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It's a grey area: Observations of the apparent area of ice adhesion to concrete

Anne Barker [a,b], Stephen Bruneau [c], Bruce Colbourne [d], Austin Bugden [e]

[a]Civil Engineering, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Canada

[b]National Research Council of Canada, Ottawa, Canada

[c]Civil Engineering, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Canada

[d]Ocean and Naval Architectural Engineering, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Canada

[e]National Research Council of Canada, Ocean, Coastal and River Engineering, St. John's, Canada

ABSTRACT

Many studies have examined ice and concrete adhesion: twist, push and pull tests on concrete piles frozen into ice; direct shear tests of ice on concrete; and investigations into the frictional wear of concrete by ice. The calculation of ice adhesion strength is dependent on knowing the contact area between ice and concrete however the true contact area may be difficult to assess. Researchers often rely on the nominal contact area (that is, based on the area of the samples in contact) to determine adhesion strength. Over the course of a study with more than 50 tests examining the adhesion of ice onto concrete, it was observed that the apparent contact area could be significantly less than the nominal area. The mean difference was 50%, with the subsequent effect of increasing the calculated strength when using this apparent contact area rather than the nominal area. This apparent area was observed despite following informal protocols for ice adhesion sample preparation. This paper provides a short overview of the test configuration and test results, then examines potential reasons for the differences, and how to observe, account for or mitigate in future test programs.

KEY WORDS: Ice; Concrete; Adhesion; Shear; Area.

INTRODUCTION

Damage by ice to 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. Lock walls, jacking of piles and removal of concrete revetement blocks lining water reservoirs are just some examples of the challenges created by ice adhesion to concrete. Design standards such as ISO 19906 (2010) direct engineers to consider adfreeze and studies of full-scale structures in ice conditions (for example, Frederking et al 2011 and 2013) have found that significant loading events can be attributed to ice adhesion to a concrete structure. Many field and laboratory studies (Barker et al, 2021) have examined ice and concrete adhesion, generally structured as twist, push and pull tests on concrete piles frozen into ice, direct shear tests of ice on concrete and more infrequently, tensile tests. Reliable calculation of ice adhesion strength is dependent on obtaining a correct measurement of the contact area between ice and concrete, however true contact area may be difficult to assess.

Over the course of a laboratory study with more than 50 tests examining the adhesion of ice onto concrete, it was observed that the apparent contact area could be (statistically) significantly less than the nominal area. These push tests examined the effects of test temperature, adhesion time and added mass on the peak load to shear the ice from the concrete. A push test is a test with the application of a point load, where the ice is pushed off of the concrete, versus a simple-shear test which has load uniformly applied across part of the ice surface. Figure 1 illustrates the laboratory test set-up. A full description of the test program and its results may be found in Barker et al. (2024). Here we focus upon the methodology for preparing the test specimens, implications for the determination of contact area and thus of ice adhesion strength and considerations for future test programs. 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.

