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ICEWEAR Program: Influences on the ice-induced wear of concrete structures in polar marine environments

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ICEWEAR is a five-year research program, seeking to improve knowledge of surface wear and surface friction influences on the ice-induced wear of concrete structures in polar marine environments. Through the program, a variety of research lines have examined these influences, through ice-concrete interaction laboratory testing, investigations of ice-concrete contact physics, wear reduction strategies and modelling and analysis. The ICEWEAR research program adds to previous research programs over the past five decades that have examined ice-concrete contact phenomena. It also goes further by investigating the hybridization of ASTM and other standardized testing procedures/equipment in order to design new, meaningful, robust ice-concrete tests that can be standardized to better-enable the comparison of results across research programs. This paper will present some of the outputs from the first of these lines of research, with examples of the construction, testing and optimization of new equipment for adhesion, friction, wear and impact ice-concrete contact studies. The paper considers the effects of experimental design, and in particular, the influence of time and pressure on the experimental results.

1. Introduction

The physical nature of concrete–ice interactions has been studied for many decades. Ice damage on concrete in marine environments could, in worst cases, reduce resistance to loading, presenting possible hazards. Durability and maintenance are also significant concerns. Despite the long history of research, the overall understanding in the field to date is not as strong as it could be due to the considerable number of intrinsic and extrinsic properties and conditions for both concrete and ice, combined with a lack of standardized practices. This results in continued uncertainty about numerous facets of the underlying process mechanics. These uncertainties include the relative role of intrinsic properties (those properties that are part of the materials being examined, such as the composition of concrete or ice) or extrinsic properties (those properties acting upon the materials, such as ambient temperature and applied load), with research programs generally focusing upon one of those categories. These variations in properties, and the accompanying design of laboratory studies to evaluate their effects, has led to a patch-work of testing methodologies that render it difficult to compare results across research programs. For an examination of these challenges, see, for example, Barker et al (2021b).

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2. Laboratory Testing of Ice-Concrete Interactions

The role of adhesion on the abrasion of concrete is not well understood. To examine the influence of adhesion on abrasion, the processes of ice-concrete bonding and the influences of extrinsic parameters such as pressure, holding time, wetting and more, on the ice-concrete bond strength should be better understood. To do so, a number of test designs were developed to examine these influences. These included novel experimental techniques aimed at isolating the influence of contact pressure, duration, saturation and other variables on the shear strength of adhesive bonds between model ice and representative concrete samples. For all test designs, considerations for functionality included: standardization, to improve the ability to compare with future research (see Barker et al, 2021a); accurate load application for reliable results; and portability, to enable easy transport and easy change of testing environment. The ICEWEAR research program has included development of ice-concrete testing apparatus for friction (Nuus et al, 2019), tension (Pramanik et al, 2020), impact (Costello et al, 2019), long-term abrasion (wear) and shear studies (images for the first three of these shown in Figure 1). The abrasion and shear studies are presented in this paper.

2.1. Concrete

Concrete samples were prepared according to ASTM C192: Standard Practice for Making and Curing Concrete Test Specimens (ASTM 2019). A mid-strength concrete, commonly used in marine environments, was chosen for most tests (the long-term abrasion tests also used high and low strength concrete mixes). A mid-strength concrete allows easy reproduction for other experiments, and a relatively fast means of seeing experimental wear results. Table 1 shows typical concrete mix properties. Strength after 28 days of curing was approximately 65 MPa. A grinding machine was used to smooth the surface of the cylinders resulting of an average roughness of 8.21 Ra, measured using a Starrett SR400 roughness measuring device. The surfaces of 20 cylinders were analyzed using Image J software to find an average aggregate to paste ratio of 1.3 on the ground cylinder surfaces.

