CONCRETE-ICE ABRASION: SURFACE ROUGHNESS AND MEASUREMENT METHOD

Guzel R. Shamsutdinova[1]*, Max A.N. Hendriks*[2]*, and Stefan Jacobsen*[3]

[1] PhD candidate, Norwegian University of Science and Technology, guzel.shamsutdinova@ntnu.no.
[2] Professor, Norwegian University of Science and Technology & Delft University of Technology, max.hendriks@ntnu.no.
[3] Professor, Norwegian University of Science and Technology, stefan.jacobsen@ntnu.no.

ABSTRACT

The wearing of concrete material due to ice movement is a cutting edge problem for offshore and coastal engineering. The phenomenon is often referred to as concrete-ice abrasion, but the physics of this process is not clearly understood yet. A possible mechanism to explain concrete-ice abrasion is the formation of cracks on the concrete surface, due to excessive tensile stresses induced by sliding of ice asperities. Concrete surfaces exposed to moving ice are subjected to wear at various rates depending on concrete and ice properties.

At NTNU, Department of Structural Engineering, we are studying ice abrasion phenomena both theoretically and experimentally. This paper analyses the wear rate of concrete; concrete surface roughness and its relevance for the abrasion mechanism. The results indicate that increasing concrete-ice abrasion relates to increasing surface roughness. Furthermore, measurement of abrasion mechanically and with an optical scanner gave similar average abrasion.

Keywords: *Concrete, Ice Abrasion, Roughness.*

Guzel Shamsutdinova, PhD
Norwegian University of Science and Technology
7034, Richard Birkelands vei 1A
Trondheim
Norway

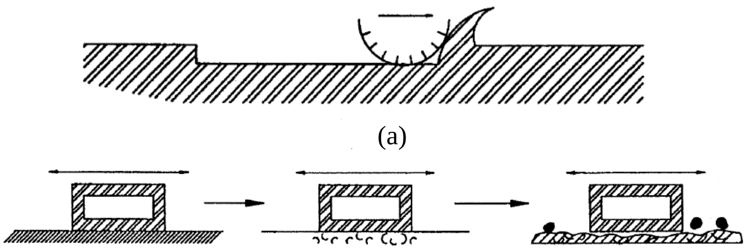
Email: Guzel.Shamsutdinova@ntnu.no
Tel: +47 97607645

1. INTRODUCTION

Industrial exploration of the Arctic demands new materials to be utilized in severe conditions. For this purpose the effects of environment on structures should be clearly understood. This paper focuses on wearing of the concrete material due to ice movement. Although such surface degradation is induced with simultaneous action of mechanical sliding, freeze-thaw cycles, chemical aggressive sea water and water pressure, it is reasonable to consider wearing mechanism due to sliding contact separately.

2. WEARING MECHANISM

The damage of concrete surface induced with ice movement is often referred to as concrete-ice abrasion [1, 2], but the physics of this process is not clearly understood yet through recently the concrete-ice abrasion mechanics were reviewed in [3]. The abrasion in tribology relates to single-cycle deformation mechanism [4] (Figure 1(a)). This mechanism describes surface degradation during sliding motion, when the abrasive material is harder than the wearing surface [4, 5, 6, 7]. Although pure ice crystals can be of relatively high hardness, up to around 70N/mm^2, indentation tests gave lower hardness compared to concrete [1].



(a)

(b)

Figure 1. Conceptual illustrations of deformation wear mechanisms:
(a) single-cycle deformation wear is illustrated as a cutting process as a harder material wears a softer substrate;
(b) fatigue process is used to illustrate repeated-cycle deformation wear [4].

In the case of concrete-ice wear, a “hard” concrete surface is abraded by a “soft” abrasive during sliding motion, and so we think that the degradation mechanism relates to repeated-cycle deformation [4]. Repeated-cycle deformation mechanism dominates in fatigue wear [4] (Figure 1(b)). The basic concept of fatigue wear is crack formation on the surface due to cyclic stress.

