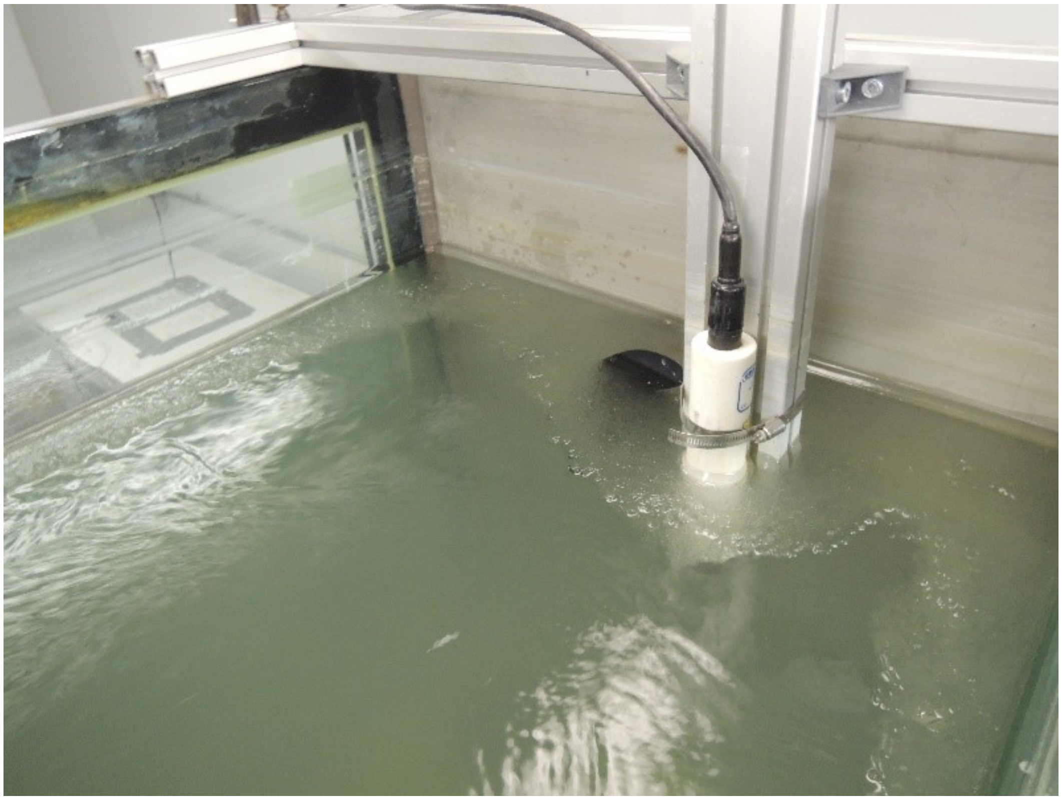

Figure 4: Photo of the frazil ice tank water surface 25 minutes after maximum supercooling showing the frazil slush that has gathered at the water surface at the edges of the tank. The Sea-Bird water temperature logger is also shown mounted on its frame.