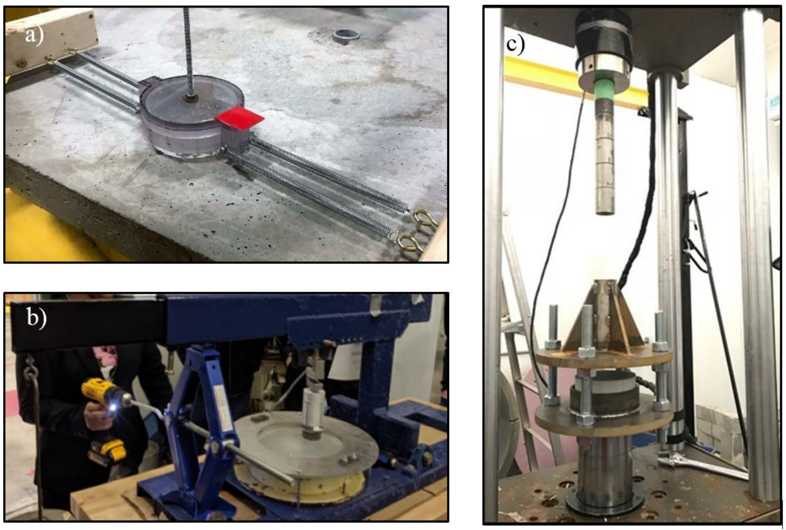


Figure 1. Test apparatus design for a) friction (stick-slip behavior), b) tension and c) impact studies (from Nuus et al, 2019, Pramanik et al, 2020 and Costello et al, 2019).

Table 1. Mid-strength concrete mix properties

Ingredient	Amount	Ratios	
Cement	18.0 kg	Cement Factor C/F	1.2
Sand	35.3 kg	Water content W/C	0.4
Fine aggregate (<10mm)	42.3 kg		
Water	7.2 kg		
Adva 190	50 mL		

2.2. Ice Samples

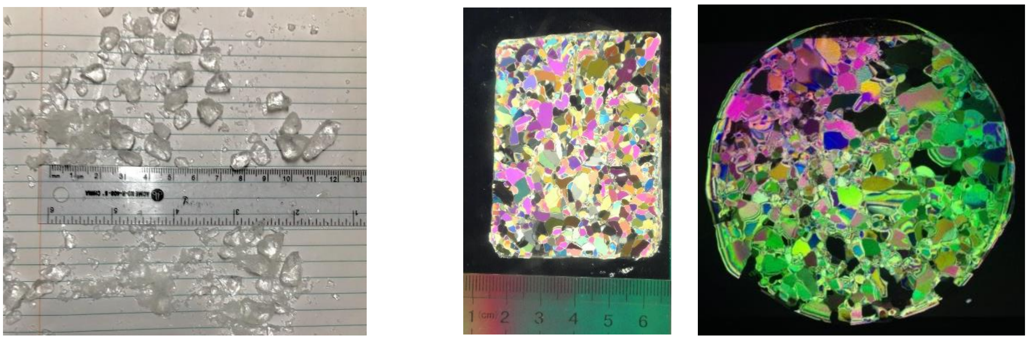
Granular polycrystalline freshwater ice with 4-10mm grain size was fabricated following the procedure in Bruneau et al. (2013), in order to facilitate comparison with other ICEWEAR projects and, again, to promote standardization across tests, through use of forms normally used to create concrete cylinders. After demoulding, the ice cylinders were shaped using an aluminium heat sink and standard, off-the-shelf plastic V-shape frames. After the concrete and ice samples were prepared, they were cooled for 24 hours in a cold room which ensured their core temperatures were approximately equal.

2.3. Simple Shear

The concept and set-up for simple shear tests are presented in Barker et al (2019). The test set-up was as shown in Figure 3. Four samples could be tested, one after the other, during each test run. These could be structured as the same test, with three repeats, or different tests, for example with samples that had the same hold, or bond, time (the amount of time the ice was left on the concrete prior to testing), but some with added pressure (280 kPa) during that period, and others without. Hold times ranged from 2 to 24 hours. The test temperature ranged from -3°C to -15°C. Tests were performed in dry (not submerged) conditions. During initial tests (44 tests, not reported here due to space considerations), the ice samples were placed onto the concrete without any wetting of either the concrete or the ice surface. The tests shown here

(36 tests) had wetting of the ice surface prior to adhesion onto the concrete surface, achieved by quickly running the ice sample over an aluminum heat sink.

