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ORIGINAL ARTICLE

Bulk adhesion of ice to concrete–strength

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Abstract This paper presents the results of a laboratory test program designed to investigate the adhesive effects of large-scale (bulk) ice on concrete. Medium-strength concrete cylinders were sawn into discs, and attached to a sample table. Freshwater ice samples, frozen using smaller, standard-sized concrete cylinders, were adhered to the concrete with both varying bond times and added weight during bonding. Shear strength tests were conducted at a set displacement rate, under a number of temperatures. The effect of these variables on the adhesive strength of ice to concrete was examined, as well as whether there was any noticeable removal of concrete cement paste or aggregate during testing. The tests indicate that the adhesive strength is negligible when the method of adhesion is "dry" (no liquid layer at the onset of adhesion). Tests with "wet" adhesion indicated a significantly higher strength. The nominal versus the apparent contact area had significant implications for the determination of the adhesive strength of the bond between the ice and the concrete. Removal of cement paste was evident in a number of tests, however the amount was not significant. The results have relevance for design of structures in a marine environment, such as revetement dams or rubblemound breakwaters, as well as for the standardization of adhesion tests with ice and concrete.

Keywords Concrete · Ice · Adhesion · Laboratory · Wear

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1 Introduction

Damage by ice on concrete in a marine environment could, in the worst case, reduce a structure's resistance to loading, presenting a safety hazard. Design longevity and maintenance costs are also significant concerns. What role does ice adhesion to concrete play in the initiation of abrasion of concrete? Examples of reported instances of challenges with

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significant ice damage to concrete infrastructure include the removal of concrete revetement blocks lining water reservoirs [1], lock walls [2] and jacking of piles (USACE, Designing Small-Boat Harbors For Ice Conditions https://rivergages.mvr.usace.army.mil/WaterControl/Districts/MVP/reports/ice/docs/sbh4ice/sbh4ice.pdf). Previous experimental and analytical studies have generally focused upon the adhesive bond strength between ice and concrete, with little mention as to whether or not cohesive failure of concrete surfaces has occurred. The ability to prevent (or at least impede) the initiation of abrasion of concrete at the outset of a structure's encounter with ice would be beneficial for reducing the maintenance requirements of marine concrete, and increasing the design life of a structure in cold climates. To examine whether ice adhesion could lead to cement paste erosion and subsequent plucking of aggregate within the concrete interface, a study of the contact between ice and concrete was carried out, using simple shear adhesion tests of bulk ice on concrete as its basis. This study was part of a larger suite of investigations within the IceWear program at the Memorial University of Newfoundland. The overall test program used a variety of testing conditions to examine ice–concrete adhesion, including tension, double-shear, and simple shear tests, as well as an examination of the constituent components of concrete. The present investigation will inform design of structures in a marine environment, such as revetement dams or rublemound breakwaters, as well as the standardization of adhesion tests with ice and concrete.

2 Experimental approach

Barker et al. [3] presented a state-of-the-art review of previous studies examining the bulk adhesion of ice to concrete. As noted in that article, research that has involved the adhesion strength of bulk ice has primarily focused upon the examination and reporting of the break-out loads of ice and concrete (or other material) piles or other marine structures, not on the removal of concrete cement paste or aggregate, to which adhesion may lead. Similarly, icing-focused studies have examined and reported upon the effects of the application of coatings on the adhesion strength of ice, and again, not upon the removal of concrete cement paste or aggregate. There is little consistency in approach between studies in terms of experimental set-up for bulk ice–concrete adhesion studies. While that is partially due to the differing focus areas of the studies-for example, examining pull-out forces on piers versus ice-shove events on revetments versus abrasion of offshore structures such as wind turbine tower foundations-it does make the comparison of resultant adhesion strengths more challenging. For the current study, an objective included evaluating the incorporation of standard-size concrete samples, creating ice samples using similarly standardized molds, and comprehensive documentation of test parameters for reproducible test procedures. The test series was designed to step away from situation–specific test programs, to establish a more universally-usable data set. Doing so also provides a foundation to link adhesion to wear through the removal of material. Unlike steel structures, concrete is a porous, composite material; we postulate that the surface interactions between dry and wet ice are important to both the adhesion and the potential for damage to concrete by ice.

2.1 Concrete

Concrete cylinders were prepared according to ASTM C192 [4], using standard, readily available, 100 mm diameter, 200 mm high moulds for direct shear tests. To maintain consistency between test set-ups within IceWear, a standard concrete mix was used. This mix design was chosen based upon prior testing of a mid-performance concrete mix [5–7] (see Table 1). The compressive strength of this mix design was

Table 1 Mid-performance concrete mix design

Component	Mix content
Cement (kg/m^3)	400
Coarse aggregate content C. Agg. (kg/m^3)	113
Fine aggregate content F. Agg (< 10 mm) (kg/m^3)	94
Water (kg/m^3)	160
Cement factor C/F (course to fine aggregate ratio)	1.2
Water-to-cement ratio W/C	0.4
Air volume (%)	3–5
Absorption C. Agg (%)	0.01
Supplementary cementing materials SCM (%)	0
Plasticizer (mL)	50

approximately 36 MPa. This strength is lower than the high-performance concrete that would typically now be used at the waterline, for example, in a marine environment. When seeking to evaluate the basic properties of adhesion in a laboratory setting, a lower strength concrete provides a better platform for seeing experimental results, is consistent with previous test programs, and is easily reproducible for other experiments. This type of mix is also reflective of older structures in a marine environment, where substantial wear has occurred (for example rates, [8]). The concrete mix was modified slightly in order to satisfy ASTM requirements [4] that the diameter of the cylinder be at least three times larger than the largest aggregate size. Given that the same mix was used for both shear and tension tests, the latter of which used a smaller mould size, the mix was modified accordingly. A plasticizer, Adva 190, was used to enhance workability. No air-entraining admixtures were used.

Concrete samples were allowed to cure for 28 days prior to compression testing and being used in the test program. Although Huovinen [9] recommends 50 freeze–thaw cycles in order to be able to differentiate between freeze–thaw and mechanical impacts of abrasion, Itoh et al. [10] indicated that in the field it is extremely difficult to attribute degradation to one of these (or other) factors. For these tests, no freeze–thaw cycling of the concrete occurred prior to testing.

After curing, the concrete cylinders were stored, wrapped, in a freezer until the test program was ready to begin. At that time, the concrete cylinders were cut using a saw into disks, with each disk approximately 35 mm high (Fig. 1). A notch was put into the disks for testing in direct shear, which facilitated attaching the concrete sample to a jig, to prevent pitching of the sample as the ice was sheared. The disks were rinsed of debris from the saw. Initially, the test plan was going to either leave the samples as-cut or further roughen them using a wire brush. However, due to the number of variables already in play for typical studies between concrete and ice, it was decided that the concrete samples would be left as-cut. A Starrett surface roughness tester was used to measure the surface roughness of representative concrete samples. From that device, an average Ra (Arithmetic Mean Deviation) value of 0.0081 mm was established for the disks, which is considered a smooth surface. Prior to testing, all concrete samples were left in the test chamber for at least 24 h at the desired test temperature.

