Proceedings of the Twenty-seventh (2017) International Ocean and Polar Engineering Conference
San Francisco, CA, USA, June 25-30, 2017
ISBN 978-1-880653-97-5; ISSN 1098-6189
www.isope.org

Conceptual Design for Testing Ice Abrasion on Offshore Concrete Surfaces

Amanda Ryan, Steve Bruneau, Bruce Colbourne
Faculty of Engineering and Applied Science,
Memorial University
St. John's, Newfoundland and Labrador, Canada

ABSTRACT

This paper provides the rationale and proposed conceptual design of a test setup to induce and monitor the effects of ice wear and abrasion on marine concrete. Concrete wear from ice contact is a prevalent concern that requires standardized examination. Particular attention will be paid to loss of concrete due to simulated pack-ice interaction situations, as seen in ice prone environments. Opportunities for concrete submergence and long duration testing are the key features of the proposal. Construction of the proposed setup will occur immediately upon completion of the feasibility study.

KEY WORDS: Ice abrasion; friction; pack-ice; concrete wear; conceptual design; laboratory testing.

INTRODUCTION

Pack-ice interactions with marine structures are characterized by long duration loading that can be applied by normal forces, shear forces or a combination of the two. The continuous frictional interaction between the ice and the structure results in gradual abrasion of the concrete. This is in contrast to other forms of ice interaction such as infrequent iceberg loadings that exhibit brief, but high-impact, interactions. Structures like Atlantic Canada's Confederation Bridge in the Northumberland Strait can be exposed to approximately 1000km of ice drift per month (Brown et al, 2001) during the January-April winter season. As seen in Figure 1, ice movement against the bridge piers over time has worn away the cementitious material. The gradual wearing process exposes the aggregate, increases concrete porosity and reduces the durability and integrity of the structure over time. This poses a risk to any marine concrete structure including bridge piers, lighthouses and offshore gravity based drilling and production structures that are located in ice prone environments.

Figure 1: Abrasion of Confederation Bridge Piers (Newhook and McGuinn, 2007)

Existing conventional test setups are most often borrowed from other disciplines in material testing (Fosså, 2007). However, concrete surfaces are porous, rough and non-uniform, therefore the interaction between ice and concrete poses an even greater challenge than most materials. In order to make progress with this problem, testing must be completed to specifically isolate the abrasive effects of ice. Detailed research must be conducted into the roles of pressure, sliding velocity, distance, environmental conditions and the pre- and post- contact surface characteristics of both the ice and concrete.

Purpose of Study

There are few tools in existence that effect and measure concrete wear from long term ice contact. The opportunity therefore exists to build upon previous research and to develop a standardized laboratory testing environment that accurately simulates, monitors and measures prolonged realistic ice-concrete friction interactions.

The initial project objective is to complete a conceptual design study for a testing apparatus and procedure that targets specific wear inducing factors. Upon completion, the designed apparatus will be constructed in order to conduct physical experiments. The experiments will follow a designed process that will ensure minimal statistical error. As the interaction is complex, the experimental factors will be chosen in such a way that the interaction is simplified to obtain useful and significant data. As further research in this area progresses, additional experimental factors can be incorporated in the test setup to allow analysis of potential interactions between contributing factors.

Ultimately, the objective is to develop an improved understanding of the abrasive effects of pack-ice on marine concrete. This will help develop abrasion resistance strategies and enhance the performance of concrete subject to harsh ice abrasion conditions. The conceptual design is constrained by the obtainability of machine components and an available temperature-controlled testing environment.

This paper provides a review of relevant previous studies and a discussion of issues that inform the design criteria and design process for a new apparatus to measure ice-concrete friction and abrasion.

CONCEPT GENERATION

Setup Proposal

Previous research into ice-concrete friction has shown that there is a spike in friction during the interaction at the start of a test, during a stop in movement and during a direction change. This indicates adhesion between the ice and concrete samples (Fiorio et al, 2002). Typical test setups that have been used slide the ice specimen back and forth on the concrete surface; this motion promotes this form of adhesion and interrupts, or possibly augments, the continual wear.

The idea for this research is to achieve longer testing distances between the ice and concrete samples, as well as to reduce the stops in motion and direction changes. Additionally, the ability to generate ice crushing loads simultaneously with frictional sliding loads is desired. To accomplish this, the proposed setup will make use of a rotary machine that will continuously revolve the formed concrete samples. A pre-made ice sample will be normally loaded to the side of the concrete sample as it spins. The only necessary pause in testing will be to replace the ice samples as they continue to be worn away.

