ABRASION OF CONCRETE STRUCTURES BY ICE

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ABSTRACT

In arctic sea regions a concrete sea structure in subjected to heavy mechanical loads near the water level due to the moving ice sheet. Moving ice sheets load protruding aggregate stones, and the loads are considerably greater than the compressive strength of ice as determined in uniaxial compressive tests. This is due to the triaxial compression stress in the ice surrounding the stone surface.

Also, recurrent freeze-thaw cycles in the concrete wetted by waves and the tide expose the concrete to damage if it has not been designed to resist recurrent freezing in marine conditions. Temperature changes that exceed the approximate value $\Delta T = 40$ °C also deteriorate the bond between the cement stone and the stones and increase cracking in the cement stone between the aggregate stones.

This paper deals with the abrasion problem. The abrasion depth and resistance of concrete in arctic sea conditions can in practice be determined by calculations and laboratory tests.

1 ABRASION MECHANISMS

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 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.

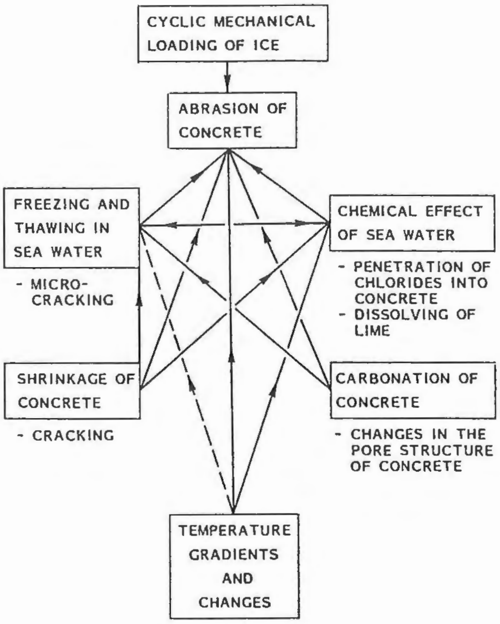


Fig. 1. Effects causing damage to concrete in sea water /1/.

2 ABRASION TESTING

2.1 General

The solution to the abrasion problem of concrete sea structures has been sought both by developing abrasion testing methods for laboratory use and by measuring the abrasion depths of lighthouses and other sea structures. The friction forces between concrete and ice have also been measured. The most dominant factors found to affect abrasion are the temperature of the ice, the stress intensity of the ice against the concrete surface in a friction test, the strength of concrete and especially the durability of the strength during freeze-thaw cycles. The lower the temperature of the ice and the higher the stress intensity, the greater is the abrasion. The ice abrasion problem, however, is more complex than a simple abrasion of the concrete measured in a few tests /2, 1/.

In a Finnish study /1/ the determination of abrasion of concrete in arctic offshore structures was based on four different methods:

- 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 concrete 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 concrete 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 /1/.

2.2 Field studies

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 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 /1/.

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 /1/.

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

Table 1. Compressive strength of concrete in lighthouses /1/.

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

In a Swedish abrasion study of concrete lighthouses in the Baltic Sea, the abrasion problem was studied by both measuring the abrasion depths in, and analysing the concrete cores of, the lighthouses. The following formula shows the relationship between abrasion rate and ice drift velocity, ice thickness and time /2/.

Abrasion rate ABR/year

$$(\text{ABR/year}) = \int v_i \, h_i \, dt + 0.08 \text{ [mm/year]} \qquad (1)$$

where v_i is ice drift velocity is knots
h_i ice thickness in [mm]
t time in days.

According to the results of the field study, the abrasion rate varied from 0.2 - 7.0 mm/year. The abrasion rate is obtained by dividing the maximum abrasion depth by the number of years /2/.

The abrasion of concretes was also studied at sea with an icebreaker. the test specimen was placed on the bow of the icebreaker on water level. The test arrangements are presented in Fig. 2. 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 /1/.