2.2 Ice

Ice samples were prepared according to the Memorial University of Newfoundland's standardized ice production technique [11]. Freshwater ice was chosen to minimize the number of variables to be examined, given the already extensive mechanical and environmental variations at play for ice and concrete. Similar to the concrete samples, ice samples were frozen in standard 50.8 mm by 101.6 mm concrete cylinder moulds (Fig. 2). Samples were frozen and remained in a freezer, wrapped, until used for testing. When ready for testing, the samples for the direct shear tests were cut using a band-saw to be approximately 40–50 mm high, to facilitate use with the test apparatus (Fig. 3). Thin sections of some of the samples were examined, to ensure consistency with the procedure outlined in Bruneau et al. [11]. See Fig. 3 for an example of a typical thin section from one of the ice

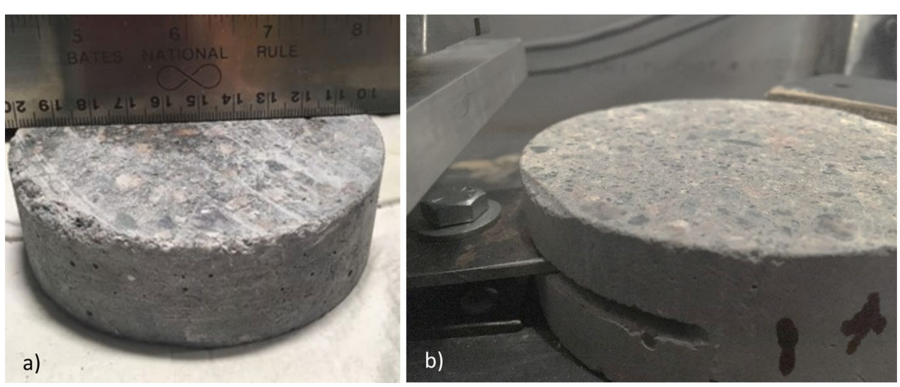


Fig. 1 Concrete cylinder disk ready for testing: **a** dimensions, **b** notch to avoid pitching of sample

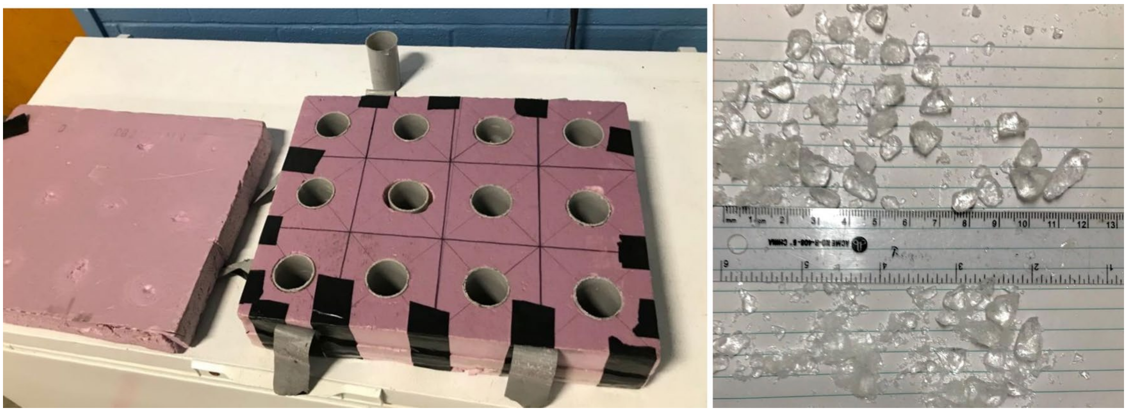


Fig. 2 (left) Moulds used to create ice samples and (right) typical piece sizes of crushed ice used to create samples

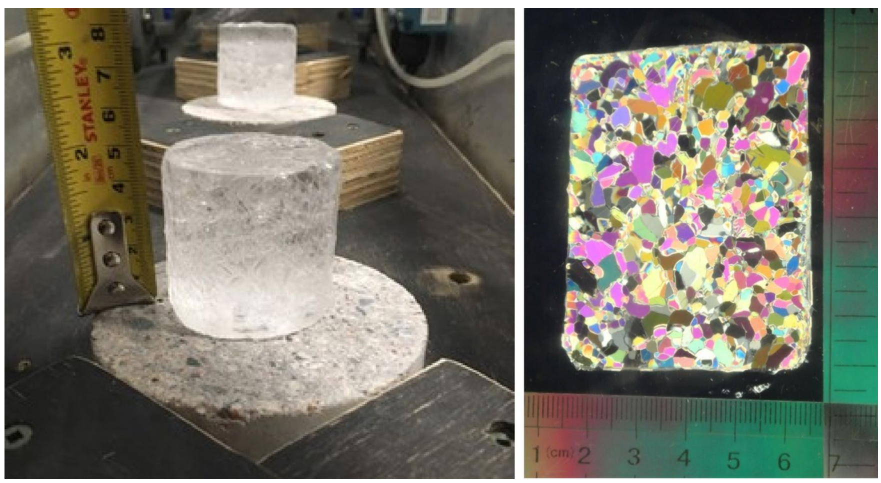
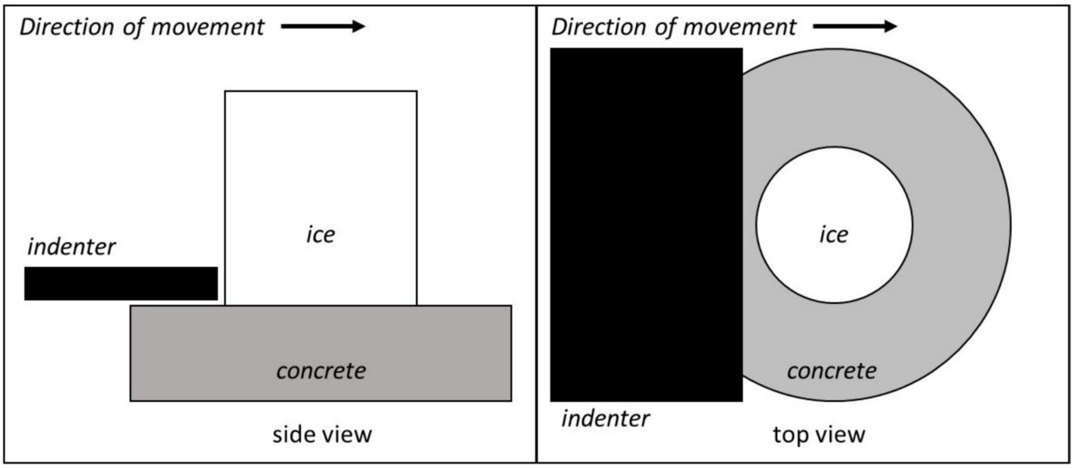


Fig. 3 (left) 40 mm ice sample after being cut with a band-saw and adhered to the concrete disk and (right) vertical thin section of one of the ice samples

samples. The nominal contact area for the ice samples on the concrete surface was 0.002 m^2.

