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Adhesion of Ice to Concrete: Studies and Standardization

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ABSTRACT

Maintenance of ice-worn concrete structures in marine environments is an ongoing challenge. Practical solutions for reducing ice-wear for large-scale applications have had marginal success rates to date, or require frequent re-application of coatings. 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 presents key research programmes over the past five decades that have investigated the adhesion of ice to various surfaces. Their results are then compared, to examine if there are trends that can be gleaned from disparate testing methodologies and conditions. With an eye towards future test programmes, the amassed data are presented in tabular form, as well as an analysis of commonalities, discrepancies and testing challenges.

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

INTRODUCTION

The process of abrasion of concrete by ice is complicated, due to the numerous interactions occurring in the marine environment. In an effort to better-understand the effects of ice upon concrete abrasion rates in a marine environment, an extensive body of field, laboratory and numerical study results has been developed. While researchers such as Itoh et al (1987) and Huovinen (1990) agree that there are three stages to the abrasion process (initial, high abrasion rate, followed by a transition and then a steady-state rate), there remain many questions. For example, what are the factors that result in that initial, high rate of abrasion, at the outset of the interaction between ice and concrete? Adhesion of ice to concrete may play a role in this initial rate, but to what extent? Although, from a loading perspective, an adfreeze condition (when ice has adhered to a structure) may be an engineering design criteria, it is unclear how much of a role adhesion plays in the initiation of abrasion of concrete by ice. Does the adhesion strength affect the amount of damage through material loss?

Even though many studies have been performed looking at the adhesion strength of ice when adhered to other materials, these studies have generally not reported on any observed damage to a structure; rather, they have focused upon failure strengths. Additionally, the authors of those studies have noted that it can be challenging to compare results between testing programs due to the variety of testing methodologies and the extensive number of variables that come into play for both ice and concrete.

The present paper will provide an examination of the results from previous studies that have examined the effects of large-scale ice adhesion to infrastructure. Similarities and differences in methodologies, test conditions and structures of interest, such as piles at wharfs, dam interfaces or locking systems along waterways will be presented. The analysis will investigate if there are empirical relationships that can be gleaned across test programmes.

PREVIOUS TEST PROGRAMMES

Barker et al (2021) presented the state of knowledge of the adhesive effects of large-scale (bulk) ice on concrete and an overview of the challenges in comparing results across test programmes due to the lack of standard test procedures. As discussed in that article, the absence of a standard method of testing ice adhesion, whether in shear, torsion or tension, combined with many intrinsic and extrinsic factors when testing materials such as concrete and ice, has had a net result of many test programmes whose results are challenging to compare across those programmes. Table 1 highlights some of the test programmes reviewed in Barker et al (2021), for which data were able to be gleaned from either tables of data or plots found within previous reports, articles and conference papers, and that focused upon testing ice and concrete.

Test programmes are divided between those that study the adhesion of ice to concrete piles, examining pull-out forces, and those that examine the adhesion of a bulk wedge (cylindrical or block) of ice to a flat concrete surface, examining direct shear or tensile adhesive strengths.

Pile-focused test programmes used a variety of testing methodologies, including twist, push-out and pull-out tests. Ohtsuki et al (1988) noted that for pile-test programmes, the results differed little between these methodologies.

Direct shear test programmes used methodologies that were either akin to standardized soil test programmes, wherein ice frozen in circular rings adhered to a concrete substrate were pulled to break the bond, or used larger blocks of ice adhered to concrete and pushed to break the bond. Tensile tests were much more uncommon; early tests used ice with a rope frozen into the same, adhered to concrete and then pulled to break the bond.

Most of the test programmes involving studies of adhesion of ice to concrete have used freshwater ice. Clearly, the use of freshwater ice reduces the number of variables that may impact the results, given the presence of brine in sea ice.

All but two of the test programmes highlighted here were laboratory-based tests. The Makkonen et al. (1986) and some of the tests by Saeki et al (1981) were conducted in the field; the former examining the adhesion of ice to lock walls, and the latter examining the effect of changing water levels on ice pull-out forces on piles in a saline bay.

