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Mechanical Properties Between Ice and Various Materials Used in Hydraulic Structures: The Jin S. Chung Award Lecture, 2010

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Ice has been a serious obstacle and problem for the construction of hydraulic and marine structures, lighthouses, and the like in cold regions. For these structures, ice forces are the major design criteria. Because the ice loads caused by sea ice on offshore structures have been fully reviewed a few times, they are purposely set aside in this paper. Instead, two major problems are discussed here in some detail: The adfreeze bond strength of sea ice and the abrasion by ice on hydraulic and marine structures. These discussions are mainly based on the results of the studies carried out by the author and various combinations of colleagues, postgraduate and graduate students under his Chairmanship for over 20 years; these groups are hereafter referred to as the SCS.

INTRODUCTION

Cold regions, for engineering purposes, have generally been defined by the 0°C isotherm for the average temperature of the coldest month. In Japan, Hokkaido and the northern portions of Honshu Island are classified as a cold region, where engineering problems associated with freezing temperatures, ice, snow and frost heave occur.

In regard to hydraulic and marine structures in cold regions, one of the most important forces in their design is the force applied to them by a solid ice sheet or large ice block, even in the regions where ice-free conditions are dominant through the year and fluid-dynamic forces, such as waves and wind forces, have to be taken into account. There are essentially 4 modes of ice action against these structures:

- static force from expanding or contracting ice sheets;
- dynamic force of moving ice sheets, etc.;
- pressure of unconsolidated ice accumulations; and
- vertical force exerted by ice.

Hokkaido University has long investigated every mode of ice action and developed preventive measures against damage caused by ice forces as well as the means to reduce the risk of damage.

In order to respond to growing world energy demand by exploiting and transporting energy resources deposited in the Arctic Ocean, ice engineers have had to face the problems of dynamic ice loads on offshore rigs and vessels. The focus has been on global and local ice loads on structures, because in design practice, vertical forces on a hydraulic structure have often been neglected. The adhesive strength of ice on various construction materials is high. With a rise in water level, piers, piles, caissons and wharf sheeting may be partly lifted off their foundations and damaged. The risk of damage depends on the following: adfreeze bond strength to the surface of materials; the adfrozen area on the surface of materials; temperature and temperature gradient between ice and the surface of materials; ice properties with and without solid particles; velocity and amplitude of water level fluctuations.

Abrasion of the surface of materials has often caused serious damage to hydraulic and marine structures, and it has a complex feature: The abrasion rate depends on temperature, contact pressure (vertical stress), relative velocity, total sliding distance of the ice sheet onto the surface of structures, physical properties and roughness of material surfaces.

In this paper, the discussion on the adfreeze bond strength and abrasion of materials by ice is mainly based on the results of studies carried out by the author and various combinations of colleagues, postgraduate and graduate students under his Chairmanship; these groups are hereafter referred to as the SCS.

This paper summarizes the theoretical and experimental results on adfreeze and abrasion problems of ice carried out by the SCS. Because the SCS has extensively studied ice loads on structures for over 20 years and these subjects have already been fully reviewed a few times, these matters could be set aside.

ADFREEZE BOND STRENGTH

Adfreeze to Structures

Changes in water level produce vertical forces on hydraulic and marine structures—such as offshore structures, wharves, bridge piers, intake towers in rivers, lakes and seas—when ice sheet-to-structure adfreeze bonding is present, as shown in Fig. 1.

The ice load required to cause the adfreeze bond to fail essentially depends on the shear strength of the adfrozen ice and cone angle of the structure. However, even when the ice sheet does not adfreeze to an inclined structure, the fluctuation of the water level may exert ice forces on the structure. A major feature of an inclined structure is that it provides the possibilities for the ice to ride up on the structure and fail to bend.

Some reports have described failures of structures due to the vertical ice force, such as pullouts of piles of pier structures and collapses of intake towers.

Fig. 2 shows the SCS calculation scheme with which to estimate a vertical ice force due to changes in water level, based on the theoretical approaches proposed by the SCS (Saeki et al., 1983; Nakazawa et al., 1988; Terashima et al., 2006).

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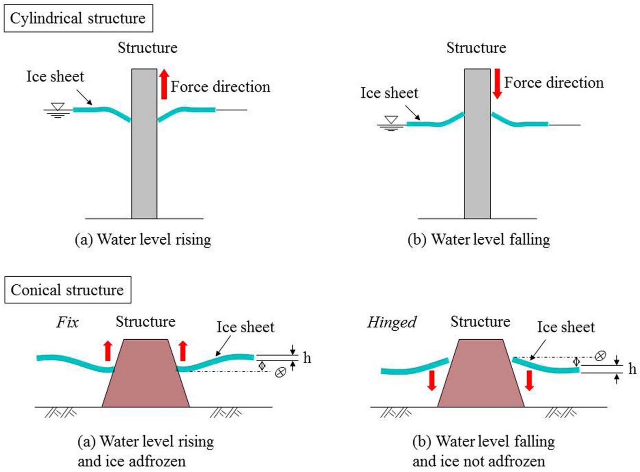
KEY WORDS: Adfreeze bond strength, abrasion by ice, friction coefficient of ice, sea ice, hydraulic structure, marine structure, coating material.



(a) Water level rising

(b) Water level falling

(a) Water level rising and ice adfrozen

(b) Water level falling and ice not adfrozen

Fig. 1 Vertical forces exerted on cylindrical and conical structures

MEASUREMENTS OF ADFREEZE BOND STRENGTH

Adfreeze bond strength is an essential parameter for vertical ice force estimation. No reliable means have ever been developed to theoretically calculate the strength of the adfreeze bond. Bond strength data could be provided by model tests or actual field measurements. However, the test results vary with the test conditions and procedures.

Notations of the test conditions and procedures are vital for the evaluation of adfreeze bond strength data.

Fig. 3 illustrates the possible forces typically exerted on the interface between adfreeze bond ice and a material.

The roughness of the surface of structures always plays an important role in the formation of cracks in adfreeze bond ice, particularly in actual fields. As shown in Fig. 3, the features of breaks of adfrozen ice are classified into 2 cases: Whether the principal force is horizontal (a) or vertical (b). In the case of Fig. 3a, both the shear strength of the ice on the rough surface of a material and interfacial free energy affect the adfreeze bond strength. In the case of Fig. 3b, interfacial free energy governs the adfreeze bond strength, which works between the ice and the surface of a material and varies with the actual contact area of the ice to the rough surface of the material.