Example images from some of the simple shear tests are shown in Figure 4, including an image of cohesive failure through the ice sample (that is, the failure was through the ice, not the bond with the concrete), and an image of an ice surface, post-test, through polarized light. This later image is of interest, as comparing this image with the "shadow" of where there was ice penetration into the concrete paste, we can deduce the "true" contact area between the two surfaces. Figure 5 shows the results from the simple shear tests. It can be seen that there is quite a large range for all bond times, as well as across temperatures and pressures.



a) (b)

Figure 2. (a) Ice grains used in creating polycrystalline ice and (b) thin sections photographed with polarized lens.

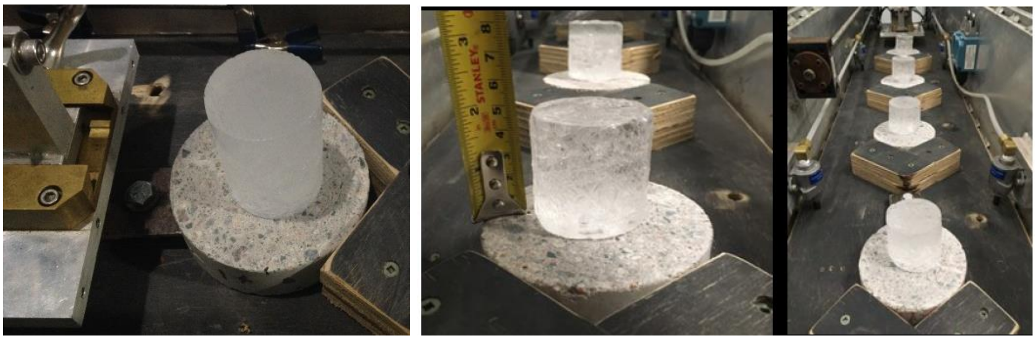


Figure 3. Simple shear test set-up.

a) b) c)

Figure 4. (a) Cohesive failure in the ice during an early test, (b) close-up of ice on sample post-test and c) an ice sample post-test under polarized light, showing the "actual" contact area with the concrete.