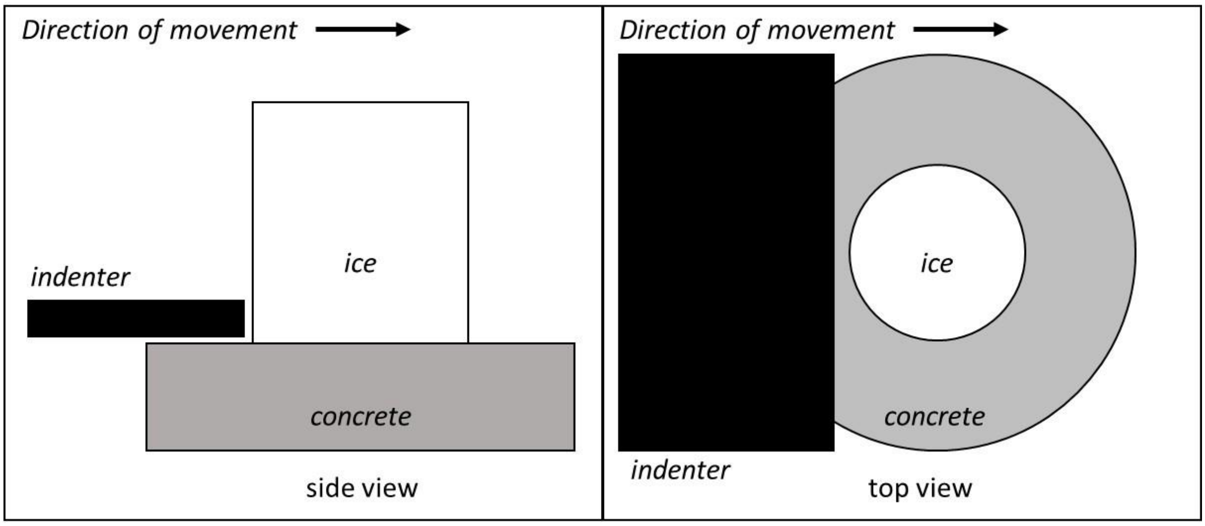

Figure 1. Schematic of push test laboratory set-up.

TEST PREPARATION METHODOLOGY

Concrete preparation

Concrete cylinders were prepared according to ASTM C192 (2018), using standard, readily available, 100 mm diameter, 200 mm high moulds. The compressive strength of the concrete mix design was approximately 36 MPa, considered a mid-strength concrete. This type of mix is reflective of older structures in a marine environment, where substantial wear has occurred. 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 the test program. 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 (Figure 2). The disks were rinsed of debris from the saw.

Figure 2. Concrete sample as prepared for testing and loaded into test apparatus.

Originally, the test plan was going to leave some of the samples as-cut and to further roughen other samples using a wire brush. However, it was decided that the concrete samples would be left as-cut. This also had the benefit of removing a test methodology – roughing – that would be hard to replicate across test programs. While a variety of standards exist for measuring surface texture, such as ASTM E1845 – 23 (2023) and ASTM E965 – 15 (2024) in the context of pavements, generally a laser scanner is required to carry out such measurements, which may not be available in all facilities, and thus also potentially challenging for cross-program comparison. For this test program, 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 hours at the desired test temperature.

Ice preparation

Ice samples were prepared according to the Memorial University of Newfoundland's standardized ice production technique (Bruneau et al, 2013). In this technique, ice is crushed into small pieces then frozen with de-aerated water into moulds. Freshwater ice was used in this study. The ice samples were frozen in standard 50.8 mm by 101.6 mm concrete cylinder moulds (Figure 3). Samples were frozen and remained in a freezer, wrapped, until testing. When ready for testing, the samples for the tests were cut using a band-saw to be approximately 50 mm high, to facilitate use with the test apparatus. The nominal contact area for the ice samples on the concrete surface was 0.002 m².

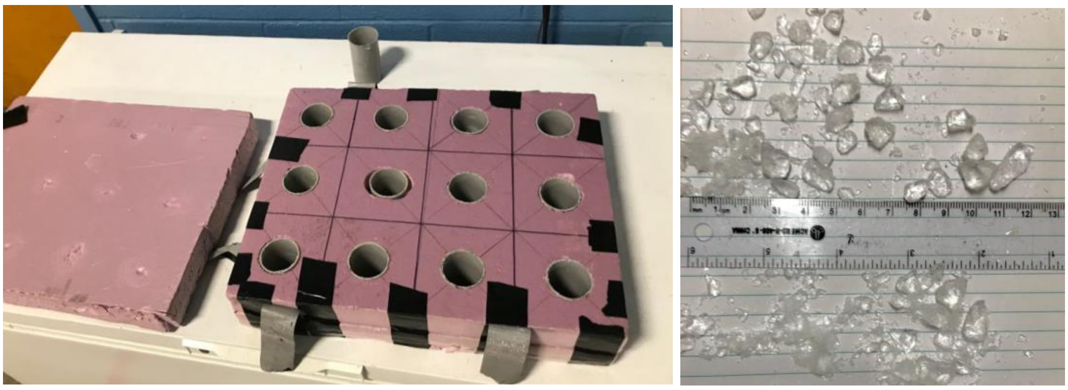

Figure 3. (Left) Cylindrical moulds and (right) typical ice piece sizes for ice sample preparation.