The possible vertical and horizontal forces are:

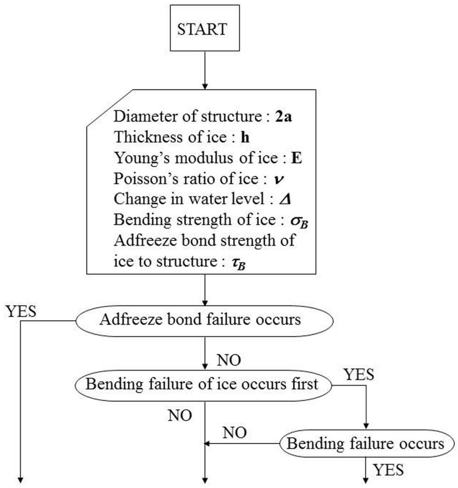
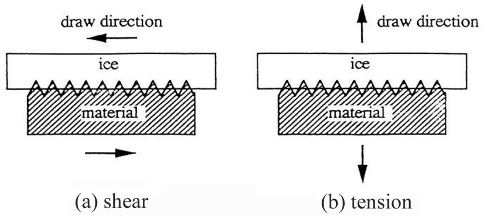


Fig. 2 Calculation scheme for vertical ice force



(a) shear

(b) tension

Fig. 3 Possible forces exerted on interface of adfreeze bond ice and a material

- vertical force exerted due to tidal motion, and abrupt changes in water level due to heavy rainfalls; and
- horizontal force due to wind and current.

In general, breaks of adfreeze bond ice have rarely occurred by such an external force as Fig. 3b. In the measurement of adfreeze bond strength, we will then be able to focus our attention on the physical feature (Fig. 3a). In the SCS study, the adfreeze bond strength was measured by the following 4 types of test procedure, and their adaptabilities were examined:

1. Pushout test
2. Pullout test
3. Twist test
4. Shear test

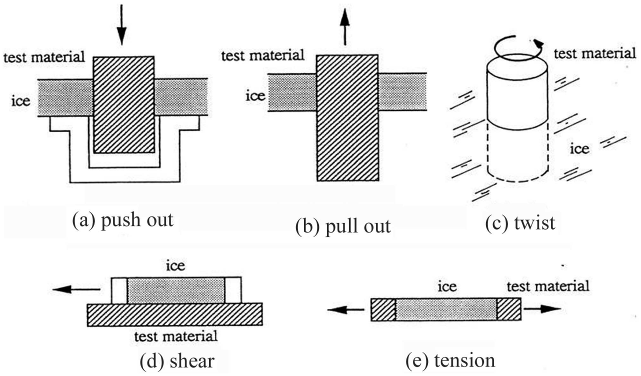
Fig. 4 summarizes the test procedures.

Pushout Test

The pushout test has advantages in the ease of test samples of ice and test execution. Once the ice sheet surrounding a test pile had grown to the desired thickness, the ice sheet was cut into specimens, which were then removed from the site. The specimen was prepared to uniform thickness with the test pile perpendicular to the ice sheet. The test specimen was then turned upside down, and the test pile's lower end inserted into a test pile whose flange was in contact with the ice sheet. A steel cap was put on the exposed upper end of the test pile. A hydraulic jack was often used to push the test pile out of the ice sheet. The adfreeze bond force was measured by a conventional load cell in the load path to the steel-capped test pile. The pushout velocity was obtained by a displacement transducer attached to the load cell. Stress rate and pushout velocity were controlled by varying the hydraulic pressure applied to the jack (Fig. 5).

Pullout Test

As in the pushout test, after the ice grew to the desired thickness, the pullout test apparatus was set on the test pile. The ice



(a) push out

(b) pull out

(c) twist

(d) shear

(e) tension

Fig. 4 Test procedures for measuring adfreeze bond strength

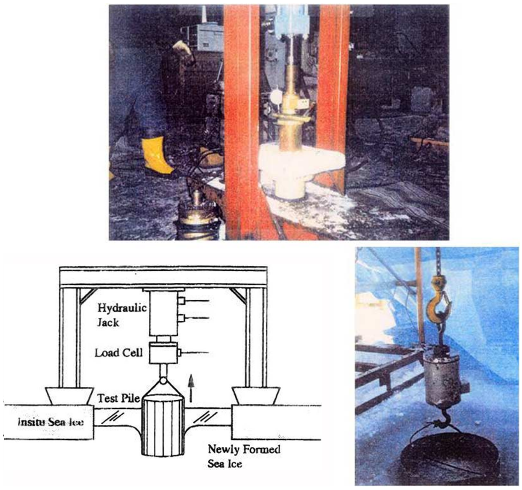


Fig. 5 SCS test apparatuses for measuring adfreeze bond strength: pushout, pullout and shear

specimen was prepared as for the pushout test. The ice specimen was pulled out by the hydraulic jack mentioned above, through a wire connecting between the test pile and the load cell (Fig. 5).

Twist Test

A rectangular hole was drilled on the upper face of a test pile to twist the specimen by a hydraulic jack. After adfreeze bond ice grew to the desired thickness, the ice sheet was cut into a rectangular plate large enough to be able to avoid disturbances from the ambient environment.. The adfreeze bond force was measured by rotating a test pile horizontally (Fig. 6).

Shear Test

The shear test is the method mostly used to measure adfreeze bond force by use of a cut-off ice specimen in the manner illustrated in Figs. 4d and 6.

Fig. 5 shows the outline of the SCS test apparatuses for measuring adfreeze bond strength by the pushout and pullout tests.

Fig. 6 shows the outline of the SCS test apparatuses for measuring adfreeze bond strength by the twist and shear tests.

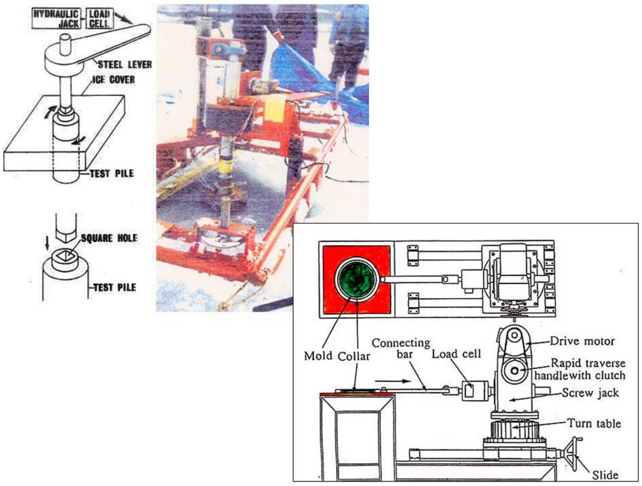


Fig. 6 Outline of SCS test apparatuses for measuring adfreeze bond strength: twist test and shear test

Ice Properties and Adfreeze Bond Strength

Ice behavior under a load is viscoelastic. The adfreeze bond strength varies with pushout velocity and the stress rate. However, in the case of the experiments carried out by Nakazawa et al. (1988), where uncoated steel piles were tested in varying loads and rates, the adfreeze bond strength did not show marked differences between the pushout velocity in a range of 0.001 to 10 mm/s and strain rate in a range of 0.0002 to 10 MPa/s. However, it might be said that the adfreeze bond strength decreases slightly with the increase of velocity and strain rate.

This result of adfreeze bond strength was in good agreement with the test results on sea ice carried out by Saeki et al. (1985), from which it could be concluded that the load and its rate do not affect the adfreeze bond strength, at least in the pushout test.