2.3 Test apparatus

The direct shear apparatus was a modified friction table, built by the National Research Council of Canada. Originally designed for friction testing of paint on model marine hulls, the table was modified by installing a 300 lb *S*-type load cell. In order to configure the table for adhesion tests, a number of different arrangements were considered. The final design had the concrete samples clamped in place in a jig and braced against moments. The jig could accommodate four samples at one time. This type of set-up was chosen due to the number of tests that could be performed under the same test conditions at approximately the same time. The actuator was used in its lowest position, with a horizontal load applied by a clamp, normally used to hold an ice sample in the case of the apparatus' original purpose for friction testing. The height of the horizontal bar indenter was 12.5 mm, and at the lowest position of the actuator, contacted the ice samples slightly above the contact point between the ice and the concrete. The load is applied at a single point on the ice, rather than distributed around the perimeter as one might observe in a standard soil shearing test frame. This affects the stress distribution within the ice, as a point load is being applied rather than a distributed load along the entire circumference of the ice sample. A sketch of the layout for one sample on the jig along with a view of the set-up are shown in Fig. 4. The clamp assembly (indenter) was set to move at a relatively



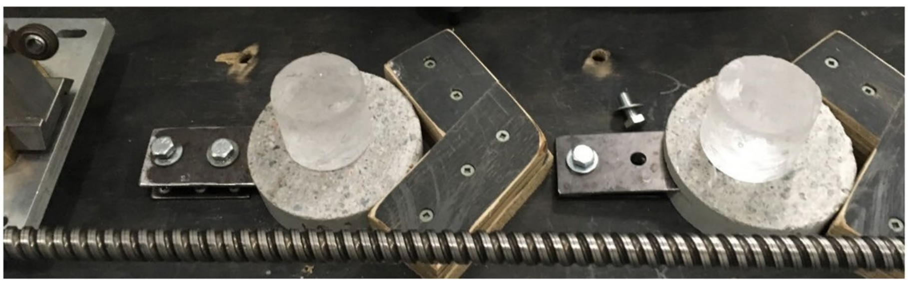


Fig. 4 (top) Sketch of test apparatus set-up, as shown from the side and the top and (bottom) Image of test assembly with bonded ice-concrete samples in place

fast displacement rate of 1 mm/s, but could have been adjusted faster or slower as required. The rate was kept constant for the test series. At this rate, testing of four samples, with the established spacing on the jig, took approximately fifteen minutes. The data acquisition system was set to sample at a rate of 500 Hz.

Testing took place in two different research facilities. One set of tests were carried out in the Memorial University of Newfoundland Faculty of Engineering cold room. This facility can house a variety of test equipment, and was used to prepare the ice samples and to conduct the dry adhesion tests. As a focus of the study was to examine longer (24 h) bonding time between samples, the second set of tests were moved to the National Research Council of Canada's (NRC) Ocean, Coastal and River Engineering cold room, due to the inability to control the defrost cycles of the cold room at the university as well as cold room availability. The former may be challenge for tests that are close to the freezing temperature of water. Pre-test temperature monitoring of the chamber showed that defrost cycles for the refrigeration system used in the cold room, when examining the effects of longer adhesion times at − 3 °C, would bring the temperature in the chamber above 0 °C, resulting in melting at the adhesion interface and thus creating a wet bond when a dry bond was sought. When holding the chamber at lower temperatures, this did not occur, and was not a concern for adhesion times shorter than the defrost cycle. The NRC facility has the ability to suppress defrost cycles if required for a period of time, so testing was subsequently moved to that facility. Depending on the position of the jig in either cold room, it was possible that air circulation systems could result in slightly different test temperatures between the first and the fourth samples on the jig, as the first sample would be somewhat more sheltered from air circulation due to the raised sides of the apparatus itself. However, temperature readings taken at each sample during preliminary tests indicated that the difference was less than 1 °C, if at all. The dry-bonded tests were filmed from a single view-point, from the end of the test jig. All wet-bonded tests were filmed from two positions for each test, one side-view and one viewing the test as on-coming towards the camera, with both repositioned for each sample.

2.4 Test conditions

2.4.1 Adhesion bonding

Dry versus wet bonding was of interest for this study. Under most marine conditions, ice is bonded "wet" to a structure. For example, in a lock, repeated raising and lowering of water creates a gradual build-up of ice bonded to the lock walls. A low-angled revetment at a dam could similarly see ice floes floated onto concrete during periods of elevated water levels, then adhered as those water levels drop. An offshore wind turbine tower or a marine terminal with piers could see ice form and gradually freeze in place, encircling the structure. All of these scenarios complicate the investigation of the adhesion of ice. Why? As Schulson [12] has described, amongst others, the influence of pore water pressure, with water freezing within the concrete matrix, is difficult to separate from the actual adhesion of ice to concrete. In order to examine whether a noticeable difference in adhesion strength is observed based on the type of adhesion, tests were carried out where the ice samples were simply placed on the concrete, and allowed to remain there for a defined period of time. For tests with wet bonding, a metal heat sink was used to lightly melt the bottom surface of the ice samples, which were then quickly adhered to the concrete.

2.4.2 Adhesion time

The role of time in the adhesion process was examined by varying the bonding time between 2 and 24 h. One important aspect to be monitored, especially during the longer bond times, was the defrost cycle(s) of the cold rooms used, as this could inadvertently affect the bond by leading to the melting of the ice sample should the temperature go above 0 °C during this cycle. This was especially important for the dry-bonded tests.

2.4.3 Applied weight

Added weight was included during the bonding time for some samples in order to increase the adhesion pressure. To do so, a mass of 2.27 kg was placed on top of approximately half of the samples during the bonding period. The added weight was removed immediately prior to testing. All weights remained in the test chamber at the test temperature prior to being placed on the ice samples, to ensure that they were not an added heat sink. Disposable plastic wrap was placed between the ice and the mass to prevent unintended adhesion between the two.

2.4.4 Temperature

Temperature in the test chambers was varied, with selected test temperatures − 3 °C, − 6 °C, − 10 °C or − 15 °C. The temperature of the test chamber was also monitored during the bonding time, using an Omega datalogger connected to the laboratory computer, to ensure that chamber defrost cycles did not affect the type of bond (dry or wet). It was more challenging to maintain test temperatures in the cold room chamber used for the dry-adhered tests, for which the test temperatures ended up with a range between 0 °C and − 20 °C.