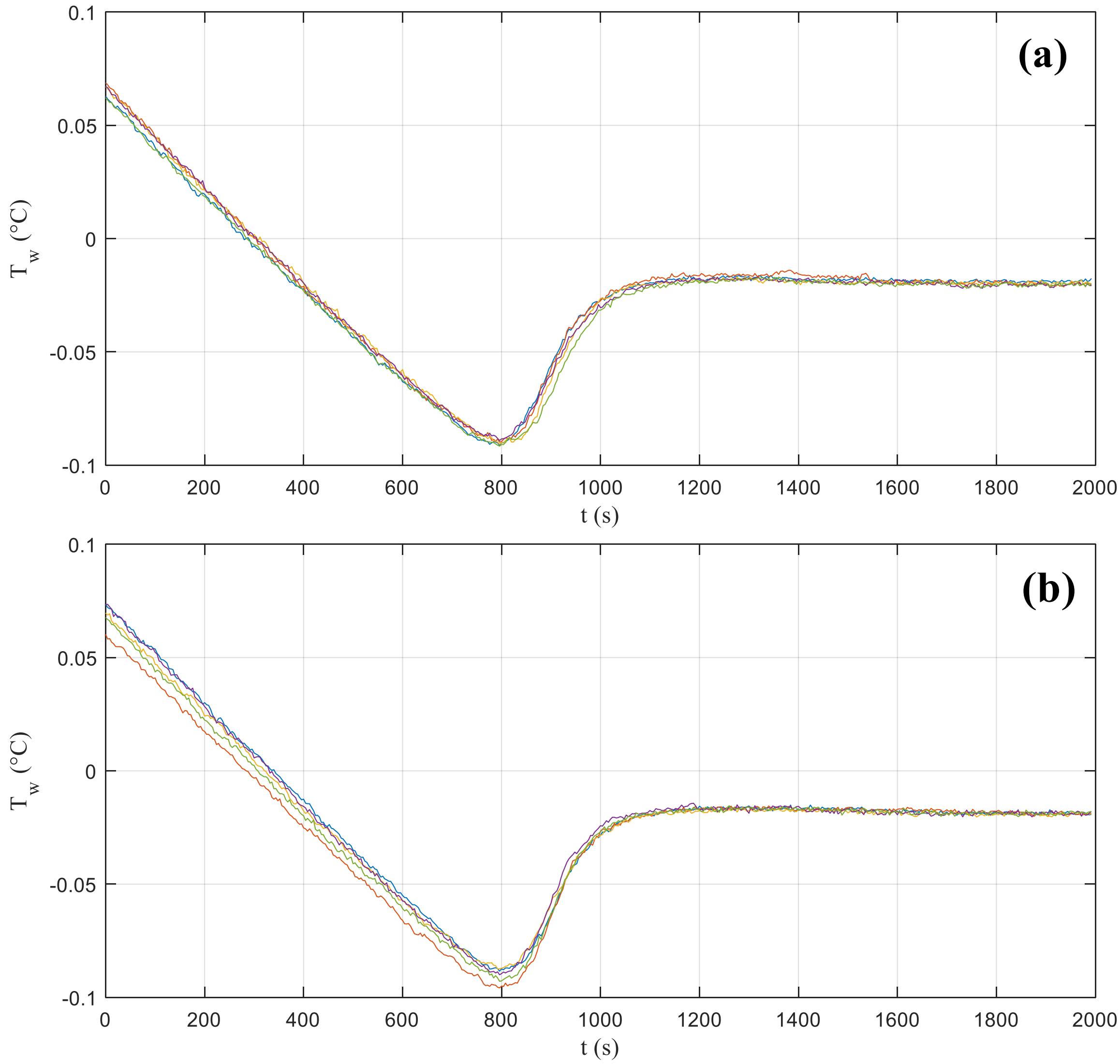

Figure 5: Superimposed water temperature time series plots from five repeated experimental runs of (a) the most repeatable and (b) the least repeatable series.