Testing temperatures varied considerably, with some test programmes at a constant testing temperature, and others designed to examine a range. Loading rates were mentioned in most previous programmes, however in cases where a variety of loading rates were used, tabular data were rarely available.

Finally, the contact area that formed the bond between the ice and the concrete is described here as a nominal contact area, as the precise amount of bonding between the ice and the concrete is not known. In pile-based tests, where previous authors reported on the ice thickness in contact area with the pile, that value has been converted to the surface area of the pile in contact with ice.

Table 1: Compilation of previous laboratory- and field-based adhesion test programmes. Units for loading rates are as-reported. After Barker et al (2021)

Reference	Material	Ice	Test Type	Test Temperature	Loading rate	Adhesion strength*
Ashworth et al (1979)	Concrete cylinders	Freshwater	Laboratory; tensile	-3°C to -19°C	0.2 kg cm^{-2} sec^{-1}	0.59 to 1.08 MPa
Ashworth et al (1982, 1989)	Concrete cylinders	Freshwater	Laboratory; shear	- 5°C and -15°C	2 kg cm^{-2} sec-$^{-1}$	0.049 to 0.88 MPa
Parameswaran (1981)	Cylindrical, smooth concrete piles	Freshwater	Laboratory; push-out	-6°C	$1.26x10^{-2}$ - 3.2 kN/min (test results seemed to be independent of rate)	0.624 – 1.117 MPa (average 0.8 MPa)
Frederking and Karri (1981, 1983)	Concrete piles (other materials also tested, only concrete reported here)	Freshwater	Laboratory; push-out, pull-out (shear)	-14°C (ice sheet temperature -1° to -3.5°C)	0.1 – 0.8 kN/s (manually operated hydraulics)	0.4 to 0.47 MPa
Makkonen et al (1986)	Concrete (lock wall), bare and with various coatings	Freshwater, cylinder	Field; shear	Ice-wall interface temperature -3°C	1.5 kN/min	0.6 MPa (bare concrete)
Makkonen and Lehmus (1987)	Steel (with various coatings), concrete	Freshwater and saline	Laboratory; shear for tests with concrete	Most tests at -10°C, but a range of -3°C to -50°C for one type of coated plate specimen;	Not reported, but deflection rate of 0.4 mm/s (manually operated hydraulics). Pile test set up same as Frederking and Karri (1981), so may be 0.1 – 0.8 kN/s; long-term tests 13-16 kPa/s (manually operated hydraulics)	No adhesion values reported for concrete shear tests. Only mention was that the ratio of saline ice adhesion to freshwater ice adhesion was 18% on smooth concrete and 82% on rough concrete.
Nakazawa et al (1988) (and other tests, including Saeki et al (1981), Hara et al (1994), Matsushita (1997), Saeki (2010))	Piles of various materials, including steel (coated and uncoated) and concrete (new and old). Matsushita (1997) used plates.	Saline	Field and laboratory; primarily push-out, but also pull-out and twist. Matsushita (1997) performed shear.	-5°C to -20°C	0.01 to 0.2 kg/cm^2	0.1 to 0.5 MPa; 0.4 MPa at -3°C (Saeki et al, 1981)
Jia et al (2011)	Concrete slabs	Freshwater, block	Laboratory; shear	-2°C to -10°C	Varying displacement rates, 10^{-4} to 10^{0} mm/s	0.29 to 0.81 MPa
Sobolev et al (2013)	Concrete slabs, coated and uncoated	Freshwater, concrete slabs, or cylinders	Laboratory; splitting, shear	-10°C	0.06 KN/s	1.8 to 4.86 MPa for splitting; 0.03 to 0.33 MPa for shear (coated specimens 1/6 strength of uncoated)
Huang et al (2017)	Concrete slabs, smooth and rough	Freshwater, block	Laboratory; shear	-2°C to -10°C	10^{-1} - 10^{3} kPa/s	0.17 to 0.49 MPa, with smooth samples having lower strengths
*As the exact amount of contact area between the ice and the material to which it is adhered is not known, the reported adhesion strength values are effective adhesion strengths.						