2.4.5 Displacement rate

As in other ice strength tests, and as discussed in Frederking and Karri [13] and Oksanen [14, 15], high strain rates generally result in brittle failure of ice. For these tests, a relatively fast displacement rate was used, 1 mm/s, for all tests. This value was chosen to examine strength at the high end of tests that have been carried out to date [16].

2.4.6 Wear

This test program was an initial stage of a program that ultimately sought to measure wear or loss of material in the concrete samples arising from the detachment of adhered ice. It was recognized early on that measuring such wear in discrete tests would be a challenge mainly because of a need to quantify minute amounts of wear. Thus a secondary objective of this test series was to explore some methods of detecting and quantifying the loss of material from the concrete, and the conditions under which such loss occurred. Unlike frictional studies of ice on concrete, where visible degradation of a concrete surface can quickly be ascertained, this study would likely only have very small amounts of cement paste removed from the bonded surface. Two methods to examine wear were undertaken, both using measurements before and then at the end of the study, of the same concrete samples. To do so, the four concrete samples used in each test series were reused for each subsequent suite of tests. The first method used a hand-held portable microscope, a Dino-Lite Edge series AM7915MZT, to take images of select locations on the concrete disk surfaces, before the wet series tests began, and then at the conclusion of those tests. In order to align the before and after imagery, an indexer template was created, using marks placed on the sides of each sample to guide the process.

For the second method, 3D scans of the concrete surfaces were taken before and after the tests using a FARO Platinum Arm with a Laser Line Probe. While the use of the hand-held microscope would largely provide qualitative imagery of changes to the concrete surface, it was anticipated that the 3D scans could potentially provide a quantitative assessment of wear.

3 Data, discussion and observations

3.1 Test data

Test results are shown in Table 2. Cells are blank when either fewer tests were conducted, or if there was an error in the running of the test, such as an ice sample getting caught under the actuator after failure. Two tests at the end of the series were conducted with a bond time of 18 h rather than 24 h, due to an issue with timing of the test. Examining the histogram of the peak load values for the wet-adhered tests (Fig. 5), the two bins in the tail corresponded to tests where there was cohesive failure through the ice (failure modes are discussed in a later section). The distribution is skewed to the lower end. For the wet-adhered tests, the mean peak load was 245 N, with a large standard deviation of 162 N. Neither the wet nor the dry test peak loads were normally distributed.

3.2 Discussion

3.2.1 Dry versus wet adhesion

The dry tests had, for the most part, no meaningful degree of adhesion between the concrete and the ice, regardless of whether a weight was applied during bonding, the test temperature or the length of the bonding time prior to testing. The mean dry test adhesion peak load values were at most one-half of those of the wet tests. As mentioned in Sayward [17], air pockets not only reduce bonding, but may also be the loci for stress concentrations for propagation of adhesive failure. In the dry tests, with intentionally no pre-wetting of the surface, the presence of multiple air pockets, combined with imperfect contact between the concrete and ice surfaces, are believed to have prevented any significant bond from forming, an important outcome. While no air pockets were able to be observed, with no liquid layer deliberately created between the ice and the concrete, it is likely that they were present. This corresponds with Sayward's [17] suggestion, amongst others, that "poor wetting and occlusion of air may be a way to bring about poor adhesion of ice". Indeed, icing research has examined superhydrophobic surfaces to entrap air bubbles that prevent ice formation and adhesion to surfaces such as wind turbine blades (for a summary, see Dyhani et al. [18]). Also, as discussed in Emelyanenko et al. [19], amongst others, surface wettability plays an important role in adhesion. Unfortunately, as documented in Barker et al. [3], this factor via its general measurement through surface roughness and surface energy measurements, is rarely documented in the literature for bulk adhesion of ice on concrete. The remainder of the analysis presented will report upon the wet-adhered tests.

3.2.2 Temperature, adhesion bond time and added weight during bonding

Comparing the effect of test temperature on the peak load, while there was a noticeable increase in mean peak load at − 6 °C for the wet-adhered tests, tests at that temperature also had the largest standard deviation. The test series at − 6 °C also contained the test with the highest peak load of all of the tests, with cohesive failure through the ice taking place, leading to the skewed effect of that very large standard

Table 2 Test results

Wet or Dry	Tempera-ture-tests (°C)	Added weight (kg)	Bond time (hr)	Peak load 1 (N)	Peak load 2 (N)	Peak load 3 (N)	Peak load 4 (N)	Adhesive strength 1 (kPa)	Adhesive strength 2 (kPa)	Adhesive strength 3 (kPa)	Adhesive strength 4 (kPa)	Test #s
Wet	−3	0	2	132	606			65	299			5,6
Wet	−3	2.27	2	451	63			223	31			7,8
Wet	−3	0	6	385	613	248	217	190	302	122	107	9,10,11,12
Wet	−3	0	2	223	230			110	113			13,14
Wet	−3	2.27	2	97	101			48	50			15,16
Wet	−6	0	2	200	224	839	110	99	111	414	54	17,18,20,21
Wet	−10	2.27	2	88	161	91	151	43	79	45	75	22,23,24,25
Wet	−10	0	2	352	462	109	335	174	228	54	165	26,27,28,29
Wet	−10	2.27	6	176	271	85	177	87	134	42	87	30,31,32,33
Wet	−15	2.27	2	447	176	141	139	221	87	70	69	34,35,36,37
Wet	−10	2.27	24	315	215	212	202	155	106	105	100	38,39,40,41
Wet	−3	0	24	334	301	333	361	165	149	164	178	42,43,44,45
Wet	−3	0	18	133	85			66	42			46,47
Wet	−15	0	6	124	235			61	116			48,49
Wet	−15	2.27	6	47	257			23	127			50,51
Dry	−12	0	2	0	36	0	0	0	18	0	0	
Dry	−9	2.27	2	34	8	14	9	17	4	7	4	
Dry	−20	0	6	2	0	9	0	1	0	4	0	
Dry	−20	2.27	6	14	0	0		7	0	0		
Dry	−12	0	24	112	108	0	2	55	53	0	1	
Dry	−11	2.27	24	37	227	0	0	18	112	0	0	
Dry	−3	0	2	1	1	0	0	0	0	0	0	
Dry	−3	2.27	2	110		3	0	54		1	0	
Dry	0	0	6	17	72	73	305	8	36	36	150	
Dry	−3	2.27	6	5	11	10		2	5	5		
Dry	−7	0	24	30	12	0	0	15	6	0	0	
Dry	−3	2.27	24	16	11	3	6	8	5	1	3	