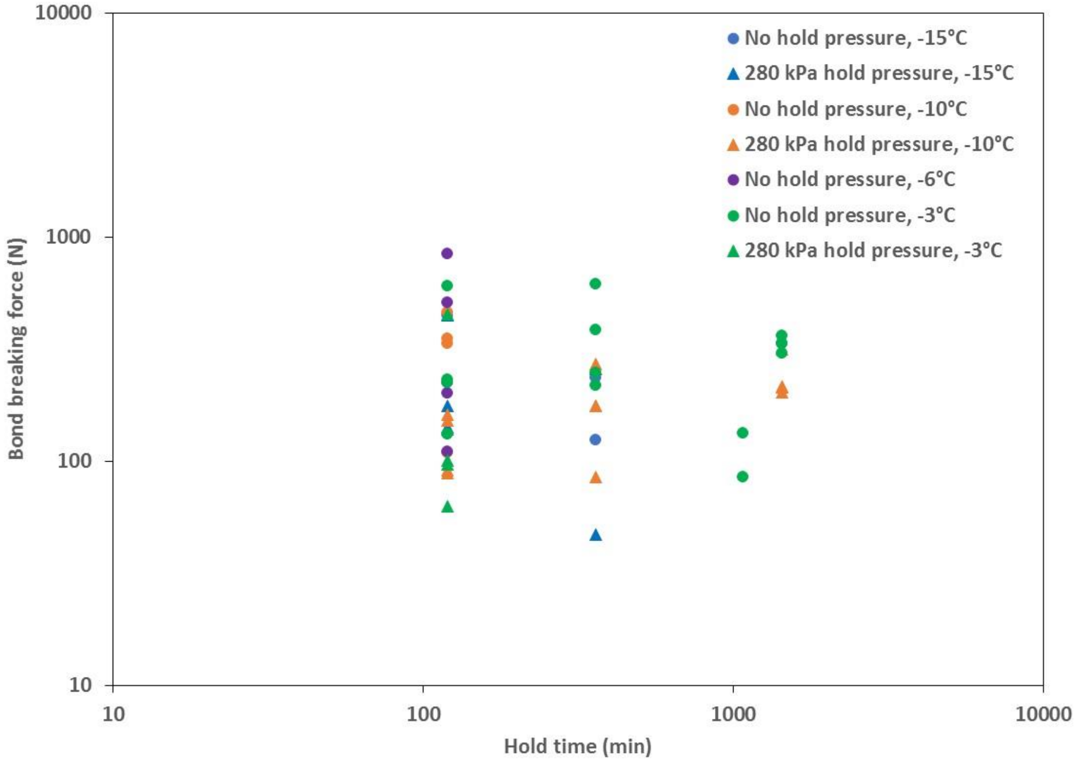


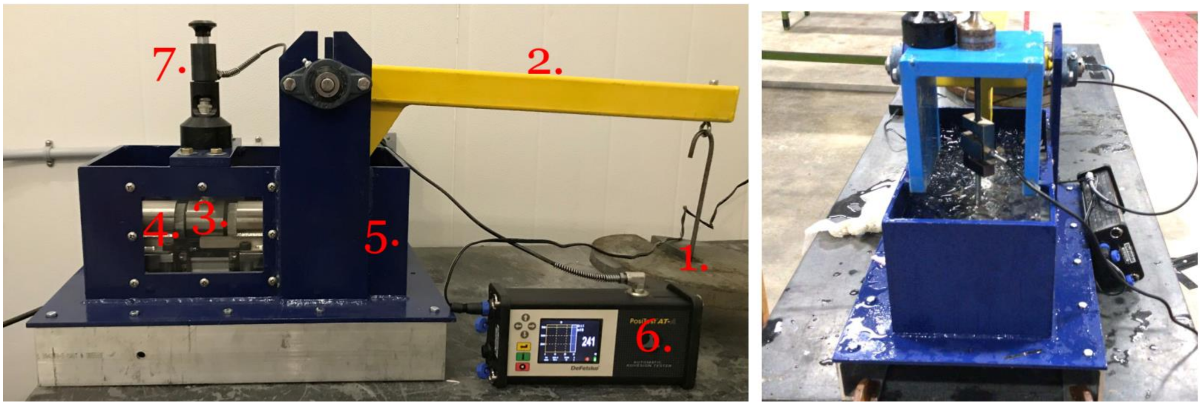
Figure 5. Bond breaking force plot from simple shear tests. All tests were dry tests. Note that for ease of viewing, each axis has been chosen to start at 10.

2.4. Double Shear

In development of a double-shear (with shearing on two sides of an ice specimen) test apparatus, two additional considerations were to eliminate machine friction and balance out unwanted moments induced by the shearing actuator on the ice. A further objective was to compare dry with wet adhesion by adding the ability to submerge the samples. This double-shear apparatus is shown in Figure 6 with components described in Table 2. In the first test sequence, a variety of weights were hung on the lever arm and the actuator pulled out the ice after waiting for a chosen time duration. In the second sequence, the weight and thus resulting normal load on the ice-concrete interface, were removed before pulling out the ice. In the third sequence, a cut concrete surface, a pure paste surface and a pure aggregate stone surface were used and in the fourth sequence, the whole set-up was submerged, simulating an arctic offshore environment. The values of the peak force, when the ice first starts moving and thus breaking the ice-concrete bond, were plotted for varying pressures and hold times. Figure 7 and Figure 8 show the bond breaking force for the first two test sequences. A general trend of increasing bond breaking force can be seen for longer holding times. The results of test sequence 2 are significantly lower than the results of sequence 1. A dimensionless bond breaking force is introduced in order to compare results from different pressure tests. This is done using Equation 1, which is derived from Coulomb's friction model.

$$\mu_{pullout} = F_{Bond\ breaking\ force} / (2 * A_{surface} * \sigma_n) \qquad \textbf{[1]}$$

Here, $A_{surface}$ is the surface area of the ice and concrete cylinders. σ_n is the applied normal pressure. $F_{Bond\ breaking\ force}$ is the force at which the ice-concrete bond breaks. Figure 9 shows the plotted result of formula 1 for test sequence 1. While not shown on this figure, cohesive failure was generally observed for longer holding times; for further discussion, the reader is referred to Westerveld (2019).



a) b)

Figure 6. (a) Double shear apparatus and (b) submerged setup; parts described in **Table 2**. From Westerveld (2019).

Table 2. Parts of the double shear apparatus and their function. From Westerveld (2019).

