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Adhesion of Ice to Concrete: Bonds and their Influence on Abrasion Mechanisms

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ABSTRACT

Maintenance and repair of ice-worn concrete structures in marine environments are ongoing challenges. Practical solutions for reducing ice-wear for large-scale applications have had marginal success rates to date. We still do not really know the relative degrees of abrasion caused by mechanical wear, freeze-thaw cycling, pore water pressure, or seawater chemical effects. What is happening at the interface between ice and concrete and is there a link between wear and adhesion processes? 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. How do contact mechanics influence the shear and tensile adhesion bonds between these two substances? This paper outlines a programme that seeks to inform not only our knowledge of adhesion loading, but also how adhesion may influence the initial high rate of wear that is common to ice abrasion of concrete. The presented test programme is using a suite of methodologies to examine ice-concrete adhesion. Three approaches are outlined, with an eye towards answering the questions above, for a comprehensive evaluation of ice-concrete adhesion bonding.

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

INTRODUCTION

In an effort to better-understand the effects of ice upon concrete abrasion rates in a marine environment, an extensive body of literature has been developed, of field, laboratory and numerical study results. In the worst case, ice-concrete abrasion could present a safety hazard to a structure’s load resistance. Design longevity and maintenance costs are also significant concerns. Newhook and McGinn (2007) document an average aggregate abrasion rate of the concrete piers of the Confederation Bridge in Canada at 0.31 mm/year, with an average paste abrasion rate of 0.33 mm/year, over a four-year study period (which started 4 years after the bridge opened). Similar studies of lightpiers in the Baltic have documented abrasion rates of 0.2 – 11.6 mm/year, and in Japan of 1 – 5 mm/year (Jacobsen et al, 2015), for a variety of concrete strengths.

The process of abrasion of concrete by ice is complicated, due to the numerous interactions occurring in the marine environment. As described in Itoh et al (1987) and Huovinen (1990), there are three stages to the abrasion process. Initially, the cement is worn away, which is followed by a loosening of the larger aggregate. If removed from the concrete, the holes where the aggregate had been lead to further wear of the cement, continuing the abrasion cycle. This type of process was quantitatively and qualitatively observed for the Confederation Bridge (Newhook and McGinn, 2007). Hara et al (1997) noted that these cycles also resulted in different abrasion rates, one for the initial abrasion on a structure, one during a transition phase, and the third for a steady-state abrasion. The latter was measured experimentally only if tests were performed for a sufficiently large duration, in that case the equivalent of 11 km of ice or more passing a structure. Hara et al (1997) further noted that at this steady-state condition, the abrasion rate was the same (0.012 mm/km) regardless of the strength of the concrete that they examined. This rate was about 1/7 the abrasion rate at the surface of the samples. This is slightly contradictory to the results of Huovinen (1990), who indicated that the strength of the concrete was key to resistance to abrasion, due to its influence on bond strength between cement and aggregate, which also impacts damage due to freeze-thaw cycles. The question arises as to what are the factors that result in that initial, high rate of abrasion, at the outset of the interaction between ice and concrete? Knowing those factors, can we design more resistive concrete or more effective repair methodologies?

Recently, state of the art reviews and theses have been produced, that examine the effects of ice properties on concrete abrasion, as well as those that examine the role of concrete properties in resisting abrasion by ice (see, for example: Jacobsen, 2015; Bekker et al, 2013; Saeki, 2010; Vershinen and Truskov, 2010; Moen et al, 2007). These reviews have provided overviews of the roles that ice friction, adhesion and other mechanisms play in abrading concrete. Some of these studies, amongst others, have noted that despite the extensive amount of research that has examined ice abrasion of concrete, it can be challenging to compare results due to the variety of testing methodologies, never mind the extensive number of variables that come into play for both ice and concrete.