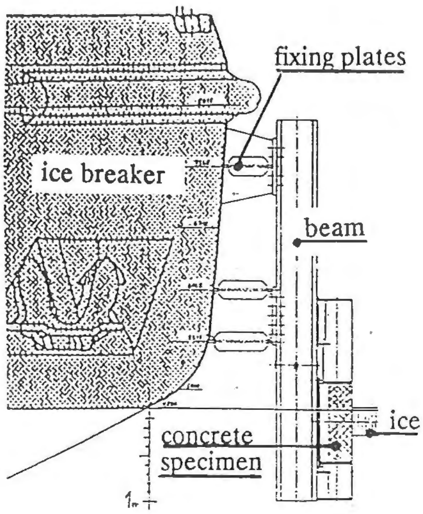
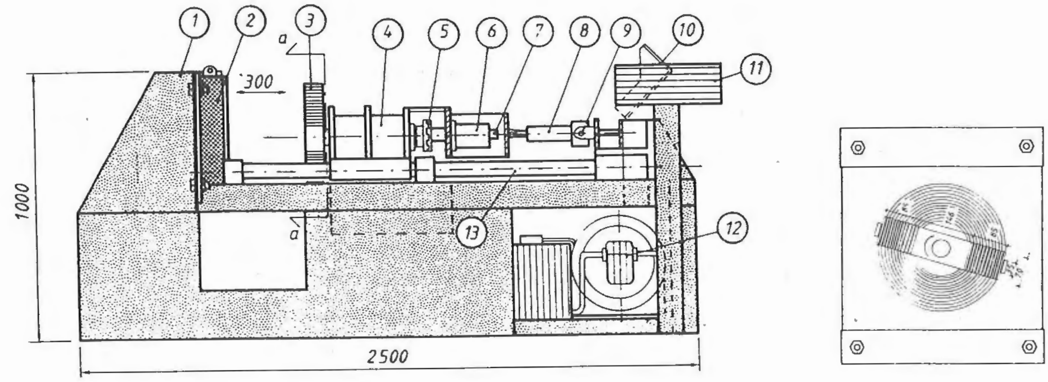


Fig. 2. Test arrangements of icebreaker test /1/.

2.3 Laboratory studies

2.3.1 Abrasion durability

In the Finnish study 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. 3 shows the structure of the abrasion machine and the slab subjected to abrasion /1/.



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

Fig. 3. Abrasion machine and the test specimen /1/.

2.3.2 Concrete strength versus freeze-thaw cycles

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. The temperature varied from -40 °C to +20 °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 /1/.

Other studies in the Finnish study were the studies of the stress-stain 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) /1/.

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) /1/.

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 /1/.

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 /1/.

In Fig. 4 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.

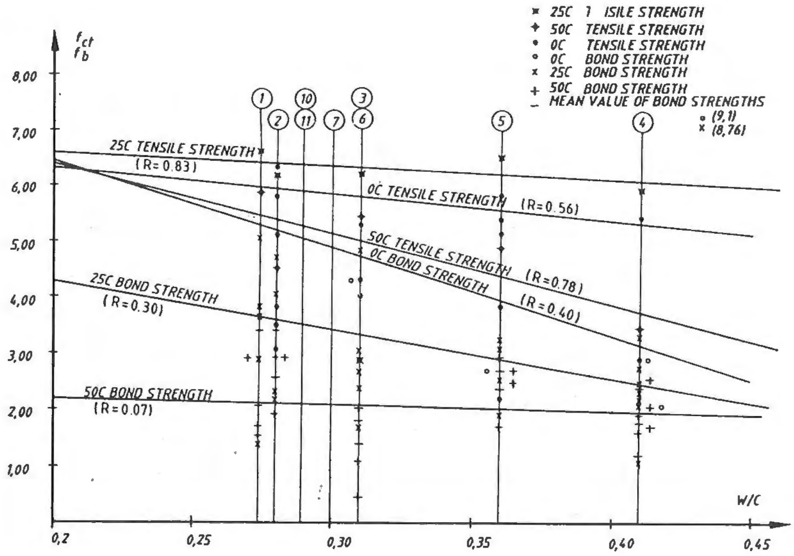


Fig. 4. Flexural tensile strength of concrete and the bond strength of aggregate stones as the function of the w/c ratio and number of freeze-thaw cycles /1/.

2.3.3 Ice forces against protrudent aggregate stones

In the Finnish study 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. Fig. 5 shows the force components. The values are needed in the abrasion calculations /1/.

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 /1/.