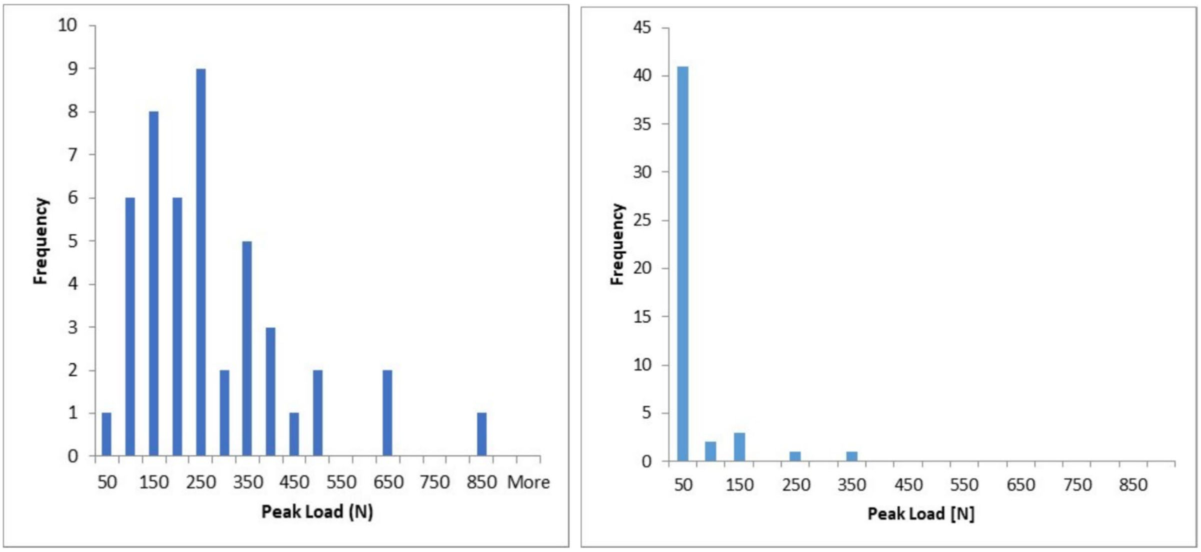
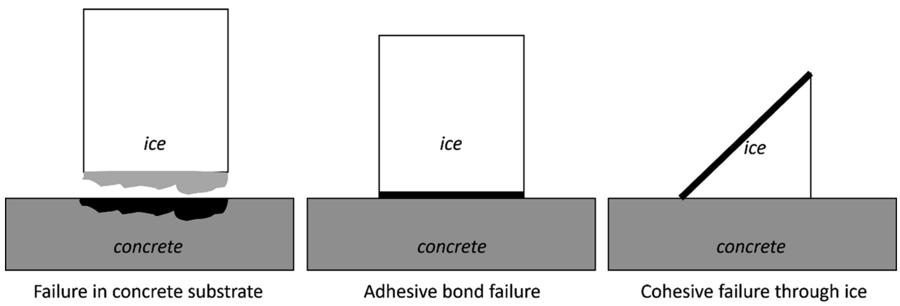


Fig. 5 Histogram of peak load for (left) wet-adhered tests and (right) dry-adhered tests

Fig. 6 Failure mode schematic. Black areas indicate where failure would occur



deviation. Overall, for the wet-adhered tests, the mean peak load for the tests at each temperature was similar, varying by less than 150 N. Examining the effects of bond time and whether or not a mass was applied during bonding through regression analysis, there was no strong evidence of a relationship between these parameters and the measured peak load.

3.2.3 Failure modes

There are generally three expected failure modes possible for adhesion studies: failure of the concrete surface, adhesive bond failure, or cohesive failure through the ice, as illustrated in Fig. 6. The most common failure mode for these tests was adhesive bond failure. There were two instances of clearly evident cohesive failure through the ice (see, for example, Fig. 7) as well as a number of tests where there

Fig. 7 Cohesive failure through ice sample: −6 °C, 2 h bond time, no applied pressure during bonding

was slight cohesive failure through the ice, but at an edge. It is noted that for those tests where the failure was through the ice surface, this then indicates that the adhesive bond strength itself was stronger than the failure strength of the ice. While there was no evidence of any tests with cohesive failure of the concrete, grains of cement paste were evident on the bottom surface of some ice samples post-test.

3.3 Observations—wear

It was hypothesized that the adhesion tests would show only very minute amounts of concrete wear over the course of a number of tests, despite using medium strength concrete, when compared to the rapid wear typically observed in friction studies of ice-concrete wear conducted in laboratory settings. Due to the limited number of tests, it was not reasonable to quantify the amount of degradation on the surface of each of the four concrete disks after each test. Rather, the decision was made to take imagery before any testing began and then at the completion of the laboratory tests. Qualitatively, the microscope (Fig. 8) and surface scans (Fig. 9) performed before and after each test provided interesting imagery, but little information. The microscope imagery did seem to show that after repeated tests, the cement paste was removed to a small degree. However, the change in appearance of the samples could be due to other factors, such as repeated wetting of the surface when adhering the ice samples. One ice sample did appear to have some cement paste embedded in it, upon visual inspection post-test. Similarly, comparing the laser surface scans of the concrete pucks before and after testing using Autodesk Viewer did not yield any measurable differences (Fig. 9). As with the microscope images, any small differences would be difficult to attribute to wear versus repeated surface wetting.

