

ABRASION OF CONCRETE BY ICE IN ARCTIC SEA STRUCTURES

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ABSTRACT

In the research, abrasion of the concrete in arctic sea structures is examined, especially near the water level. The concrete structure is subjected to a heavy mechanical load near the water level, due to the moving ice sheet as it breaks against the structure. Furthermore, recurrent freeze-thaw cycles deteriorate the concrete, if it has not been designed to resist recurrent freezing in marine conditions. The abrasion of concrete in arctic sea structures can be estimated by means of the laboratory abrasion test development in connection with the research and other laboratory tests. The estimation of abrasion depth can also be carried out by means of diagrams based on calculations and laboratory test results.

1. ABRASION MECHANISM

A concrete offshore structure in arctic conditions is subjected to various damage and load effects. On the basis of their effect they can be classified as mechanical, physical or chemical action causes damage to concrete. The damage effects are set out in Fig. 1.

When a moving ice sheet breaks against a structure it causes abrasion in the concrete. If the concrete aggregate stones are protruding (the finer concrete substances having worn off), ice produces forces with various directions, depending on the route of the ice in relation to the concrete structure surface. Ice frozen onto the concrete may, in addition, cause external mechanical forces in the aggregate. The magnitudes of the forces depend both on the ice properties and the size of aggregate stones. Loads due to ice are recurrent owing to the way ice breaks.

Physical damage is attributable to the pressure of freezing water present in the concrete and the shrinkage of concrete as well as thermal gradients. The freezing of water present in the concrete is also recurrent.

Shrinkage as well as temperature gradients cause cracks in the concrete, which enable the penetration of moisture and salts.

Naturally, shrinkage does not occur if the structure is continuously in contact with water after hardening of the concrete.

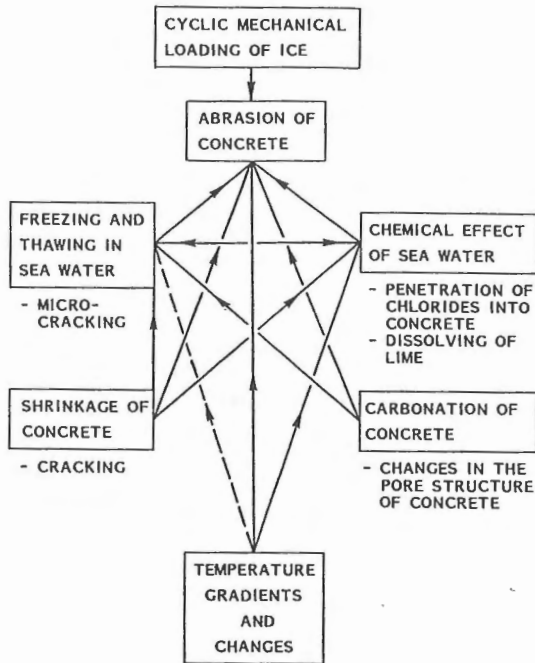


Fig. 1. Effects causing damage to concrete in sea water.

Chemical factors that damage concrete result from the chemical effect of sea water and the carbonation of concrete. Sea water may dissolve lime in some concretes: the permeability of concrete increases and the penetration of chlorides and water into concrete becomes easier. On the basis of studies, the chemical damage to concrete in cold areas is slight, however. The carbonation of concrete may cause changes in the concrete microstructure and thus affect the durability, particularly with regard to the resistance to freezing and thawing.

As seen in Fig. 1 the effect of damage may be direct or it may be a combination of two factors.

Sea water may also cause complicated chemical reactions between the sulphates in sea water and the constituents of hydrated cement. The reactions may expand the cement stone in concrete, which further weakens the mechanical properties of concrete.

This study focuses on the examination of the effect of the two most important deterioration factors i.e. the mechanical loading due to ice and the repeated freezing and thawing of concrete in sea water.

2. DETERMINATION OF ABRASION OF CONCRETE

2.1 General

The determination of abrasion of concrete in arctic offshore structures is based on four different factors:

- laboratory tests
- tests with an icebreaker
- abrasion studies on Finnish lighthouses
- computer calculations.