Part	Device	Function
1	Weight	Exerts force on the lever arm
2	Lever arm	Transfers load to apply pressure at ice-concrete interface
3	2" diameter ice puck holder	Positions the ice and exerts force on ice puck
4	2" diameter concrete cylinder holder	Maintains position of concrete
5	Outer metal casing	To allow for submered tests
6	DeFelsko Positest At-A	Contains hydraulic system to actuate part 7
7	Actuator assembly	Pulls the ice-puck when initiated by part 6

Different surfaces were also examined. Results (not shown here) showed a lower bond breaking force for the pure stone aggregate surfaces and the highest bond breaking force for the pure paste surface. Visual observation showed cohesive failure of the paste.

A significantly lower force was required to pull out the ice for the submerged tests, with pressure held when pulling out the ice. The submerged test were performed in water containing melting ice thus resulting in higher test temperatures then the dry tests. An increase in pressure does not necessarily result in an increase of bond strength. The difference in pullout force between dry and wet adhesion was larger for larger pressures, as can be seen in Figure 10.

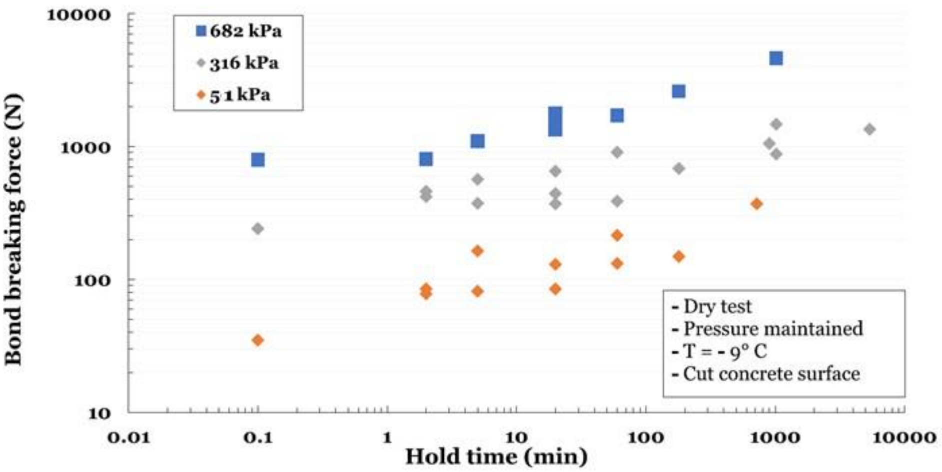


Figure 7. Bond breaking force vs. hold time. Normal pressure maintained for pull out. From Westerveld (2019).

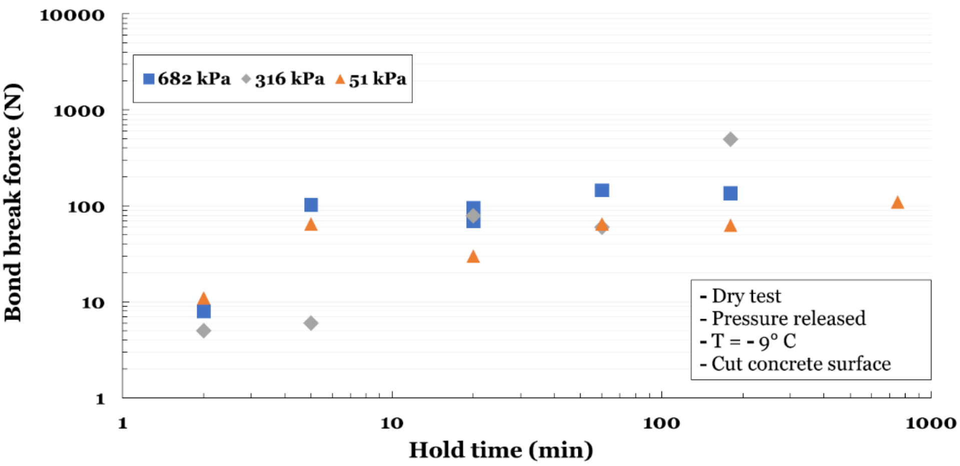


Figure 8. Bond breaking force vs. hold time. Normal pressure released for pull out. From Westerveld (2019).