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

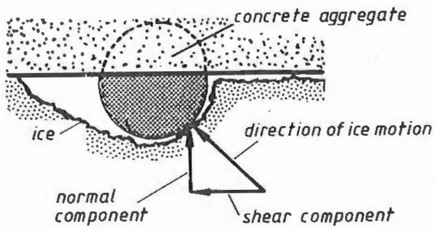


Fig. 5. Forces against protrudent aggregate stones /1/.

3 MODELLING OF ABRASION DEPTH

The abrasion mechanism due to crushing ice sheets against the concrete surface is of three kinds; abrasion of cement stone (Fig. 6 a), abrasion of cement stone + loosening of protruding aggregate stones (Fig. 6 b), and abrasion of cement stone when the bond strength between larger aggregate stones and the cement stone is so weak that the stones loosen during the first ice impact (Fig. 6 c).

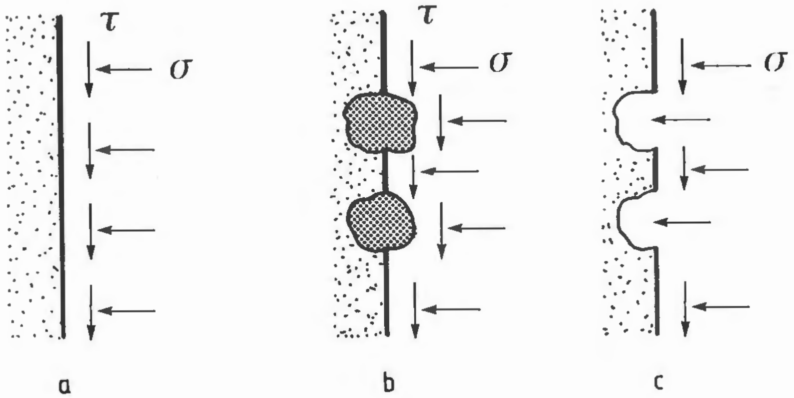


Fig. 6. Abrasion mechanisms /1/-

The calculation models for the actual abrasion mechanism 6 of concrete are presented in Fig. 7. The elements of the calculation models are parametric elements with 8 nodes /1/.

The crack length L_{cr} is calculated by increasing the loads little by little to the values corresponding to σ_i and τ_i /1/.

The effect of ice is inserted in the calculation model to act as external load. the 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 /1/.

The material constants and the strength and strain values were determined in laboratory tests and they also inserted in the model /1/.

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 encertain the loosening of the stone from the surface.

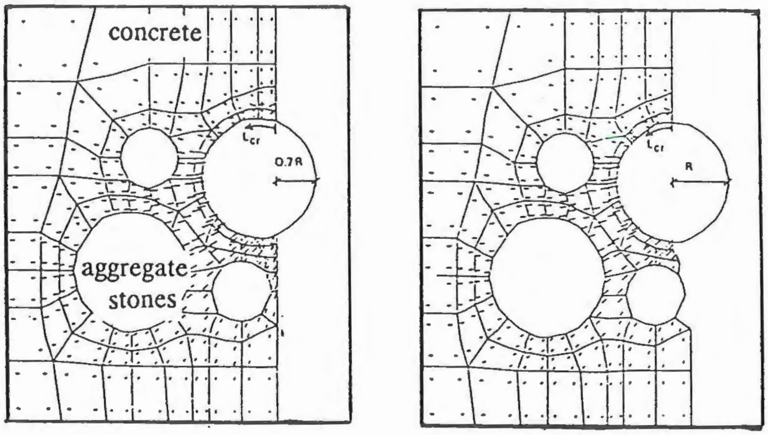


Fig. 7. Calculation models /1/.

The following formula takes into account the recurrence of ice loads in damp concrete /3/.

$$\log N = 13.92 - 14.42 \frac{\sigma_{max}}{f_{ab}} \qquad (2)$$

where N is 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 = 5 000 $\sqrt{f_c}$ 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.

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 icebreaker tests at sea and the loosening of aggregate stones from concrete surface /1/.

As the condition for the loosening of the aggregate stone can be considered

$$L_{cr}/R = 1 \tag{3}$$

where R is the radius of the aggregate stone and
L the crack length /1/.