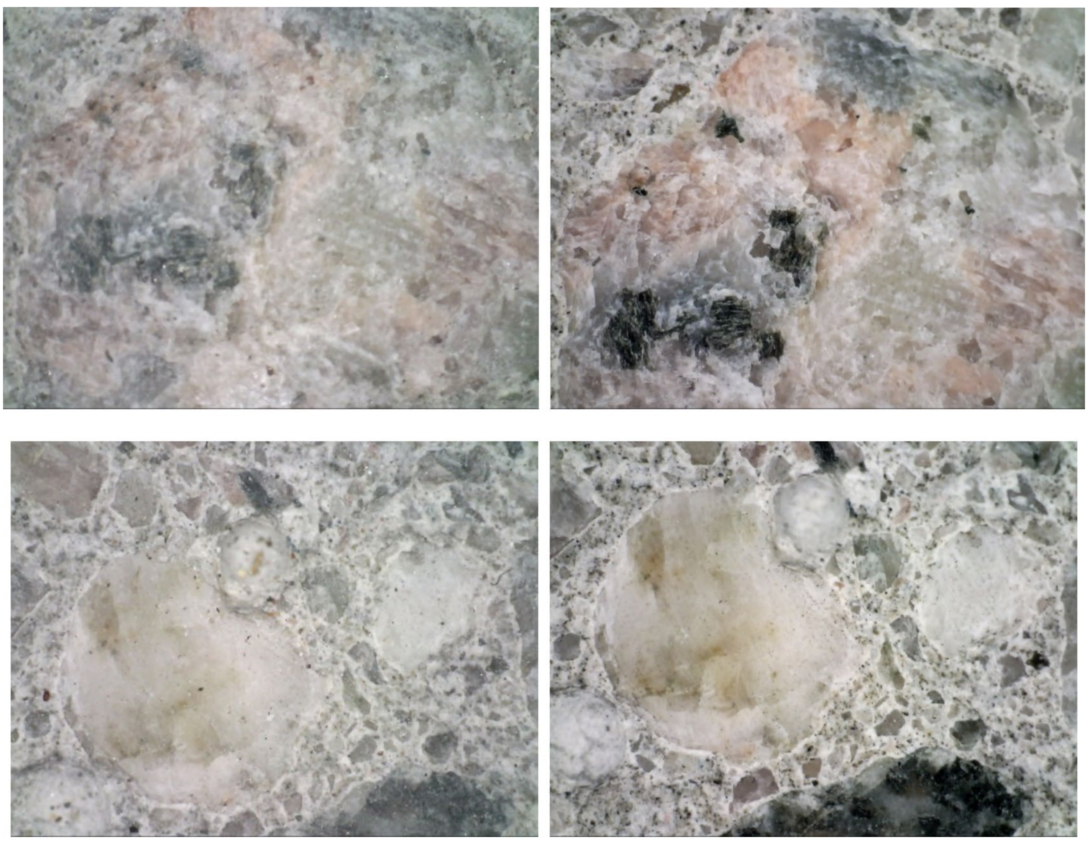


Fig. 8 Before (left) and after (right) images of the concrete surface, taken with portable microscope, for (top) concrete sample #1, and (bottom) concrete sample #2. The field of view for each image is approximately 2.5 cm

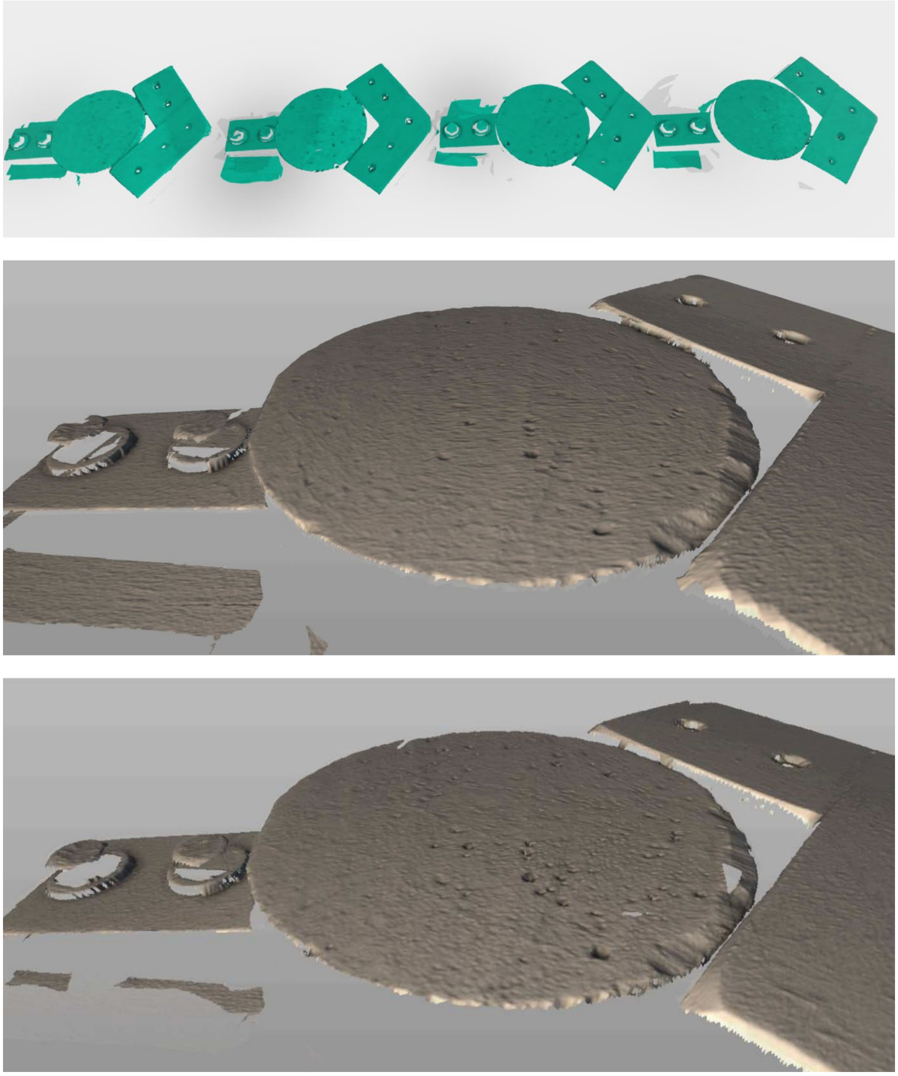


Fig. 9 Overall (top), single-sample before (middle) and after (bottom) images of the concrete surface, taken with 3D surface scanner

A recommendation for future testing would be to include more regular surface measurements, including surface energy and roughness, of the concrete samples. Due to the minute quantities of concrete debris being removed in these experiments, however, the equipment used to do so would need to be relatively easily deployed, without needing the samples to be removed and scanned elsewhere, using handheld scanning equipment, for example. Additionally, after each test, it could be feasible to melt each ice sample in a sterilized container, in order to collect the minute amounts of cement debris that may have been removed in each test. Whether this latter effort would provide valuable data at the current test scale is questionable, however.

3.4 Observations—contact area

Shortly after beginning the wet-adhered ice samples test series, it was observed that there remained a "shadow" of the ice adhered to the concrete surface (Fig. 10) post-tests. In some cases, it appeared that this area may have been where the thin layer of liquid at the base of the ice permeated into the concrete. In others, this was the remnants of small pieces of ice, still adhered to the concrete. Subsequently, a photograph was taken of the surface of the concrete after most tests, upon removal of the ice sample. Using the analysis software, ImageJ, each photograph of the concrete was imported into the software, and the associated "shadow", if there was one, was outlined

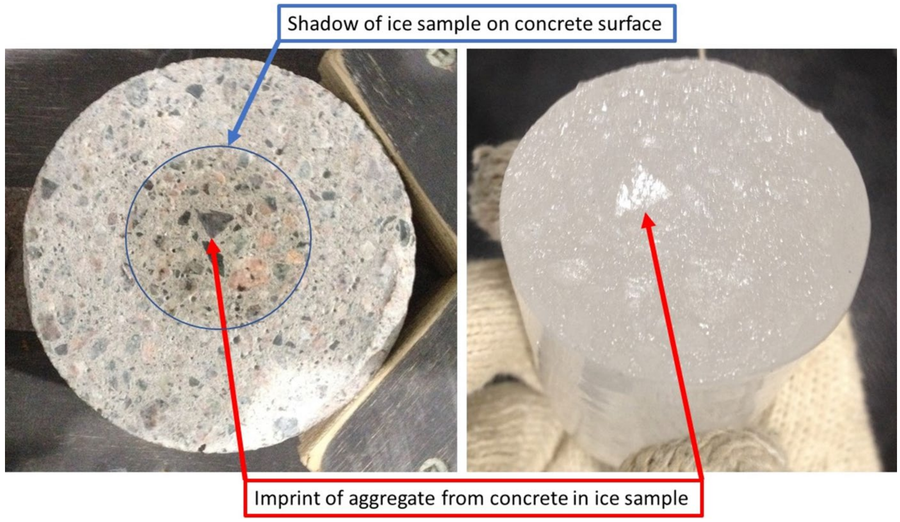


Fig. 10 "Shadow" from ice bond with concrete. What appeared at first to be ice crystals in the image of the bottom of the ice sample turned out to be imprints of the concrete aggregate in the ice sample

using freehand tracing. After scaling the image to the size of the concrete disc, the area of the shadow was calculated. Table 3 shows a summary of the apparent area calculated for most of the samples.