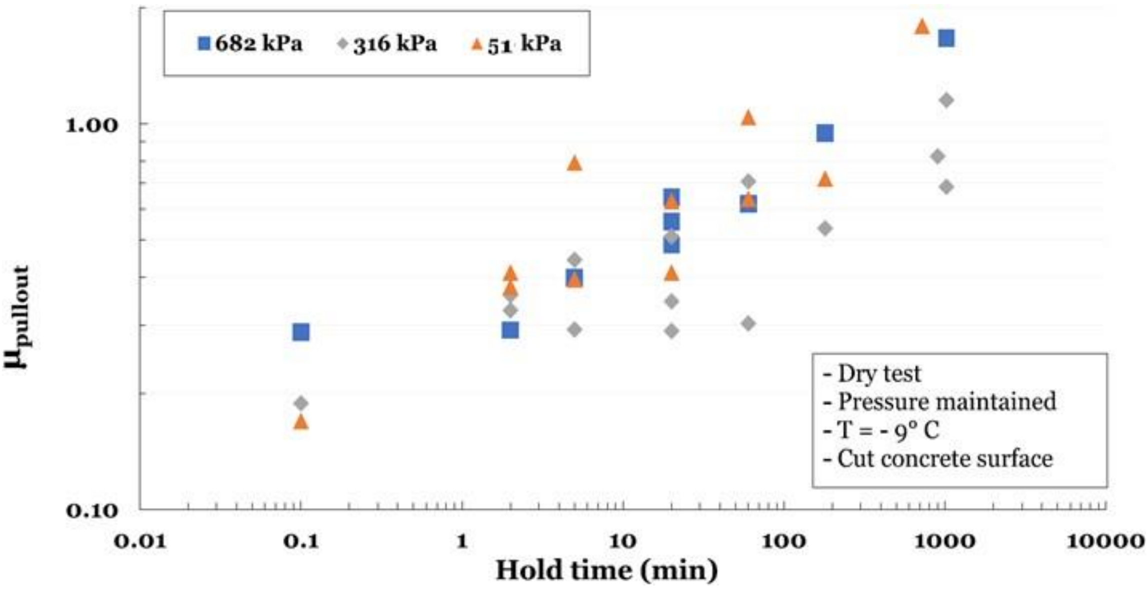


Figure 9. Dimensionless bond breaking force. From Westerveld (2019).