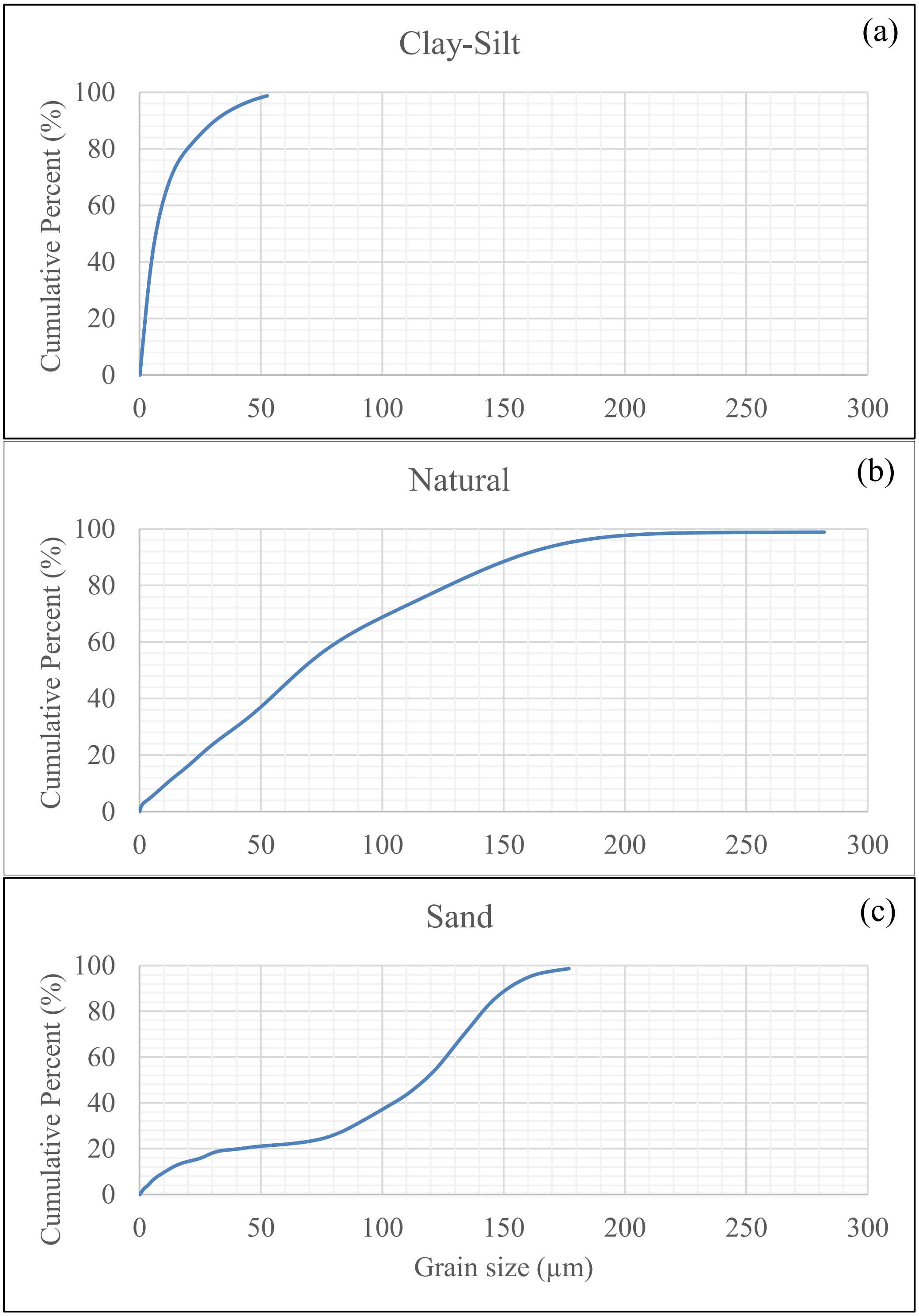

Figure 6: Cumulative percentages of grain size distribution of (a) clay-silt, (b) natural, and (c) sand series from laser particle analysis.

