DURABILITY OF CONCRETE IN ARCTIC OFFSHORE STRUCTURES

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ABSTRACT

Concrete is a suitable material for arctic offshore oil and gas drilling and production platforms. In the splash and tidal zone of these structures concrete is subjected to severe frost-salt attack, chemical attack of sea water and ice abrasion. In the test series a method for accelerated testing of the arctic freeze-thaw durability in sea water was developed. High-strength superplasticized concretes were tested. The test was found to be very severe; the more entrained air the concretes included and the higher their protective pore ratio, the better was their durability.

Key words: Concrete, durability, arctic,
offshore structures

1. GENERAL

In the search for oil and gas under the Arctic Ocean both steel and concrete have been used as materials for drilling platforms. Concrete is a suitable material for harsh arctic sea conditions and it is probable that concrete structures will also be used in the future. Under these conditions concrete is subjected to far worse external factors affecting its durability than in milder regions. Practical experience of the durability of concrete in arctic offshore structures is so far very scarce.

2. EXTERNAL FACTORS AFFECTING DURABILITY

The most critical part of the structure is its splash and tidal zone, which lies between the highest and lowest levels reached by the waves. Within this zone concrete is subjected to the following factors:

- frequently repeated freezing and thawing in wet state
- chemical attack of seawater
- abrasion of ice, waves and accompanying sand.

In arctic regions frost attack is more severe than in subarctic regions due to the lower temperatures. As the temperature falls, the water freezes in ever-decreasing pores with a resulting increase in internal pressure. In the tests /1/ it has been found that during repeated freezing and thawing in the +20...-70 °C temperature region concrete looses its strength much faster than in the +20...-30 °C temperature region. In the Arctic Ocean the lowest air temperatures range from -40...-50 °C /2/.

In offshore structures frost attack is also worsened by seawater salts. Under repeated freezing and thawing in chloride salt solution concrete looses its strength much faster than in fresh water and the effect is most pronounced in solutions with chloride contents of 2...4 % /3/. Salinity in the surface waters of the Arctic Ocean is 2,85...3,35 % /2/, the largest portion of which clearly consists of chlorides, so their frost-salt attack is very severe in arctic offshore concrete structures.

In addition to chlorides, seawater also includes other harmful chemical compounds. The salts found in ocean water are shown in Table 1. Of the compounds found in ocean water the aggressive ones are carbon dioxide (CO_2), magnesium chloride ($MgCl_2$), magnesium sulfate ($MgSO_4$) and sodium chloride (NaCl) /4/.

Table 1. Typical contents of chemical compounds in ocean water /5/.

Compound	Content (g/l)
Sodium chloride	26,9
Magnesium chloride	3,2
Magnesium sulfate	2,2
Calcium sulfate	1,3
Others	< 0,1

Ice abrasion is very high in arctic offshore structures, due to thick moving ice fields which induce both dynamic and abrasive loads when moving against the structure. Ice frozen to the surface may also tear concrete when it moves.

3. REQUIREMENTS FOR CONCRETE

In international standards and codes (FIP, ACI, DNV, CSA, BSI, API) concrete requirements for use in sea structures vary as follows:

- minimun cement content 356...445 kg/m^3
- water-cement ratio lower than 0,40...0,45
- compressive strength at least 35...40 MN/m^2 and when subjected to abrasion at least 42...50 MN/m^2.

In arctic offshore structures these values can also be used as minimum requirements, but in practice lower water-cement ratio and higher strength (over 60 MN/m^2) may be required. Since the structures are quite massive heat generation should be investigated when using high cement contents.

Due to the heavy ice loads the structures are heavily reinforced; therefore the concrete mix should possess very high workability in order to ensure complete compaction. The required slump may be over 150...200 mm, which necessitates the use of superplasticizers.

