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REVIEW OF METHODS FOR TESTING OF VARIOUS MATERIALS FOR ICE ABRASION RESISTANCE

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ABSTRACT

Ice and severe climate conditions give serious challenges to the creation of means of shelf and, above all, have no analogues in the engineering practice of ice-resistant platform for the drilling and production of oil and gas. The main factor affecting the conditions of use and reliability of hydraulic structures located in these areas is the ice conditions in the area of construction and, as the result, ice loads and impacts on construction. As a result of the cyclical ice load surface structures in contact with the ice, always wears ("smoothed"), which promotes the formation of fatigue cracks, accelerates the corrosion of metal abrasion helps cement, coarse aggregate loss and reduce the strength of concrete with repeated blows. Currently, there is no reasonable theory of calculating the intensity of ice abrasion, and as the result there are no requirements for materials for operation in ice-covered seas. To assess the strength of materials in ice abrasion conditions laboratory studies specifically designed for this purpose are required. The present paper represents an analytical review of systems for testing the abrasion resistance of the ice of different materials (concrete, steel, various types of coverage).

Keywords: shelf, ice abrasion, testing rig, test method, ice.

INTRODUCTION

The presence of ice cover and severe climate conditions create serious challenges for constructing technical equipment of offshore development and, primarily, ice-resistant platforms for drilling works and oil and gas production that have no analogue in engineering practice.

The main factor affecting the conditions of using and reliability of offshore structures located in these areas is sea ice conditions in the area and, as the result, ice load and impact on the construction.

Under the cyclical ice load the surface of structures in ice zone always abrases (is "smoothed"), and it promotes the formation of fatigue cracks, accelerates the corrosion of metal, promotes cement stone abrasion, coarse aggregate loss and reduce the strength of concrete with repeated cracks. Currently, there is no reasonable theory of calculating the intensity of ice abrasion, and as a result there are no requirements for materials to operate in ice-covered seas.

To estimate the strength of materials to ice abrasion you need to undertake laboratory studies on specifically designed for this purpose test machines. The work presents the analytical review of systems for testing ice abrasion resistance of different materials (concrete, steel, coverings of different types) and conditions of the experiment.

By long term investigations Saeki et al (1985, 1987) discovered three main factors affecting ice abrasion rate:
– contact pressure of the ice sheet on surface of structure;
– path of interaction length (ice sheet displacement along the structure);
– ice abrasion resistance properties of construction materials.
(Saeki et all 1985) introduced the next formula to calculate the total ice abrasion depth:

$$S = S_r \cdot \sigma_v \cdot L \qquad (1)$$

where S – total ice abrasion depth, mm; S_r – ice abrasion resistance coefficient, (mm/km)/(kgs/cm2); σ_v – contact pressure, kgs/cm^2; L – total path of interaction length, km.
Hanada et al (1996) used the next formula to calculate the mean abrasion rate:

$$\bar{S} = S' \cdot L \qquad (2)$$

where L – path of interaction length (ice sheet displacement along the structure), km; S' – abrasion rate (mm/km), , where 0,0003 - ice abrasion resistance coefficient for steel, (mm/km)/(kgs/cm2)
In 1994 г. Itoh et al (1994) basing on their previous investigation (Itoh et al., 1988a, b) proposed using an empirical formula for concrete ice abrasion rate calculation S' (mm/km) of function of ice temperature T (°C) and contact ice pressure σ_v (MPa), $S' = f(T, \sigma_v)$.
Main idea for further investigations was discovering the ice abrasion common factors, determination of ice resistance coefficients for various materials and empirical functions for ice abrasion rate.
The first attempts to establish experimentally the resistance of ice abrasion for various materials were made more than 30 years ago. To carry out this type of test special units were developed; the experimental conditions had to meet the following requirements:
- The ability to change the pressure at the contact, the test temperature and the speed of the test;
- The ability to create static and kinetic friction during the test;
- Easy and accurate method for measuring the amount of ice abrasion's depth (volume);
- Ability to save the permanent friction coefficient between ice and concrete;
- The ability for test results verification.

BACKGROUND

Test machines for measuring the resistance of ice abrasion for various materials were the following:
- Machine of comparative type;
- Machine “a rotating disk”;
- Machine “abrasion drum”;
- Machine “friction sliding”.