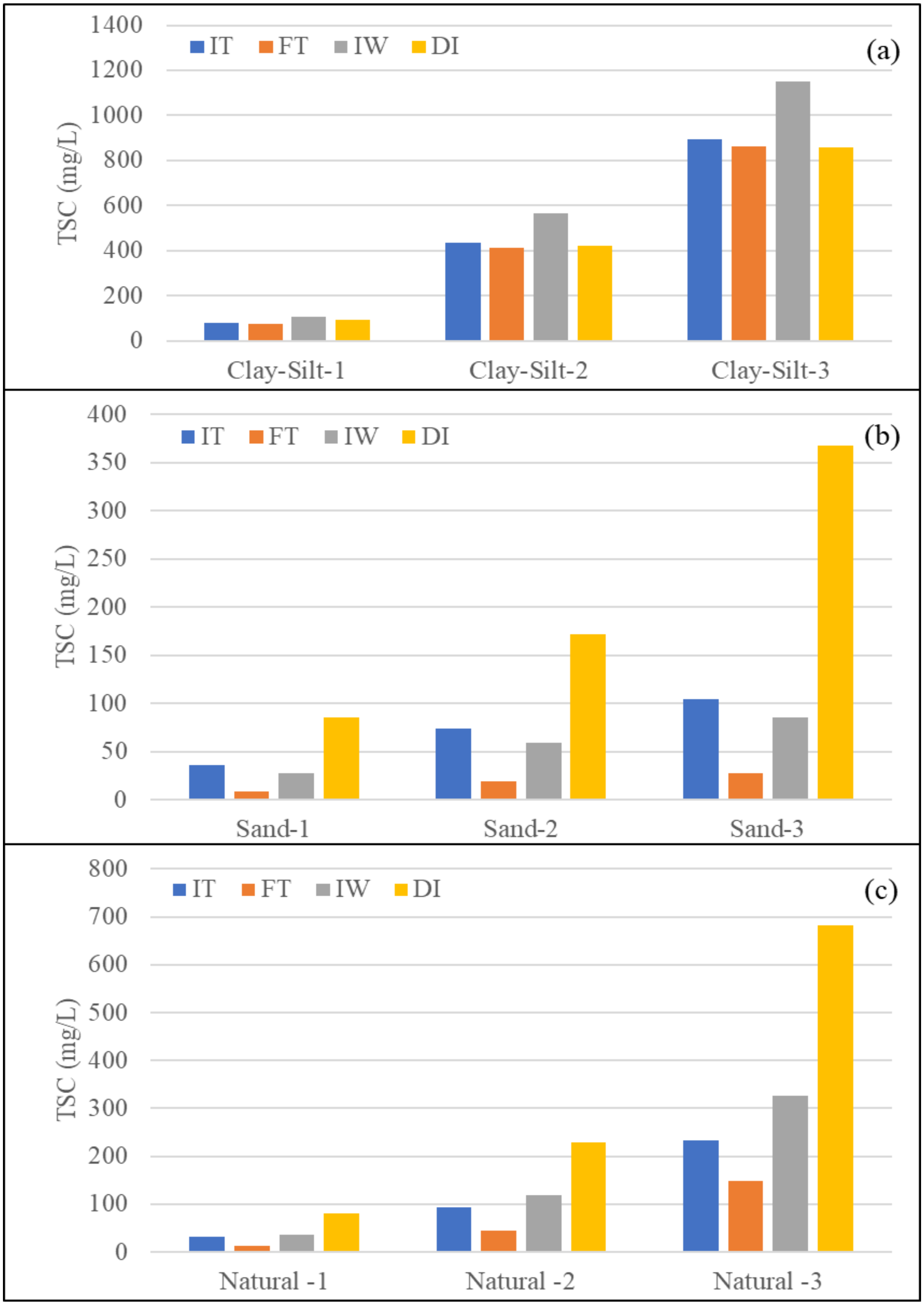

Figure 7: Bar graphs showing averaged total solids concentrations (TSC) of samples from (a) clay-silt series, (b) sand series, and (c) natural series at 1-low, 2-medium, and 3-high initial concentrations, including samples of initial tank water (IT), final tank water (FT), interstitial water (IW), and drained ice (DI).