In order to render concrete frost-resistant its air content is usually required to be from 3...4 to 7...9 %, its protective pore ratio over 0,20...0,25 or its spacing factor less than 0,20...0,25 mm. When air-entraining admixtures are used together with superplasticizers, air often tends to leave the mix and it is difficult to procuce mixes with high air contents and low spacing factors. It has been reported /6/ that superplasticized air-entrained concretes have a good frost-resistance in normal freeze-thaw tests in spite of their low air contents and high spacing factors. However, after a large number of tests Fagerlund /7/ has reached the conclusion that, under the combined attack of frost and salt concrete, also superplasticized concrete, should have a spacing factor of less than 0,16...0,18 mm. Research data on the frost-salt resistance of concrete at very low temperatures has not been available to date and practical experience is very scarce; it is therefore unclear whether superplasticized concrete used in arctic offshore structures should be required high air content and protective pore ratio and low spacing factor.

Requirements for resistance to chemical attack of sea water in the Arctic Ocean do not differ from those in other oceans. Sulfate resistant cement should be used. Resistance to ice abrasion is improved by high strength and compaction. It can further be improved by using abrasion-resistant coatings and coatings which reduce ice adhesion to concrete. The coating should be water-vapour permeable in order to prevent water coming from inside the structure from accumulating behind the coating. When accumulated water freezes the surface of the concrete may spall together with the coating and the result may be worse than without coating.

Corrosion of reinforcing steels cause cracking of concrete. In order to prevent corrosion, concrete should be highly impermeable.

4. TEST SERIES

In the test series the suitability for arctic offshore structures of some special concrete mixes was investigated. A new method was developed for accelerated testing of frost-resistance under arctic conditions.

4.1 Test specimens

Eight concrete mixes were investigated, three of which were special offshore concretes produced by a Finnish company, and their composition is not given. The other five mixes were made in the Laboratory and their composition is shown in Table 2. One of these was made using ordinary Portland cement with high C_3A-content as the binder, another was made with sulfate resistant Portland blast furnace slag cement and yet another with low-heat cement having a low C_3A-content and silica fume. F-concrete was made according to the developer´s instructions with an admixture which lowers the air content. F-concrete made in this way normally has good chemical and frost resistance and is therefore suitable for offshore structures. An attempt was made at fashioning lightweight aggregate concrete with high strength but with a density of less than 2000 kg/m^3. The properties of the mixes are shown in Table 3. A 60 MN/m^2 compressive strength and 200 mm slump for all mixes were aimed at.

4.2 Tests

4.2.1 Freeze-thaw test

For testing the freeze-thaw resistance a method was developed where specimens (500 x 100 x 100 mm^3) submerged in a seawater solution made according to Table 1 were subjected to repeated freezing and thawing in the temperature region of +20...-55 ^oC. Each specimen was constantly surrounded by a thin layer of seawater solution in its own steel container (figure 1). During the latter part of the thawing phase warm water (+20 ^oC) was run inside the freeze-thaw box, surrounding the steel containers with warm water and subjecting the specimens to a temperature shock. The procedure for one cycle is shown in Figure 2. Deterioration was followed by measuring the change in speed of ultrasound through the specimens. The cycles were repeated until the durability factor, which is the ratio of the square of the ultrasound speed measured during the test to the square of the speed measured before the test, was lower than 0,6. When the test was started the specimens were about two months old.

Table 2. Composition of the mixes. Maximum aggregate size 32 mm (LWA 10 mm).

Symbol	Binder	Binder content (kg/m^3)	Binder: Water + admixtures: Aggregate	Admixtures (% of the weight of the Binder)		
				Air-entrainer	Superplastieizer	Others
OPC	Ordinary portland cement	457	1: 0,34: 3,9	Parmix L 0,055 %	Parmix N_n 3,0 %	-
PBC	Blast furnace slag/ OPC 72/28	437	1: 0,35: 3,9	Parmix L 0,06 %	Parmix N_n 1,5 %	-
F-CON	Alkali activated blast furnace slag	400	1: 0,40: 4,7	-	-	F-admixture 22%
LWA	Blast furnace slag/ OPC 72/28	470	1: 0,35: 2,3 (60% of aggregate keramzit)	Cemos 110 3,0 %	Fliesmittel SF 2,0%	silica 12 %
LHS	Low - heat cement	442	1: 0,35: 3,9	Parmix L 0,03 %	Parmix N_n 1,8 %	silica 8 %

Table 3. Properties of the mixes.