COMPARISON OF PREVIOUS TEST PROGRAMME RESULTS

There are many variables that can be manipulated in both ice and concrete, as well as extrinsic testing parameters that make it difficult to compare results between test programmes. In addition, gaps in data reporting make it additionally challenging to compare results between test programmes. Common omissions include:

- data tables for the test matrix
- testing temperature (bonding temperature is often reported)
- method of adhering ice to the concrete surface
- whether there was a period of time for a bonded sample to reach an equilibrium testing temperature after the initial freezing period (and how long that time was, if so)
- concrete material properties, including strength, composition and surface roughness
- bonding time
- testing strain rate or stress rate
- time to failure (to calculate stress rate, which is the adhesion strength divided by the time to failure) and
- failure mode.

These omissions are such that it is not possible to compare results without making some inferences. For example, without the availability of tabular data, while an article may contain a plot that shows the effects of contact area on adhesion, and another that shows the effects of temperature on adhesion, from the same test series, without the ability to correlate data points between plots, inference is needed to match data points between plots.

When the failure mode is not noted, it is then unclear whether the adhesion strength recorded is a lower bound, in the case of cohesive failure through the ice, or the actual adhesion strength of the bond. Ashworth et al (1979) did not that all of the failures in the reported tensile tests were cohesive failures; that is, the bond between the ice and the concrete never failed before there was failure in the ice itself. Those tests were conducted across a range of temperatures, from -3°C to -19°C.

The means of adhering the ice to the concrete greatly impacts the adhesive strength recorded. Wet-bonding, where the concrete surface is pre-wetted (naturally, in the case of field studies, or by either adding water to the concrete surface or lightly melting the base of the ice sample) creates a much stronger bond, by creating a near-perfect contact area between the two surfaces. Dry-bonding, where the ice is simply set upon the concrete surface and allowed to bond, either under some applied load or not, therefore results in a potentially weaker bond.

Ohtsuki et al (1988) noted that previous test programmes results showed little dependence upon stress or strain rates, however Saeki et al, (1981), as well as Parameswaran (1981), and Frederking and Karri (1981), all noted an increase in adhesion strength with increasing push-out speeds, at very low speeds, to a peak, at which point the strength decreased again.

Data that is most consistently reported include the thickness or contact area of the ice to the concrete and temperature. This allows a comparison across test programmes, being mindful that simply looking at the impact of a single variable on adhesion strength paints a limited picture. Figure 1 plots the nominal contact area of results from ten test programmes examining ice adhesion to concrete, while Figure 2 plots the temperature versus adhesion strength.

In Figure 1, the wide spread of adhesion strength values may be seen, across a wide range of nominal contact areas. Nakazawa et al (1988), amongst others, examined the effects of contact area on adhesion strength, noting that with increasing ice thickness, in the case of pile-focused test programmes, the strength values increased with increasing ice thickness until a point where they appeared to plateau, becoming relatively constant. Also within those pile-focused tests, as the pile diameter increased, the ice adhesion decreased, becoming a constant at a particular ratio of the pile diameter to the average ice grain size. This ratio value remained the same regardless of the temperature of the tests or the test type (twist, push-out or pull-out). As many test programmes focused upon a singular test set-up and testing methodology, in can be difficult to assess the impact of changing the contact area on adhesion strength, which points to the value of being able to compare results across test programmes.

Figure 2 shows a weak trend confirmed by individual test programmes of increasing adhesion strength with decreasing temperature. Most test programmes have focused on temperature ranges from -1°C to -10°C. Limited studies have been conducted at colder temperatures. It is noted that the choice of temperatures in which to test is rarely discussed in the literature accompanying test programmes. It is not clear if temperatures have been chosen based upon the mechanical capabilities or availability of cold rooms and freezers, or if the temperatures reflect the expected temperatures under which a particular type of infrastructure may be reasonably expected to operate.