Initially generating the concrete sample shape required the consideration of several factors. The concrete sample must be of circular shape to accommodate the continuously revolving testing concept. Additional concerns include adequate aggregate distribution, robustness and portability. To increase the ease of concrete pouring and the removal from the forms, a truncated cone has been proposed. This solution will satisfy the design criteria. Once mechanical equipment has been finalized, the concrete forms will be modified to reduce the material used in the centre of the concrete samples, thereby reducing the weight. While dimensions have not been finalized, the sample will remain within a size limit that allows easy handling and transportation. Nominal values for the initial design sketches are a 1m bottom diameter with a 45° angle. This was chosen in consideration of overall sample size and positioning of the loading application tools. Figure 2 depicts the concept of the preliminary concrete shape using Rhinoceros software for 3D modelling.

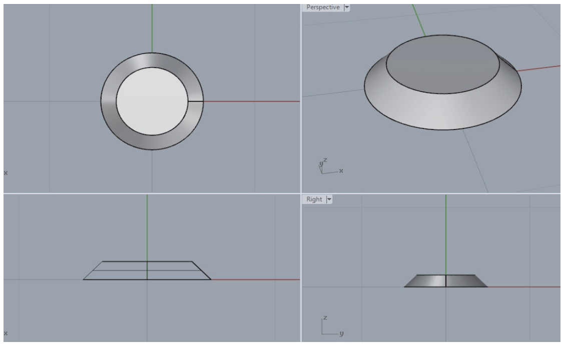

Figure 2: Proposed Concrete Sample Shape

The ice-abrasion process can occur above, at or below the waterline level. Thus a requirement of the research proposal was to allow the experiments to be conducted in an environment where the concrete sample could be dry, semi-submerged or completely submerged in water. The solution was to incorporate a water bath into the design, in which the water level can be easily controlled. Figure 3 provides a look at the preliminary proposal for positioning of the concrete sample, water bath and frame using SOLIDWORKS software.

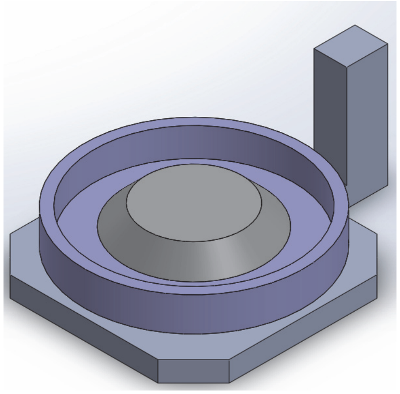

Figure 3: Preliminary Setup Layout

Application of Forces

In dense ice floe environments, structures are subject to significant loading. Pressurized forces cause ice crushing against fixed structures. As well, applied tangential sliding forces from currents, wind and surrounding ice, continually cause wear to the exposed concrete. Previous studies (Itoh et al, 1988) confirm that there is a positive relationship between contact pressure and the amount of material loss. Figure 4 depicts a simplified free body diagram of the dual directional applied forces from the ice floes with respect to the direction the ice is moving. The force is applied as an orthogonal load to the concrete surface. Whereas the shear force is taken as a parallel sliding force that acts on the larger aggregate stones. Also shown, are the normal and frictional forces resulting from the ice-concrete interaction. The stones become increasingly exposed as the cement and fine aggregate wear away (Huovinen, 1990).

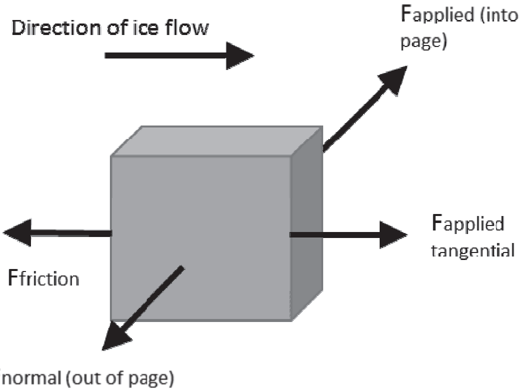

Figure 4: Free Body Diagram of Applied Loads

During testing and ice load application, the machine must have the capacity to produce sufficient torque to overcome the frictional forces and turn the concrete sample. As can be seen from equations (1) through (4), the required torque (τ) is a function of the concrete sample radius (r_{con}), the frictional coefficient (μ), the applied pressure (P) and the cross-sectional area of the ice sample (A_{ice}). An increase in either of these factors will result in a higher required torque.