When we carry out a model test, we have to take the scale effect into consideration. In this sense, to clarify the scale effect on adfreeze bond strength experimentally, the effects of ice thickness and specimen size are to be investigated. As regards the effect of ice sheet thickness on the adfreeze bond strength, the SCS experiment data had not always been consistent. The real contact area depends on the topology of the interfacial surfaces. The apparent contact area is defined as the geometrical area of a specimen assumed to be in contact with ice. The difference between the apparent and real contact areas in the adfreeze bond interface brought about the scatter of the data, as the difficulty lies in measurements of the real contact area. However, adfreeze bond ice increases its adhesive strength as the ice thickness increases, and after the ice sheet attains a thickness of about 8 cm, the strength does not increase but keeps constant. The constant level of adhesive strength of ice was found to depend on materials and their surface conditions (Nakazawa et al., 1988).

Effect of Test Procedures

It is not easy to evaluate accurately the effect of testing apparatuses and procedures, since the effect might vary with salinity of water as well as the temperature differential between air, water, ice and the surface of structural materials. There is a lack of a comprehensive data set clarifying the effect of each factor.

For an overview of the effect on the adhesive strength due to test procedures, the comparison was then presented of the measured adfreeze bond strength between the 3 test procedures—pushout, pullout and twist tests—without deepening of analyses of the effect. The specimens were uncoated but rust-free steel piles. The diameters of the piles were: 3, 5, 10 and 15 cm in the pushout test; 3, 10, 15, 27 and 41 cm in the pullout test; and 5, 10, 15, 27 and 41 cm in the twist test.

In Fig. 7, τ_B, $\pi\varphi$ and Dgr are adfreeze bond strength, pile circumference and average ice-grain size, respectively. In those tests, Dgr was found to be 0.8 cm. The ice temperature was stable at -1.7°C.

As far as those tests are concerned, there was no noticeable difference between the data obtained by the 3 different test procedures. The SCS then carried out additional similar tests. The repeated test results confirmed the fact that those 3 test procedures provide almost the same results. The adfreeze bond strength of ice decreases with the increase of nondimensional pile diameter, $\pi\varphi$/Dgr, and approaches a constant value when $\pi\varphi$/Dgr is larger than 80.

The shear test has a different physical feature from the other 3 test procedures. Using a cylindrical pipe 5 cm in diameter, the SCS conducted a comparative test between pushout and shear tests. To prevent a corrosive effect on a pile surface, titanium was chosen as a material of a pipe, as the surface conditions of a pile

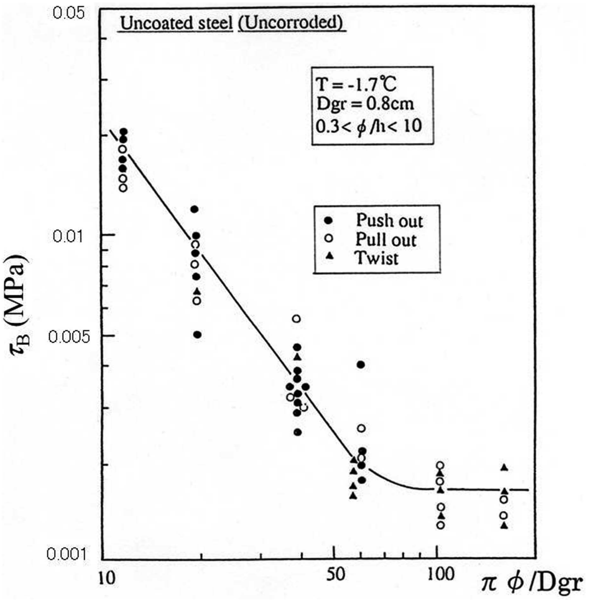


Fig. 7 Comparison of adfreeze bond strengths measured by pushout, pullout and twist tests

will differ in pushout and shear tests. The test room temperature was controlled to be −20°C. Fig. 8 shows a comparative test result.

While the pushout tests covered a relatively narrow range of pile size, there still were no noticeable differences in the results between pushout and shear tests, while the ice-grain size was difficult to control. The dependency of adfreeze bond strength on the pile size was found to be similar in Fig. 7.

As a consequence, adfreeze bond strength would not largely depend upon the test procedures. The strength is greatly dependent upon pile size, and more accurately, upon the actual adfrozen area. The strength decreases with the increase in pile size, and when the size is larger than 20 or 25 cm in diameter, the strength tends to a constant value.

Effects of Temperature

The physical property of ice depends on its own temperature and on the ambient one. As regards adfrozen ice on a construction material, the roughness of the material surface works to extend the contact area of ice to the material. Hence, when a temperature differential exists at the interface, this makes an evaluation of adfreeze bond strength complicated.

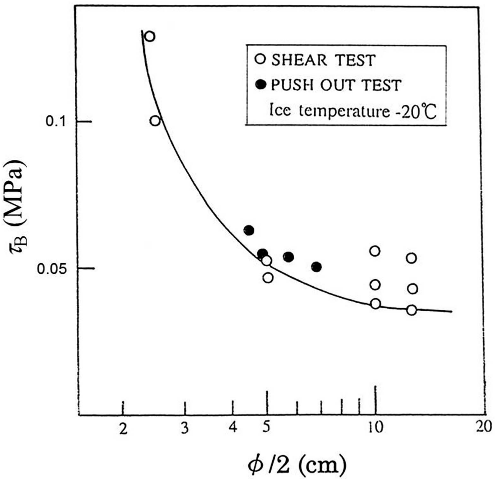


Fig. 8 Comparison of adfreeze bond strength measurement by pushout and shear tests

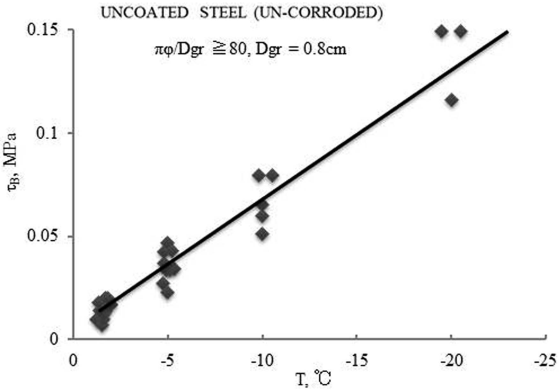


Fig. 9 Effect of temperature on adfreeze bond strength

As the shear strength of ice increases with a decrease in temperature, the adfreeze bond strength, which largely depends on the shear strength, increases with the decrease of the temperature in general. Fig. 9 shows the effect of the temperature on adfreeze bond strength.

Fig. 10 shows another example of the effects of temperature and pile size; here, the size effect due to the temperature has a similar tendency, which suggests a relatively simple relation between the pile size and adfreeze bond strength.

Adfreeze Bond Strength to Various Materials

Even when the temperature distribution is uniform and stable, and heat transfer is negligible at the interface between ice and construction materials, the surface conditions of construction materials are varied. The shear strength of ice embedded to a material depends on its surface roughness, when the ice moves horizontally on the material.