Ostensibly, one of the most important variables, surface roughness of the concrete, is also one of the least reported or measured. At a coarse level, surface roughness may be characterized as “smooth” or “rough”, with roughened samples generally manually roughened prior to bonding of the ice. At a fine level, some authors have measured the surface roughness of the concrete through standard, but expensive, tools, such as the use of laser/optical instrumentation, to measure the roughness in mm (or expressed as wave height, length and steepness), over either a strip or the entire surface prior to bonding. Surface energy, which measures the ability of a material to wet another, with higher “wettability” indicative of a stronger adhesive bond by maximizing the contact area, is clearly of relevance to a material such as ice bonding to concrete. Surface energy is typically determined through the application of a bead of liquid to a surface, measuring the contact angle of the liquid, and then relating this though an empirical relationship to the difference between the surface energies of the liquid to the substrate (in this instance, concrete). Surface energy is even more rarely reported than surface roughness, although it is a common measurement in pavement engineering, for example, with many standard tools commercially available for this measurement. Overall, there is insufficient data from previous test programmes to be able to examine the effects of either surface roughness or surface energy across these previous tests.

Ideally, a dimensionless comparison of a number of variables would enable an examination of the results across previous test programmes, to evaluate the effects of a variety of variables upon the adhesion strength of ice to concrete. However, with the available data sets providing a piece-meal set of information, it is not possible to do so across a compelling number of test programmes.

The difficulties in comparing results across adhesion test programmes has been highlighted for many decades by many research teams. Standardization of both reporting and test techniques would overcome some of the challenges mentioned here. This can be accomplished while still acknowledging that tests are performed for a variety of purposes. An examination of existing standards for complimentary areas of research (icing on road surfaces, for example, and concrete and soils strength tests), provides a starting point to develop methodologies that can lead to both robust test programmes as well as the ability for those test programmes to feed into a larger body of international research.

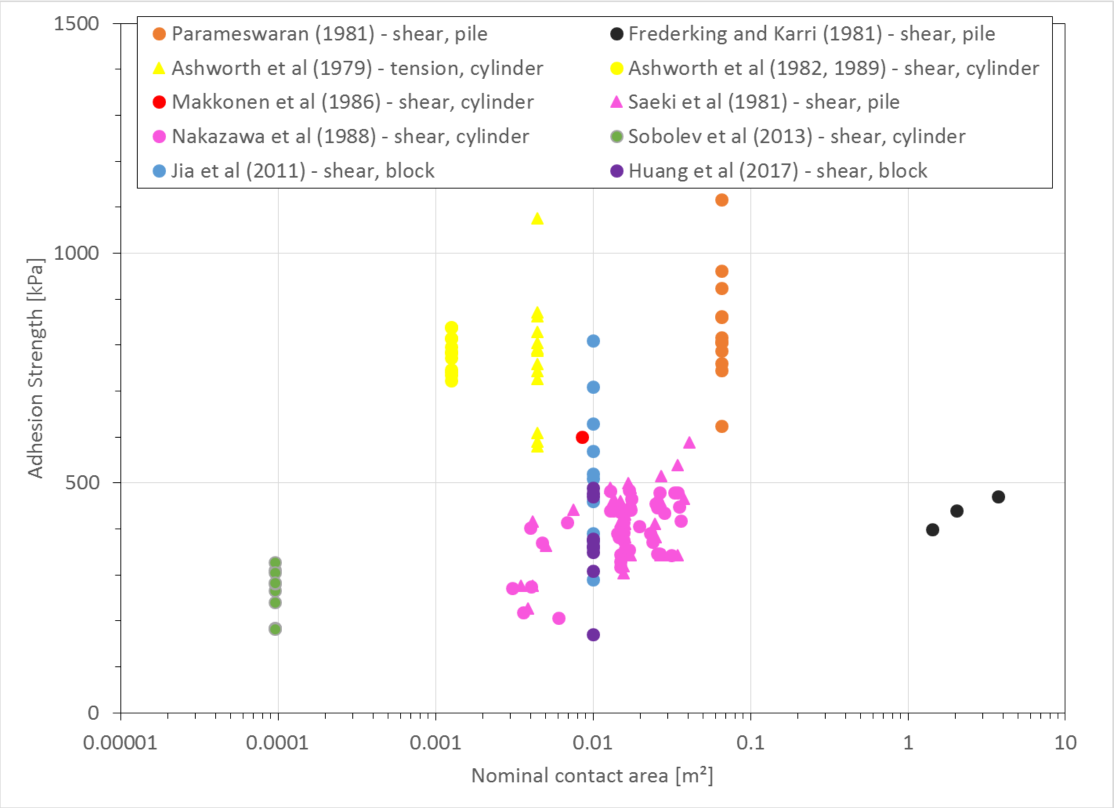

Figure 1 Compilation of previous testing programme results – effect of nominal contact area on adhesion