$$P = \frac{F_N}{A_{ice}} \therefore F_N = PA_{ice} \quad (1)$$

$$F_f = \mu F_N \quad (2)$$

$$\tau = r_{con} F_f \quad (3)$$

$$\tau = r_{con} \mu F_N = r_{con} \mu P A_{ice} \quad (4)$$

The sliding velocity is another important factor. Previous studies have shown that slow ice velocities give rise to viscoelastic deformation and failure properties of ice resulting in high global pressures (Tijsen, 2015). It is essential that the sliding velocity between the ice and concrete samples is slow enough to avoid melting of the ice sample.

Magnitude of Forces

For the conceptual design, it is important to be able to generate forces and speeds that could be expected in realistic environments where ice abrasion is a recurring issue. To achieve this, the research team is reviewing load applications in previous test setups, as well as full scale ice load data from existing structures. There are several predominantly studied offshore concrete structures which have already shown signs of concrete wear due to seasonal pack-ice. Lighthouses in the Baltic Sea are primarily included in European studies. While in North America, bridge pier and oil and gas platform studies have provided significant data (Bjerkas, 2007). Figure 5 illustrates a global map of previously studied areas as well as the general timeline during which the studies took place.

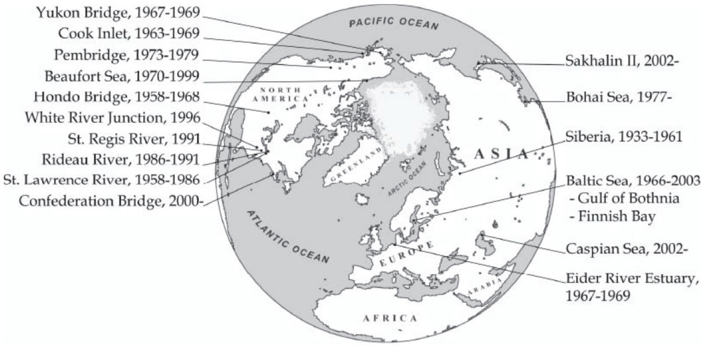

Figure 5: Map of Previously Studied Structures (Bjerkas, 2007)

Ice monitoring systems have been established on structures in these locations and continuously collect data throughout the ice season. Full scale data collection provides the opportunity to examine annual ice loading events and seasonal averages. This important analysis will ensure that the appropriate magnitude of forces will be applied during laboratory testing.

Tibbo et al (2009) collected data from the Confederation Bridge, sshown in Figure 6, in an effort to compare design predictions to actual occurring loads. 0.25m^2 load panels were placed on two bridge piers and for the purposes of the research, recorded ice loads larger than 0.75MN, or 3MPa, were considered significant as the researchers were interested in maximum loads experienced throughout each season (Tibbo et al, 2009). While recorded loads that were less than 0.75MN (3MPa) were considered insignificant, they would contribute to continual abrasion to the structure and are important to note for gradual wear studies.

Figure 6: Ice Buildup on Confederation Bridge Piers (Newhook and McGuinn, 2007)

As part of the Validation on Low Level Ice Forces on Coastal Structures (LOLEIF) project, studies of the Norströmsgrund lighthouse saw static ice loads ranging between 1 and 1.5MPa (Fransson and Lundqvist, 2006). Bjerkas (2007) provided a summary of full scale maximum load data collection and noted that commonly seen global load pressures in North America ranged from 0.7 - 1.5MPa. Additionally, global load maximums experienced by the Kemi-2 lighthouse, Vallinsgrund lighthouse and the Kalix River Bridge piers in Europe were 4.3MPa, 3.4MPa and 3.0MPa, respectively. From all data presented by Bjerkas (2007), 2.2MPa is the average peak global ice pressure for European structures.

Reviewing previous laboratory testing setups and associated load applications will provide the scope of what tests have been completed and the accompanying results. Comparing these values to full scale data collections will provide the background information needed to move forward and use realistic ice loads in the proposed design.