An abrasion machine was developed for laboratory use. The abrasion resistance of different concretes can be studied with the abrasion machine so that the concretes will have under gone cyclic freezing-thawing tests before the abrasion tests.

The abrasion resistance of similar concrete mixes was also studied at sea with an icebreaker. In icebreaker tests the specimens were fastened onto the bow of the icebreaker at water level. The abrasion of the concrete specimens was measured at the end of the tests.

The abrasion of Finnish lighthouses was measured at four lighthouses in the Gulf of Bothnia.

The abrasion and fracture of the concretes were also studied with computer calculations. The ice pressures against small areas such as aggregate particles that are protruding from the surface of a concrete structure were measured with laboratory tests. Also the bond strength between aggregate particles and cement stone was measured in tests. These values were needed in the computer calculations. On the basis of the calculations, using the calculation model, the abrasion of concrete was estimated as the function of ice sheet movement.

2.2 Field and laboratory tests

The field investigation of the Finnish lighthouses showed that ice had abraded concrete significantly. The abrasion of the lighthouse in Helsinki was measured to be about 300 mm over 30 years. The lighthouses in the Gulf of Bothnia had abrasions of 15 - 50 mm at water level. The ages of these lighthouses were between 22 - 24 years. The principal reasons for the abrasion were the low resistance of concretes to frost in combination with the abrasion by ice. The ice had worn off the frostdamaged part of the concrete surface. Subsequently, the new surface had been damaged during the repeated freezing and thawing. In this way the damage mechanism had been repeated.

The compressive strength of the lighthouse concretes was measured on the surface of the structure both at water level and at 1.5 m above water level. The strengths of concrete at water level were found to be 53 - 58 % of the strengths of concrete above water level.

The strength results are set out in Table 1 and they have been determined using both drilling samples and a rebound hammer.

The changes of the strength and strain properties of different concretes during the freeze-thaw cycles were examined by means of laboratory tests. The test specimens were frozen and thawed in synthetic sea water corresponding to ocean water.

Table 1. Compressive strength of concrete in lighthouses.

Light-house	Strength of concrete [MPa]	
	water level	1.5 above water level
Oulu 1	40	71
Oulu 2	39	73
Oulu 3	46	80
Raahe	35	65

The temperature varied from -40°C to $+20^{\circ}\text{C}$. The concretes were subjected to 50 - 100 freeze-thaw cycles. The properties examined comprise concrete strengths, such as compressive and tensile strength, and the bond strength between the aggregate and the cement stone that is critical in abrasion of concrete when ice presses against the structure and breaks.

Other studies were the studies of the stress-strain relationships as well as of the changes of fracture energy measured in the compression test during the freeze-thaw cycles. In addition, the reduction in the fatigue strength of concretes due to repeated freezing and thawing was studied by means of mechanic cyclic loading tests. The studied concrete mixture were

- Ordinary cement concrete (binder amount 500 kg/m^3)
- Blast furnace cement concrete (binder amount 500 kg/m^3)
- Portland cement concrete with added silica (binder amount 420 kg/m^3 and about 9 % silica)
- Concrete with light-weight aggregates (binder amount 438 kg/m^3).

The air volumes of concrete were varied (3 - 8 %). The design strength of the concretes was 60 MPa besides concrete with light-weight aggregates (30 MPa).

The best results in the strength tests after freeze-thaw cycles were achieved with concretes containing silica and blast furnace slag and the worst results with light-weight aggregate concretes. The fracture energies decreased in all concretes during freeze-thaw cycles.

In the case of ordinary cement concretes, the bond strength of aggregate stones at the concrete surface was reduced during the repeated freezing-thawing tests more rapidly than the compressive or tensile strengths. The ratio of the bond and tensile strengths was about 0.7 at the beginning of the freezing-thawing tests and about 0.3 - 0.5 at the end of the tests.

In Fig. 2 the flexural tensile strength of test concretes and the bond strength of aggregate stones are presented as the function of w/c ratio after 0, 25 and 50 freeze-thaw cycles. Regression lines have also been calculated for the test results

after a varying number of freeze-thaw cycles and they are set out in Figure.