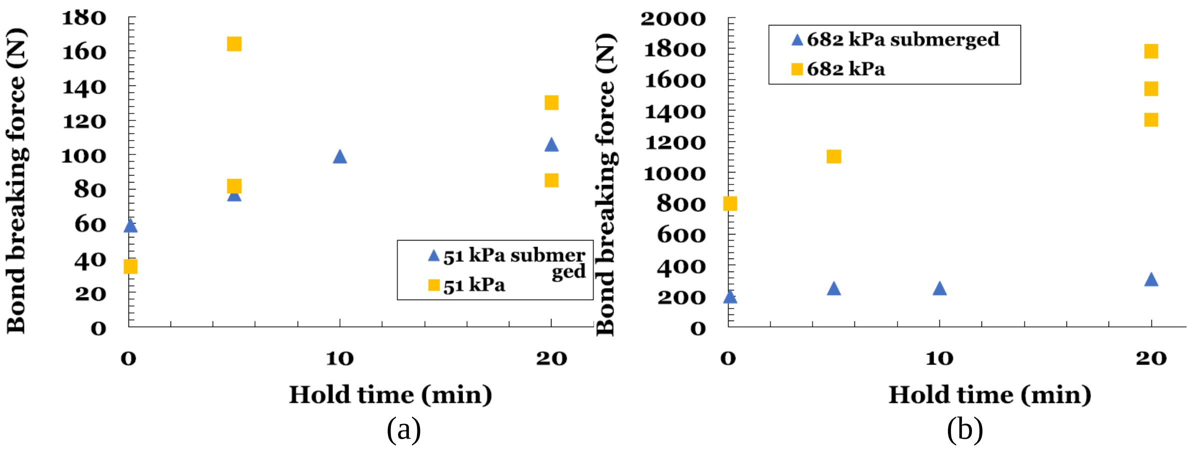


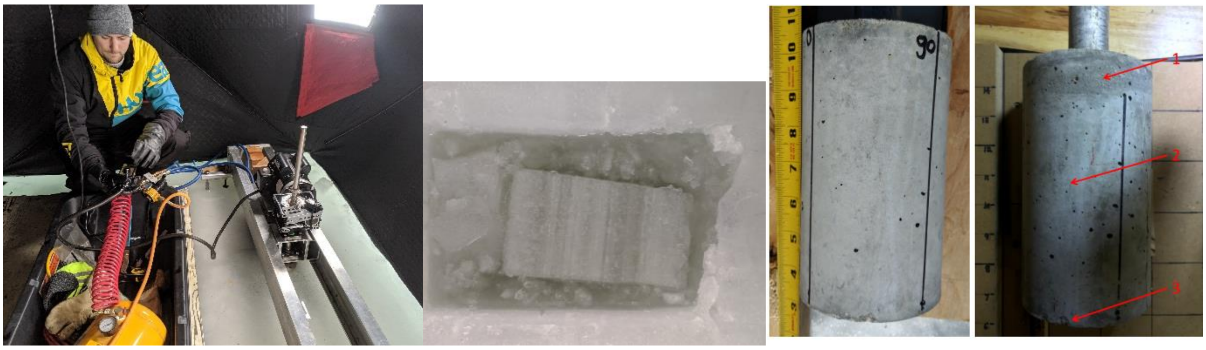
Figure 10. Submerged versus dry tests for (a) 51 kPa and (b) 682kPa adhesion tests. From Westerveld (2019).

2.5. Long-term concrete abrasion

It is complicated to mimic the long-term effects of concrete structures abraded by ice, especially when conducting tests in a laboratory setting. There are relatively few field studies of ice abrasion. Based on a state of the art review (Tulp, 2020), the following were identified as important in the design of a field ice-concrete abrasion apparatus: a continual movement with minimal start-stops and no reversal of motion; ice pressure; relative velocity; ease-of-use; and long operation time. These features allow simulation of long-term ice-concrete abrasion, like that of the Confederation Bridge. For this program, a rotating cylinder was pushed with a constant force against ice in the field to satisfy the criteria of continual movement with minimal start-stop and no reversal of motion.

The field apparatus design (Figure 11a) permits long duration wear tests with a rotating concrete cylinder pressed against a stationary natural floating ice cover. The device can run for days without replacing ice samples. The equipment is portable and could be lowered into a precut hole in the ice sheet. The total length of the apparatus is 180 cm long, big enough to give representative results, but able to be handled by a single person. Most parts were made out of aluminum, a lightweight metal, easy to fabricate and without corrosion risks.

A freshwater pond near St. John's, Canada was chosen for the field work. The ice contained multiple layers due to freeze-thaw cycles, as shown in Figure 11b. Due to the onset of the COVID-19 pandemic, it was not possible to do strength testing of the ice in the laboratory. The field tests included low, medium and high-strength concrete samples. The total duration of the field tests varied between 24 and 74 hours, with total rotations of the concrete samples between 42120 and 128436, for total representative distances of 6.7 to 20.5 km. This distance is based on approximately 50% of the concrete being in contact with the ice at any given time. These distances are in line with the observations of Itoh et al (1987) that indicated that approximately 7 km or more of equivalent movement of ice in laboratory testing was required to reach a steady abrasion rate. This rotary experiment was able to achieve a longer duration of continuous ice wear with higher realistic pressures. There were a smaller number of stops, and the experiment was able to continue overnight. It was, however, more complicated to determine the amount of wear during the experiment, and weather conditions also make the test conditions more variable.



a) b) c) d)

Figure 11. (a) Rotating head field apparatus, (b) layers inside the freshwater ice, and images of the medium-strength concrete before (c) and after (d) field testing. The arrows indicate particular areas of abrasion and/or voids that became exposed after wear. From Tulp (2020).

Observations from these pilot tests included that a thin layer of ice formed on the concrete surface during each experiment. This has been observed in other tests, such as those of Nawwar and Malhotra (1986). This could be due to temperature changes due to friction, resulting in adhesion between the (failed) ice and the concrete surface. The thin layer of ice results in a decreasing coefficient of friction. Another interesting observation was the horizontal banding of abrasion, as shown in Figure 11d). The horizontal lines are likely related to differences in the strength of the ice in the vertical direction, as visually depicted in Figure 11b). Table 3 shows the results of this test program.