It is unclear how much of a role adhesion plays in the initiation of abrasion of concrete by ice. From a loading perspective, an adfreeze condition (when ice has adhered to a structure) may be an engineering design criteria. While there certainly have been extensive studies examining adhesion, most have focused upon atmospheric icing of infrastructure such as roads (some of which may be concrete), energy or electrical systems. There have been studies that have examined the effects of large-scale ice adhesion to infrastructure such as piles at wharfs, dam interfaces or locking systems along waterways, for example, however these usually have a focus upon steel-based structures, coated or un-coated. Some examples of adhesion studies include those of Oksanen (1983) and Jia et al (2011). Oksanen (1983) examined the stress distribution at the interface, taking into account the difference in the elastic modulus between the sample and the ice. If the liquid layer could be better understood, Oksanen (1983) hypothesized, there could be practical applications for the reduction of ice forces on a material. Jia et al (2011) found that adhesion strength did not follow a linear relationship with displacement rate, observing that adhesion strength increased with increasing displacement rate (in the ductile region), reaching a peak at the ductile-brittle transition point of the ice, and thereafter the strength decreased with increasing displacement rate. The authors also found that lower temperatures, at low displacement rates, were associated with peak adhesion strengths, while rough samples consistently had peak adhesions strengths greater than smooth concrete samples at the same temperature. A more thorough examination of the role of previous adhesion studies has been submitted for publication by the present authors.

To examine the role of such mechanisms on concrete wear, and to provide guidance on methods to inhibit abrasion of concrete by ice in a marine environment, the Memorial University of Newfoundland's (MUN) IceWear project, a five-year research programme, has the goal of improving the knowledge of surface wear and friction influences on the iceinduced wear of concrete structures in polar marine environments. This progamme is examining both the properties of concrete that affect wear as well as the ice properties that impact the abrasion mechanism. The programme contains four research thrusts: ice-concrete interaction laboratory testing; contact physics between ice and concrete; wear reduction design strategies; and modelling and analysis. This paper describes components of the first thrust, laboratory testing, with a focus upon the relationships between bonding, surface characteristics and wear.

Numerous studies have indicated challenges when comparing results between test programmes, not only due to the complexity of the variables to be studied, but also due to the variety of testing methodologies. As a result, an additional focus of the IceWear Project is to examine standardizing test methods, to facilitate future analyses. As much as possible, ASTM International (www.astm.org) standard testing methods are being followed, using conventionally-sized samples.

TEST PROGRAMME

Concrete Preparation

Concrete cylinders are prepared according to ASTM C192 (2018), using standard, readily available, sized 100 mm diameter, 200 mm high moulds for direct shear tests, or 40 mm diameter, 80 mm high moulds for the tension tests. To maintain consistency between test programmes within IceWear, a standard concrete mix is being used. This mix design has been chosen based upon prior testing of a mid-performance concrete mix (Ryan, 2018, Ryan et al, 2017, and Tijsen, 2015) (see Table 1). The compressive strength of this mix design is approximately 36 MPa. It has been modified slightly in order to satisfy ASTM requirements (ASTM C192, 2018) that the diameter of the cylinder be at least three times larger than the largest aggregate size. Given that the same mix is to be used for both shear and tension tests, the latter of which may use the smaller mold size, the mix was modified accordingly.

Table 1 Mid-performance concrete mix design

Component	Mix Content
Air Volume	3-5%
Supplementary Cementing Materials SCM	0%
Binder	300
Cement Factor C/F	1.2
Water-to-Binder ratio W/B	0.5
Absorption	0.01
Cement (kg)	360
Silica Fume	0
Coarse Aggregate content C. Agg. (kg/m^3)	1070.39
Fine Aggregate content F. Agg (<10mm) (kg/m^3)	891.99
Water	150
Total Water	169.62

Concrete samples are allowed to cure for 28 days prior to compression testing and being used in the test programme. Although Huovinen (1990) recommends 50 freeze-thaw cycles in order to be able to differentiate between freeze-thaw and mechanical impacts of abrasion, Itoh et al (1987) indicate that in the field it is extremely difficult to attribute degradation to one of these (or other) factors. For preliminary tests within the programme, no freeze-thaw cycling of the concrete has occurred prior to testing.

After curing, the concrete cylinders are cut using a saw into disks, with each disk approximately 35 mm high (Figure 1). A notch is put into those disks that are used for testing in direct shear, which facilitates attaching the concrete sample to a jig, to prevent pitching of the sample as the ice is sheared. The disks are rinsed of debris from the saw, and samples are either left as-cut or are further roughened using a wire brush.

Figure 1 Concrete cylinder disk ready for testing.

Ice Preparation

Ice samples are prepared according to MUN's standardized ice production technique, as described in Bruneau et al (2013). Similar to the concrete samples, ice samples are frozen in either standard 100 mm by 200 mm or 40 mm by 80 mm cylinder molds (Figure *2*). Samples are frozen and remain in a freezer, wrapped, until used for testing. When ready for testing, the smaller samples, for the direct shear tests, are cut using a band-saw to be approximately 40 mm high, to facilitate use with the test apparatus (Figure 3).