Fig. 11 shows an outline of the temperature effects on adfreeze bond strength of a few pile materials: cement concrete, low-density polyethylene (LDPE), uncoated and uncorroded steel, and coated steel with INERTA 160, often in use for coating the hull surfaces of ice-transiting vessels.

The temperature effects on adfreeze bond strength vary with the surface conditions of construction materials. The increase in strength with decrease in temperature was marked for the

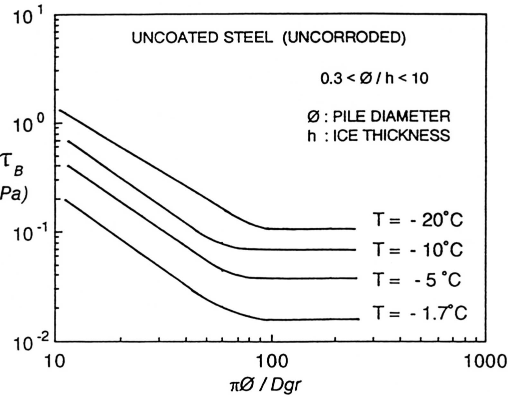


Fig. 10 Effects of pile diameter and temperature on adfreeze bond strength for uncoated steel pile (uncorroded)

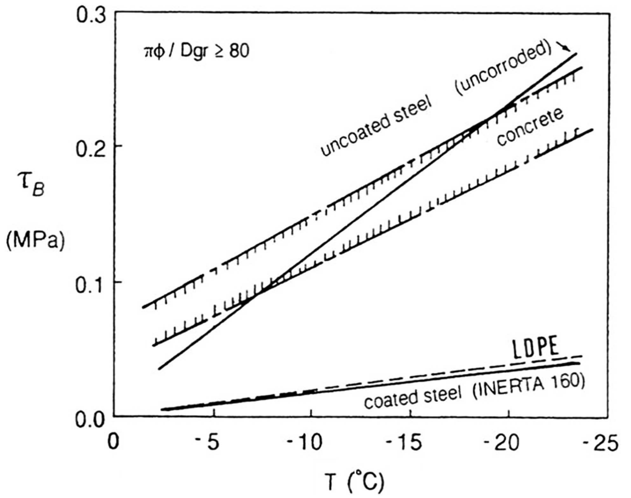


Fig. 11 Effects of ice temperature on adfreeze bond strength of various materials

uncoated steel and the concrete, both of which had relatively coarse surfaces.

The temperature effect of the strength largely depends on the coarseness of material surfaces. The past measurements of the static friction of ice against various materials endorsed these results.

Roughness of Surface of Materials

Surface analyses are vital for evaluating adfreeze bond strength. By using a High-Accuracy Surface Roughness Meter, roughness measurements were taken on all test piles. Fig. 12 shows the surface roughness effect on the adfreeze bond strength of various materials at −5°C, where the roughness was determined as the mean measured amplitudes of irregularities of the surface at 10 different parts of a specimen.

In the case of the surfaces of materials whose roughness is less than 20 μm, the ice bond strengths of the materials tested were almost at the same level. For such smooth surfaces, other factors—such as interfacial free energy—presumably affect the bond strength between ice and materials.

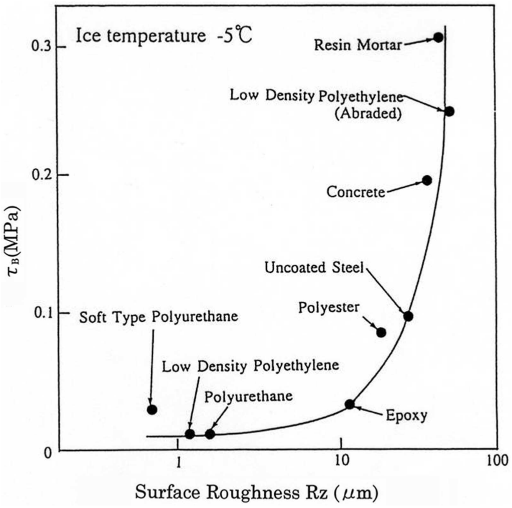


Fig. 12 Surface roughness effect on adfreeze bond strength of various materials at −5°C temperature

Beyond 20 μm of roughness, the ice bond strength greatly depends on the surface roughness, and corrosion and fouling of material surfaces have an important effect on the ice bond strength.

Murase and Nanishi (1985) pointed out that, when the interfacial free energy increases, adfreeze bond strength becomes larger and there is a linear relationship between adfreeze bond strength and interfacial free energy in the case of fresh-water ice and high-density polymers. Although their experiments were limited to fresh-water ice and high-density polymers with smooth surfaces, in general, it could be concluded that as far as smooth surfaces are concerned, adfreeze bond strength depends on the interfacial free energy of the surface of materials.

Break formation of the adfreeze bond between sea ice and various materials could be classified into 2 types:

1. Surface of a material is rough, and shear break occurs.
2. Surface of a material is smooth, and exfoliation of sea ice occurs, when external force exceeds the interfacial free energy.

Concluding Remarks on Adfreeze Bond Strength

The following conclusions can be derived from SCS and other studies:

- Afreeze bond strengths obtained by 4 different test procedures—pushout, pullout, twist and shear—are approximately of the same values. We can then use easier test methods to determine the strength for the design of hydraulic and marine structures.
- Adfreeze bond strength is largely dependent upon the diameter of a pile, or more accurately upon the adfrozen area. The larger the diameter, the less the adfreeze bond strength. The strength tends to a constant value beyond 20 or 25 cm in pile diameter.
- Adfreeze bond strength depends on the ice temperature, and it increases with decrease of the temperature. The strength does not depend on the kind of structure materials, but largely on the surface roughness of a material.
- Break mechanisms of adfrozen sea ice onto various materials are classified into 2 types:
  1. A shear break occurs at an adfrozen area on a rough surface of a material.
  2. Exfoliation of sea ice occurs at an adfrozen area on a smooth surface of a material.
- Adfreeze bond strength is dependent upon the roughness of the surface where the roughness is larger than 20 μm. The strength is dependent upon the interfacial free energy where the surface roughness is less than 20 μm.

ABRASION BY ICE

When a moving ice sheet driven by wind, current and tidal motion breaks against a concrete structure, it causes abrasion in the concrete.

A reinforced concrete structure composed of relatively thinly covered bars and lighthouses, is subject to load effects and various damage. In some cases, an accident to a structure was caused by serious abrasion of the columns, due to reinforcement bars being cut off and torn away. According to Janson (1988), lighthouses in the Gulf of Bothnia had abrasions of about 140 mm in depth and the average yearly rate reached 7 mm. The lighthouses in Helsinki were measured at about 300 mm over 30 years (Huovinen 1990). Abrasion has occurred in lakes and rivers on hydraulic structures. Fig. 13 is an example of abrasion damage to a hydraulic structure in the Saroma Lagoon in Hokkaido; Fig. 14 is an abrasion example in Cook's Inlet.