By order of the ABAMEngineersInc company the general research program of high-strength lightweight concrete for offshore ice-resistant structures started in 1982. The program included three stages: Phase I, Phase II, Phase III, and five different methods of evaluating the abrasion of concrete. The project involved design, construction, transportation and installation of the offshore ice-resistant platforms, now called: «ABAM-I», «ABAM-II» and "ABAM-III" respectively (Hara at al. 1995).

MACHINE OF COMPARATIVE TYPE.

This method was developed by ABAM Inc. in the test associated with the first phase of the project "Developmental Design and Test of High - Strength Light-Weight Concrete Structures in the Polar Ocean Region" Phase I (Hara at al. 1995). Schematic diagram of the machine is shown in Fig. 1.

This method has the following disadvantages:
- During the test only kinetic friction was produced because the samples were rotated in one direction at a constant speed;
- Speed of the test was too high in comparison with the speed of ice drift;
- At low speeds there was a problem caused by icing of test samples;
- During the test ice blocks were melting, it widened the contact area, so that it wasn't possible to maintain a constant contact pressure;
- It was difficult to measure the intensity of ice abrasion, because this method allowed only to compare which of two concrete specimens wore out faster under the same conditions.

Because of the inability to eliminate the disadvantages mentioned above further studies had to abandon this concept of ice resistance testing.

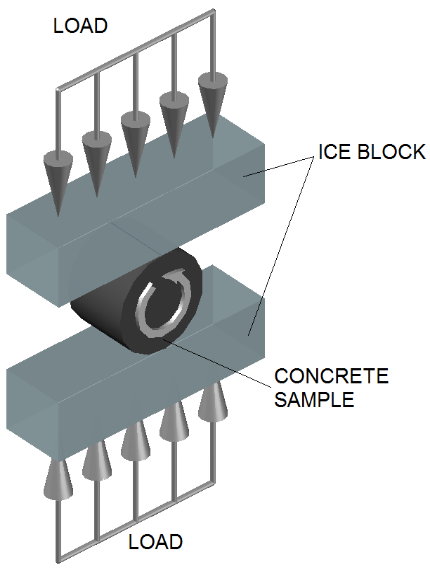

Figure 1. Machine of comparative type

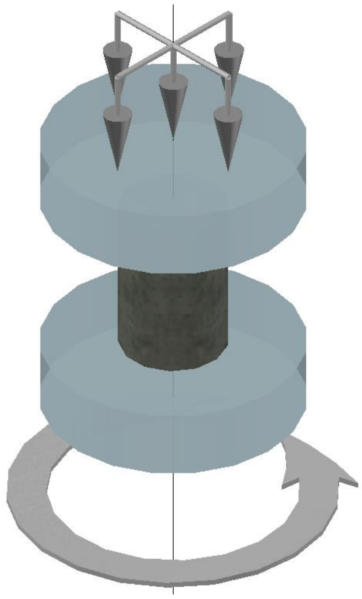

Figure 2. Machine "a rotating disk"

MACHINE "ROTATING DISK":

This method was developed by ABAM Inc. for Phase II of the project mentioned above (Hara at al. 1995). This machine had the following characteristics: speed - 60 rpm, the sample of concrete with outer diameter of 300 mm, inner diameter of 190 mm, and height of 100 mm. Cylindrical blocks of ice with a diameter of 400 mm and thickness of 120 mm squeezed from both sides of the ends of the sample of concrete. Schematic diagram of the test is shown in Fig. 2.

Experimental conditions: rotation speed 60 rpm. relative rotation speed concrete/ice 77,0 cm/s; ice temperature minus 15°C; contact pressure from 0,45 to 0,98 MPa; ice salinity from 7 to 8‰.

This test method for ice abrasion resistance has the following disadvantages:
- During the test only kinetic friction was modeling because the samples were rotated in one direction at a constant speed;
- The relative speed of rotation varies and depends on the cross-section;
- On the concrete surface the formation of unwanted ice is possible, because the whole the sample is surrounded by ice.

The same principle was used later (Huovinen S., 1990), for VTT, Finland. Test rig included mechanical cutter which was used for concrete durability analysis by mechanical wear.

The major requirement for ice abrasion testing according to Houvinen et al (1990,a) is preliminary testing of concrete for frost resistance, so that concrete strength should be determined after certain amount of freeze-thaw cycles (0, 5, 25 and 50 cycles).