To adhere the ice to the concrete, a passive heat sink was used for what were named “wet-adhered tests”. Other tests, not reported here, examined the adhesion strength when no heat sink was used. The heat sink is a small piece of metal, kept inside a jacket when in a cold room to maintain it at a temperature above 0°C. The heat sink is rubbed quickly across the surface of the ice to be adhered (Figure 4, left). The amount of melt using this process is small, creating a liquid layer sufficient for adhesion but presumably not penetrating far into the ice surface. However, it is noted that this penetration depth was not measured. The as-bonded ice is shown in Figure 4 (right).

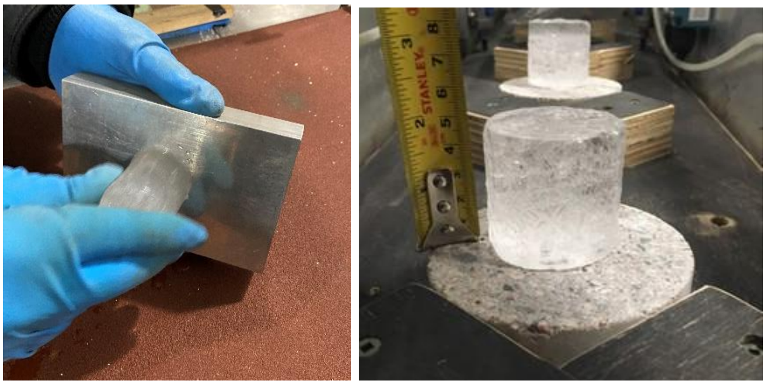

Figure 4. (Left) Using a metal heat sink to prepare an ice sample for bonding to a concrete sample and (right) as bonded to the concrete.

OBSERVATIONS OF APPARENT ICE ADHESION AREA

For this discussion, we will define two types of areas, nominal and apparent. The nominal area is the calculated area of the ice surface that is adhered to the concrete. In this case, the gross area of the circle of the ice sample, as calculated using the diameter of the ice sample. The apparent area is that which is perceived to be (visually in this case) the actual contact area of the ice surface to the concrete. Figure 5 provides an illustration of these definitions. It is noted that using the term “actual” (or “true or “real”) to describe the apparent contact area is still a subjective term, as the actual area is not known and could be debated by discussing other experimental scales, such as at a nano- or microscopic scale. In addition, the term “effective area” is used in many types of engineering analysis. Here, we will stick to using the term “apparent”, with the understanding that we are speaking only at the bulk adhesion scale of ice to concrete, and that it represents the actual contact area at this scale.

Further, for tests where the failure mode was clearly cohesive failure through the ice (where the entire ice remained on the concrete and had to be melted to be removed), we will describe these as having 100% apparent area coverage compared to the nominal area, given that the area could not be directly determined due to the need to melt the sample off of the concrete. For samples where the apparent area is less than the nominal area, we describe a percentage of coverage. For example, in Figure 5, we could say that the apparent area is approximately 80% of the nominal area.

During the test program described in Barker et al (2024), it was observed that there remained a darker grey “shadow” of the ice adhered to the concrete surface post-testing (Figure 6). 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 other cases, this grey area contained the remnants of small pieces of ice, still adhered to the concrete. These latter tests indicate a degree of cohesive failure through the ice; that is, in some cases the strength of the bond between the concrete and the ice was greater than the ice strength. The tests were performed at a relatively fast displacement rate, 1 mm/s, in order to examine failures at the higher end of previous studies, leading to brittle failure mechanisms. After these grey areas were initially observed, the test program was modified so that 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 using freehand tracing. After scaling the image to the size of the concrete disc, the area of the shadow was calculated. This shadow area is the apparent area as previously defined.

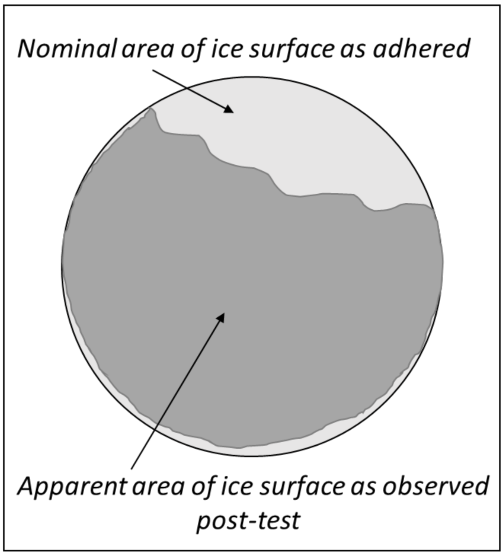

Figure 5. Schematic of the definitions of area used in this paper. The light grey area, a complete circle, represents the nominal area, while the dark grey area superimposed on top of the complete circle represents the apparent area.