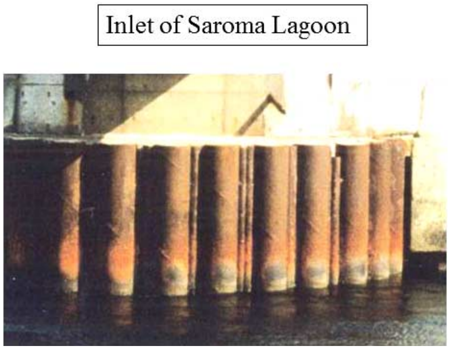


Fig. 13 Abrasion damage to hydraulic structure in Hokkaido

Increase in the thickness of a covering does not bring about a reasonable solution to preventing the damage to a reinforced concrete structure. This results in the increase of the cross-sectional area, followed by the increase in global ice loads on the structure. When the concrete aggregate particles are protruding, ice forces have even worse direction and abrasion feature changes. In addition, adfrozen ice onto the concrete in cold circumstances may cause an external force in the aggregate. Even in a steel structure, abrasion depth may reach the safety limit of the structure due to repeated actions.

The abrasion rate is defined as the depth of the abraded material surface of a structure when the ice sheet passes through a structure for 1 h in close contact with the structure surface.

In designing a marine concrete structure, mechanical, physical and chemical actions to the structure are to be taken into account. However, in this paper, abrasion as a mechanical aspect of the actions to a structure is reviewed based mainly on the SCS studies over the long term.

Test Scenario

Hydraulic and marine structures subjected to abrasion are affected by the following major factors:

- Contact pressure of ice sheet on surface of structure
- Concentration of sand as salinity of ice
- Structure's material properties

In other words, abrasion depends on:

- ice load: ice properties
- breaking features: crushing and sliding
- concrete properties: aggregate and reinforcement properties
- temperature: ice, water and air

The test apparatus for the evaluation of the abrasion of various materials by ice must meet the following requirements:

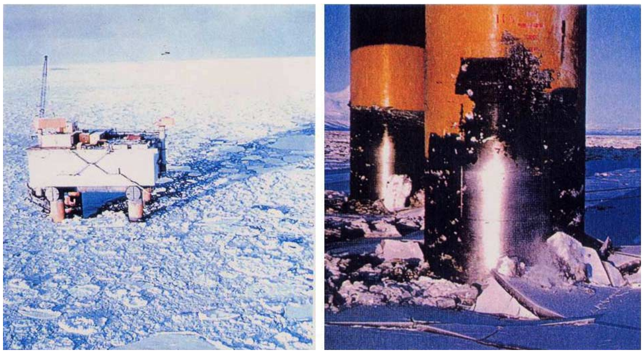


Fig. 14 Abrasion damage to marine structure in Cook's Inlet

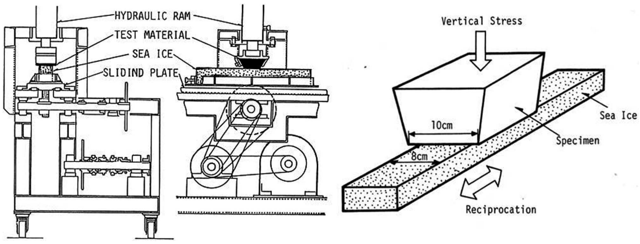


Fig. 15 SCS test apparatus for evaluation of abrasion by ice

- The contact pressure, temperature of ice, and relative sliding velocity are to be controlled.
- Static and kinetic friction forces must be continuously workable.
- The amount of abraded materials must be easily and accurately measurable.
- The ice sheet properties are required to be stable and unchanged during the test. Friction generated between ice and structure may cause melting of ice in the contact area.
- The device is required to be capable of appropriately removing torn-off ice and structure materials from the contact points or area.
- The friction coefficient between ice and material surface must be capable of keeping constant in air and water portions, respectively.
- The data obtained should be capable of scaling up to an actual abrasion rate and be useful for prevention measures against abrasion.

Fig. 15 presents the outline of the SCS test device for abrasion.

The ice specimens in the test are 8 cm wide, 70 cm long, and 8 to 12 cm thick. Material specimens were 10 cm wide. An ice specimen moved back and forth horizontally, while a material specimen of various materials was pressed down onto the ice specimen under a controlled pressure. The width of material specimens against abrasion were then 8 cm, and each of their sides had a 1-cm-wide unabraded edge portion, which made it easy to measure abrasion depths. However, when the abrasion becomes too deep, the edge effect of moving ice specimens on abrasion might be taken into account. The relative velocity of sliding of the ice was determined by the friction coefficient measurement tests, and ice specimens moved back and forth at 2 cm/s, 5 cm/s and 20 cm/s. Static and kinetic friction forces thus acted on the interface alternately. The test apparatus was installed in a cold room, where the temperature could change widely and remain stable. The contact pressure varied from 0 to 70 MPa. An air blower was applied to remove abraded fragments of ice and materials by blowing cold air of the controlled temperature. This also worked for blowing on ice specimens to cool down to a desired temperature.

The test device is superior to others in many points. However, a weak point of this device originates from the mechanical property of the ice specimens themselves, that is, the ice specimens under high contact pressure (over 1.5 MPa) were broken due to the fatigue of the ice after a certain number of back-and-forth movements, and replacement of ice specimens was rather frequent.

Hara et al. (1995) examined each test equipment for abrasion on its capability, accuracy, ease of use, etc. and discussed its merits and demerits. They concluded that the reciprocal motion type, which featured back-and-forth sliding of a material specimen on an ice specimen, could produce the most reasonable data on abrasion by ice. At that time, in total, there had been 7 types of test devices developed in the world.

Fig. 16 shows the relationship between the average amount of material abrasion and total sliding distances. In this figure, N.C.

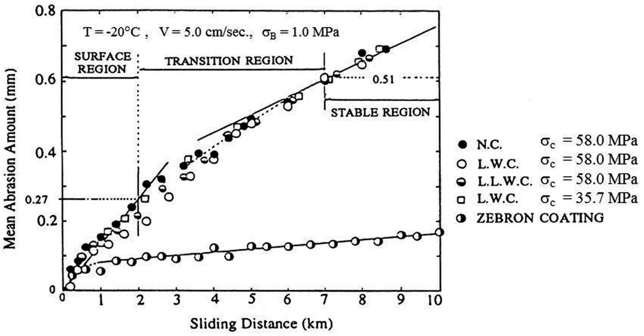


Fig. 16 Relationship between amount of material abrasion and total sliding distance

is of normal concrete containing ordinary fine and coarse aggregates with unconfined compressive strength $\sigma_c = 58$ MPa, and L.W.C. is of high-strength and light-weight concrete containing ordinary fine and coarse aggregates with the same strength as N.C. L.L.W.C. is of high-strength and light-weight concrete containing light-weight fine and coarse aggregates with the same strength as N.C. L.W.C. is of light-weight concrete with unconfined compressive strength 35.7 MPa. Only L.W.C. has compressive strength weaker than the others.

Fig. 16 shows that the evaluation of the mean amount of the abraded materials divided the abrasion process into 3 main stages: surface region, transition region and stable region. It is noted that the abrasion process seemed to be independent of the kinds of concrete, aggregates and compressive strengths of materials.