Symbol	Slump (mm)	Density (kg/dm^3)	Air content 10 minutes after mixing (%)	Compressive strength (MN/m^2)			
				7 d	28 d	74 d	91 d
PAR 1	150	2450	1,7	-	58,5	66,3	-
PAR 2	160	2360	3,2	-	58,0	66,2	-
PAR 3	140	2400	2,4	-	70,0	79,2	-
OPC	210	2394	3,5	-	54,2	-	68,9
PBC	180	2293	8,3	30,8	60,1	-	64,1
F-CON	220	2439	1,6	32,2	47,7	-	57,1
LWA	210	1812	4,3	33,8	47,4	-	54,9
LHS	180	2354	8,0	44,2	63,1	-	69,0

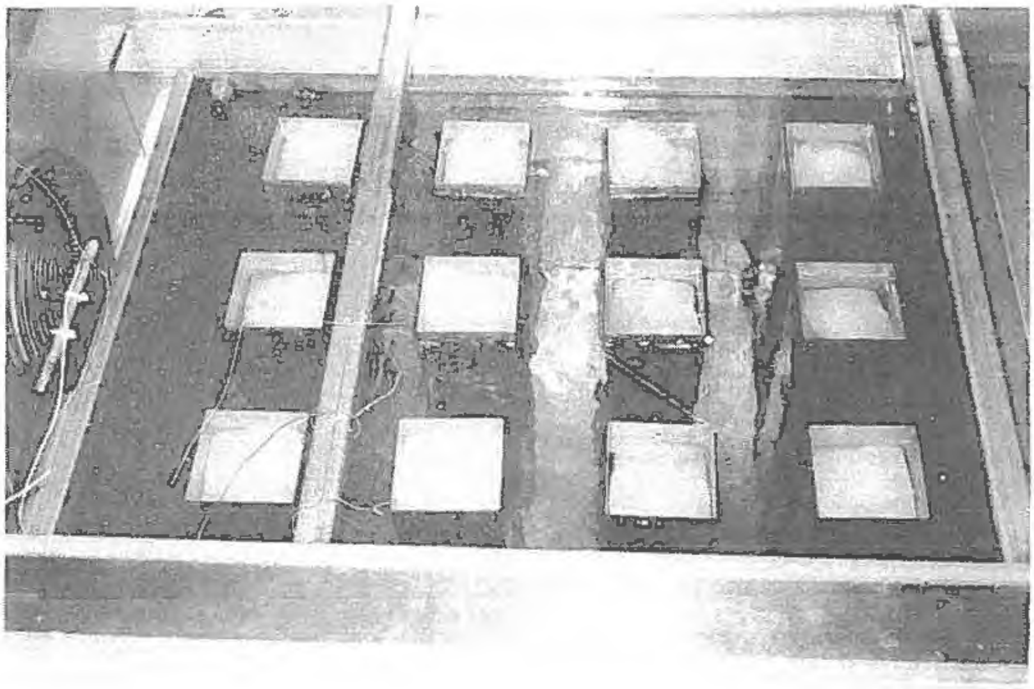

Fig. 1. Specimens inside steel containers in the freeze-thaw box during a thawing phase. The steel containers are surrounded by water.