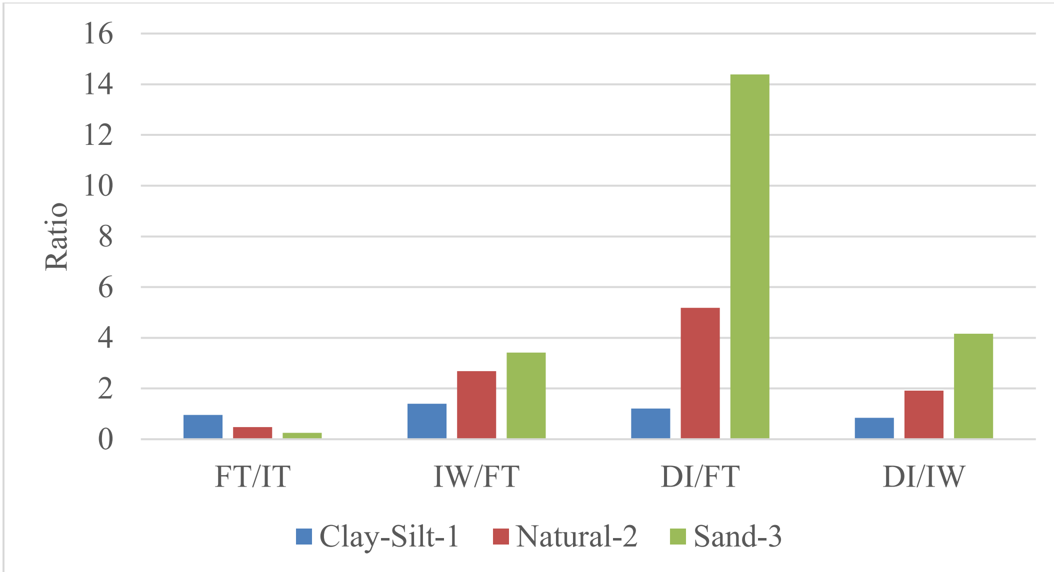

Figure 8: Averaged entrainment ratios - total solids concentrations (TSC) of the initial tank (IT), interstitial water (IW), and drained ice (DI) versus final tank water (FT), as well as drained ice to interstitial water cross-comparison of series with similar initial sediment concentrations, clay-silt-1, natural -2, and sand-3.

Tables

Table 1: Statistical analysis of the repeatability of each series of experiments. The mean (μ) and the coefficient of variation (COV) for the cold room air temperature, water maximum supercooling temperature, and the cooling rate of water temperature are presented.

Sediment type	Series #	Air temperature		Water temperature			
				Maximum supercooling temperature		Cooling rate	
		μ (°C)	COV (%)	μ (°C)	COV (%)	μ (°C)	COV (%)
Clay-Silt	1	-10.795	0.5	-0.091	2.0	-0.012	1.7
	2	-10.830	0.5	-0.092	2.0	-0.011	1.8
	3	-10.726	0.4	-0.087	2.5	-0.011	1.8
Natural	1	-10.680	2.1	-0.091	3.8	-0.011	2.7
	2	-10.768	0.8	-0.092	2.9	-0.011	2.7
	3	-10.815	0.8	-0.091	1.2	-0.011	1.9
Sand	1	-10.927	0.7	-0.100	3.0	-0.011	6.3
	2	-10.765	0.7	-0.101	1.7	-0.011	3.7
	3	-10.833	0.7	-0.091	1.3	-0.011	2.8

Table 2: Summary of frazil ice field sampling conditions.

Trip #	Site	Date	Time	Air Temperature (°C)
1	Quesnel Bridge	Nov. 18th	6 PM to 1 AM	-5 to -7
2	Quesnel Bridge	Nov. 20th	4 PM to 11 PM	-10 to -17
3	Laurier Park Boat Launch	Dec. 3rd	4 PM to 11 PM	-10 to -14
4	Laurier Park Boat Launch	Dec. 12th	4 PM to 11 PM	-10 to -15

Table 3: Summary of sample-averaged total solids concentrations (TSC) of initial tank water (IT), final tank water (FT), interstitial water (IW), and drained ice (DI). Results of experiments at low (1), medium (2), and high (3) initial sediment concentrations for three series, clay-silt, sand, and natural sediments.

TSC (mg/L)	Clay-Silt-1	Clay-Silt-2	Clay-Silt-3	Sand-1	Sand-2	Sand-3	Natural-1	Natural-2	Natural-3
IT	79.4	434	892	35.8	73.6	104	31.5	92.5	234
FT	76.0	411	861	8.51	19.3	26.1	12.3	44.0	148
IW	107	566	1150	27.3	58.5	88.9	35.6	118	326
DI	91.6	422	859	84.9	171	375	80.8	228	683

Table 4: Sample-averaged ratios of the total solids concentrations (TSC) comparing initial tank (IT), interstitial water (IW), and drained ice (DI) with the final tank water (FT), as well as the comparison within ice slush, ratios of TSC of drained ice versus interstitial water.

TSC - Ratios	Clay-Silt-1	Clay-Silt-2	Clay-Silt-3	Sand-1	Sand-2	Sand-3	Natural-1	Natural-2	Natural-3
FT/IT	0.96	0.95	0.96	0.24	0.27	0.25	0.39	0.48	0.63
IW/FT	1.40	1.38	1.34	3.22	3.05	3.47	2.87	2.69	2.21
DI/FT	1.20	1.03	1.00	10.0	8.86	14.3	6.60	5.18	4.62
DI/IW	0.85	0.74	0.74	3.14	2.90	4.12	2.28	1.92	2.08

Table 5: Sample-averaged fixed solids concentrations (FSC) and volatile solids concentrations (VSC) of initial tank water (IT), final tank water (FT), interstitial water (IW), and drained ice (DI) of the natural sediment series.