While the total sliding distance was less than 2 km and the mean abrasion amount was less than 0.27 mm, the abrasion rate was as high as 0.135 mm/km. In this range, the uneven concrete and cement pastes in the surface layer were mostly abraded, and the aggregates were rarely observed on the material specimens after the abrasion tests.

Where the total sliding distance ranged from 2 km and 7 km and the mean abrasion amount ranged from 0.27 mm to 0.61 mm, the mean abrasion rate was lower than in the surface region and 0.77 mm/km in average. In the transition region, the fine and coarse aggregates were partially exposed on the surface.

In the range where the total sliding distance was longer than 7 km, the mean abrasion rate decreased to approximately 0.15 mm/km, which was about 1/5th of the rate in the surface region. In this range, much more coarse aggregates were exposed.

In these tests, after the total sliding distance reached 10 km and the mean abrasion amount came to about 0.76 mm in abraded depth, a question arose as to the continuation of this tendency. We then carried out additional tests with concrete specimens with coarse aggregates exposed on their surfaces. The specimens were made by cutting the surface layer of concrete by 6 to 10 mm. Fig. 17 shows the test result.

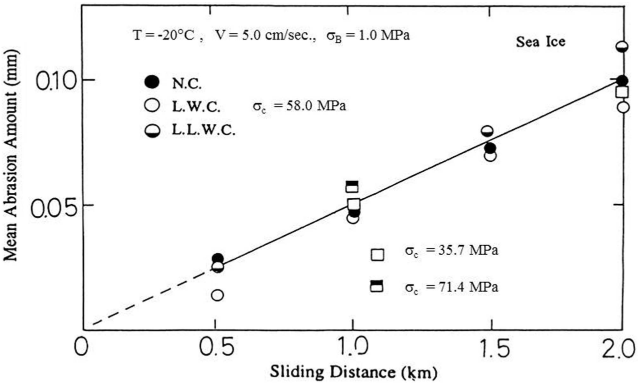


Fig. 17 Abrasion tests with surface-layer-cut concrete specimens

The mean abrasion amount was found to have a linear relationship with the total sliding distance, and the mean abrasion rate was 0.055 mm/km. The results indicated that, when the mean abrasion amount exceeded 0.61 mm in depth from the surface of the concrete, the mean abrasion rate became constant, bearing no relation to the strength of concrete and the kinds of aggregates in concrete. This finding allowed us to shorten the test time considerably, and the SCS used such specimens in the later tests.

As far as the SCS tests are concerned, it could be concluded that the mean abrasion amount and the mean abrasion rate by sea ice are not affected by the kinds of aggregates and the strength of concrete, and the abrasion rate in the stable region should be adopted for the design purpose.

In the case of the materials whose surfaces are coated by Zebron and smooth and uniform such as uncorroded steel and synthetic materials, the abrasion process could be divided into 2 stages: surface and stable regions.

Abrasion Rate and Relative Velocity

The abrasion rate was supposed to be affected by the relative velocity at the surface of materials.

Fig. 18 shows the relationship between the relative velocity and the mean abrasion rate for different types of concrete with different unconfined compressive strength.

The available maximum relative speed was 20 cm/s in the tests and an unstable range in velocity control existed, which resulted in rather a small number of data obtained. Within the data obtained, it could be said that, as the relative velocity increased, the mean abrasion rate decreased, and the decrease extent of the mean abrasion rate in the low velocity range was higher than in the high velocity range. This tendency is very similar to the case of the friction coefficient as shown in Fig. 19.

Since the total sliding distance did not increase much in the low velocity range, the relative velocity should be set at 5 cm/s or higher in order to study concrete abrasion practically. If the relative velocity was set at about 20 cm/s, the test time required

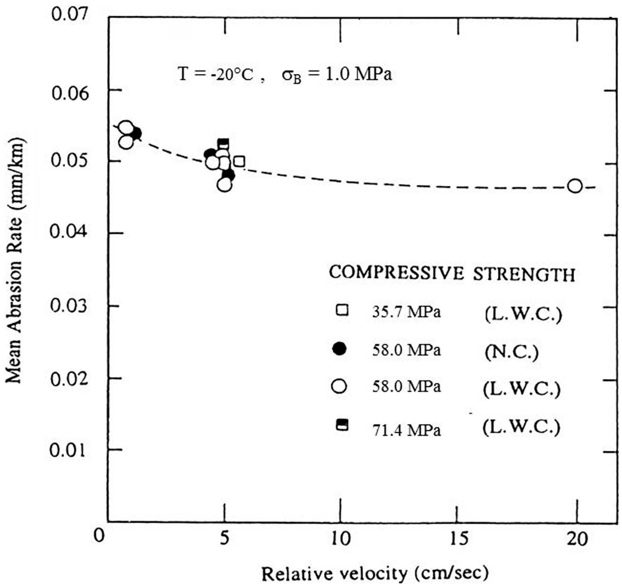


Fig. 18 Mean abrasion rate and relative velocity

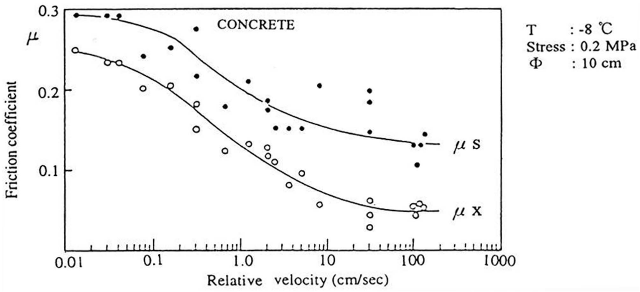


Fig. 19 Friction coefficient and relative velocity

could be reduced. However, at such high velocity, replacement of ice specimens becomes too frequent, and the test device might be swayed by the overload and vibration troubles. The SCS adopted the relative velocity of 5 cm/s as the standard in the later tests.

Abrasion Rate and Ice Temperature

The friction coefficient of sea ice against a material depends on the ice temperature. Fig. 20 shows the mean abrasion rate at different ice temperatures.

The kinds of aggregates seemed to have no effect on the friction coefficient. When the temperature went to −10°C and lower, the mean abrasion rate increased rapidly with increase in temperature. The noticeable temperature dependence of the friction coefficient was not observed in these. According to the phase diagram for sea ice ("standard"), solid salts appear at different temperature when sea ice continues to cool. Solid salt $Na_2SO_4 \cdot 10H_2O$ appears under −8.2°C, and $NaCl \cdot 8H_2O$ is observed in a solid phase under −22.0°C. Such solid salts accelerated abrasion at temperatures lower than about −10°C.

Fig. 21 shows the effect of vertical stress (contact pressure) on the mean abrasion rate. The relative velocity was 5.0 cm/s in each test.

The mean abrasion rate had a linear relationship with vertical stress on sea ice, at least within the test range. The mean abrasion rate was nearly constant at temperatures higher than −1°C. When the temperature went down from −10°C to −20°C, the rate went higher with much increment.