The numbers in the figure refer to the test concretes.

The abrasion of concretes was also studied at sea with an ice-breaker. The test specimen was placed on the bow of the ice-breaker on water level. The test arrangements are presented in Fig. 3. The abrasion of the concrete on the surface of the specimens varied between 2 - 15 mm (mean values) when the compression strength varied between 30 - 60 MPa and the movement of the icebreaker was about 40 km.

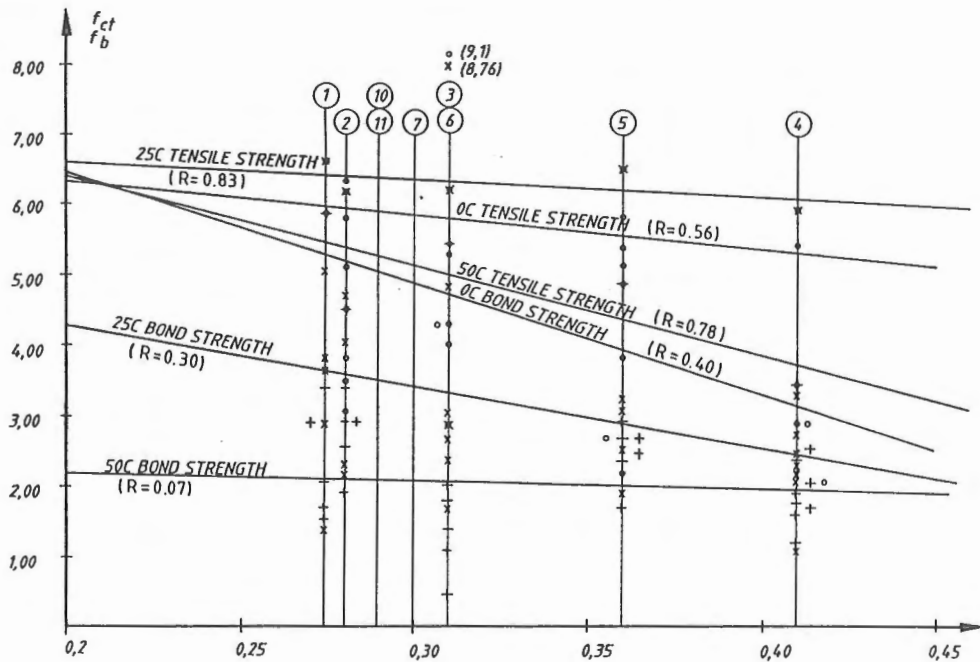


Fig. 2. Flexural tensile strength of concrete and the bond strength of aggregate stones as the function of the w/c ratio and number of freeze-thaw cycles.

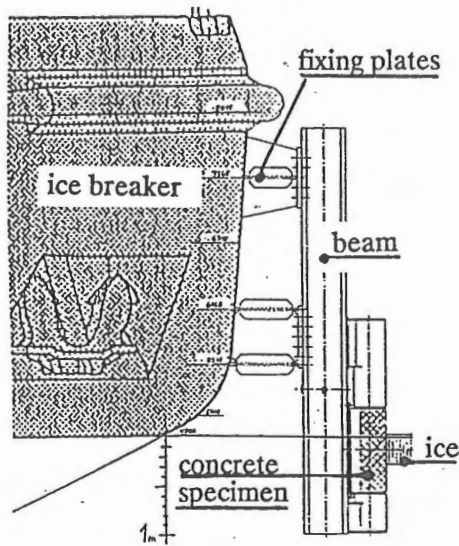
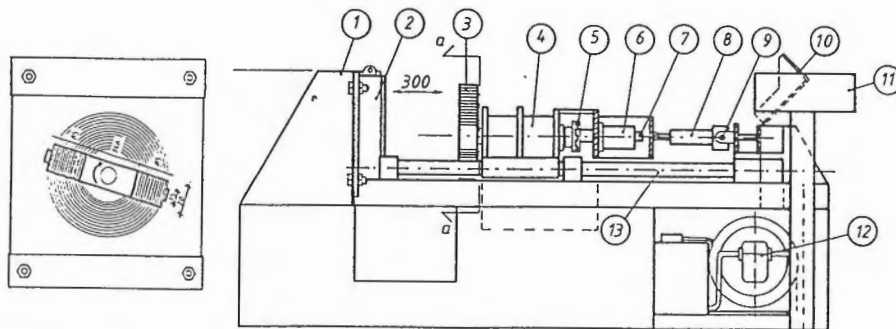