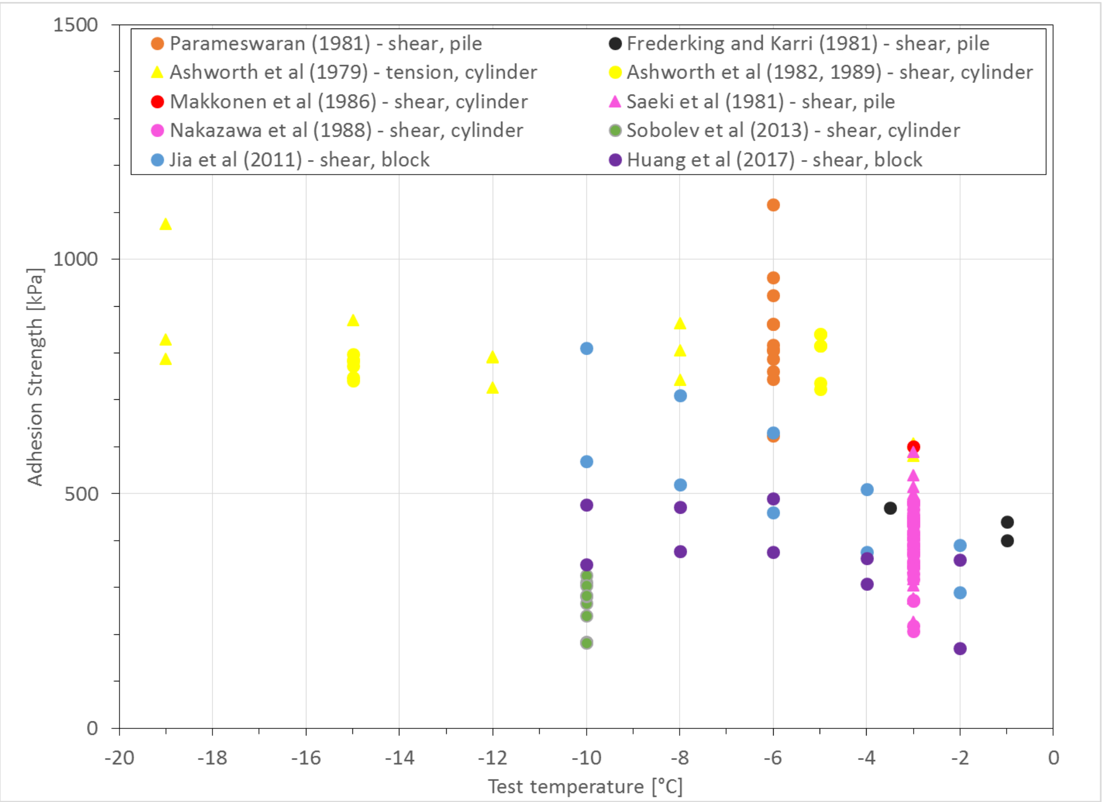

Figure 2 Compilation of previous testing program results – effect of temperature on adhesion strength

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. Many adhesion studies have examined the load of ice adhered to other materials. The results are challenging to compare due to a lack of standardization of test procedures, differences in the objectives of the studies (for different applications) and the enormity of test variables that come into play when examining materials such as ice and concrete.

These previous test programmes are being studied to examine the potential information that may be gleaned on how adhesion of ice to concrete may impact the wear of concrete. The test results examined here will be combined with new data, from tensile and direct shear experiments of ice adhesion to concrete, to further investigate the role that adhesion of ice to concrete may play in the wear of cement paste in concrete infrastructure. In addition, the variety of methodologies and reporting of variables are being compiled in order to develop a suggested approach to the standardization of adhesion studies, to design future test programmes with an eye to their use in subsequent analyses.

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