A summary of applied loading from previous researchers can be seen in Table 1: Laboratory Scale Ice Load Data Summary. Similar magnitudes of pressure application are clear between Itoh et al (1994), Bekker et al (2011) and Møen et al (2014). While the pressures applied by Fiorio et al (2002) and Fiorio (2005) are much smaller, this can be attributed to the small scale form of testing that was completed for the scope of that work. Some setups varied the applied pressure throughout testing (Fiorio et al, 2002 and Fiorio, 2005), while other tests were held constant for the duration (Bekker et al, 2011). Tijsen et al (2015) completed testing using cone shaped ice samples therefore the applied load is provided as a force value, rather than as a pressure.

Table 1: Laboratory Scale Ice Load Data Summary

Research	Applied Load	Applied Load (MPa)
Itoh et al (1994)	10 kgf/cm^2	0.98
Fiorio et al (2002) (small scale)	25-800 kPa	0.025-0.8
Fiorio (2005) (small scale)	25-800 kPa	0.025-0.8
Bekker et al (2011)	0.5, 1.5, 3.0 MPa	0.5, 1.5, 3.0
Møen et al (2014)	0.5 - 1.5 MPa	0.5 - 1.5
Tijsen et al (2015)	10 kN	10 kN

Considering full scale data, it is reasonable to design the proposed laboratory test setup to sustain a minimum applied pressure of 2MPa. This is consistent with real loading scenarios while remaining feasible for testing purposes. Pressures can be applied to replicate higher loading patterns which can be seen in the laboratory scale experiments, as shown in Figure 7. Laboratory grown cylindrical ice samples, with a diameter of approximately 150mm, will be used to induce wear and should withstand the applied crushing loads.

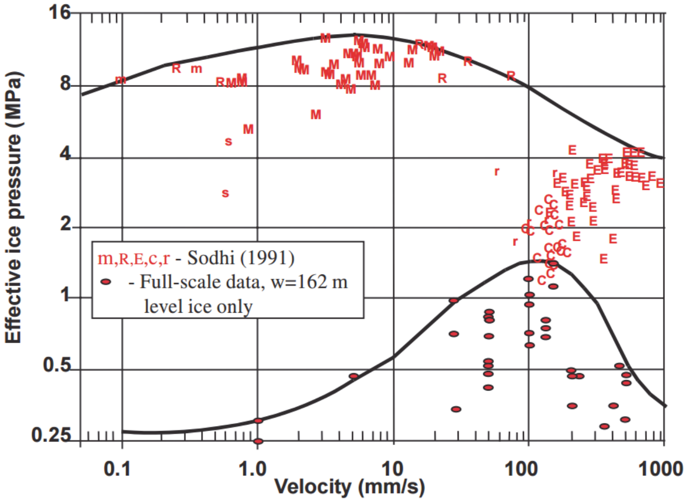

Figure 7: Effective Ice Pressure Data (Blanchet, 1998)

SIGNIFICANT FEATURES

Concrete Sample Submergence

Induced concrete abrasion by pack-ice is a slow loading process that occurs around the waterline; therefore it is natural to assume the concrete at the interface will be partially or fully wet. Creating a testing environment that accounts for the liquid in the interface zone would provide improved insight into the real abrasion process. According to Jacobsen et al (2015), the fluid that remains in the contact zone can actually increase the amount of abrasion. The highly pressurized liquid (p_w) can be forced into cracks and flaws in the concrete surface, depicted in Figure 8, causing additional stresses (σ_x) in the concrete.

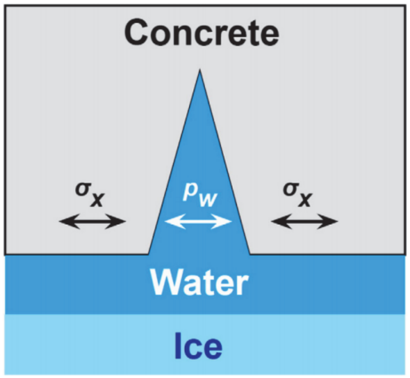

Figure 8: Pressurized Liquid in the Contact Zone (Jacobsen et al, 2015)

Tensile stresses produced by the ice friction will cause more cracks and pore space in the concrete. This in turn allows more water within the contact zone to be pushed in these resulting cracks. Additionally, previous tests have shown that wet concrete has a lower strength than when it is dry (Jacobsen et al, 2015).