The loads from ice drift have complex influences on vertical offshore structures and could be subdivided in general into: static and dynamic [8]. So the actions from moving ice have a cyclic nature [9, 10]. Hence fatigue-wear is relevant for all three fracture cases reviewed in [3]: contact mechanics by indenting and sliding ice, brittle fracture by hard particles between ice and concrete and water pressure at ice impact on submerged cracks.

3. FACTORS INFLUENCING WEAR RATE

As was said above, the concrete wear phenomenon is induced by various actions. From this, one may conclude that a lot of factors have influence on wear rate. It can be environmental factors, such as temperature, currents, wind, ice origin, ice features, ice strength, ice thickness and others. The scenario of ice structure interaction depends on these factors. Concrete material properties are important, like strength, hardness, elastic modulus, tensile strength and surface properties of paste and aggregate. Besides, structure geometry influences too: type of structure, width, and so on. In this paper we would like to look at the concrete surfaces of offshore structures, mainly roughness, and its influence on wear rate.

3.1. Roughness effect

The simplest definition in 2D is the average roughness with y the height at any point along a line with length l through valleys and peaks of a surface.

$$R_a = \frac{1}{l}\int_0^l |y(x)|\,dx \qquad (1)$$
$$R_a = \frac{1}{n}\sum_{i=1}^{n} |y_i|$$

Where R_a is the average roughness, y is the height at any point along a line, l is the length of the line.

The influence of roughness of a metallic abrasive on the wear of polyethylene (UHMWPE) was studied [11]. UHMWPE was abraded by 5 metallic balls. Their mean roughness R_a (micron) varied from 0.12 to 0.33. The results [11] showed quantitative dependence on wear volume (mm^3) by varying roughness. Wear volume increased with increasing initial average roughness of abrasive.

The wearing resistance of UHMWPE was studied with ice sliding test, with different ice surface roughness [12]. This study was based on two types of ice roughness. The value of roughness here was the mean attack angle between ice surface and abraded material. The results of the paper showed that wear of UHMWPE varied with initial ice roughness R_1 = 0.66 (rad) and R_2 = 0.95 (rad). Higher wear of polyethylene abrasive related to ice with bigger surface roughness.

The effect of concrete surface roughness on the wearing process in an ice sliding test was studied too [13]. Experiments were performed for a smooth and a rough concrete plate with R_a = 0.11 and 0.28 (mm) respectively. Results showed higher wear depth for the rough plate.

The results above seem to confirm the idea that the roughness of both concrete and ice surface influences the wear rate. Based on this idea an analysis of roughness effect on wear rate was performed based on some recent NTNU laboratory test results.

3.2. Analysis of NTNU laboratory results

Test results of a recent Master's thesis [14] were used for this analysis. Concrete samples were casted approximately 5 years before the experiment. The first two years they were stored in moist conditions and then open to air. There were 15 samples of w/c = 0.60 with 40% volume of paste and granitic aggregate with 8 mm maximum particle size [14]. 12 of the 15 samples had a sawn surface, while 3 had a cast surface. The average 10 cm cube compressive strength after 5 years was 51 MPa [14]. All tests were performed in the ice-concrete abrasion rig at NTNU's department of structural engineering (Figure 2). The rig performs a sliding contact type. A fixed concrete sample is exposed to horizontal movement of a cylindrical ice sample under vertical pressure. The studied concrete samples were tested with five types of ice samples that were prepared according different procedures [14]. The first and second types were frozen tap water in cylindrical moulds with different diameters in a cold room at -10 °C; the third type was frozen mixture of tap water with ice slush in a cold room at -20 °C; fourth was frozen carbonated water in a cold room at -10 °C; and the fifth sample was drilled from ice that was grown unidirectionally in a Frost lab tank at temperature -10 °C and tank walls were 0 °C.

The sliding distance was 500 m during the tests. Surface roughness was measured with digital indicator Mitutoyo before and after tests. Mean abrasion rate was obtained as ratio of mean abrasion depth and effective sliding distance.