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

$$b = \frac{3}{f_c}\, s \text{ [mm/km]} \tag{4}$$

where s is the movement of ice sheet in [km] and
f_c the compressive strength of concrete in [MPa] /1/.

The total abrasion depth can be calculated with the formula

$$ABR = \sum_{i=1}^{n} a_i \frac{\lg n_s}{\lg n_1} R_i + (1 - \Sigma a_i) \cdot b \tag{5}$$

where a_i is the proportional amount of aggregate stones of radius R_i
n_s number of ice impacts during ice sheet movements
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 calculated using the formula (5) is graphically presented in Fig. 8.

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 /1/.

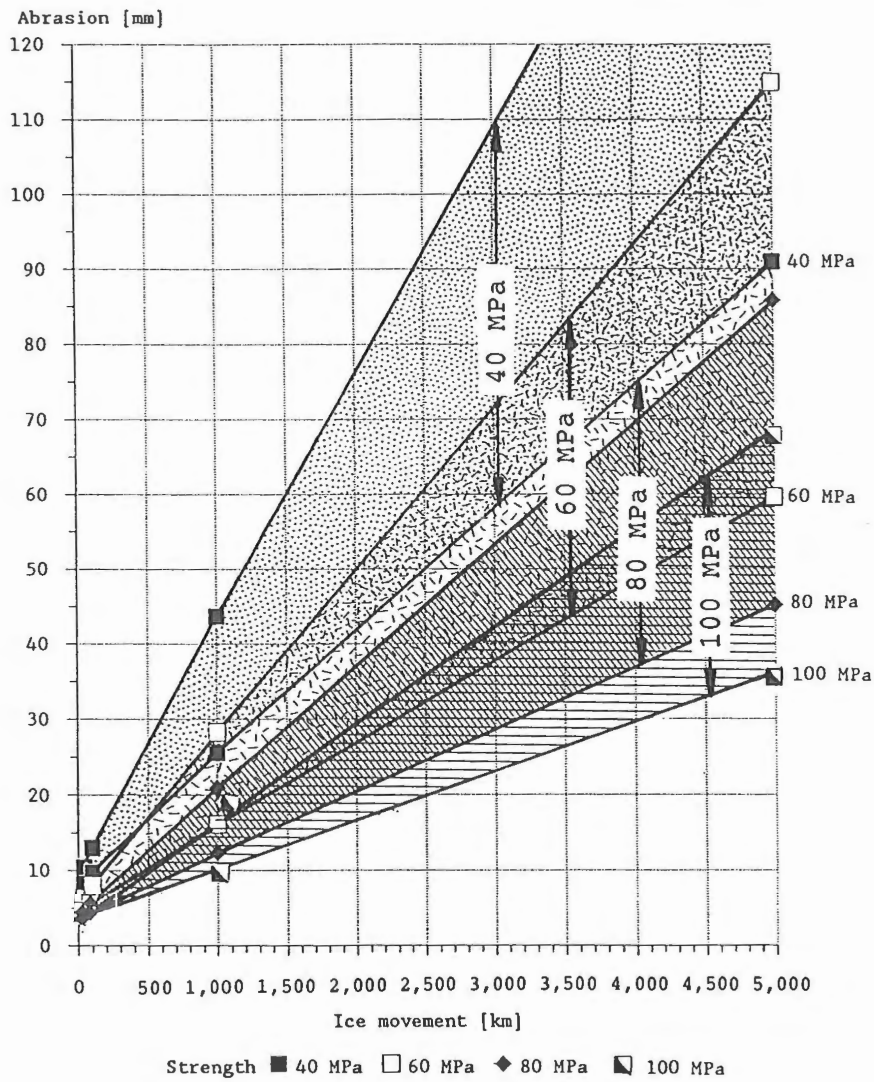


Fig. 8. Abrasion of concrete strengths f_c = 40, 60, 80 and 100 MPa as the function of ice sheet movement /1/.

If the bond between aggregate stones and cement stone has been deteriorated under freeze-thaw cycles the abrasion depth can be calculated with the formula:

$$ABR = \frac{1}{(1 - \Sigma a_i)} \frac{3}{f_c} s \qquad (6)$$

where s is the movement of the ice sheet [km] and
Σa_i the total proportional volume of aggregate stones in concrete.