It is also important to note that uncertainty and conflicting reports exist regarding water and its effect on abraded concrete debris in the interface zone. While some researchers believe the water promotes grit removal and decreased friction, there are others who note that it may result in debris retention and therefore enhance the abrasion process (Jacobsen et al, 2015). A direct study of liquid layers at the ice-concrete interface has not been completed (Tijsen, 2015) and would increase current understandings of abrasion rates. There have been previous observations that higher abrasion rates can be seen below the water surface rather than above (Tijsen, 2015).

An important and unique feature of the proposed conceptual design is the opportunity to complete the testing while varying the depth of submergence of the concrete test samples. It is proposed that the concrete sample will continuously revolve in a water bath resulting in a more accurate simulation of authentic interactions. The partial submergence of the concrete will allow the ice load to be applied directly at the waterline level. Use of a water bath has not previously been used when testing concrete for ice abrasion. Dry testing can also be achieved by simply emptying the water bath. The use of a bath also allows the abraded ice and concrete material to be collected either after or during a test to allow analysis of the rates of material loss in either ice or concrete.

Once the proposed setup is finalized and constructed, initial testing will begin. As results are obtained, the opportunity will exist to further determine the significance of additional factors that are thought to contribute to abrasion. The water bath will allow further investigation into observing differences between freshwater or saline baths, the effect of varying levels of sand concentration in the water as well as different temperatures of the setup materials. The tests can be carried out on different mixtures of concrete and with various ice samples. The desired outcome will be to provide more cohesive and complete findings.

Increased Test Duration

Pack-ice interactions with marine concrete, resulting in significant material loss, are not a short process. Throughout the course of a winter season, thousands of kilometers of pack-ice can continuously wear away the cementitious material and underlying aggregate. This can either be new pack-ice that continuously passes a structure, or broken up floes that pass back and forth throughout the season (Tibbo et al, 2009).

Research by Fiorio et al (2002) was completed under the premise that in order to better predict the abrasion process, further understanding of ice friction during the ice- concrete interaction was required. The experimental results showed that friction evolves as the procedure progressed from an initial cycle to the tenth cycle (Fiorio et al, 2002). The final and more stable friction coefficients were higher than the initial friction coefficients. The researchers also found a spike in friction when there was a stop in motion, either at the beginning of the test or when the sliding ice sample changed direction. This is indicative of adhesion between the ice and concrete.

An extension in this research completed by Fiorio (2005) found there were two divisions of abrasion: general and catastrophic wear. Additionally, his experiments showed an initial stage of general wear, followed by a permanent stage after 5000mm of sliding. Figure 9 details the evolution of friction as sliding distance continues over two concrete surfaces of different average roughness. It can be seen that after the 5000mm mark, the slope of the line, indicating amount of abrasion, becomes flatter.

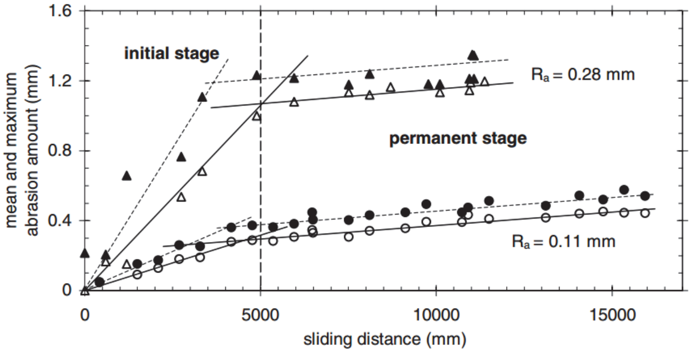

Figure 9: Evolution of Friction (Fiorio, 2005)

From both tests (Fiorio et al, 2002 and Fiorio, 2005), it can be seen that the friction does evolve over time. Fiorio et al (2002) found the friction coefficient increased from initial to final values. In comparison, Fiorio (2005) found that the abrasion rate decreases from the initial stage to the permanent stage. An explanation for this is that the coefficient of friction increases as the coarse aggregate is exposed and the concrete surface becomes rougher. However, the aggregate is more resistant to abrasion than the cement and therefore reduces the abrasion rate.

It is already known that as the abrasion process progresses there is a change in the friction and wear rate between the ice and concrete. However, there is a significant difference between a laboratory test that runs for 15000mm and a full winter season with thousands of kilometers of pack-ice that is contributing to concrete wear. Performing longer duration testing would better simulate full scale interactions and achieve a more constant abrasion rate. This would decrease the amount of error and uncertainty that arises from data extrapolation.