To be added (figure)

Figure 2 Ice samples freezing in mold.

Figure 3 40 mm diameter ice sample.

Direct Shear Testing

The direct shear apparatus is 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 has been modified by installing a 300 lb S-type load cell, removing the original 50 lb load cell. In order to configure the table for adhesion tests, a number of different arrangements were considered. The current design, Figure 4, has the concrete samples clamped in place in a jig and braced against moments. The jig can accommodate four samples at one time. The actuator is 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 is 12.5 mm, and at the lowest position of the actuator, contacts the ice samples slightly above the contact point between the ice and the concrete. The clamp assembly is set to move at a rate of 1 mm/s, but can be adjusted faster or slower as required. The rate has been kept constant for the preliminary series of tests. At this rate, testing of four samples, with their current spacing on the jig, takes approximately fifteen minutes. The data acquisition system is set to sample at a rate of 1 Hz.

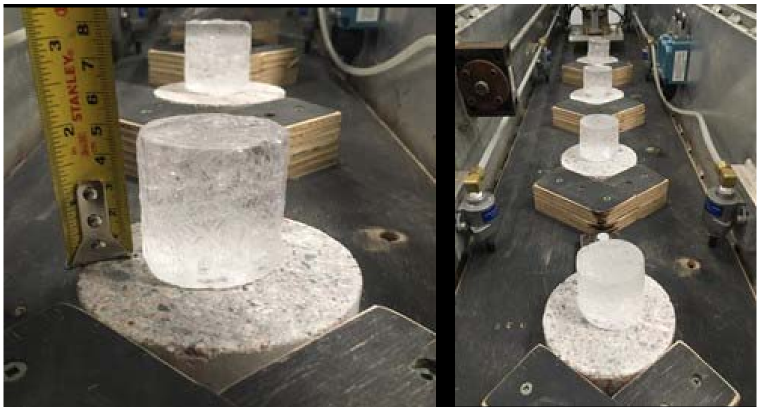

Figure 4 Ice samples ready for testing in direct shear.

Double Direct Shear Testing

A double direct shear apparatus is in the process of being fabricated (Figure 5). The apparatus will accommodate standard-sized concrete and ice cylinders, and will be mounted in a Universal Testing Machine (UTM). The set-up is similar to testing methodologies for soil shear testing. Tests are underway using this set-up, however results are not available at the time of publishing.

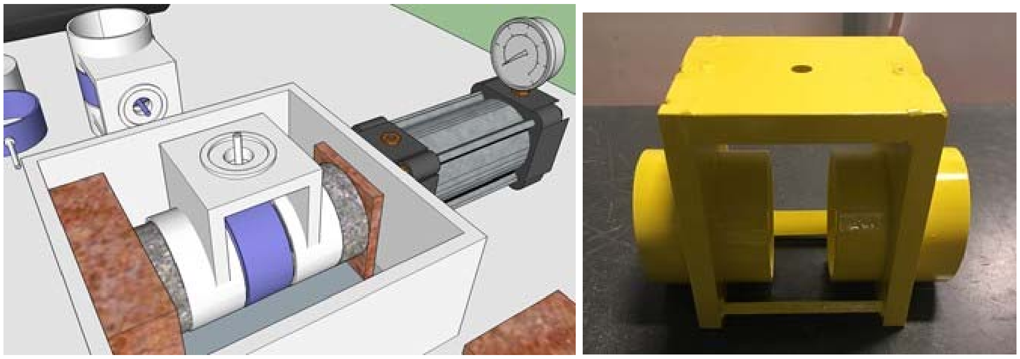

Figure 5 Double shear apparatus concept drawing (left) and as-built specimen holder (right).

Tension Testing

As part of the effort to look into standardization of adhesion testing, the initial thought for performing adhesion tests in tension was to replicate test procedures similar to those found in ASTM C1583/C1583M − 13 (2013), a test methodology for evaluating the adhesion of concrete repairs and overlays. This type of set-up (Figure 6) would have the advantage of not only a standard procedure already in place, but also commercially available test equipment. At the time of writing, preliminary tests have shown that while the equipment shows promise, the high loads associated with ice-concrete adhesion may be too great for the off-the-shelf apparatus. Instead, a set-up is being developed to make use of a UTM. Further information on the plans for this test programme may be found in Titli's paper reference.

Figure 6 Various concepts for tension testing apparatus.