4 COMPARISON OF TEST RESULTS AND COMPUTER CALCULATIONS

In Fig. 9 a comparison of 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.

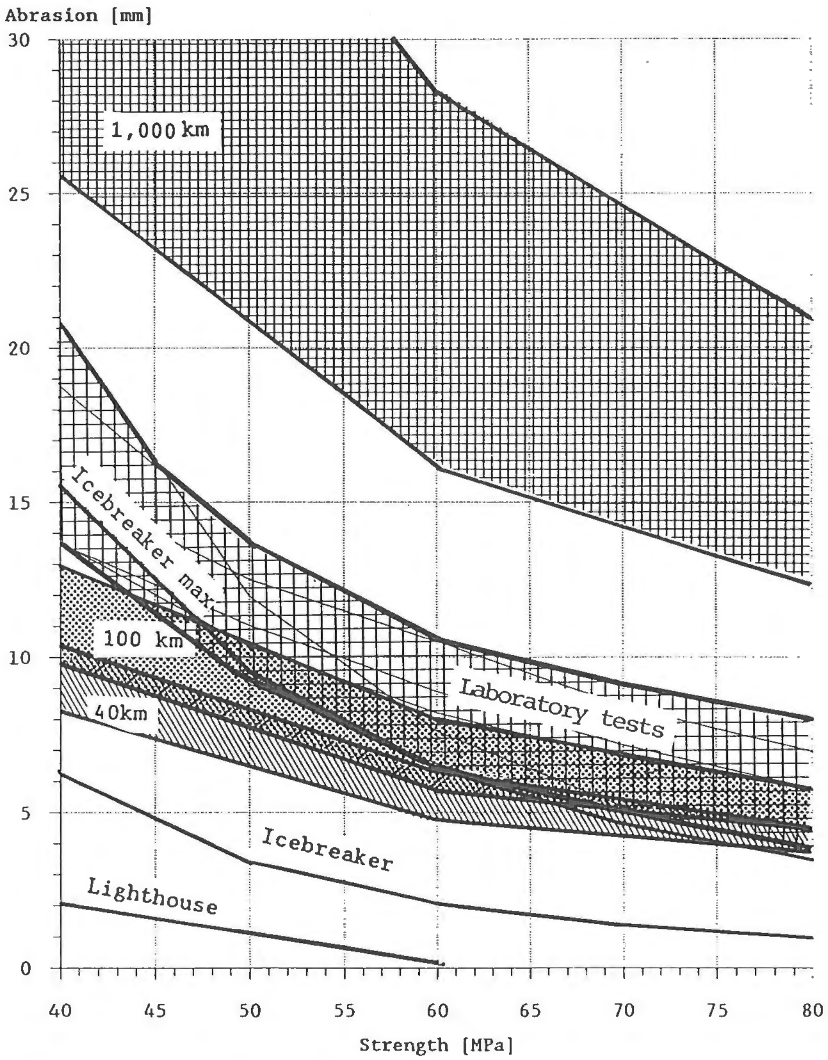


Fig. 9. Abrasion of concrete as the function of compressive strength /1/.

5 CRACKING OF CONCRETE DUE TO CHANGES IN TEMPERATURE

Owing to different coefficients of thermal expansion for concrete aggregate and cement stone, a change in temperature causes internal stresses in the concrete.

Since the coefficient of thermal expansion of the aggregate in usually smaller than that of the cement stone, and naturally also smaller than that of the concrete, tension is produced in the aggregate stones perpendicular to the surface as the temperature rises, and compression is produced as the temperature drops, in relation to the hardening temperature of the concrete. However, a drop in temperature produces fairly large tensile stresses in the cement stone parallel to the aggregate stone surfaces and in the areas between the stones.

Stresses due to changes in temperature and cracking were examined with calculations as follows: An even temperature change was inserted into the calculation model. The casting and hardening temperature was assumed to be +10 °C, and in the hardened state the temperature of the concrete was assumed to drop gradually to -30 °C. The change was assumed to be of short duration, and thus the creep in concrete would not have any influence.