Keeping this in consideration, the currently proposed testing setup is unique as this new design would allow continual loading. The circular concrete sample will be placed in the water bath and slowly revolve. Laboratory-made ice samples will be formed into cylinders that can be placed and piston loaded onto the side of the concrete. The ice sample will wear away and therefore must be changed periodically. This changing process represents the only break in the continuous loading and the goal will be to minimize the amount of necessary changes.
Bekker et al (2011) note that to improve the accuracy of laboratory results, testing should be continual until there exists a more uniform area of abrasion formed along the entirety of the concrete sample. For this proposal, abrasion will be induced along the circumference of the concrete samples and the testing will be run for an adequate length of time, such that uniform and consistent results will be attained.

FURTHER CONSIDERATIONS

In addition to concrete submergence and testing duration, there are other experimental factors and problems that need to be considered and solved. As stated, initial testing will be simplified with many of the factors fixed for all runs and once testing proves fruitful, additional factors will be considered for significance. Experimental design software will be used to design the experiments to ensure factor significance is statistically determined. Factors such as water presence and ice salinity and sliding velocity are all important in recreating representative simulations. Some of the problems that must be also considered while moving forward include environmental temperature control and use of a cold room, removal of worn away ice from the concrete sample, abrasion measurement method and use of concrete and ice samples.

Itoh et al (1994) noted that brine pockets, which only exist in seawater formed ice, would increase the surface roughness and therefore have positive impact on concrete abrasion. Despite this, previous testing by Fiorio et al (2002), Fiorio (2005), Møen et al (2015) and Schulson (2015) was completed using laboratory grown freshwater ice samples as the brine pockets of saline ice were assumed to have a negligible effect on ice abrasion. In general, freshwater ice is considered to have higher strength than saline ice and is consequently the worst case scenario for abrasion. For the purposes of initial testing, freshwater ice samples and water will be used. As testing continues, experiments can begin to incorporate runs using varying degrees of ice and water salinity to answer questions and definitively determine the statistical significance of this factor.

Concrete sample mixture and preparation will need to be controlled for all testing. There is agreement among previous research that higher compressive strength properties and fly ash admixtures are beneficial in resisting abrasion. Special regard for water-content ratio, aggregate size and use of additives will be considered. The potential to test ultra-high strength concrete also exists.

Early studies by Itoh et al (1994) showed that sliding velocity has a negligible effect on abrasion rate. However, recent studies by Fiorio et al (2002) and Schulson (2015) prove that sliding velocity plays a significant role in the abrasion process, specifically regarding the coefficient of friction of ice during ice-concrete interactions. A higher sliding velocity directly produces higher strain rates against the raised portions of the concrete surface; this increases tangential stress and therefore produces higher friction (Fiorio et al, 2002). Schulson (2015) studied ice on ice friction; nonetheless the results are also relevant for ice on concrete friction. Slow sliding velocities which are considered less than 10^{-5}m/s results in ductile creep of the ice asperities that risks adhesion to the concrete sample (Schulson, 2015). Conversely, higher sliding velocities can produce frictional heating and create a wet interface between the two surfaces. Figure 10 provides an overview of the findings (Schulson, 2015). It can be seen that at higher velocities, there is a wetted portion between the asperities of the two contacting surfaces.

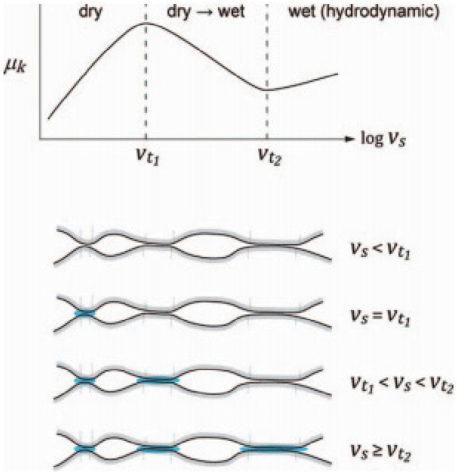

Figure 10: Effect of Sliding Velocity on μ_k of Ice (Schulson, 2015)

It is desired that the proposed design will have the capability of producing a range of sliding velocities that reflect ice passing rates seen by existing structures. The maximum sea current seen by the Kemi-I lighthouse is 0.1m/s while the Confederation Bridge can be subject to currents greater than 1.5m/s (Brown and Määttänen, 2009). Ice passing rate is generally linked to water current velocity and unlikely to exceed measured current velocity maxima. Conducting the experiments with a range of velocities will determine significance of current on the abrasion process. An additional feature of this proposal will be the capability to start and stop the rotating concrete sample at planned times. This will allow the introduction and control of stick-slip action and adhesion processes.