EXAMPLE TESTING RESULTS

Preliminary testing has occurred using the direct shear apparatus. The initial test matrix (

Table 2) focused upon the effects of loaded or unloaded ice samples, loading duration, air temperature and concrete roughness.

Figure 7 shows a test set-up, with 2.25 kg weights, prior to testing. The temperature of the cold room is recorded throughout the pre-testing adhesion period, as well as during the tests. Weights are removed immediately prior to the start of the tests and the ice and concrete temperatures are noted prior to testing. The test sequence is filmed using a GoPro camera for later review. While testing, notes are taken for qualitative observations, such as noise (cracking) and the observed failure mechanism. For the latter, it is noted whether the failure occurred at the bond between the concrete and ice (adhesive failure), through the ice (cohesive failure) or through the concrete. The measured load trace is the primary output from the data acquisition system. In these preliminary tests, the surface roughness of the concrete before and after testing is not quantified, rather notes are taken on its appearance before and after testing, and whether there are concrete particles adhered to the ice upon shearing of the ice cylinders.

In the preliminary tests, all ice samples are dry-adhered to the concrete. That is to say, there is no pre-wetting of the ice samples. The test programme will take into account pre-wetting of the samples at a later time. In those cases, ice samples will be dipped into chilled water or quickly rubbed on a metal plate that is at room temperature, then adhered to the concrete samples.

Table 2 Matrix for preliminary direct shear tests

Test Parameter	Units	Variables		
Concrete surface roughness	mm	as-cut	rough	
Cold room temperature setting	°C	-10	-2	
Adhesion time	hr	2	6	24
Adhesion load	kg	0	2.25	

Figure 7 Samples with 2.25 kg weights, after 24 hours of loading, ready for testing. Weights were removed immediately prior to the start of the tests.

An example of the force output plot for a series of tests, after 24 hours of loading by 2.25 kg weights, at an air temperature of -11°C, is shown in Figure 8. In this particular test, the failure strength, as determined by the peak failure load divided by the ice surface area in contact with the concrete sample, was approximately 0.1 MPa. The failure mechanism of this particular sample appeared to be through the ice, rather than the adhesive bond, and the force plot is indicative of this as well. Prior to failure, audible creaks and pops can be heard on the accompanying video of the tests, as well as the visible splitting off of shards of ice at failure. An image of the cohesive failure of a different preliminary test is shown in Figure 9. For comparison, Huang et al (2017) reported adhesive strengths of approximately 0.3 MPa for smooth concrete and 0.4 MPa for rough concrete at -10°C, while Sobolev et al (2013) reported adhesive strengths between 0.18 and 0.33 MPa for uncoated concrete, also at -10°C.

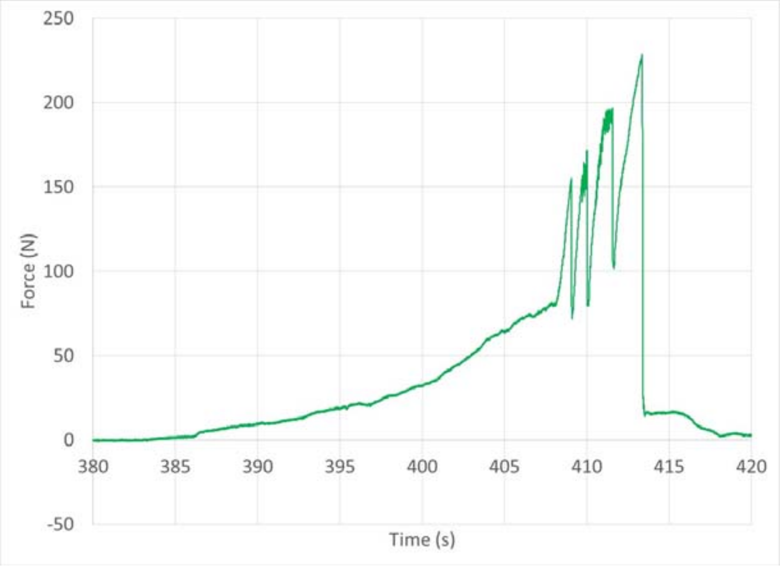

Figure 8 Measured loads for a sample, after 24 hours of loading with a 2.25 kg weight, at an air temperature of -11°C. Failure is through the ice rather than the adhesive bond, per a series

of cracking events, audible and visible in the video of the test, and observable in the load trace.