Table 3. Field test results – long-term abrasion. From Tulp (2020).

Test	1	2	3
Date	16-17 March 2020	17-19 March 2020	19-23 March 2020
Concrete sample	high-performance (mix 1)	low-performance (mix 3)	medium-performance (mix 2)
Inside the tent [yes/no]	no	yes	yes
Air temperature [Degrees Celsius]	-11<T<-1	-5<T<1	-2<T<3
Pressure ram [PSI]	80	100	100
rpm	29.25	29.25	29.25
velocity [m/s]	0.16	0.16	0.16
Pressure concrete sample [MPa]	1.7	2.1	2.1
Height concrete sample above ice surface [mm]	0	4	2
Duration [hours]	24	44.25	73
Ice abrasion distance [km]	6.722	12.39	20.50
Ice consumption [mm]	215.9	452.76	1123.95
Loss of material (dry) [mg]	7	31	34

3. What have we observed to date?

3.1. Experimental design

Simple shear experimental designs, while relatively common, are quite varied. Moments induced on test samples can influence results, but they can be mitigated, by maintaining a low contact point between the apparatus and the sample. Designing simple shear tests, that use one to three standardized contact areas between the ice and the concrete, would benefit the cross-comparison of test results. Tests with built-in repeatability, testing multiple samples at one time, may also increase the reliability of results. The main advantages of simple shear testing are the relative ease of design, and familiarity across multiple areas of research and testing. The double shear apparatus was a means of eliminating moments during testing. Its advantages were a relatively simple set-up that could use standardized ice and concrete sample sizes and the ability to test submerged samples. The apparatus can be installed in laboratories with access to either hand-held hydraulic or ASTM actuators.

The rotary device could do long-term concrete-ice abrasion experiments in real field conditions. The rotating interaction between concrete and ice led to measurable concrete wear. The biggest advantage is that the apparatus can work for multiple days continually under field conditions, and under higher pressures. The device is workable for two persons and can be located at places with a layer of freshwater or sea-ice. For this experiment, only a saturated environment for the concrete sample was used for the three tests. If the ice thickness is sufficient, and there is no thaw for a few days, a dry environment could be tested. Jacobsen et al (2015) stated that wet abrasion causes more wear than dry abrasion inside the laboratory. It would be interesting to obtain results from the rotary device in the field in a dry environment and compare it with the results in a submerged environment. The test apparatus is also larger, allowing a closer-to-full-scale testing.

3.2. Influence of pressure and hold time on ice-concrete bond strength

The double-shear tests indicate that a higher applied pressure would result in a higher force required to shear the ice (e.g. Figure 7). However, from Figure 9, no clear relation can be seen between pressure and bond strength, although visual observations show that more ice is stuck on the concrete when doing tests with higher pressures. Perhaps when applying higher pressures, more dislocations in the ice crystals occur, which decreases the overall strength of the ice. When shearing, the weakened ice breaks off easier, leaving more ice on the concrete.

There is a strong linear correlation between $\mu_{pullout}$ and holding time. The effects of hold on bond breaking strength can be explained by the increase in real contact area between the two surfaces. The actual contact area of two solids is only a small fraction of the nominal contact area, and due to the ability of ice to creep, the real contact area increases over time, shown as a power-law relationship. Makkonen (2012) states that adhesion strength depends linearly on effective contact area, thus adhesion strength scales logarithmically with time. Ice asperities might creep into concrete asperities and later creep into the pores of the concrete. This hypothesis is supported by visual observations of more ice stuck on the concrete for longer holding times. When this happens, there is no longer a straight plane interface layer between the ice and concrete. In the experiments, adhesive failure was observed for generally lower pressures and hold times and cohesive failure was observed for higher pressures and holding times.

4. Summary

The ICEWEAR program is a multi-year research effort to improve knowledge of surface wear and surface friction influences on the ice-induced wear of concrete structures in cold marine environments. This paper presents highlights from a selection of the research carried out to date. Full details of the various research streams may be found in the accompanying theses.

Acknowledgments

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