Figure 6. Darker grey “shadows” from ice bond with concrete, visible in most post-test imagery. (left) This example appeared to have near-perfect contact, with a shadow area covering 89% of the nominal contact area. In addition, there was some cohesive failure through the ice, with some ice remaining on the sample, visible in the upper left of the grey area. (middle) This sample had contact over approximately 44% of the nominal area, with ice remaining on the concrete for almost all of that area, visible as a shiny surface in this image. (right) This sample had coverage over only 20% of the nominal contact area, however it did also show cohesive failure through the ice where that bond occurred.

Analysis of the apparent area was carried out for 36 of the 46 wet-adhered tests. Tests that were not examined either had no image or the image was of insufficient quality to calculate the apparent contact area. The full table of results may be found in Barker et al. (2024). 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 an apparent area covering 20% of the nominal area). It is noted that one might speculate that perhaps the non-grey areas that make up the "missing circle" of the ice could be spots where the concrete cement remained adhered to the ice surface. However, observations of the underside of the ice did not generally find this to be the case. If this occurred, it would be a level undetectable to visual inspection.

Figure 7 shows a plot of measured peak load versus apparent contact area. Note that the values where the apparent contact area could not be determined or where there was cohesive failure through the ice are omitted, the latter since these values could not be directly determined. Many of the tests at -3°C had greater apparent contact areas as well as corresponding higher peak loads. Similarly, tests with longer adhesion time generally had corresponding higher peak loads.

The effect of the apparent versus nominal contact area naturally impacts the calculation of the adhesion strength of ice to the concrete:

$$\sigma_a = \frac{F}{A} \quad (1)$$

where σ_a is the adhesion strength, F is the peak load and A is the adhesion area. Barker et al. (2024) recalculated adhesion strength values for the test series using the apparent contact area instead of the nominal contact area. Comparing a histogram of wet-adhered adhesion strength values using the nominal contact area with a histogram using the strength adjusted for the apparent contact area it is shown that doing so changes the distribution from a roughly lognormal distribution into a closer representation of perhaps a normal or bi-modal distribution (Figure 8).