The same principle is used in USA Standard ASTM C779(Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces), and is a common durability test method.
Schematic diagram of the rotating disk also has a number of disadvantages:
- Heterogeneity of abrasion material on the area, that leads to the error of measurement results of intensity attrition;
- The complexity of fixing both samples and ice;
- Most of the machines of this type is designed for the studying of the mechanical wearing of materials and cannot be used for research on the ice abrasion
Taking into consideration these shortcomings, this type of installation is not used in further studies on the resistance of the material of ice abrasion.

MACHINE "ABRASION DRUM":
This test method of ice abrasion was proposed by ABAM (Hoff, 1988). In the installation the principle of rotating drum made of concrete plates mounted on its inner walls was used, Fig. 3. Drum was filled with a mixture of ice and abrasives. The material was abrased because of the drum rotating and moving of abrasive surface on test samples. The results of the test are not related directly to ice abrasion, so this principle scheme of research will not be used further.

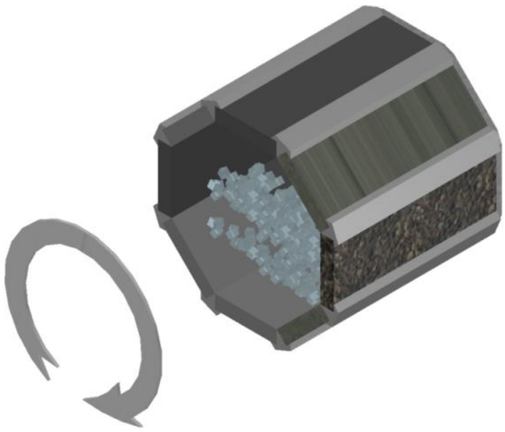

Figure 3. Machine "abrasion drum"

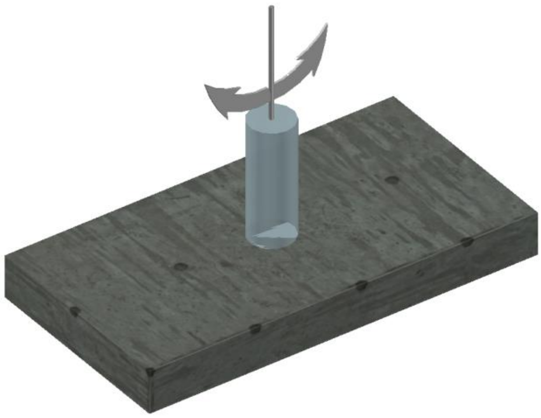

Figure 4. Machine "friction sliding"

SLIDING FRICTION MACHINE:
This test procedure was part of the ABAM's project (Hara at al. 1995). Schematic diagram of the test is the following: a concrete specimene is suspended vertically and moves back and forward in an arc of 20 °, the ice block is located under the test sample with a normal contact pressures of 1.7 MPa. Schematic diagram of the test is shown in Fig. 4.
Experimental conditions: concrete specimen diametr 76,0 mm; ice salinity 12‰; contact pressure 1,72 MPa; temperature range from -29,0 to +2,8°C; duration of cycle from 1,75 to 3,5 s; contact speed from 10,1 to 20,2 cm/.
This machine gives an accurate representation of actual events on contact, though revealed some imperfections of the test set-up:
- At high contact pressure, the concrete specimen tended to crash into the ice block;
- The relative rate of reaction was due to variations in the trajectory of the arc, resulting in a difference of intensity of wearing;
- In terms of the rate of wear can't allocate an exact surface of the sample that can be taken as the average surface to measure the depth of abrasion.
Further studies had to abandon this type of plant resistance to ice abrasion.
The principle of sliding friction was used by H. Saeki and his co-authors. From 1981 to 1986 H. Saeki et al conducted experimental studies of various building materials to wear ice. The