Figure 9 Example of catastrophic cohesive failure during a preliminary test.

SUMMARY

Abrasion of concrete in a marine environment due to structural interactions with ice is a common global concern. High initial abrasion rates, as concrete paste is abraded off of a structure, have been observed in previous laboratory tests. 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. To examine the role adhesion bonds play in this process, a three-pronged test programme is underway to investigate the influence of air temperature, loading, duration of loads, and surface roughness. Results will point to means to refine concrete mixtures and develop remediation methods to prolong structure life, increase safety and decrease maintenance costs over the life of a structure.

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REFERENCES

ASTM C192 / C192M-18. 2018. Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. ASTM International, West Conshohocken, U.S.A., www.astm.org

ASTM C1583 / C1583M-13. 2013. Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method). ASTM International, West Conshohocken, U.S.A., www.astm.org

Bekker, A.T., Uvarova, T. E., Pomnikov, E.E., and Tyutrin R.S. 2013. Review of Methods for Testing of Various Materials for Ice Abrasion Resistance. Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'13). Paper #POAC13-013. Espoo, Finland

Bruneau, S.E., Dillenburg, Anna K., and Ritter, S. 2013. Ice Sample Production Techniques and Indentation Tests for Laboratory Experiments Simulating Ship Collisions with Ice. In International Society of Offshore and Polar Engineers Proceedings 23rd International Ocean and Polar Engineering Conference, Anchorage, USA. ISOPE-I-13-002

Hara, F., Ohshima, K., Hanada, M., Ujihira, M., Tachibana, H., and Saeki, H. (1997) Design Method to Counter the Abrasion of Hydraulic Structures Due to Ice Sheet Movements. Proceedings of the 9th Workshop on River Ice. pp. 183-196. Fredericton, Canada.

Huovinen, S. (1990) Abrasion of concrete by ice in arctic sea structures, (Doctoral thesis), Publications No. 62, Technical Research Centre of Finland.

Itoh, Y., Yoshida, A., Asai, Y., Sasaki, K. and Saeki, H. (1987) Testing Methods on Sea Ice-Concrete Sliding Abrasion. Proceedings Port and Ocean Engineering under Arctic Conditions (POAC'87). Vol. 3, pp.89-96.

Jia, Q., Tian,W., Lu, Y., Peng, X. and Yu, J. (2011) Experimental Study on Adhesion Strength of Freshwater Ice Frozen to Concrete Slab. Advanced Materials Research, Vols. 243-249, pp 4587-4591, doi:10.4028/www.scientific.net/AMR.243-249.4587

Jacobsen S., Scherer, G.W. and Schulson, E.M. (2015) Concrete–ice abrasion mechanics. Cement and Concrete Research 73 (2015) 79–95.

Møen, E., Jacobsen, S., Myra, H. (2007) Ice abrasion data on concrete structures — an overview, Nordic Concrete Federation Workshop Proc. No. 6, pp. 59–103.

Newhook, J.P. and McGinn, D.J. (2007) Ice Abrasion Assessment – Piers of Confederation Bridge, Proceedings of the Confederation Bridge Engineering Summit. pp. Ice 3-1 – 3-13. Charlottetown, Canada.

Oksanen, P. (1983) Friction and Adhesion of Ice (Doctoral thesis). Publications No. 10, Technical Research Centre of Finland, Espoo, Finland.

Ryan, A., Bruneau, S.E. and Colbourne, B. 2017. Conceptual Design for Testing Ice Abrasion on Offshore Concrete Surfaces. In International Society of Offshore and Polar Engineers Proceedings 27th International Ocean and Polar Engineering Conference, San Francisco, USA. ISOPE-I-17-254

Ryan, A. 2018. Ice Wear and Abrasion of Marine Concrete: Design of Experimental Apparatus and Procedures. Master's Thesis – Memorial University of Newfoundland.

Saeki, H. 2011. Mechanical Properties Between Ice and Various Materials Used in Hydraulic Structures: The Jin S. Chung Award Lecture 2010. International Journal of Offshore and Polar Engineering, Vol. 21, No. 2, pp. 81–90

Tijsen, J. 2015. Experimental Study on the Development of Abrasion at Offshore Concrete Structures in Ice Conditions. Master's Thesis - Delft University of Technology.

Vershinin, S.A. and Truskov, P.A. (2010) Offshore Structures: Friction and Ice Abrasion. Atlet-press. Moscow, Russia.