Many previous researchers including Itoh et al (1994), Fiorio et al (2002), Fiorio (2005), Bekker et al (2011), Møen et al (2014) and Tijsen et al (2015) made use of a cold room to control the atmospheric temperature with a range varying within -5°C and -20°C. It is important to note however, that a water bath was not used for these tests. Use of a cold room that is set for previously used testing temperatures would freeze the water and prove detrimental to the results. The proposed solution is to perform the tests with a higher atmospheric temperature around 0°C. This is in agreement with Sodhi (2001) who noted that pack-ice which floats at the waterline typically exists at a temperature near the melting point.

To gather accurate data from testing, worn ice can form a protective layer over the concrete and should be removed from the interface. As an example, Møen et al (2014) achieved this by attaching a heated plate to the concrete sample and making use of the thermal conductivity of the concrete to control the surface temperature and ensure worn ice did not build up. According to Nawwar and Malhotra (1988), submerged and wet concrete and ice interactions prohibit ice layer formation. For that reason, it is expected that there will be negligible amounts of worn ice during the wet experiments. In the case of the dry experimental setup, brushing and air blowing techniques are being evaluated for ice removal options.

One of the most important considerations for the proposed experimental setup is the abrasion measurement technique. In the past, abrasion has been measured using laser scanning, optical microscopy, and linear variable differential transformers (LVDTs). The proposed plan, at this point in time, is to make use of optical technology to measure material loss and determine abrasion rates. In addition, as shown in Figure 11, the ice sample diameter will be smaller than the concrete sample side surface. During testing, the centre area will be abraded while the outer edges can be used as reference points as they will not experience abrasion.

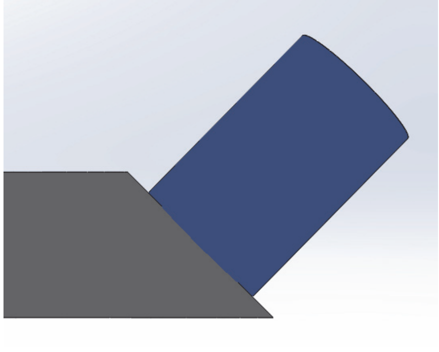

Figure 11: Proposed Ice-Concrete Sample Interaction Layout

CONCLUSIONS

Experiments covering ice-concrete abrasion and friction have been completed on small and large scales in laboratory settings; in addition some in situ testing and full scale load data has been compiled. Abrasion test methods have evolved over the years with varying test setups, assumptions and results. These have been driven by both practical considerations and differing ideas of the important parameters of the problem. The proposed conceptual design makes use of this valuable prior research and aims to standardize the testing methods for concrete wear due to moving pack-ice. The current study has drawn on the experiences of previous work to identify the important issues, including those areas where different approaches may be beneficial. This has resulted in the conceptual design of a new apparatus that will allow higher normal loads, longer test durations and the introduction of surrounding water.

Gaps in knowledge are still apparent for physical abrasion mechanisms including the effect of high-pressure loads, pressurized fluid and abraded debris in the contact zone, and stick-slip action. The ability to perform long duration testing with submergence of the concrete sample during interactions will provide further insight into the abrasion process. Specifications of the design including frame and sample size measurements, mechanical components and testing location will be finalized, followed by construction. Once experimentation begins, the results gained will aid in service life predictions of new and existing marine concrete structures.

REFERENCES

Bekker, AT, Uvarova, TE, Pomnikov, EE, Farafonov, AE, Prytkov, IG and Tyutrin, RS (2011). "Experimental Study of Concrete Resistance to Ice Abrasion," *Proceedings of the Twenty-First International Offshore and Polar Engineering Conference,* Maui, Hawaii, ISOPE, (1) 1044-1047.