studies were conducted at the facility where there was a chance to sample a variety of construction materials, changing the normal stress and the relative speed of movement.
The sample of construction material was securely attached to the mobile test platform that moved by a hydraulic jack, and the pattern of sea ice was placed on the sample of construction material and didn't not move relatively to the test platform. The relative velocity between the sample and ice material changes due to change the pressure in the hydraulic jack. Static vertical load created by cargo space on a steel bar, which is pressed on the ice sample, transferring the load on the sample of concrete (Saeki at al., 1981).
Experimental conditions: ice temperature T = –10 °C; contact pressure p = 1,0MPa; sea ice salinity from 3,0 to 5,0 ‰; ice density from 0,90 to 0,91 g/cm3; specimen speed from 2,0 to 20,0 cm/s; material specimen width 10,0 cm; dimensions of the ice block L×W×H 70×8×12 cm.
After that this setting has been improved by Y. Itoh et al, Figure 5 (Itoh at al. 1988).
The concrete specimen moved back and forth along the fixed block of ice, the speed changed the pressure on the contact, and crushed slices of ice were removed by the air of the same temperature as the ice sample.
The test machine allows to model both kinetic and static friction due to the variable nature of the motion of the sample. Width of the sample was 10.0 cm, while the width of the ice block was 8.0 cm, it means, that 1.0 cm of fresh surface remained on each side. These surfaces were used as basic reference standards in measuring the depth of abrasion. In this study, the depth of abrasion was determined as an average depth of abrasion, measured on five transverse lines.
The only drawback was that the ice began to break on the contact at high pressure (1.5 MPa).
In further investigations Itoh et al (1988a, b) changed test conditions that substantially influenced the ice abrasion: ice temperature (–5 ºC, –10 and –20 ºC); contact pressure (5,0 kgs/cm2, 10,0, 15,0, 20,0 and 30,0 kgs/cm2); relative speed (1,0 cm/c, 5,0 and 20,0 cm/c); ice: salinity from 3,0 to 5,0 ‰; density from 0,90 to 0,92 g/cm^3.
At the same time A.M. Nawwar and V.M. Malhotra (Nawwar & Malhotra, 1988) were proceeding the abrasion resistance of the ice on a specially designed test rig, Figure 6.

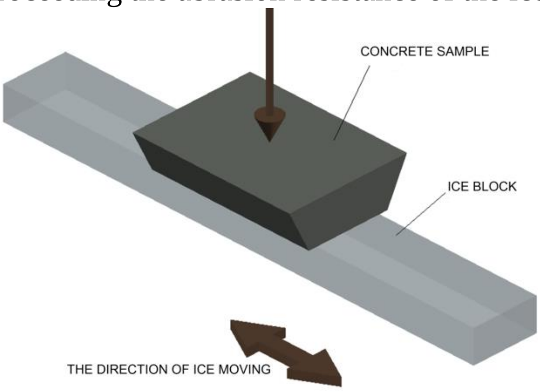

Figure 5. The principle of sliding friction test method

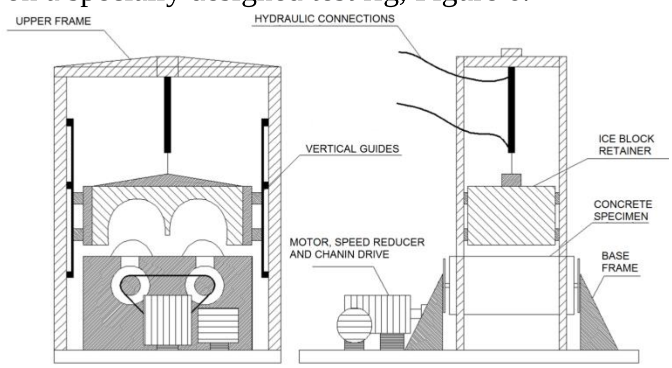

Figure 6. The principle of Machine A.M. Nawwar and V.M. Malhotra

Cylindrical samples of concrete with diameter of 300 mm and length of 500 mm were used in testing. The ice block with the temperature of -10 °C was placed over the rotating concrete specimens. Rotating speed of the samples was 1.0 m/s ÷ 2,5 m / s. Concrete images loaded onto third in salt brine with a temperature between -3 (±2) °C to prevent icing of the sample surfaces. Therefore, the test temperature was warmer than -10 ° C, an ice block was wearing out faster, and that resulted in higher consumption of ice. The ice that was used was grown in the laboratory with a salinity from 3,0 ‰ to 5,0 ‰, and its properties were close to full-scale, one-year sea ice.

MODERN SYSTEMS FOR TESTING ICE ABRASION.

Given everything that was written above it is possible to outlined the following test machine for ice abrasion resistance at the present stage:

H. Saeki et al use installation described earlier - with the principle of sliding friction – for their studies.

R. Abdelnour and co-workers developed a test rig for testing ice abrasion resistance of metal coatings for research on the basis of the concept-Test-AM Nawwar and V.M. Malhotra , it was proposed for using on the offshore ice-resistant platform "Molikpaq" during its updating to work on Sakhalin's offshore in 1990 (Abdelnour et al., 2006).