Do these areas represent the apparent (or real) area of adhesion between the ice and the concrete, compared to the nominal area as determined by the surface area of the adhering-face of the ice sample? Analysis of the selected areas was carried out for 36 of the 46 wet-adhered tests. Failure modes that were clearly cohesive failures, where the ice remained on the concrete and had to be melted to be removed, were taken as having 100% area coverage compared to the nominal area. The mean difference in area between the nominal and apparent areas was 50% of the nominal area, with a maximum difference of 20% (that is to say, the sample that had the least amount of area shadowed on the surface was covering 20% of the nominal area). A t-test analysis with unequal variances comparing the nominal and apparent contact areas indicated that the difference between the means of the areas was statistically significant. The effect of the apparent versus nominal contact area naturally impacts the calculation of the adhesion strength of ice to the concrete. These recalculated values are also in Table 3, and can be seen to be substantially greater than the values calculated with the nominal surface area of the ice samples. Comparing a histogram of wet-adhered adhesion strength values with a histogram using the strength adjusted for the apparent contact area it was shown that doing so changes the distribution, into a closer representation of a normal distribution.

In addition to examining this "shadow" area, the bottom surface of the ice was examined for cement paste debris, photographed and, in some cases, photographed under polarized light for greater visibility of surface defects. In Fig. 11, the cohesive failure that occurred at the edge of the ice is evident. Examining Table 3, the peak load was relatively low, 47 N, despite this cohesive edge failure. Note that the rest of the surface is very smooth; with this test conducted at − 15 °C, perhaps the melt from the heat sink froze before being able to create a more complete bond between the surfaces, except at that edge. Figure 12 highlights a few examples of the bottom surface of the ice samples viewed under polarized light. While qualitative, it is interesting to note the impressions of the concrete surface, despite being very smooth, in the bottom of the ice surfaces. All four tests depicted were conducted under similar conditions: − 15 °C, with a bond time of 6 h. However, tests 50 and 51 had an applied weight during bonding. Examining the images in Fig. 12 and comparing with the associated data from Table 3, it may be seen that in general, as the rough-looking parts of the ice depicting the apparent contact area increase in area, this also approximately corresponds with increasing measured peak loads. That is to say, as the images seem to show increasing "roughness" on the bottom of the ice surface, so too does the measured peak load increase, indicating those ice samples that had a stronger bond

Table 3 Contact area analysis. Rounding of strength values was carried out for the difference in adhesion strength

Test #	Peak load (N)	Nominal contact area (m^2)	Apparent contact area (m^2)	% difference in area	Nominal adhesion strength (kPa)	Apparent adhesion strength (kPa)	Difference in adhesion strength (kPa)
5 a	132	0.002	N/A	N/A	65	N/A	N/A
6 c	606	0.002	N/A	N/A	299	N/A	N/A
13 ce	223	0.002	0.00103	49%	110	217	106
14 ce	230	0.002	0.00121	40%	113	190	77
17 ce	200	0.002	0.00065	68%	99	308	209
18 ce	224	0.002	0.00119	41%	111	188	78
20 c	839	0.002	0.002	1%	414	420	6
21 ce	110	0.002	0.0007	67%	54	167	112
26 c	352	0.002	0.0011	48%	174	332	158
27 c	462	0.002	0.0015	25%	228	306	78
28 ce	109	0.002	0.0004	80%	54	273	219
29 c	335	0.002	0.0011	46%	165	305	139
7 ce	451	0.002	N/A	N/A	223	N/A	N/A
8 a	63	0.002	N/A	N/A	31	N/A	N/A
15 a	97	0.002	0.00061	70%	48	159	111
16 a	101	0.002	0.00071	65%	50	142	92
22 ce	88	0.002	0.0005	75%	43	173	129
23 ce	161	0.002	0.0009	56%	79	179	99
24 ce	91	0.002	0.0004	80%	45	228	183
25 ce	151	0.002	0.0010	52%	75	156	81
34 c	447	0.002	0.0013	36%	221	344	123
35 ce	176	0.002	0.001	51%	87	176	89
36 a	141	0.002	0.0007	64%	70	193	124
37 a	139	0.002	0.0008	59%	69	165	97
9 ce	385	0.002	N/A	N/A	190	N/A	N/A
10 c	613	0.002	0.002	1%	302	307	4
11 a	248	0.002	0.00088	57%	122	282	159
12 ce	217	0.002	0.00143	29%	107	152	45
48 ce	124	0.002	0.00071	65%	61	175	113
49 ce	235	0.002	0.00116	43%	116	203	87
30 a	176	0.002	0.00094	54%	87	187	100
31 ce	271	0.002	0.00102	50%	134	266	132
32 a	85	0.002	0.00059	71%	42	144	102
33 a	177	0.002	N/A	N/A	87	N/A	N/A
50 a	47	0.002	0.0006	70%	23	77	54
51 ce	257	0.002	N/A	N/A	127	N/A	N/A
46 a	133	0.002	N/A	N/A	66	N/A	N/A
47 a	85	0.002	N/A	N/A	42	N/A	N/A
42 c	334	0.002	0.0018	13%	165	190	25
43 c	301	0.002	0.0016	23%	149	193	44
44 c	333	0.002	0.0018	11%	164	185	21
45 c	361	0.002	0.0017	17%	178	215	37
38 ce	315	0.002	N/A		155	N/A	N/A
39 ce	215	0.002	0.0011	48%	106	205	99

Table 3 (continued)

Test #	Peak load (N)	Nominal contact area (m^2)	Apparent contact area (m^2)	% difference in area	Nominal adhesion strength (kPa)	Apparent adhesion strength (kPa)	Difference in adhesion strength (kPa)
40 ce	212	0.002	0.0012	40%	105	174	69
41 ce	202	0.002	0.0010	53%	100	210	111

