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ICE ABRASION DATA AT LAOBORATORY AND FIELD EXPERIMENT

Abstract: *For the last decades, the performance of concrete structures under severe marine environmental conditions has gained considerable attention. There are still a number of unknown factors related to design and material selection of concrete structures exposed to ice abrasion. The amounts of published data on this subject are relatively few and it is the aim of this document to collect and present some of these in terms of abrasion rates/depths, together with the material parameters of both ice and concrete. The objective is to identify the abrasion data and the differing exposure conditions as objectively as possible without going detailed into any models, in order to draw cross over conclusions with respect to wear rates and possible materials effects and to prepare for a continued study on the subject.* *The fundamental mechanism behind the ice abrasion of a concrete structure is more complex than barely the force of friction between moving ice and concrete. Field investigations and laboratory tests suggest that the observed abrasion is a result of the combination of environmental causes together with the ice impact forces*

Key words: Ice abrasion, Concrete, Laboratory, Field, Experiment.

The sea ice properties range from sheet ice to unconsolidated pressure ridges to multi-year consolidated floes and ridges. The ice exerts its force in a variety of different modes, depending on the structure's geometry and the ice parameters involved. Failure modes differ between crushing, flexure, buckling and shear. The overall force is limited by the driving force of the ice sheet behind the largest feature that can hit the structure without failing. It is observed that larger contact areas fail at lower unit forces, whereas smaller faces fail at higher unit forces due to confinement and homogeneity of the ice. Local ice forces are limited only by the crushing strength of the ice and might be increased by a factor of 3 or more compared to the uniaxial strength, due to confinement. The effective strength is also dependent on temperature, salinity, crystal orientation and strain rate. It is generally accepted that these high local unit forces will occur only over limited areas and they will decrease significantly as contact area increases. The ice movement, caused by wind, currents and thermal expansion/contraction are the fundamental driving forces behind the phenomenon of ice abrasion. In rivers, lakes and oceans where periodic ice floes occur, concrete structures such as e.g. bridge piers, guide walls, docks, lighthouses etc. experience damage at or near the waterline due to impact with ice floes. Moving ice has, in extreme cases, been known to remove all of the concrete cover at or near the waterline for marine structures.

Author	Abrasion/ Abrasion rates	Material Parameters	Exposure	Exposure (lab/field)	Observation	Ice conditions
Huovinen Field (1990)	22-39 mm after 22-24 years (mean, all faces)	At water level: fc = 35-46 Mpa 1,5m above WL: fc = 65-80 MPa	Combination of freezethaw cycles and moving ice	Lighthouses in the Gulf of Bothnia	Largest abrasion rate observed 0,1-0,3 m below water level	
Huovinen Lab (1990)	> 25 mm 2,5 - 11 mm 3,2 - 7 mm	LWA, fc=41-42 MPa ND1, fc=68-98 MPa ND2, fc=76-81 Mpa, blast furnace slag cement	50 freezethaw cycles and 10 min in abrasion machine	Lab, abrasion machine (rotating cutter)	No ice.	
Malhotra Field (1996)	No visible abrasion observed after 7 years of exposure.	LWA: fc = 37-45 MPa ND: fc = 42-56 MPa Steel Fibers (SF): 50kg/m3 w/c ratio: 0,37- 0,42	“Very severe exposure, included freeze-thaw cycles, ice abrasion, ice impact, and sea water attack.	12 panels mounted in a dock at Nanisivik (73° North),	No description of the ice conditions. Test panels were in good to excellent	

				Baffin Island, Canada	conditions after 7 years of exposure. Local corrosion of the steel fibers.	
Janson Field (1988)	Abrasion depths: 0-140 mm Abrasion rates: 0,2-7,0 mm/year	ND (rounded shape) fc = 40 MPa Cement: 300-400 kg/m3 Additives: Air-entraining agent (after 1965)	Location in Baltic Sea with low salinity, hence strong ice compared to Arctic seas (first year ice	Field study of More than 30 light houses examined in 1983-84	Abrasion depths increased further north (more severe ice conditions). No abrasion in areas where the level ice thickness	sea ice block was 80 mm wide, 50 to 100 mm high and 700 mm long. a temperature of -20°C with an ice pressure of 1 MPa and an ice speed of 50 mm/sec.

					never exceeded 0.3m	
Itoh, Lab (1988, 1994)	Abrasion rate (steady state): 0,05 mm/km for ice parameters given under “exposure”	ND, fc = 57 Mpa LWA, fc = 70, 57, 35 Mpa Dmax = 25 mm	Ice velocity: 5 cm/sec Ice temp: -20 ºC Contact pressure: 1 MPa	Completely exposed aggregates made by cutting the top surface by 6-10 mm	Abrasion rate of concrete due to sea ice is mainly determined by the contact pressure and the ice temperature.	
Hanada Lab (1996)	Abrasion depth: r v S S = ·σ · L Assume: r S = 0.0178 σ v = 1 MPa L = 1000 km Abrasion	N.A.	Sea ice: 3-5 ppt salt Ice velocity: 5 cm/sec Ice temp: -10ºC Contact pressure: 1 MPa		Study of ice abrasion rates of different aggregate stones and a single concrete sample.	