For the practical range of load in the interaction of ice-structure contact voltage should vary between about 0.5 MPa and 10.0 MPa, depending on many factors. Therefore, experimental studies of ice abrasion resistance of the materials were developed to make provision of the changes of the pressure on the contact and the length of interaction (attrition). In this case, the tests were conducted long enough - to reach a stable region attrition (less than 10 km).

Tests were carried out on the basis of laboratory ice BMT Fleet's in the freezing chamber 7.5 m x 7,5 m x 3,5 m. The temperature varied from -8 ° C to -10 ° C. with some improvements, with the biaxial loading and used machine-friction bearings.

Test machine creates permanent contact pressure of 1.0 MPa. Freshwater ice was used, because its strength is higher than the strength of sea ice, which leads to greater wear. A great emphasis was made on prevention ice formation on the surface of the sample, for this purpose a combination of ventilation and heating was used.

The samples of A and B coatings were plotted on steel plate with thickness of 12.7 mm, length of 750 mm and width of 240 mm. Used for the investigations stainless steel plates with thickness of 6.35 mm were used in the research. The coating thickness was controlled to 2,54 x10-3 mm (0,1 mil).by means of an ultrasonic measuring device

B. Fiorio and colleagues conducted a set of tests, designed primarily to test the soil (Fiorio et al., 2002). Concrete plate was placed on a moving platform that moved horizontally under the ice cylinder in the range of 30.0 mm. The rate remained constant during each test. Speed range varied between 10-6 and 10-4 m / s, measurements were taken at five different speeds within this range. Cylindrical ice sample was fixed with a gap of 1.0 mm above the concrete surface to avoid physical contact between the ice and concrete. The normal force is applied through a lever with computer control. Laboratory-grown ice from fresh water witg columnar structure S2 was used. Dimensions of cylindrical ice samples: diameter - 60.0 mm, height - 96.0 mm. Concrete specimen dimensions: 175 mm x150 mm with a possible deviation of 0,6 mm grain size from 0.2 mm to 5.0 mm.

R. Frederking and A. Barker developed the testing of samples of various materials on the ice abrasion (Fig. 7, Fig. 8) to simulate the process of attrition, adjusting the speed of interaction (Frederking & Barker, 2002).

The tests were conducted in ice tank at National Research Council's Canadian Hydraulics Centre. Tank of 21.0 m long, 7.0 m wide and 1.2 m deep was equipped, truck towing capacity of 50 kN, which covered the entire width of the tank. The reservoir was located in an area where conditions were close to the natural and it was possible to change the temperature of the air for each series of experiments in the range of -10 ° C to -20 o C.

Test Procedure: trolley was used to move blocks of ice back and forward by the samples of different building materials frozen on the floor of the tank. The normal and tangential forces were measured between ice and material's surface.

Samples of ice of 120 mm tall, 95 mm wide and 155 mm long were drank from a block of ice and oriented so that the lower surface of the sample of ice (the base of the original ice block) was rubbing against the surface of the material being tested.

Figure 7. A general view of the sample on the floor in a tank (Frederking & Barker, 2002)

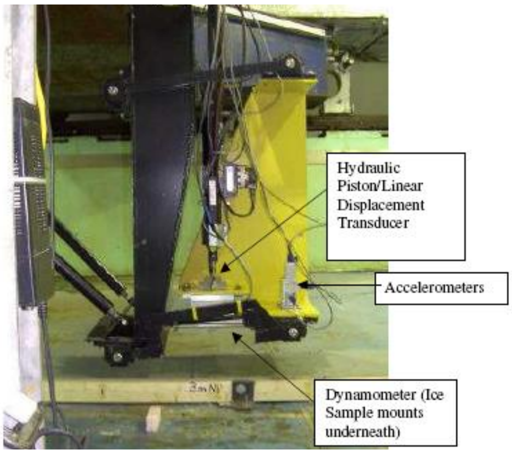

Figure 8. The testing of ice abrasion materials (Frederking & Barker, 2002)

S. Jacobsen in the ice laboratories based on NTNU used a modified setup for testing the resistance of concrete specimens to ice abrasion, Fig. 9 (COIN, 2008). This plant was originally designed to study soil shear. The machines used the principle of friction-slip. Ice sample (70 mm diameter and 150 mm in height) was attached to a mobile cart and made reciprocates over the sample of concrete in the speed range from 0.06 m/s to 1.56 m/s. The contact pressure was changed with the hydraulic system from 0.0 MPa to 2.0 MPa.