The difference in the coefficients of thermal expansion was $\Delta\alpha = 6 \cdot 10^{-6}$ 1/°C (α of aggregate stone smaller than a of cement stone), because the coefficient of aggregate has a value $\alpha_a = 5 \cdot 10^{-6}$ 1/°C and the value of cement stone varies between $\alpha_{cs} = 11 - 16 \cdot 10^{-6}$ 1/°C.

The following values were used for the strength and strain of concrete and aggregate stones:

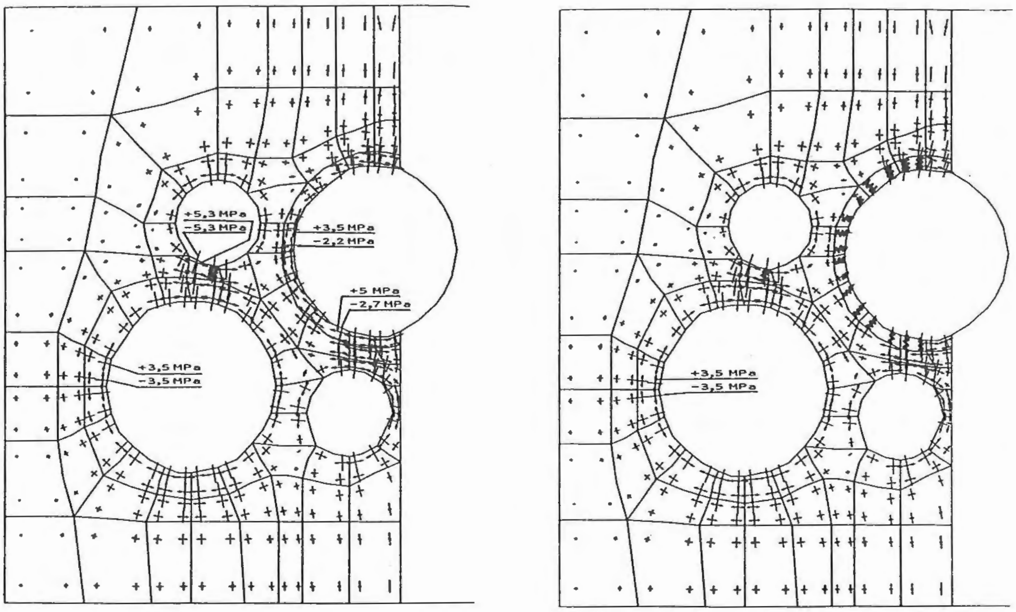
f_c = 60 MPa
E_c = 39.000 MPa
E_a = 50.000 MPa
f_{ct} = 6 MPa
f_{ab} = 2 or 6 MPa
ε_{cu} = 3.5 ‰
ε_f = 2.0 ‰

On the basis of the calculation results the following can be concluded: when the temperature is T = -15 °C and the tensile strength of the concrete is f_{ct} = 6 MPa, no cracking in the concrete occurs in the area of the transition layer. According to the calculation, the greatest tensile stress is σ_t = 5.3 MPa, as seen in Fig. 10 a. However, if the tensile strength of the transition layer is f_{ab} = 2 MPa, cracking is certain to start near the stone surface, as Fig. 10 b shows.

As the temperature drops it can be seen that at T = -30 °C cracking has increased considerably (Figs. 11a and 11b). As the tensile strength of the transition layer is reduced, cracking naturally increases.