Abrasion by Fresh-Water Ice

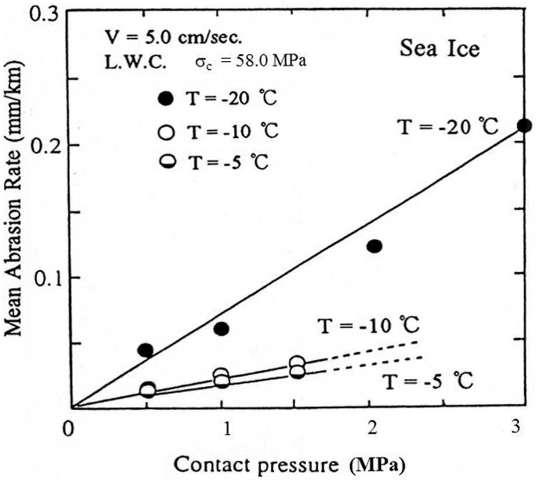


Fig. 21 Effect of contact pressure on abrasion

Abrasion problems by fresh-water ice have also been investigated by the SCS. Being similar to sea ice, the abrasion process for fresh-water ice was found to divide into 3 stages: surface, transition and stable regions. The dependence of the mean abrasion amount on the total sliding distance was found to be almost the same as the abrasion by sea ice. No meaningful difference was observed in the mean abrasion amount through the tests with different kinds of aggregates of concrete and different strengths of concrete.

Fig. 22 shows the test results on the mean abrasion rate under different vertical stresses and different temperatures. The rate had a similar linear relationship with the vertical stress.

Fig. 23 shows the relationship between the mean abrasion rate, ice temperature and vertical stress on ice.

When the temperature was higher than −10°C, no difference was observed in the mean abrasion rate between sea ice and fresh-water ice. However, at a temperature as low as −20°C, the mean abrasion rate by sea ice was much higher than by fresh-water ice.

Effect of Solid Substances in Ice on Abrasion

Solid salts in ice accelerated the abrasion, as observed in the case of sea water at low temperature. A similar effect was expected even in the abrasion by fresh-water ice, since the ice often contains various small particles such as sand, clay, powered concrete, etc. Tachibana et al. (1991) carried out a survey of the contents included in the Hokkaido ice, snow and water. The diameters of solid particles in ice had relatively wide distributions, and the median values were adopted. The ice on the seashores

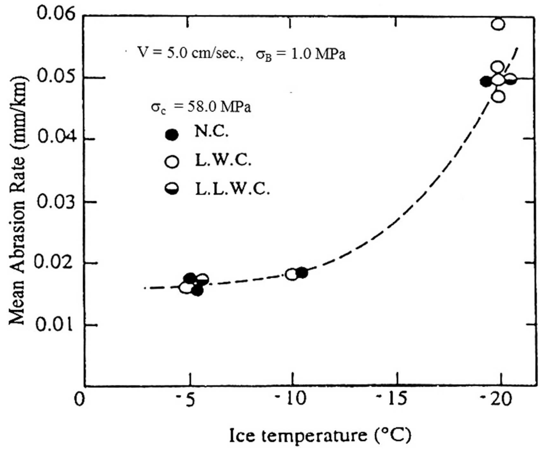


Fig. 20 Temperature dependence of abrasion

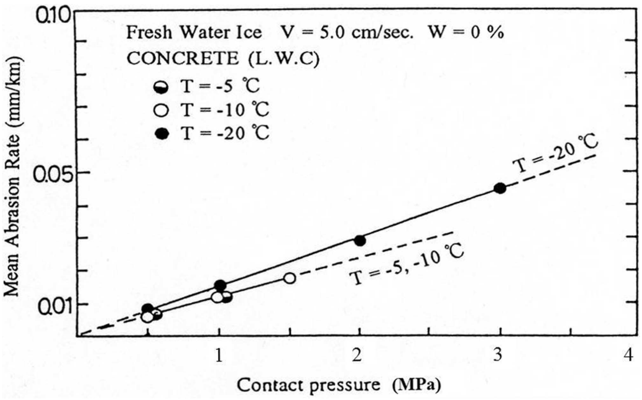


Fig. 22 Effect of vertical stress on mean abrasion rate (fresh-water ice)

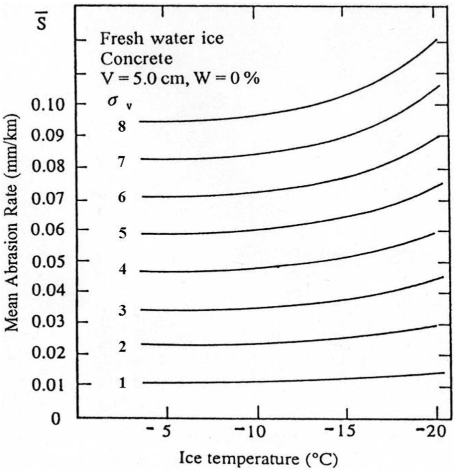


Fig. 23 Relationship between mean abrasion rate, ice temperature and vertical stress on ice (σ_v in MPa)

in Horonai and Kitamiesashi was rich in solid substances, and its concentration was about 0.37%. In Barato Lake, the largest particles in median diameter were observed in ice; the largest was about 0.2 mm. Naturally, all ice contained a certain amount of minute solid particles.

Fig. 24 shows the test results on abrasion by fresh-water ice containing solid particles, where the concentration of sand particles is denoted by w and the median diameter of solid particles by d. In this test case, the concentration of sand particles was 0.4%, nearly the maximum value in the surveyed area. The ice temperature was −10°C. The relative velocity of the ice movement was 5 cm/s. The median diameters of the sand particles were chosen to be 0.03, 0.14 and 0.7 mm, respectively. The test results were quite natural: Ice abrasion containing solid particles is much more marked than by pure ice, and the concrete becomes weaker against ice abrasion when the ice contains larger solid particles on average and the materials suffer higher vertical stress by ice.

Table 1 is a summary of sea-ice abrasion rates of various materials and coatings and rocks. In this table, the numerals in red (inside parentheses) show the mean abrasion rates by fresh-water ice, and the numerals in blue (inside brackets) show the unconfined compressive strength of rocks.

To sum up, the mean abrasion rates of all of the materials tested increase with decreasing temperature, and the rates by sea ice are higher than by fresh-water ice. As to rocks, the mean abrasion rates decrease with increase of the unconfined compressive strength.