During tests ice-coating was formed on concrete specimens. To resolve this problem, the installation was equipped with a special device for heating samples of concrete.

In this test ice abrasion of materials was negligible, and to measure its magnitude very precision equipment was required.

Concrete specimens had a size larger than the block of ice, fresh edge concrete specimen were used to measure the depth of ice abrasion.

The disadvantage of this setup is using of freshwater ice, because using salty ice can erode the unit itself, and using freshwater ice that has a hardness greater than the sea (salty) ice, increases the depth of ice abrasion, which affects the final outcome, making a certain error in the results of research;

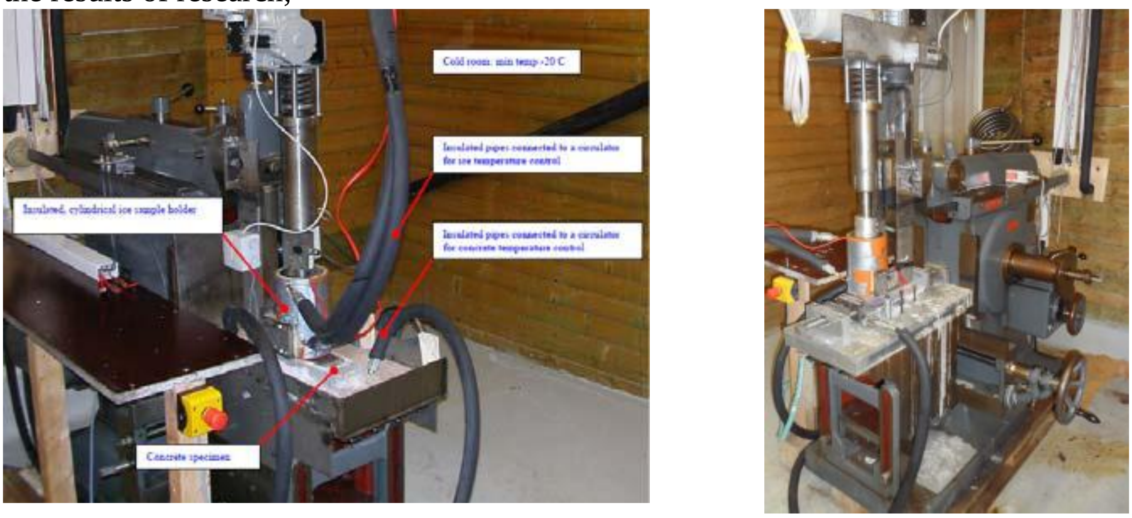

Figure 9. The testing on the ice abrasion NTNU (COIN, 2008)

A.T. Bekker and colleagues studied samples of different compositions of concrete gravity base A-D that were built under the project "Sakhalin-1" for Aker Engineering and Technology

(Bekker et al. 2011). This result was used later to make design decisions on the ice protection to support concrete gravity base.
To conduct the research ice abrasion machine and ice laboratory were used, it allows to produce ice with characteristics similar to real.
Installation for the studying of ice abrasion was developed and manufactured in the company NPO "Hydrotex." General view of the basic structure and design of the facility is shown in Fig. 10.
The designed test machine meets the following requirements: amplitude of horizontal displacement 2000 mm vertical travel range 700 mm horizontal travel speed (adjustable) from 0.2 m/c to 0,2 m/c; rate of vertical movement in the positioning from 1.0 mm/s to 5.0 mm/s, the pressure of the sample from 1.0 kN to10,0 kN.
This unit is designed to test for resistance of different materials (steel, concrete, coatings of various types) to ice abrasion, both marine (salt), ice, and fresh ice.
As part of the experiment a special system for the preparation of model ice, which included forms, pre-cooling, water tanks and piping has been designed and constructed.
The system ensured the maintenance of water circulation within the form, maintenance of adequate salinity and water temperature, air circulation on the forms, that contributed preparation of model ice with properties similar to natural.