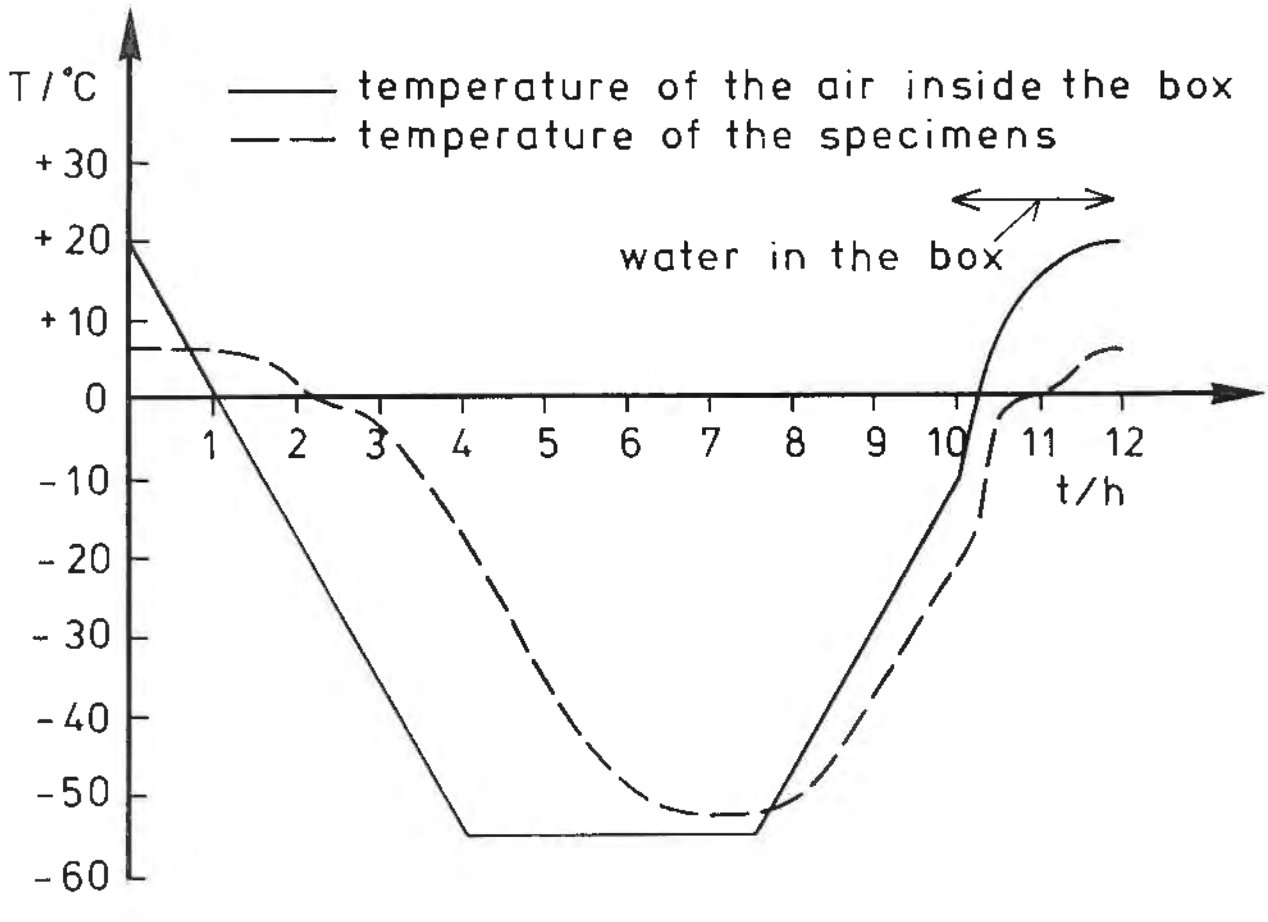

Fig. 2. The test procedure during one cycle.

4.2.2 Other tests

The air content and the spacing factor of hardened concretes was calculated with an automatic pore structure analyzer. The protective pore ratio was measured using the pressure method and the capillary water absorption method.

The abrasion resistance of the concretes was tested using sand paper and the water permeability was tested by means of a Finnish standard method under a pressure of 1 MN/m^2 during the course of one day.

The heat generation of the mixes was measured using an adiabatic calorimeter.

4.3 Test results

The changes in durability factor during the freeze-thaw test are shown in Figure 3 and the air contents of hardened concretes, protective pore ratios and spacing factors are shown in Table 4.