	Natural-1		Natural-2		Natural-3	
	FSC (mg/L)	VSC (mg/L)	FSC (mg/L)	VSC (mg/L)	FSC (mg/L)	VSC (mg/L)
IT	27.6	3.94	83.2	9.36	212	21.9
FT	9.16	3.17	36.9	7.17	130	18.3
IW	29.2	6.41	106	12.5	297	28.6
DI	67.6	13.3	201	26.7	612	70.3

Table 6: Inorganic content (fixed solids concentrations (FSC) divided by total solids concentrations (TSC) of the samples) and organic content (volatile solids concentrations (VSC) divided by total solids concentrations (TSC) of the samples) in the natural sediment series.

	Natural-1		Natural-2		Natural-3	
	FSC/TSC	VSC/TSC	FSC/TSC	VSC/TSC	FSC/TSC	VSC/TSC
IT	0.87	0.13	0.90	0.10	0.91	0.09
FT	0.74	0.26	0.84	0.16	0.88	0.12
IW	0.82	0.18	0.89	0.11	0.91	0.09
DI	0.83	0.17	0.88	0.12	0.90	0.10

Table 7: Total solids concentrations (TSC), fixed solids concentrations (FSC), volatile solids concentrations (VSC), and the organic contents (VSC/TSC) of river water samples from each field trip.

Date	Site	TSC [mg/L]	FSC [mg/L]	VSC [mg/L]	VSC/TSC
Nov. 18	Quesnel Bridge	56.2	46.2	10	0.18
Nov. 20	Quesnel Bridge	27.4	20	7.4	0.27
Dec. 3rd	Laurier Park Boat Launch	8.1	3.2	4.9	0.6
Dec. 12th	Laurier Park Boat Launch	10.4	6.2	4.2	0.4

Table 8: Mean (μ), standard deviation (σ), and coefficient of variation (COV) values of total solids concentrations (TSC) in interstitial water (IW) and drained ice (DI) samples.

Date	Interstitial Water				Drained ice			
	μ	±	σ	COV	μ	±	σ	COV
Nov. 18	48.9	±	14.2	0.29	76.7	±	28.4	0.37
Nov. 20th	48.5	±	30.5	0.63	244	±	346	1.42
Dec. 3rd	15.1	±	8.16	0.54	339	±	263	0.78
Dec. 12th	23.8	±	8.68	0.37	1244	±	984	0.79

Table 9: Mean (μ) and standard deviation (σ) values of ratios of total solids concentrations (TSC) in drained ice (DI) and interstitial water (IW), averaged for each sampling date.

Date	DI / IW (μ±σ)		
Nov. 18	1.67	±	0.71
Nov. 20	5.32	±	8.50
Dec. 3rd	26.3	±	17.8
Dec. 12th	51.4	±	27.0

Table 10: Mean (μ) and standard deviation (σ) values of organic contents (VSC/TSC), represented by volatile solids concentrations (VSC) versus total solids concentrations (TSC), of interstitial water (IW) and drained ice (DI) samples.

Date	VSC/TSC (μ±σ)					
	IW			DI		
Nov. 18th	0.24	±	0.06	0.14	±	0.06
Nov. 20	0.24	±	0.05	0.14	±	0.08
Dec. 3rd	0.48	±	0.23	0.05	±	0.02
Dec. 12th	0.26	±	0.07	0.06	±	0.13

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Appendix A

Table A.1: Two-tails Equal Variance Independent Student's t-test at α=0.05. Degree of freedom=8. P-values comparing between total solids concentrations (TSC) of initial tank water (IT), final tank water (FT), interstitial water (IW), and drained ice (DI) for (a) clay-silt series, (b) sand series, and (c) natural sediment series. (d) shows the results of natural sediment series after burning at 550 °C, inorganic content (FSC/TSC) in initial tank water (IT) compared to that in final tank water (FT), interstitial water (IW), and drained ice (DI). Bold numbers meant the series were similar, and the difference was statistically insignificant.