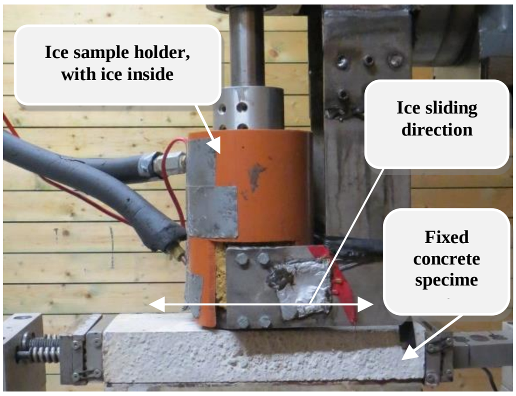


Figure 2. Ice Concrete abrasion rig.

The tests showed that only 11 samples had detectable abrasion on the concrete sample. All tests, except for the fourth ice type, had standard deviation bigger than the abrasion rate. Therefore results obtained with the fourth ice type are the most important. The graphical results in Figure 3 show how abrasion rate depends on average concrete roughness. The major part of the tests gives increasing ice abrasion rate with increasing initial concrete surface roughness. That corresponds to the increasing wear rate due to increasing surface roughness of wearing material in [12, 13]. But the fifth ice types give decreasing ice abrasion with increasing concrete surface roughness. The last results are most probably related to high scatter which makes the uncertainty high particularly at low abrasion rates.

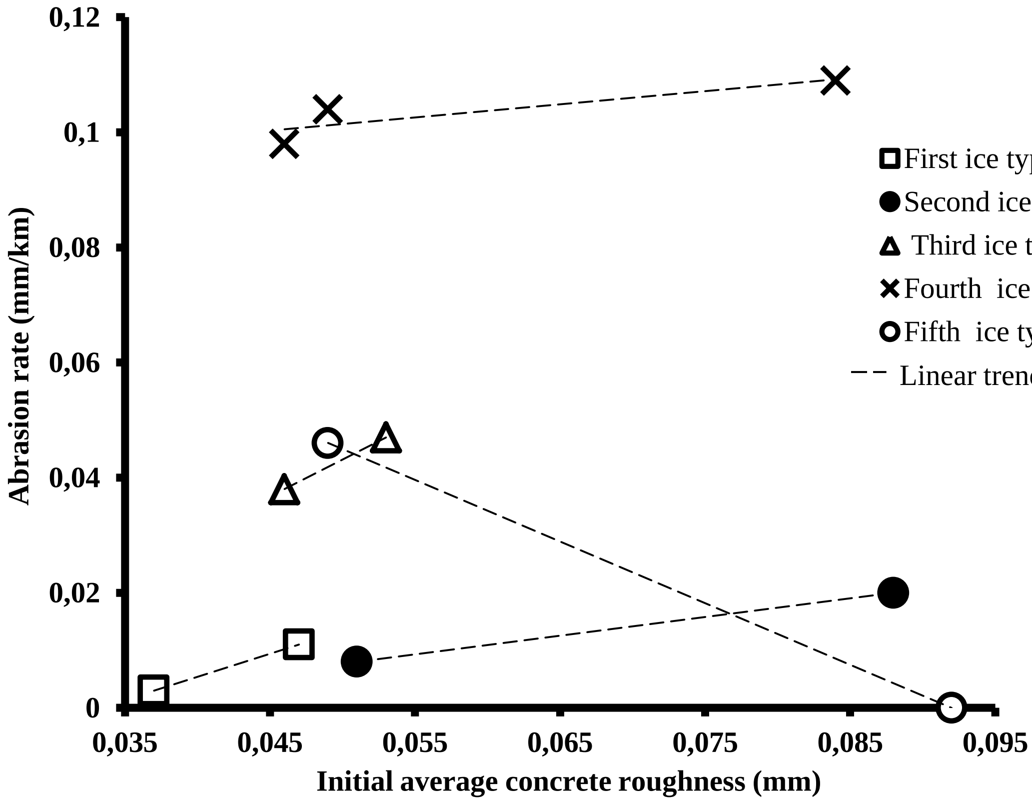


Figure 3. Relationship concrete-ice abrasion rate and average concrete roughness.