Where an image was not available to calculate the apparent contact area, a value of N/A (not available) is given. Letters by the test numbers indicate the observed failure mechanism: a = adhesive, ce = cohesive (with failure at the edge of an ice sample) and c = cohesive (with failure through the ice sample or with a noticeably more extensive amount of ice remaining on the concrete)

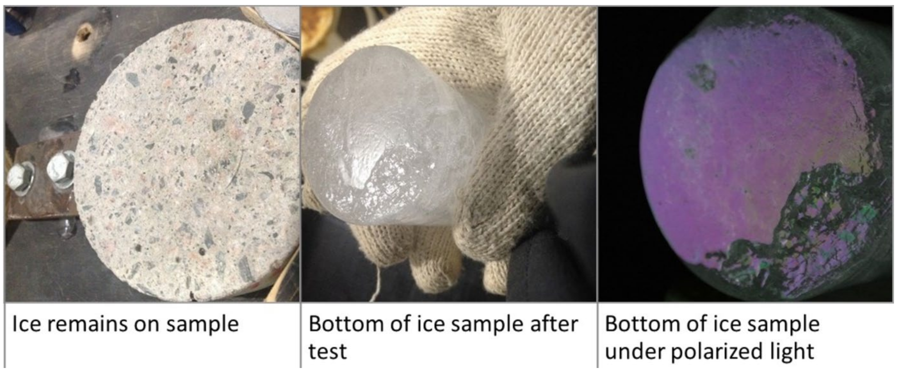


Fig. 11 Example of imagery post-test of (left) ice "shadow" on concrete surface, (middle) the bottom (adhered) side of the ice, and (right) the same surface under polarized light for greater visibility. Test #50

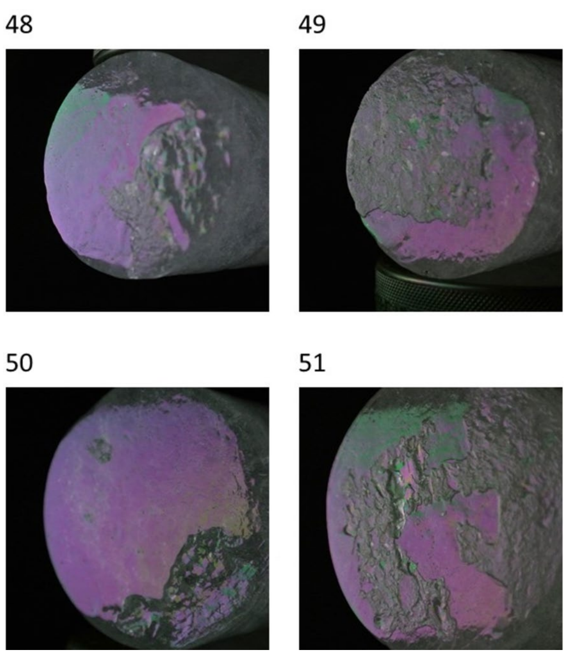


Fig. 12 Examples of the bottom surfaces of ice samples post-test. Test numbers are in the upper left of each image

between the ice and the concrete discs. The tests at − 3 °C tended to have both greater apparent contact areas as well as the corresponding higher peak loads. Similarly, the tests with longer adhesion time, when considering the apparent contact area, also had corresponding higher peak loads.

This points to the need to better-understand the apparent contact area for laboratory tests where ice is manually adhered to a sample (versus tests where a concrete sample is submerged and ice growth develops with time, such as is typically the case for pile push-out/pull-up/torsion tests).

Test temperature, applied load and bond time can have interdependent effects on the peak load, and by extension the adhesion strength, for the bond between ice and concrete. Multilinear regression was also performed on the data set, using the apparent contact area along with temperature, normal pressure (from the added mass), and bond time. Values where the apparent contact area could not be calculated were omitted from the analysis. Interestingly, analysis showed that the normal pressure and temperature variables were not statistically significant. The intercept, area and bond time did have statistical significance for this data set, however all values were left for calculating measured versus calculated load. Reperforming regression analysis with normal pressure and temperature variables removed, the resulting analysis gave an equation with an r^2 value of 0.78:

$$P_A = -128 - (-0.001) * L - 3.3 * T - 6 * t + 364884 * A \tag{1}$$

where P_A is the calculated peak load in Newtons, L is the added normal pressure, T is the test temperature in °C, t is the bond time in hours and A is the area in m^2. At the highest measured load, the regression analysis underpredicted the load. That failure case was a clearly cohesive failure through the ice, as shown in Fig. 7. It is noted that the apparent contact area was not calculated for that sample nor was it omitted from the tests used for regression analysis; rather, it was presumed that the apparent contact area was the same as the nominal contact area in this instance. Naturally, this might not be the case however given the very high peak load recorded, it was decided to leave this in the sample set.

3.5 Observations—test apparatus

The test apparatus for this test series was chosen due to its similarity to existing, commercially available apparatus for adhesion testing, as well as the ability to modify the set-up in order to accommodate multiple tests at one time, for repeatability, its portability (to be moved between available cold rooms) and to serve as a basis for examining performance compared to previous adhesion test programs. The set-up also had the potential to be used with tests slightly submerged in water with the construction of a watertight basin to contain the test jig. None of the tests reported here were submerged. Drawbacks to using this apparatus included the aforementioned need to eliminate moments due to the test arm as it pushed into the sample and limits to the load that unit could withstand, as it was designed for smaller loads than those generated between ice adhesion to a concrete surface. Subsequently, a more powerful load cell was installed in order to use this apparatus. The apparatus' set-up will be compared with previous test set-ups [16] in a future discussion piece, in the context of recommendations for future test design.

4 Summary

Abrasion of concrete in a marine environment due to structural interactions with ice is a common concern for cold regions. Whilst the use of high-performance concrete can mitigate some of the damage done to these structures, we do not have a clear idea of how the process of abrasion is initiated by ice. High initial abrasion rates, as concrete paste is abraded off of a structure, have been observed in previous laboratory tests, before a steady-state abrasion rate kicks in. Why this difference in rates? A test program was carried out to examine the potential effects of adhesion of ice to concrete in this initial phase of wear. Test results indicated that the presence of a liquid layer in the initial adhesion phase was essential for adhesion to occur between ice and concrete; tests performed "dry" did not adhere to any significant degree. Inclusion of air pockets, preventing wetting where feasible, is a first-order defense to prevent ice-concrete bonds from forming. While the quantity of cement paste was too small to be accurately quantified in the current test configuration, grains of paste were observed after a number of tests. Finally, the apparent (true) versus the nominal contact area of the ice on the concrete surface has a significant effect on the calculated strength of the adhesive bond. It is recommended that future studies into the ice-concrete adhesive bond, in the context of wear of concrete, focus upon the ice-concrete interface, examining the migration of water into the top layer of cement paste. A future article will compare the present study in the context of those previously reported [16].

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Data availability Data from this study is freely available for use by others.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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