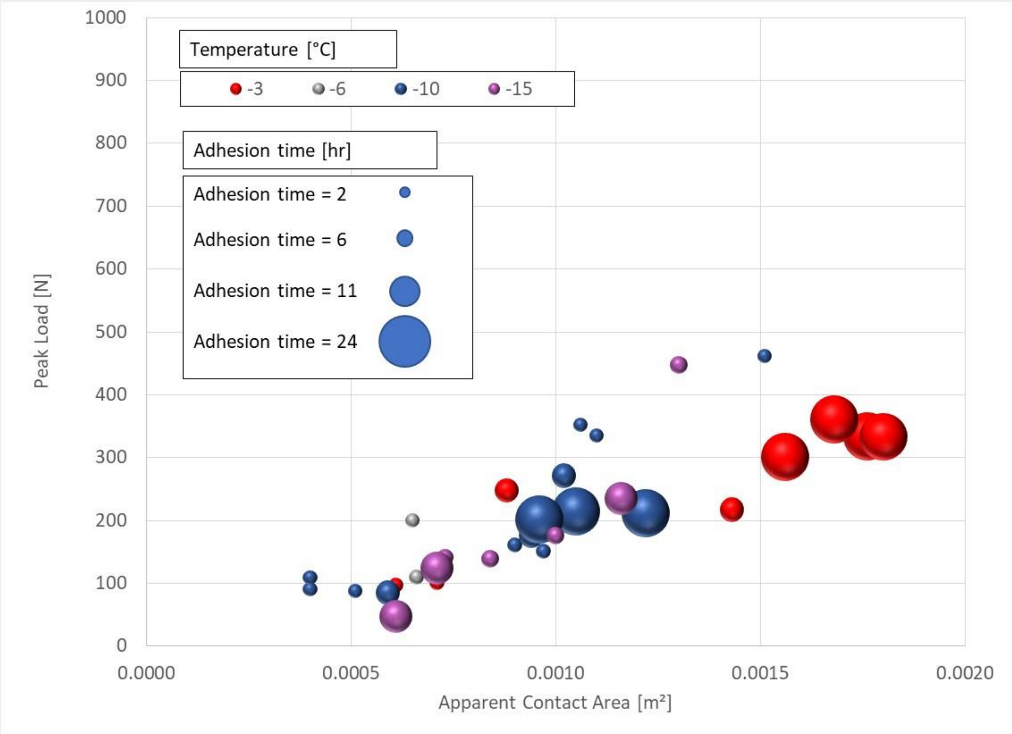

Figure 7. Peak load versus apparent contact area

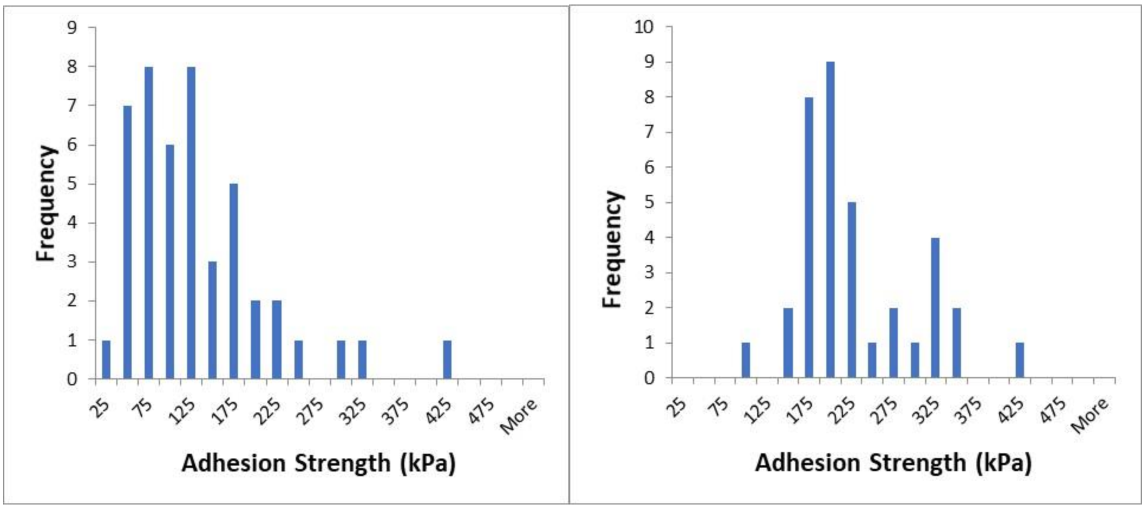

Figure 8. Histograms of the calculated adhesion strength using (left) the nominal contact area and (right) the apparent contact area.

Photographs of the adhesive surface of the ice samples post-testing indicated that, in some cases, the pieces of aggregate within the concrete matrix left imprints on the bottom of the ice surface (Figure 9). This could indicate that at least some degree of melt water permeated into the surrounding cement matrix, however it is noted that this could also be an effect of the creep of ice (that is, the movement of ice grain boundaries) into the surface. The test shown in Figure 9 was one of the longest bond times, 24 hours. For this particular test, there was a correspondingly high peak load to remove the ice from the concrete, 334N.