(a)

clay-silt	series 1	series 2	series 3
IT vs. FT	**0.101**	0.010	**0.079**
IT vs. DI	**0.069**	**0.476**	**0.366**
FT vs DI	0.027	**0.512**	**0.965**
IT vs. IW	0.000	0.000	0.000
FT vs. IW	0.000	0.000	0.000
DI vs. IW	0.032	0.000	0.000

(b)

sand	series 1	series 2	series 3
IT vs. FT	0.000	0.000	0.000
IT vs. DI	0.000	0.000	0.001
FT vs. DI	0.000	0.000	0.000
IT vs. IW	0.043	**0.061**	**0.225**
FT vs. IW	0.000	0.000	0.000
DI vs. IW	0.000	0.000	0.001

(c)

natural	series 1	series 2	series 3
IT vs. FT	0.000	0.000	0.000
IT vs. DI	0.000	0.000	0.000
FT vs. DI	0.000	0.000	0.000
IT vs. IW	**0.289**	0.011	0.006
FT vs. IW	0.000	0.000	0.000
DI vs. IW	0.000	0.000	0.000

(d)

Natural FSC/TSC	series 1	series 2	series 3
IT vs. FT	0.002	0.000	0.032
IT vs. DI	0.024	**0.062**	**0.527**
IT vs. IW	0.017	**0.471**	**0.669**

Table A.2: Summary of Coefficient of Variation (COV) in percentage calculated based on five repeated runs of total solids concentrations (TSC) of initial tank water (IT), final tank water (FT), interstitial water (IW), and drained ice (DI). Results of experiments at low (1), medium (2), and high (3) initial sediment concentrations for three series, clay-silt, sand, and natural sediments.

COV (%)	Clay-Silt-1	Clay-Silt-2	Clay-Silt- 3	Sand-1	Sand-2	Sand-3	Natural-1	Natural-2	Natural-3
IT	0.04	0.02	0.02	0.09	0.18	0.12	0.10	0.04	0.12
FT	0.04	0.03	0.04	0.04	0.06	0.25	0.15	0.05	0.11
IW	0.03	0.08	0.02	0.27	0.14	0.26	0.21	0.14	0.14
DI	0.14	0.08	0.09	0.14	0.11	0.32	0.11	0.11	0.18

Table A.3: Summary of total solids concentrations (TSC) of initial tank water (IT), final tank water (FT), interstitial water (IW), and drained ice (DI) of all runs in clay-silt series.

		Run 1	Run 2	Run 3	Run 4	Run 5	Average
Clay-Silt-1-Low	IT	84.25	78.60	79.00	76.00	79.20	79.41
	FT	78.40	72.40	76.20	74.00	79.00	76.00
	IW	110.07	106.19	109.64	102.91	104.62	106.69
	DI	107.46	82.83	102.11	78.17	87.45	91.60
Clay-Silt-2-Medium	IT	431.60	447.20	432.00	421.60	436.40	433.76
	FT	390.80	419.60	412.40	418.00	416.20	411.40
	IW	526.81	614.00	573.20	601.20	517.20	566.48
	DI	433.53	473.60	410.00	407.60	386.40	422.23
Clay-Silt-3-High	IT	903.00	888.00	870.00	895.20	904.00	892.04
	FT	868.80	896.00	820.80	835.20	883.00	860.76
	IW	1179.36	1132.76	1180.42	1135.65	1120.08	1149.65
	DI	917.33	895.08	928.05	772.81	782.34	859.12

Table A.4: Summary of total solids concentrations (TSC) of initial tank water (IT), final tank water (FT), interstitial water (IW), and drained ice (DI) of all runs in sand series.

		Run 1	Run 2	Run 3	Run 4	Run 5	Average
Sand-1-Low	IT	31.93	33.40	35.92	38.73	39.20	35.84
	FT	8.27	8.73	8.87	8.08	8.60	8.51
	IW	21.53	21.20	24.00	32.00	37.70	27.29
	DI	86.52	74.64	75.69	84.04	103.71	84.92
Sand-2-Medium	IT	83.20	87.60	67.20	75.20	54.70	73.58
	FT	18.93	17.60	19.33	20.58	20.07	19.30
	IW	50.00	67.30	65.30	50.00	59.90	58.50
	DI	147.22	157.08	180.29	189.19	182.13	171.18
Sand-3-High	IT	108.25	123.30	102.80	100.60	87.30	104.45
	FT	30.80	27.60	33.33	20.53	18.00	26.05
	IW	114.90	98.00	84.12	94.70	53.00	88.94
	DI	544.24	394.93	404.16	305.98	225.17	374.90

Table A.5: Summary of averaged total solids concentrations (TSC) of initial tank water (IT), final tank water (FT), interstitial water (IW), and drained ice (DI) of all runs in natural series.