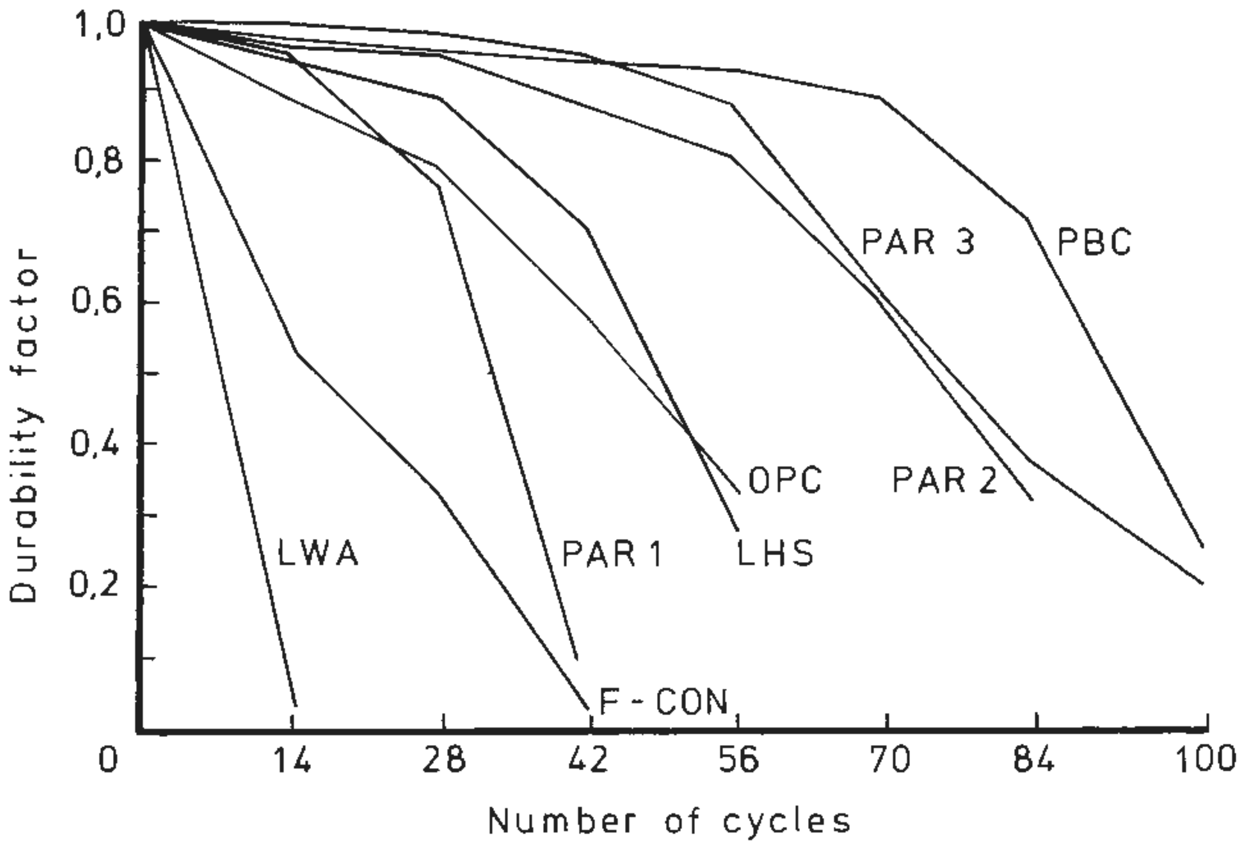

Fig. 3. Changes in durability factors of concretes during freeze-thaw cycling.

Table 4. Properties of hardened concretes.

Symbol	Air content (%)	Spacing factor (mm)	Protective pore ratio	
			Pressure method	Capillary water absorption method
PAR1	0,9	0,41	0,20	0,13
PAR2	3,3	0,26	0,31	0,13
PAR3	3,1	0,22	0,32	0,25
OPC	3,2	0,20	0,24	0,20
PBC	4,2	0,23	0,69	0,40
F-CON	0,7	0,23	0,17	0,08
LWA	3,9	0,32	(0,57)	(0,44)
LHS	3,4	0,20	0,41	0,36

The freeze-thaw test was found to be very severe. All concretes were deteriorated after less than 100 cycles and the worst ones turned into a pile of loose aggregate prior to 50 cycles. A comparison between different types of concrete should not be made as the amount of variables was too high. Factors having a strong effect on durability, such as air content and pore structure, differed to such an extent between different concrete types that they are not comparable. However, it can be said that the durability of F-concrete and the lightweight aggregate concrete was poor. A white powder was found surrounding some of the stones in the F-concrete once the molds were stripped, showing that the F-concrete quality was below normal. The poor behaviour of the lightweight aggregate concrete may be partly due to fact that the keramzite aggregate was almost soaked with water.