	depth: = 17.8 mm					
Sandwell (2003) [1,p. 6]	Approx. 10 mm estimated by size of exposed coarse aggregates (app.7 years after opening of bridge)	fc = 90 MPa w/c = 0,25 Fly ash + silica fume High Performance Concrete (HPC) Design Lifetime: 100 years	Gulf of St Laurent/ Northumberla nd strait/Canada	Confederati on bridge piers	Based on photos in Sandwell project facilities design report for Sakhalin II, Phase II	
Fiorio Lab (2005)	Mean abrasion rate: 2 mm/km	fc = 24.8 MPa w/c = 0.6 Portland CEM I 42.5 Aggregate: Fine sand (0.2 – 0.6 mm), coarse sand (3 – 5 mm)	Contact pressure ice/concrete: 0.25 – 0.80 MPa	Lab, Abrasion/ friction tests by a shearbox machine	Laboratory grown S2 columnar freshwater ice (Dgrain = 8 mm)	Diameter: 60 mm, Height: 96 mm. Contact pressure ice/concrete: 0.25 – 0.80 MPa.

						Ambient temperature: - 10 °C (+/- 0.5 °C). Sliding velocity: 1.67x10-6 – 1.67x10-4 m/s

Summary of ice abrasion data from various laboratory and field experiments, listing key parameters with emphasis on exposure conditions and concrete material parameters. Ice conditions are also presented for the experiments where these are available.

Discussions and conclusions

Itoh et al. (1988 & 94)

An Experimental Study on Abrasion of Concrete Due to Sea Ice/ Estimation Method for Abrasion of Concrete Structures Due to Sea Ice Movement [2, p. 8]

- With the given test conditions it seems that the abrasion rate depends neither on the compressive strength of the concrete nor the kind of concrete aggregate.
- It was suggested that the abrasion rate of concrete is mainly determined by ice temperature and contact pressure.
- Results of concrete abrasion due to sea ice movement. The study concluded that failure modes of ice sheets are crushing with radial cracking. The abrasion depth of the concrete is mainly governed by the ice parameters; contact pressure, temperature, and sliding velocity.

Hanada et al. (1996)

Abrasion Rate of Various Materials Due to the Movement of Ice Sheets [3, p. 8]

- The observed ice abrasion rates of rock are proportional to the sliding distance of the ice.
- The abrasion rate differs significant depending on the type of rock
- Abrasion rates of sandstone and andesite are approximately 1/3 of that of concrete.
- The smaller the grain size, the smaller the abrasion rate (related to surface roughness).
- The higher uniaxial the compression strength of a rock, the higher the ice abrasion resistance.

Malhotra et al. (1996)

Manufacture of Concrete Panels, and Their Performance in the Arctic Marine Environment [4, p. 8]

- It was concluded, after both svisual and micro structural examination that the concrete test panels after seven years of exposure in extreme exposure conditions were in good to excellent conditions. It was observed some local corrosion of the steel fibers for the fiber-reinforced concrete panels.

Janson (1989)

Field Investigation of Ice Impact on Lightweight Aggregate Concrete [5, p. 9].

- It is assumed that the ice concentration needs to be very high in order for abrasion to occur, as this gives a sufficient high pressure between the ice and the structure. This in addition to the ice thickness and ice strength are considered to be important parameters when evaluating abrasion of concrete by sea ice movement.

Huovinen (1990)

Abrasion of Concrete by Ice in Arctic Sea Structures [6, p. 9].

- The most important mechanical factor of the concrete with respect to resistance against ice abrasion is the compressive strength, which should be at least 70 MPa to secure a good resistance against abrasion.
- The concretes with water/cement ratio no higher than 0.30-0.35 showed a good resistance against abrasion.
- Normal weight concretes containing silica fume and blast furnace slag showed both a higher strength and a higher abrasion resistance than lightweight concrete with blast furnace slag.
- Increasing the maximum size of the aggregates also contribute to an increase in the abrasion resistance of concrete.
- The local ice loads acting on protruding aggregate stones are considerably greater than the uniaxial compressive strength of the ice.

Fiona (2005)

Wear characterization and degradation mechanisms of a concrete surface under ice friction [7, p. 10].

- Higher Abrasion rate of 20 mm/km than what is observed in other comparable studies be caused by the use of small sized aggregates in the micro concrete.

Discussions

In the majority of the ice abrasion studies presented in this overview, the significance of the ice conditions is emphasized, with ice temperature and contact pressure as the two most essential. Several of the tests show little or no difference of the wear resistance for different concrete qualities. Exceptions are Hanada (rock) and Huovinen (concrete) who both concluded that the ice abrasion resistance was improved by increasing the material compressive strength.

Conclusion

- The phenomenon of concrete abrasion due to sea ice movement is complex, involving different mechanisms and parameters. From the previous studies on the subject there have been somewhat scattered conclusions, and various methods of estimating the rate of abrasion have been proposed. In general it seems that:
- The rate of abrasion increases with increasing ice contact pressure and decreasing ice temperature. Ice sliding cause more abrasion than ice crushing.
- The ice abrasion is reduced with increasing material strength as observed in laboratory tests on rock and field tests combined with modelling of concrete.
- Using cement replacements like silica fume and blast furnace slag has shown a positive effect on the amount of abrasion.

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