		Run 1	Run 2	Run 3	Run 4	Run 5	Average
Natural-1-Low	IT	35.92	30.60	29.66	28.28	33.08	31.51
	FT	15.20	10.57	12.08	11.12	12.68	12.33
	IW	47.50	28.47	30.70	34.20	37.04	35.58
	DI	93.63	71.57	84.29	79.54	75.08	80.82
Natural-2-Medium	IT	96.93	90.80	87.07	93.53	94.33	92.53
	FT	47.33	44.67	43.13	44.27	40.73	44.03
	IW	133.50	128.90	123.58	90.10	116.20	118.46
	DI	266.24	209.89	238.58	216.41	209.39	228.10
Natural-3-High	IT	281.20	240.80	224.00	209.25	214.50	233.95
	FT	167.40	161.50	141.20	136.80	132.20	147.82
	IW	334.60	386.20	261.80	344.00	303.20	325.96
	DI	764.71	778.21	513.40	765.90	590.94	682.63

Appendix B

Total heat exchanged Q_{tw} $[{}^{W}/_{m^3}]$:

$$Q_{tw} = \rho C_p \frac{dT}{dt}$$

ρ is the density of water,

C_p is the specific heat of water,

$\frac{dT}{dt}$ is the cooling rate during initial cooling phase = 0.012 $^{°C}/_{min}$ = 0.012/60 =0.0002 $^{°C}/_{s}$:

$$Q_{tw} = \rho C_p \frac{dT}{dt} = 1000\ {}^{kg}/_{m^3} \times 4220\ {}^{J}/_{kg\ °C} \times 0.0002\ {}^{°C}/_{s} = 844\ {}^{W}/_{m^3}$$

The volume concentration of frazil ice M_{sp}:

$$M_{sp} = \frac{Q_{tw} t_{sp}}{L_i \rho_i}$$

t_{sp} is the principal supercooling time,

L_i is the latent heat of fusion for ice,

ρ_i is the density of ice:

$$M_{sp} = \frac{Q_{tw} t_{sp}}{L_i \rho_i} = \frac{844\ {}^{W}/_{m^3} \times 800s}{3.34 \times 10^5\ {}^{J}/_{kg} \times 917\ {}^{kg}/_{m^3}} = 0.0022\ {}^{m^3}/_{m^3}$$

Hence,

The volume of ice produced in the tank:

$$V_{DI} = 0.0022 * 1152\ L = 2.53\ L$$

The porosity of frazil ice produced in freshwater is 0.86 (Schneck 2019),

The volume of slush:

$$V_{slush} = 2.53\ L \div (1 - 0.86) = 18.1\ L$$

The volume of interstitial water:

$$V_{IW} = 18.1\ L \times 0.86 = 15.6\ L$$

Table B.1 Summarizes the percentage of sediments 'missing' after ice formation.

	Clay-Silt			Natural			Sand		
Δ Sediments	1	2	3	1	2	3	1	2	3
	2%	3%	2%	59%	50%	34%	75%	72%	73%

Mass balance sample calculation for series Natural-1:

Volume of water in the tank = 1.2m x 1.2m x 0.8m x 1000 L/m^3 = 1152 L

Initial tank sediment concentration = 31.51 mg/L

Mass of sediments suspended in the tank before ice formation = 31.51 mg/L x 1152 L = 36297 mg

Final tank water sediment concentration = 12.33 mg/L

Mass of sediments suspended in the tank after ice formation = 12.33 mg/L x 1152 L = 14204 mg

Sediment concentration in interstitial water = 35.58 mg/L

Sediment mass in interstitial water = 35.58 mg/L x 15.6 L = 555 mg

Sediment concentration in drained ice = 80.82 mg/L

Sediment mass in drained ice = 80.82 mg/L x 2.54 L = 205 mg

Sediment mass difference before – after = 36297 mg – 14204 mg – 555 mg – 205 mg = 21333 mg

Difference percentage = 21333 mg / 36297 mg = 58.77 %