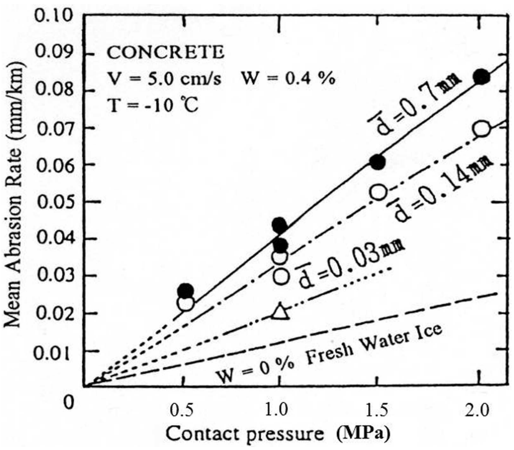


Fig. 24 Effect of vertical stress on abrasion rate by fresh-water ice containing solid particles

	$\sigma_v = 1$ MPa, $V = 5$ cm/s		
	−20°C mm/km	−10°C mm/km	
			$d = 0.14$ mm $W = 0.4\%$
Synthetic materials			
Low density polyethylene	0.0029 (0.0024)	0.0025	0.0213
Polyurethan	0.0028		
Soft type polyurethane	0.0045	0.0030 (0.0027)	0.0159
Epoxy	0.010		
Polyester	0.0169		
Resin mortar	0.017		
Uncoated steal	0.0045	0.0030 (0.0027)	0.0137
Concrete	0.050 (0.014)	0.0178 (0.012)	0.035
Zebron	0.010		
Rock			
Sand stone		0.005 [−]	
Granite		0.0216 [255]	
Tuff		0.0251 [21]	
Pyroxene andesite		0.0084 [134]	
Decite A		0.0065 [155]	
Decite B		0.0177 [150]	

( ) freshwater ice, [ ] compressive strength MPa.

Table 1 Abrasion rate due to movement of sea ice

Estimation of Amount of Abrasion by Ice on Hydraulic Structures

The factors related to the amount of abrasion rate on a hydraulic structure are ice temperature, contact pressure, and concentration and median diameter of sand particles in ice.

The amount of abrasion can be estimated by multiplying the combined abrasion rate and the travelling distance (sliding distance in model tests) of the ice sheet around the structure. However, the travelling distance of an ice sheet is hardly estimated in reality. For design purposes, the possible maximum value could be applied.

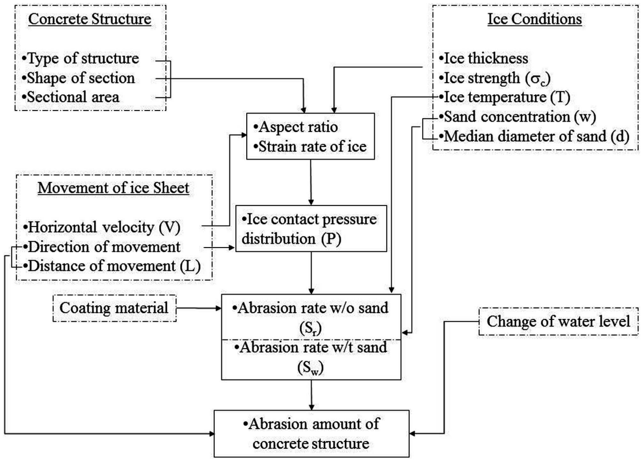
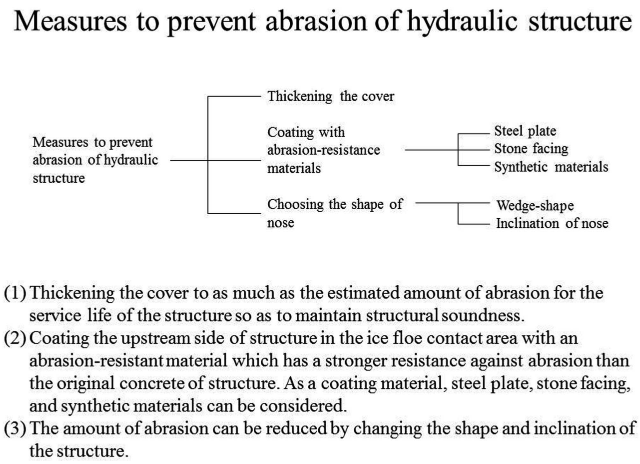


Fig. 25 Flow-chart estimate of abrasion amount


Measures to prevent abrasion of hydraulic structure

(1) Thickening the cover to as much as the estimated amount of abrasion for the service life of the structure so as to maintain structural soundness.
(2) Coating the upstream side of structure in the ice floe contact area with an abrasion-resistant material which has a stronger resistance against abrasion than the original concrete of structure. As a coating material, steel plate, stone facing, and synthetic materials can be considered.
(3) The amount of abrasion can be reduced by changing the shape and inclination of the structure.

Fig. 26 Measures to prevent abrasion of hydraulic structures

Measures to Prevent Abrasion

Various measures have been developed to prevent or reduce abrasion by ice on structures.

Based on the current damage risk analyses and repair procedures for hydraulic and marine structures facing ice and sea ice forces, the measures could be classified into 3 major categories, as shown in Fig. 26: Thickening the cover, coating with abrasion-resistance materials, and choosing the nose shape.

The first measure enlarges the cross-section as well as the weight of a structure, which results in increased damage risk of the structure due to heavier ice loads and the horizontal force caused by earthquakes, endangering the stability of the structure.

The second measure—protection by coating—asks a key question, that of finding an appropriate coating material. The SCS test results suggest that Urethane could be applied directly to concrete, as the coating thickness is easily capable of adjusting. An application of Polyester coating is rather limited, as Polyester is not an easy coating material with which to finish the surface evenly and smoothly. In addition, Polyester-coated surfaces are easily peeled off due to the ice action in cold circumstances. Synthetic materials are to be fully examined for their deterioration in original properties due to ultraviolet radiation, etc., through the outdoor exposures of the materials or other test devices so as to be able to evaluate changes in the short term. Sometimes ice contains plenty of sand particles with various sizes, and the abrasion rate of synthetic materials by such an ice was observed to be much higher than the rate of the concrete.

Concluding Remarks on Abrasion by Ice of Various Materials

The concluding remarks on abrasion by ice of various materials and measures to prevent abrasion of materials are rather simple.

From these test results and points of view, for the moment, steel and stainless steel, which have already been used in many cases, are easy and reliable materials of hydraulic and marine structures.

CONCLUSION

These discussions are mainly based on the results of the studies carried out by the author and various combinations of colleagues, postgraduate and graduate students under his Chairmanship for over 20 years; these groups are referred to as the SCS.

The SCS has carried out research on ice engineering for over 2 decades and covered almost all the subjects in ice engineering. In this paper, the author offers an outline of the SCS activities and their outcomes, limiting it to 2 basic but important subjects: adfreeze bond strength and ice abrasion of materials.

In the Arctic Ocean, with the growth in exploitation and production of energy resources and minerals, sea ice is retreating in the summer but a large amount of sea ice still covers the ocean in winter. Hence, these 2 subjects will become crucial in the decades to come.

AKNOWLEDGEMENTS

The author would like to express his deep gratitude to Prof. Jin S. Chung, who gave him the opportunity to address the subject of adfreeze bond strength between ice and various materials and ice abrasion on structures, based on the results of studies carried out by the author and various combinations of colleagues, postgraduate and graduate students under his Chairmanship for over 20 years; these groups are referred to as the SCS.

Most sincere thanks go to every contributor who collaborated on these subjects over this long span of time.

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