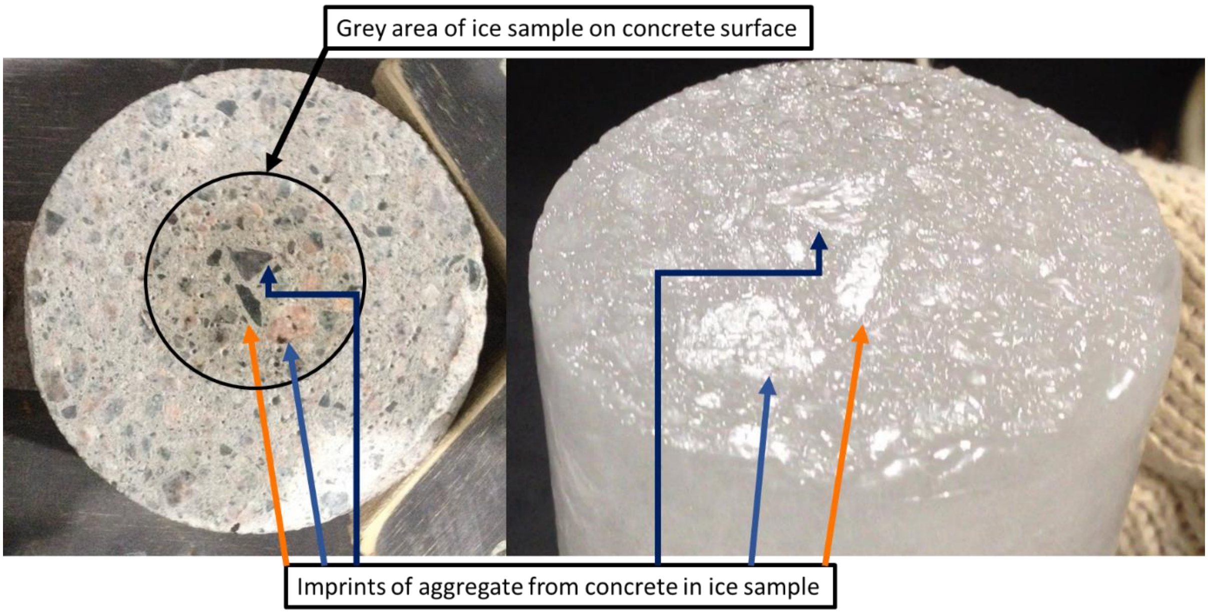

Figure 9. Imprints of concrete aggregate in the adhesive side of an ice sample. The colour of the arrows link the aggregate on the concrete surface (left) to its respective imprint on the bottom of the ice surface (right).

For some tests, the bottom surface of the ice was also photographed under polarized light for greater visibility of surface conditions. Figure 10 highlights two examples. The two tests depicted were conducted under similar conditions, -15°C, with a bond time of 6 hours, however, test 51 had an applied mass during bonding. 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 had a stronger bond between the ice and the concrete.

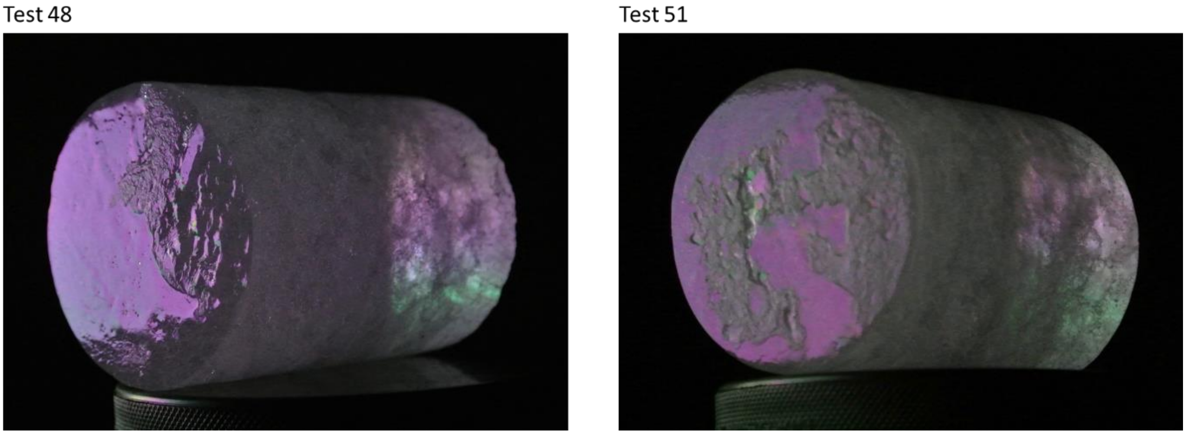

Figure 10. Polarized-light images of the bottom surfaces of example ice post-test. Test numbers are in the upper left of each image.