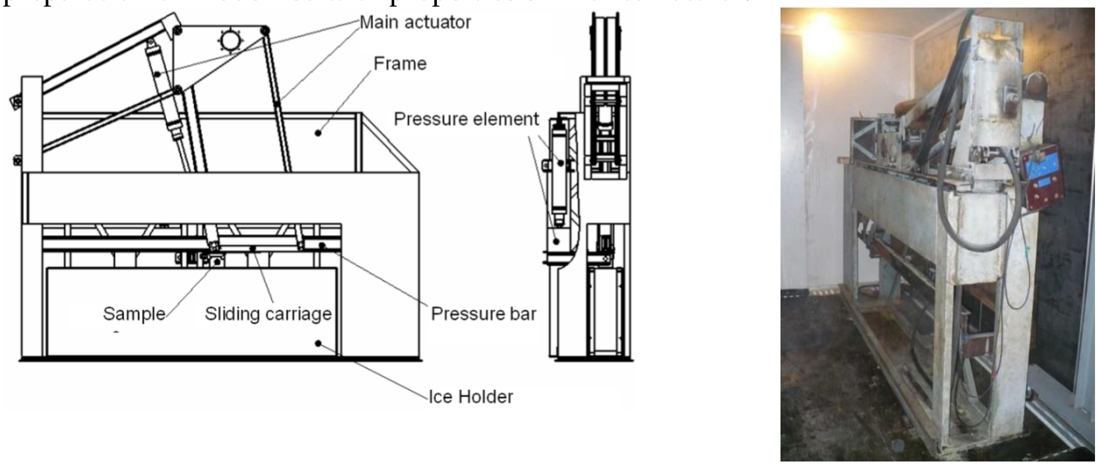

Figure 10. The testing on the ice abrasion Hydrotex Co. Ltd

CONCLUSION.

Based on the proposed analytical review and analysis of research concepts and installations the following recommendations for experimental studies of samples of materials to resist ice abrasion can be given.
The most appropriate schematic diagram of the test circuit is friction-slip and installations developed on its basis.
Recommendations for conducting experimental studies on building materials ice abrasion resistance.

• The installation must be conducted in a special freezer, where it is possible to change the temperature of the air.
• During the test, it should be possible to change a contact pressure and relative speed of interaction, and the need to continuously record the results of the tests.
• The installation must have a device for removing ice abrasives and abrasive materials and prevent the melting of ice and ice formation on the surface of the test samples.
• Machines should be able to experience the ice abrasion resistance of different materials, such as marine (salt) and fresh ice.

Summarizing the ice abrasion theoretical and experimental studies and basing the emperical models of ice abrasion rate several ***recommendations for experimental studies*** can be suggested.
1. Rigs with back and forth movement are the most convenient for ice abrasion testing. Test rig should be installed in a freezing chamber where air temperature can be changed. There should be a possibility to change parameters of a rig for testing like contact pressure, relative speed. Constant data registration should also be foreseen. A device for cleaning of the grinding surfaces should be in a construction of a rig. Ice melting and icing of a test specimen should be excluded. Test rig should be capable for ice abrasion testing of various construction materials using sea ice and pure ice.
2. In order to simulate real conditions during testing concrete specimens certain conditions should be arranged (Hoff, 1988; Itoh, 1988b; Hanada et al., 1996): ice temperature T = –5 ÷ –10 °C; contact pressure σ = 0,5÷3,0 MPa; sea ice salinity from 3,0 to 5,0 ‰.
3. From the sea ice abrasion resistance standpoint, abrasion rate should be determined at a stable abrasion stage when the rate is stable and unrelated to the type of aggregate or concrete (Hoff, 1988; Itoh, 1988b; Hanada et al., 1996). In order to get to the stable abrasion stage path of interaction length should be about 10 km.
4. The major requirement for ice abrasion testing is preliminary testing of concrete for frost resistance, according to Houvinen et al (1990,a). Concrete strength should be determined after certain amount of freeze-thaw.
5. According to Hoff (1988) and Hanada et al (1996) 1,0 cm thick layer should be removed from a test surface. This should be done to exclude the surface abrasion stage and perform testing at the stable abrasion stage. Calculation of a mean abrasion with no excluding the surface wear will highly overrate the calculated abrasion rate.
6. Ice abrasion rate is a function ot two parameters: ice temperature and contact pressure(Itoh 1994, 1995; Germanischer Lloyd 2005).

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