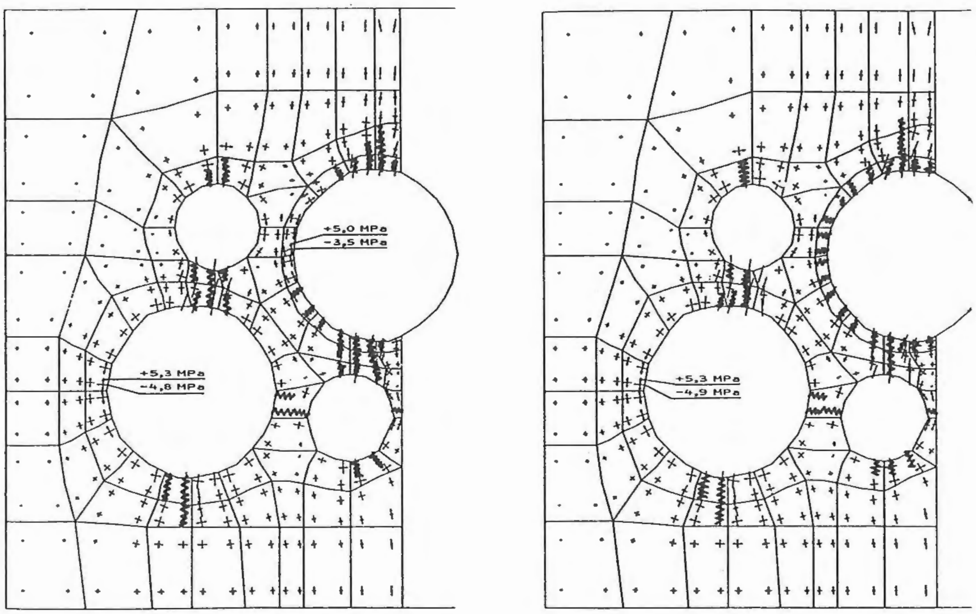
The positive stresses (+) in the figures refer to the tensile stress of cement stone parallel to the tangent of the stone, and the negative stresses (-) to the compressive stress parallel to the normal of the stone surfaces near the stone surface.

Stresses due to a change in temperature have also been calculated with the stress function in the plane stress state when the material is assumed to be elastic. The calculation results were similar when using both finite element analysis and the stress function /1/.



a) b)

Fig. 10. Greatest stresses and cracks at a concrete temperature of -15 °C (ΔT = -25 °C) and tensile strength of the transition layer f_{ab} = 6 MPa (a-figure) and f_{ab} = 2 MPa (b-figure) /1/.



a) b)

Fig. 11. Greatest stresses and cracks at a concrete temperature of -30 °C (ΔT = -40 °C) and tensile strength of the transition layer f_{ab} = 6 MPa (a-figure) and f_{ab} = 2 MPa (b-figure) /1/.

Fig. 12 shows the temperature distributions when the thickness of the concrete sea structure wall is 1 m, the air temperature -40 °C, the sea water temperature -2 °C and the inside temperature +3 °C.

The temperature distributions have been calculated at 6 hours of high water and 6 hours of low water. According to Fig. 12 the temperature change in the surface of the concrete is some 20 °C.

From the calculations it can be concluded that one reason for the deterioration of concrete in arctic sea conditions is cracking caused by temperature change in the concrete. Especially within the tidal water area, the cracking exposes concrete to penetrating water and frost damage.

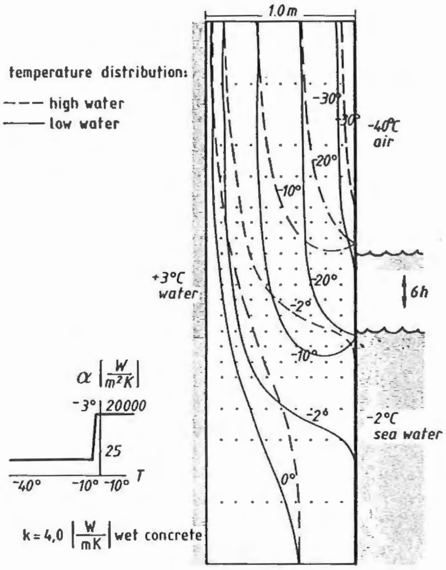


Fig. 12. Calculated temperature distribution during one tidewater cycle.

6 CONCLUSIONS

The following conclusions can be drawn /1/:

1. The abrasion depth and resistance of concrete is 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 $\Delta T = 40$ °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.

REFERENCES

1. Huovinen, S. Abrasion of concrete by ice in arctic sea structures, Publications No. 62, Technical Research Centre of Finland, 1990.

2. Janson, S. E. Long term resistance of concrete offshore structures in ice environment. 7th Int. Conf. Offshore Mechanics and Arctic Engineering. Houston. Tex., 7 - 12 Febr. 1988. New York 1988, American Society of Mechanical Engineers. Vol. III. Pp. 225 - 230.

3. Cornelissen, H. Fatigue failure of concrete in tension, Delft University of Technology, Heron, Vol. 29, No. 4 1984 Netherlands.

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