DISCUSSION

These observations point to the need to better-understand the apparent contact area for laboratory tests where ice is manually adhered to a sample. In a field setting, where a concrete sample is submerged and ice growth develops with time, a laboratory procedure for pile push-out/pull-up/torsion tests where a concrete sample is gradually frozen into ice, or smaller-scale studies where water may be frozen in a mould on a substrate, a more "perfect" contact can be expected, along with permeation of water into the concrete matrix as it freezes. In scenarios such as simple push testing (where the applied load is a point load), as in these tests, or shear testing (where the applied load is uniformly distributed), this apparent area consideration becomes more pressing.

For the cases with a very smooth underside ice surface, such as test 48 as shown in Figure 10, did the melt from the heat sink freeze before being able to create a more complete bond between the surfaces, except at that edge? The time that passes between preparing the bottom of the ice surface and placing it onto the concrete surface is relatively quick – a second or two at most. How does the heat of the system flow? Is the concrete cooling the ice or vice versa? Examining the percent coverage in area at the four test temperatures, the average percent area coverage decreased with colder temperatures, from an average of 63% at -3°C to an average of 45% at -15°C, with the associated standard deviations decreasing with colder temperatures. This indicates that as the test temperatures got colder, there was generally less of the ice area bonded to the concrete compared to the warmest temperature, when examining the apparent area compared to the nominal area. This is somewhat apparent looking back at Figure 7.

Or is this a wetting consideration, at the molecular level, with the liquid-layer water more strongly attracted to the ice surface? What role does the relative smoothness of the concrete surface play? Using a rudimentary set-up based upon that described in Lamour et al (2010), imagery was taken of distilled water drops on the surface of each of the four concrete discs at room temperature. Images were taken between 2 and 30 seconds after the water had been deposited on the surface. After a number of minutes had passed, the water had spread and penetrated into the concrete. The contact angle was calculated using plugins to the image analysis software ImageJ (Figure 11). The average apparent contact angle for water on these untreated concrete surfaces was 41° in this time frame (< 30s). This value is similar to those reported in the literature (see, for example, Al-Kheetan et al, 2019, or Zhang et al, 2017). No statistically significant differences in contact area were observed in drops that were on cement paste versus partially on a piece of aggregate.

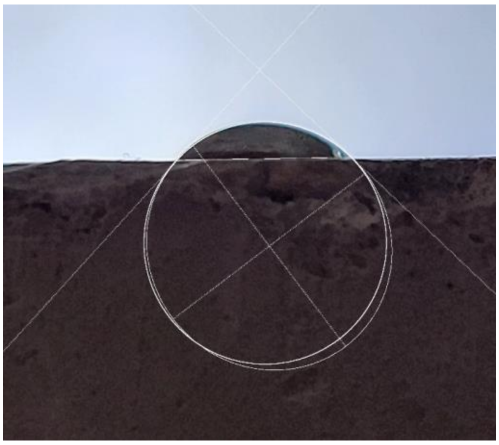

Figure 11. Water drop on concrete surface, with contact angle measurement lines shown from ImageJ software.

Knowing the contact angle, one can calculate an approximate value for the surface energy of the concrete. Surface energy can be generally described as the energy that results from incomplete bonding at the atomic level on the surface of a material, or the work required to form a unit area of new surface in the bulk of a material. Higher surface energy materials tend to result in more wetting of a surface, as is typical of untreated concrete. Using the Fowkes equation (Fowkes, 1964), the approximate surface energy of concrete may be calculated as:

$$\sigma_s = \frac{\sigma_l(1+cos\theta)^2}{4} \quad (1)$$

where σ_s is the surface energy of the solid, σ_l is the surface tension of water and θ is the contact angle of the liquid on the solid. If one takes the surface tension of water as 72 mJ/m², and using the average contact angle for these concrete samples, a surface energy value of 55 mJ/m² is calculated. Less than that of water, this indicates, not unexpectedly, good wettability and does not indicate that the liquid layer from the heat sink would have been more strongly attracted to the ice surface.