Fig. 3. Test arrangements of ice breaker test /2/

An abrasion machine was developed for laboratory use, with the help of which the abrasion resistance of concrete was examined after a varying number of freeze-thaw cycles. Fig. 4 shows the structure of the abrasion machine and the slab subjected to abrasion.

Also the ice forces against protrudent aggregate stones were measured with laboratory tests. Both the shear component parallel to the concrete surface and the normal component perpendicular to the surface was measured. The values are needed in the abrasion calculations.



- 1 machine body
- 2 concrete specimen
- 3 cutter
- 4 ... 12 machine components

Fig. 4. Abrasion machine and the test specimen /2/.

The values of the loads (impact speed 0.5 m/s) are presented in Table 2 for ice sheet thickness $d = 1000 - 1500$ when the air temperature is -40 °C and sea water temperature -2 °C.

Table 2. Loads due to ice impact on protrudent aggregate stones.

Stone size	Normal component σ_i [MPa]	Shear component τ_i [MPa]
ϕ 8	17	17
ϕ 32	10	17

2.3 Abrasion calculation models

The calculation models for the abrasion of concrete are presented in Fig. 5. The elements of the calculation models are parametric elements with 8 nodes.

The crack length L_{Cr} is calculated by increasing the loads little by little to the values corresponding to σ_i and τ_i .

The effect of ice is inserted in the calculation model to act as external load. Ice loads are produced by a normal component perpendicular to the concrete surface and also by a shear component parallel to the surface when fine binder and aggregate particles have worn off and large aggregate stones protrude from the surface. The magnitudes of these force components were determined in laboratory tests.

The material constants and the strength and strain values were determined in laboratory tests and they also inserted in the model.

The calculation model a) (protrusion 0.7 R) was chosen on the basis of the studies concerning the surfaces of actual concrete offshore structures. On the basis of the studies the protrusion of the aggregate stones on the surface offshore structure at water level was proved to be generally 0.7 R when R is the radius of the stone. The calculation model b) (protrusion R) was chosen to ascertain the loosening of the stone from the surface.

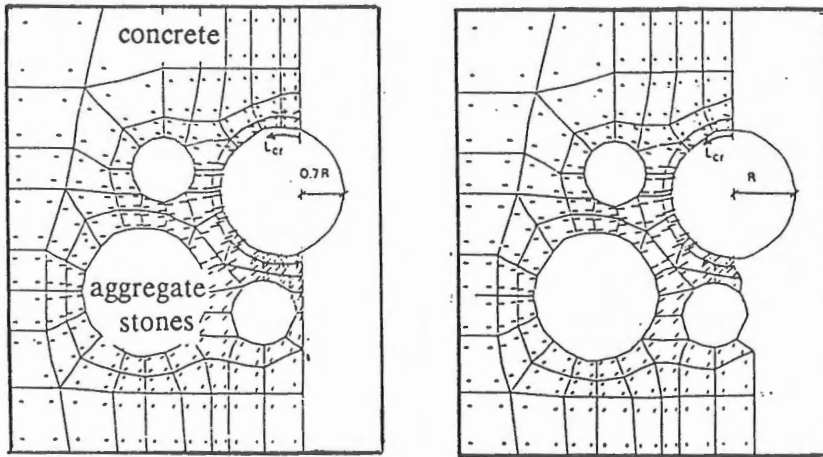


Fig. 5. Calculation models /2/.