Bjerkås, M (2007). "Review of Measured Full Scale Ice Loads to Fixed Structures," *Proceedings of the Twenty-Sixth International Conference on Offshore Mechanics and Arctic Engineering,* San Diego, 1-10.

Blanchet, D (1998).”Ice Loads from Firs-Year Ice Ridges and Rubble Fields,” *Canadian Journal of Civil Engineering,* 25, 206-219.

Brown, TG, Jordaan, IJ and Croasdale, KR (2001). "A Probabilistic Approach to Analysis of Ice Loads for the Confederation Bridge," *Canadian Journal of Civil Engineering,* 28(4), 562-573.

Brown, TG and Määttänen, M (2009). “Comparison of Kemi-I and Confederation Bridge Cone Ice Load Measurement Results,” *Cold Regions Science and Technology,* 55(1), 3-13.

Fiorio, B, Meyssonnier, J and Boulon, M (2002). "Experimental Study of the Friction of Ice Over Concrete Under Simplified Ice–structure Interaction Conditions," *Canadian Journal of Civil Engineering,* 29(3), pp. 347-359.

Fiorio, B (2005). "Wear Characterization and Degradation Mechanisms of a Concrete Surface Under Ice Friction," *Construction and Building Materials,* 19(5), 366-375.

Fosså, K (2007). "Improvement of the Ice Zone on Concrete Structures for Sub Arctic Areas," *Proceedings of the Nordic Concrete Research Workshop Ice Abrasion on Concrete Structures,* Helsingfors, 1-4.

Fransson, L and Lundqvist, J-E (2006). “A Statistical Approach to Extreme Ice Loads on Lighthouse Norströmsgrund,” *Proceedings of the Twenty-Fifth International Conference on Offshore Mechanics and Arctic Engineering,* Hamburg, 1-6.

Huovinen, S (1990). "Abrasion of Concrete by Ice in Arctic Sea Structures," *Journal of Structural Mechanics*, 23, 23-35.

Itoh, Y, Tanaka, T and Saeki, H (1994). "Estimation Method for Abrasion of Concrete Structures Due to Sea Ice Movement," *Proceedings of the Fourth International Offshore and Polar Engineering Conference,* Osaka, ISOPE, (2) 545-552.

Itoh, Y, Yoshida, A, Tsuchiya, M, Katoh, K, Sasaki, K and Saeki, H (1988). "An Experimental Study on Abrasion of Concrete Due to Sea Ice," in *Proceedings of the Twentieth Offshore Technology*

Conference, Houston, 61-68.

Jacobsen, S, Scherer, GW and Schulson, EM (2015). "Concrete-ice Abrasion Mechanics," *Cement and Concrete Research,* 73, 79-95.

Møen, E, Høiseth, KV, Leira, B and Høyland, K.V (2015). "Experimental Study of Concrete Abrasion Due to Ice Friction — Part I: Set-up, Ice Abrasion vs. Material Properties and Exposure Conditions," *Cold Region. Science and Technology,* 110, 183-201.

Nawwar, AM and Malhotra, VM (1988). "Development of a Test Method to Determine the Resistance of Concrete to Ice Abrasion and/or Impact," *American Concrete Institute*, 109, 401-426.

Newhook, JP and McGuinn, DJ (2007). "Ice Abrasion Assessment — Piers of Confederation Bridge," *Confederation Bridge Engineering Summit 1997-2007 Proceedings of the Canadian Society of Civil Engineering,* 145-157.

Schulson, EM (2015). "Low-speed Friction and Brittle Compressive Failure of Ice: Fundamental Processes in Ice Mechanics," *International Materials Reviews, 60(8),* 451-478.

Sodhi, D (2001). "Crushing Failure during Ice-structure Interaction," *Engineering Fracture Mechanics*, 68, 1889-1921.

Tibbo, J, Obert, K, Shrestha, N, Tripathi, D, Mayne, D and Brown, T (2009). "Year Twelve of the Confederation Bridge Ice Monitoring Program," in *Proceedings of the Twentieth International Conference on Port and Ocean Engineering under Arctic Conditions,* Lulea.

Tijsen, J, Bruneau, S and Colbourne, B (2015). "Laboratory Examination of Ice Loads and Effects on Concrete Surfaces from Bi-axial Collision and Adhesion Events," in *Proceedings of the Twenty-Third Port and Ocean Engineering under Arctic Conditions International Conference,* Trondheim.

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