4. ROUGHNESS MEASUREMENT

As was said above the measurement of wear depth was made with a digital indicator. The device accuracy is 0.003 mm. The measuring grid in Figure 4(a) was used. Through this procedure coordinates of 110 points were found, 40 among them were on a non-abraded part of the specimen and the mean depth of wear in the abraded zone was determined. The abrasion rate (mm/km) was found as ratio of mean wear depth and effective sliding distance.

To validate the measured result that was obtained mechanically with digital indicator, the mean wear depth was found through post processing of a surface scan with ATOS. Figure 5 shows surface 3D scans of tested concrete samples, done with ATOS 600 SO - 3D optical scanner at NTNU's department of structural engineering. Both specimens were tested in the master thesis [14] with the fourth ice type.

To find mean wear depth with surface 3D scans the GOM Inspect software was used. The mean wear depth was found two times for different measuring schemes, Figure 4 (b,c). To allow good comparison of results all schemes have approximately the same measurement zone.

4.1. A simplified scheme

In this measurement scheme the two best fitting planes were constructed with the Gaussian procedure of GOM inspect. The first plane was for the all abraded area within the measurement zone. To construct this plane the software used approximately 2400000 points. The second, reference, plane was for all non-abraded area within the measurement zone, and approximately 900000 points were used to construct this plane. 80 points were constructed on the first plane. Then the distances as perpendiculars from point to reference plane were found. Average value between 80 distances gives mean wear depth, see results in Table 1.

4.2. The scheme with 10 sections

This scheme has the same principle as the above simplified scheme, but the measurement zone was divided in ten. Each of these 10 zones had the best fitting plane for abraded and non-abraded area. As a result, there were 20 planes in total. 8 points were constructed on each Gaussian abraded plane. The x, y coordinates are the same in both the simplified and 10 sections schemes. The distances as perpendiculars from point to Gaussian non-abraded reference plane were found in each section. Average value between 80 distances gives mean wear depth, see results in Table 1.

Table 1. Measurement results

	Mechanical measurement with Mitutoyo	GOM Inspect software	
		Simplified scheme	Scheme with 10 sections
Mean wear depth [mm]			
Sample No.1	0.049	0.021	0.039
Sample No.2	0.052	0.018	0.039
Wear rate [mm/km]			
Sample No.1	0.098	0.041	0.077
Sample No.2	0.104	0.035	0.078

DISCUSSION

The ice abrasion rate of the specimens is very low in Figure 5. Still it seems that wear on concrete by ice is associated by increasing roughness. This is not surprising considering the increasing exposure of aggregate normally seen on abraded concrete surfaces. Furthermore, experimental studies of concrete-ice abrasion in the lab is very demanding and time consuming when controlling the relevant parameters (load, temperatures, speed, ice-and concrete quality, etc.). One of the most important parts of the study is the measuring procedure of surface roughness and wear depth in each test. Comparing mechanical measured wear depths obtained with digital indicator Mitutoyo and wear measured with an optical scanner ATOS 600 SO showed good agreement for wear, in case of 10 sections scheme. For the simplified scheme there is 2 – 3 times difference with mechanical measurements. One can conclude from this, that the reference plain in simplified scheme does not correspond to reality due to surface wrap. To increase accuracy, the reference plane should be constructed for the narrow section as in the 10 sections scheme or mechanical measurement. So far we have not made roughness calculations with GOM inspect, though this is possible, for example in a simplified way by extraction of selected data in 2D and application of equation (1). In [15] this was done for one sample and one interesting observation was that the roughness R_a is larger normal to the direction of ice sliding compared to parallel to the direction of ice sliding.