The following formula takes into account the recurrence of ice loads in damp concrete /1/.

$$\log N = 13,92 - 14.42 \frac{\sigma_{\max}}{f_{ab}} \quad (1)$$

where N = the number of impacts by ice
 σ_{\max} = the tensile strength of the transition layer between the stone and cement stone subjected to repeated loading
 f_{ab} = the tensile strength of the transition layer between the stone and cement stone subjected to static load.

In the computer calculations the following values have been used:

E_c = 5000 $\sqrt{f_c}$ for concrete
 E_{ctr} = 30 000 MPa for transition layer
 E_a = 50 000 MPa for aggregate
 ϵ_{fc} = 2.2 ‰ for f_c
 ϵ_{cu} = 3.5 ‰ (ultimate strain)
 f_a = 200 MPa for aggregate in compression
 f_{at} = 14 MPa for aggregate in tension
 f_{ct} = 0.1 f_c for concrete in tension
 f_{ab} = 0.9 f_{ct} for bond strength between aggregate stones and cement stone.

2.4 Abrasion calculation and test results

The abrasion depth of concrete in arctic sea structures can be calculated as the sum total of the abrasion depth of cement stone measured in ice-breaker tests at sea and the loosening of aggregate stones from concrete surface. As the condition for the loosening of the aggregate stone can be considered

$$L_{CR}/R = 1 \quad (2)$$

where R is the radius of the aggregate stone and L_{CR} the crack length.

The abrasion rate for cement stone is achieved with the results in icebreaker test

$$b = \frac{3}{f_C} s \text{ [mm/km]} \quad (3)$$

where s is the movement of ice sheet in [km] and f_C the compressive strength of concrete in [MPa].

The total abrasion depth can be calculated with the formula

$$ABR = \sum_{i=1}^n a_i \frac{\lg n_S}{\lg n_1} R_i + (1 - \sum a_i) \cdot b \quad (4)$$

where a_i = the proportional amount of aggregate stones of radius R_i
 n_S = number of ice impacts during ice sheet movement s
 n_1 = number of ice impacts when $L_{CR}/R = 1$
 b = abrasion rate of cement stone [mm].

The abrasion as the function of ice sheet movement is graphically presented in Fig. 6.

The abrasion diagrams are valid when the aggregate distribution of concrete in normal ($\phi \leq 6$ mm 43 %, $6 \leq \phi \leq 12$ 18 %, $12 \leq \phi \leq 24$ 26 %, $24 \leq \phi \leq 32$ 13 %). In addition to the compressive requirement $f_C = 40, 60, 80, 100$ MPa it is presupposed that the tensile strength of concrete f_{ct} is at least 10 % of the compressive strength and the bond strength between aggregate stones is at least 90 % of the tensile strength of concrete.

In Fig. 7 the abrasion (max. and min. values) of concrete is presented as the function of the compressive strength of concrete in laboratory abrasion tests during 10 minutes, in icebreaker tests, for ice field movements of 40 km, 100 km and 1000 km according to the abrasion calculations and in Finnish lighthouses during one year.