How else might one examine the cause of these grey areas on the concrete surface, and their effects on the strength of adhesion between ice and concrete? An alternative preparation method, such as freezing water onto the concrete surface in a mould, or an alternative view point for observing the adhesion process would be interesting examinations of the penetration of water into concrete to better understand the role of wettability in ice-concrete adhesion. For example, Figure 12 shows a schematic of an alternative set-up for examining the process of adhesion at a macro-scale. In this configuration, the sawn disks used in the current study would be sawn again, this time in half vertically, as would the ice samples. The ice samples would be adhered to the concrete disk tests both using and not using the heat sink. A portable microscope camera system would be then set at the level of the interface to take images at set time intervals to document the progression of adhesion, whether showing water permeation into the ice surface or not, after which shear testing could be carried out, followed by subsequent examination of the contact interfaces. This would have the added benefit of a means of examining whether creep of ice is occurring in tests with a longer bond time, a possible explanation for some of the imprints of the concrete aggregate in the bottom ice surface.

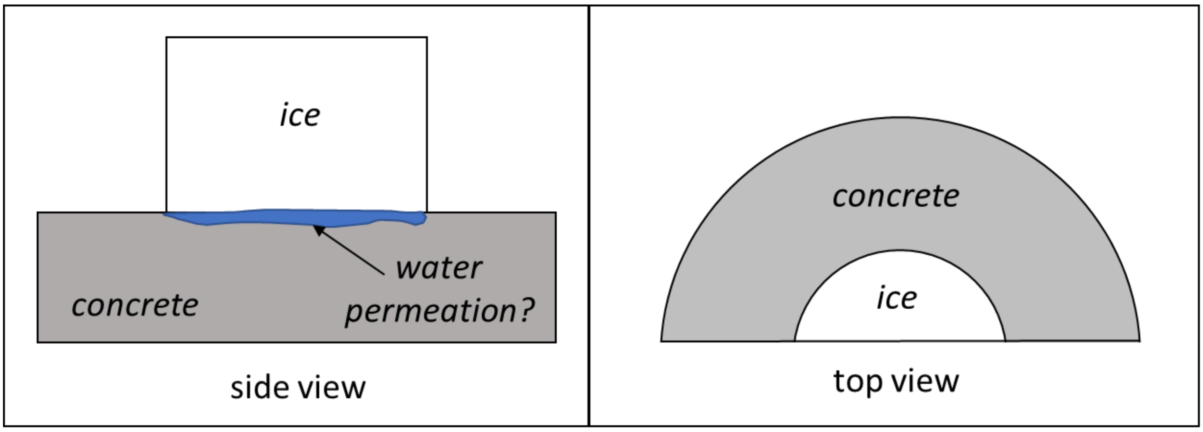

Figure 12. Schematic of a potential experimental set-up to examine macro-scale adhesion of ice to concrete.

In terms of implications for test programs, best practices for future test programs should consider incorporating the following recommendations into their test procedures, in order to have a clearer understanding of the apparent contact area between ice and concrete.

1. Ice sample preparation using a heat sink: the ice should be adhered to the concrete as quickly as possible, and also in a consistent timeframe from test to test. Prior to initiating the test program, a number of samples could be used to examine the maximum time prior to adhering the samples together before the thin layer of melt water on the ice has refrozen, potentially preventing a strong bond between the materials. This could be achieved qualitatively, by manually testing the bond between the materials, or quantitatively, by testing immediately after adhering the materials. Additionally, routine surface temperature measurements of the concrete and ice surfaces prior to adhesion should be collected. This might provide an indication of heat flow in the system during the process of adhering the surfaces together.
2. Post-test sample examination: where cohesive failure through the ice sample has not occurred, the ice adhesion surface under regular and polarized light should be examined and documented to study the apparent contact area. The concrete surface should also be examined and documented in a similar manner, for evidence of these “grey areas” of water/ice penetration into the sample.
3. Concrete variables: A broad suite of concrete sample parameters should be measured prior to testing. This would ideally include surface roughness, water absorption and contact angle using either commercially-available or more simple equipment configurations, and following standards where available such as ASTM D6489-99 (2024). These measurements will provide a better understanding of the surface energy of the samples being examined and the accompanying implications for wettability and adhesion.

CONCLUSIONS

"A grey day provides the best light" is a quotation often attributed to Leonardo da Vinci. Perhaps these grey areas on concrete surfaces likewise illuminate a detail that would otherwise have been missed, providing insight into the apparent contact area between laboratory samples. With this understanding, one can develop best practices in laboratory sample preparation and analysis, to better compare results between research programs.

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