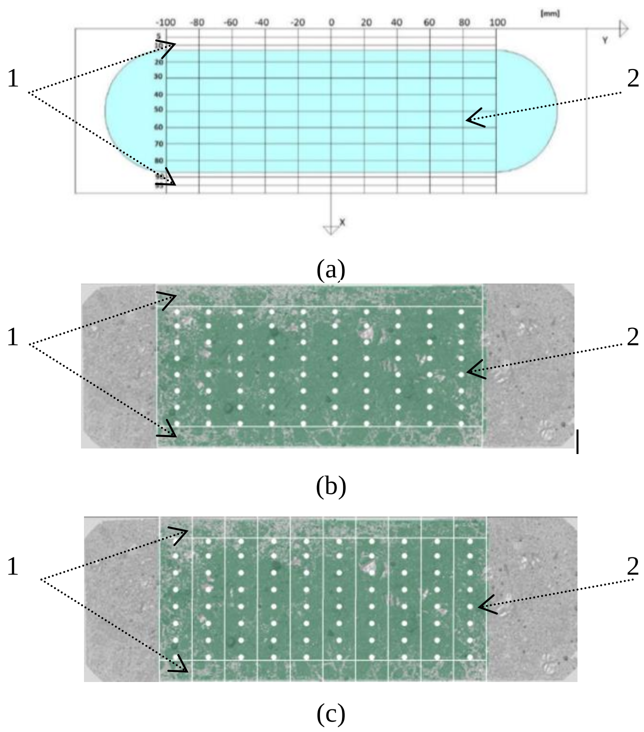


Figure 4. Measuring schemes: (a) Measuring grid for mechanical measuring by Mitutoyo [14]; (b) the simplified scheme in GOM Inspect software; (c) the scheme with 10 sections in GOM Inspect software. 1 – non-abraded zone; 2 – abraded zone.

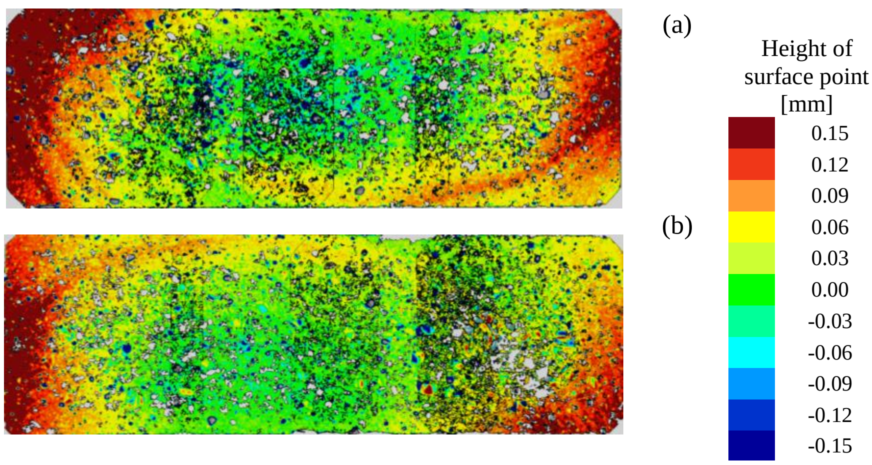


Figure 5. Surface 3D scans of tested concrete samples, w/c = 0.60 with 40% volume of paste and granitic aggregate with 8 mm maximum particle size: (a) sample No.1; (b) sample No.2.

CONCLUSIONS

The influence of roughness on concrete-ice abrasion rate was studied showing that wear depth relates to roughness, though the results are not clear (Figure 3). The major part, four of five lines give increasing abrasion rates with increasing initial roughness. The mean wear depth of a concrete sample surface was validated with 3D optical scanner showing good correspondence (Table 1). It was concluded that 10 sections scheme gives more reliable results then the simplified scheme. Although the mechanically measured results and those with 10 sections scheme obtained are in a good agreement, the scanner was found as a much more convenient equipment and more work on this kind of measurement techniques will be used in our further studies.

ACKNOWLEDGEMENT

Thanks to Professor Knut Vilhelm Høyland (supervisor) and master student Nicolai Segaard Greaker, who performed the study on effect of ice quality on concrete-ice abrasion, and to master student Kristian Sætre who performed an initial study on the use of ATOS 600 SO and GOM-inspect for concrete-ice abrasion characterization.

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