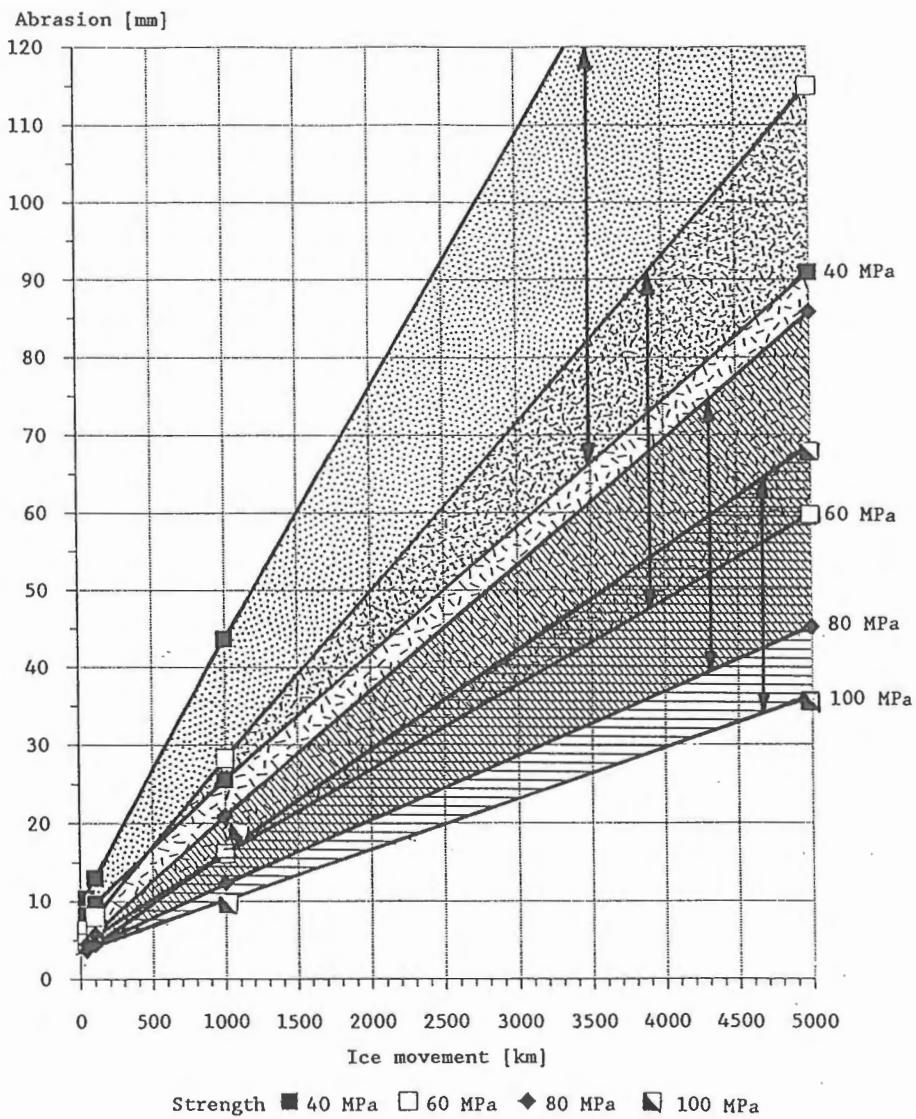


Fig. 6. Abrasion of concrete strengths $f_c = 40, 60, 80$ and 100 MPa as the function of ice sheet movement.

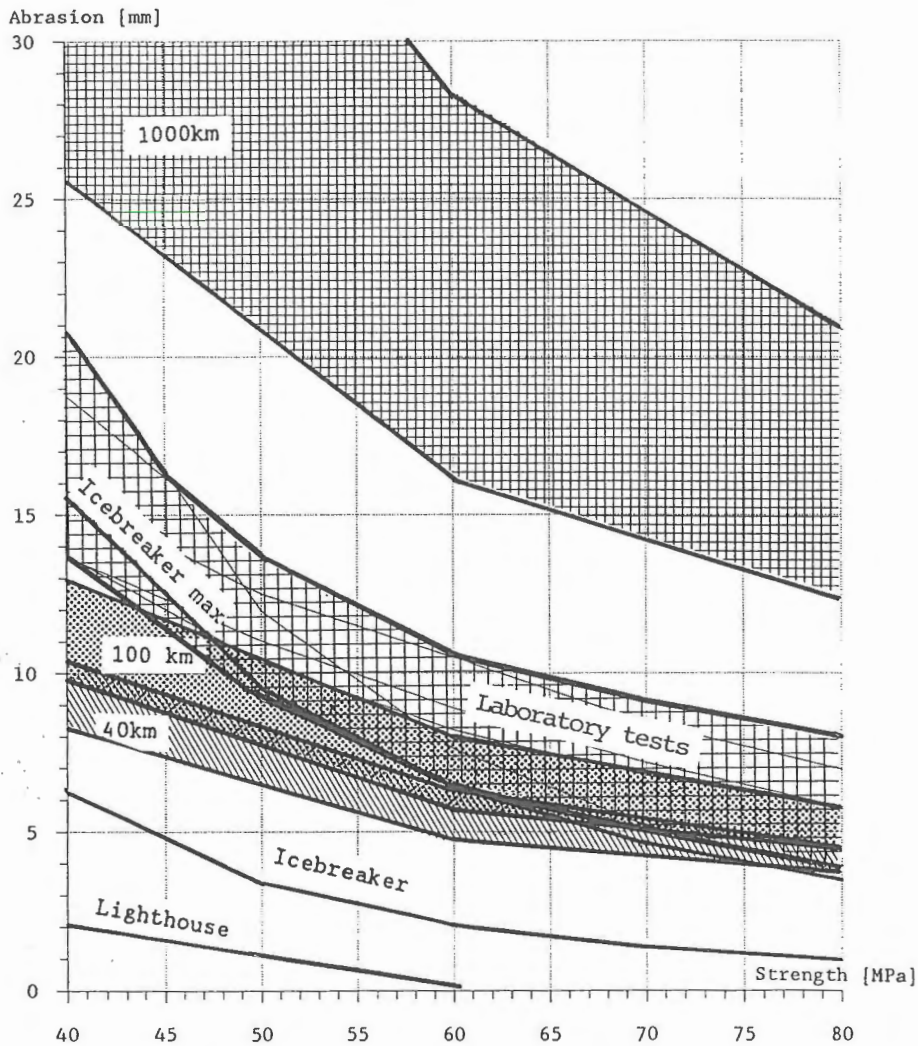


Fig. 7. Abrasion of concrete as the function of compressive strength /2/.

3. CONCLUSIONS

1. The abrasion depth and resistance of concrete in arctic sea conditions can be determined either by using abrasion diagrams or laboratory tests. The best results are achieved by using both of these methods. When using the abrasion diagrams, the abrasion depth can be estimated as a function of the compressive strength of concrete and ice sheet movement. The abrasion resistance can also be measured by using the laboratory abrasion test lasting ten minutes. Before the abrasion test, the concrete plate should undergo a cyclic freeze-thaw test in sea water for 50 cycles with the temperature varying between $-50 - +20$ °C.

2. The most important mechanical factor pertaining to the measurement of the resistance to abrasion of concrete is the strength of concrete. The bond strength of aggregate stones and cement stones as well as its resistance to repeated freeze-thaw cycles is especially crucial. For a good resistance of abrasion the compressive strength of concrete should be at least $f_c = 70$ MPa. In addition, the concrete must naturally be frost resistant. In the tests performed, the strength of concrete during the repeated freeze-thaw tests was best when the water/cement ratio of the concretes was at the most $w/c = 0.3 - 0.35$.
3. In the case of ordinary cement concretes, the bond strength of aggregate stones at the concrete surface was reduced during the repeated freeze-thaw tests more rapidly than the compressive or tensile strengths. The relation between the bond and tensile strengths was about 0.7 at the beginning of the freeze-thaw tests and about 0.3 - 0.5 at the end of the tests in ordinary cement concretes. Apparently, the changes in temperature, when they exceed approximately $DT = 40$ °C, deteriorate the bond of the stones at the surface and increase cracking, especially in the bond zone of stones.
4. The best results in both the strength and abrasion tests were achieved with concretes containing silica and blast furnace slag.
5. The resistance to abrasion of concrete can be improved by preventing frost damage either by keeping the entire wall so warm or so frozen that it is not exposed to freeze-thaw cycles.
6. If the value obtained for the bond strength of concrete aggregate stones is at least $f_{ab} = 8$ MPa, the resistance to ice abrasion of concrete is considered very good.
7. If the abrasion depth in the laboratory test after a freeze-thaw test of fifty cycles is at the most 10 mm, the resistance to ice abrasion of concrete can be considered good.
8. Increasing the maximum size of the aggregate reduces the abrasion in concrete. Large stones protruding from the concrete surface break the ice before the ice affects the finer concrete substances.
9. The use of hard homogeneous concrete in the ice abrasion zone reduces abrasion because the surface is subjected to even abrasion and there are no detaching stones.

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