The relations between the durability of different concretes and their air contents, protective pore ratios and spacing factors are shownin Figures 4 and 5. As can be seen from Table 5, the correlation between air content and durability is good and the correlation between protective pore ratio and durability is quite good, but there is very little correlation between spacing factor and durability. Higher air contents and protective pore ratios clearly seem to have resulted in better durability.

Table 5. The correlation factors.

	Air content	Protective pore ratio		Spacing factor
		Pressure m.	Capillary m.	
Durability	0,85	0,78	0,63	-0,24

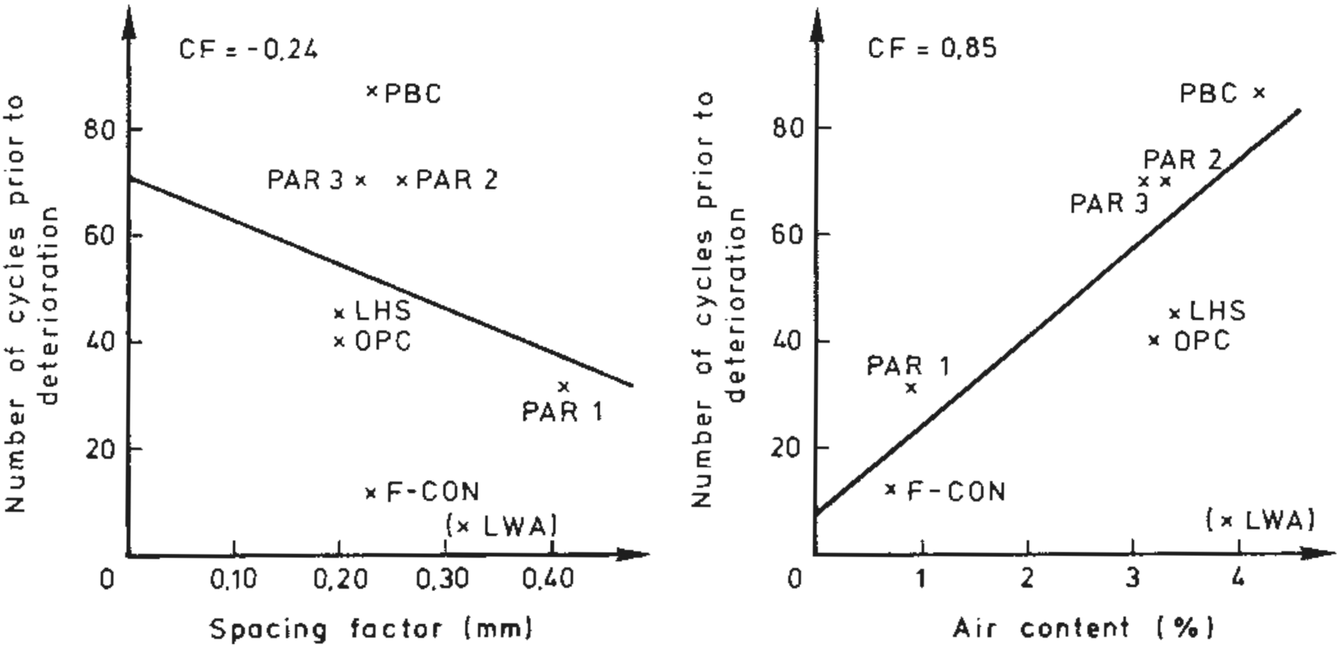

Fig. 4. Relation between durability in the freeze-thaw test and the spacing factor and the air content of concretes. CF = correlation factor.

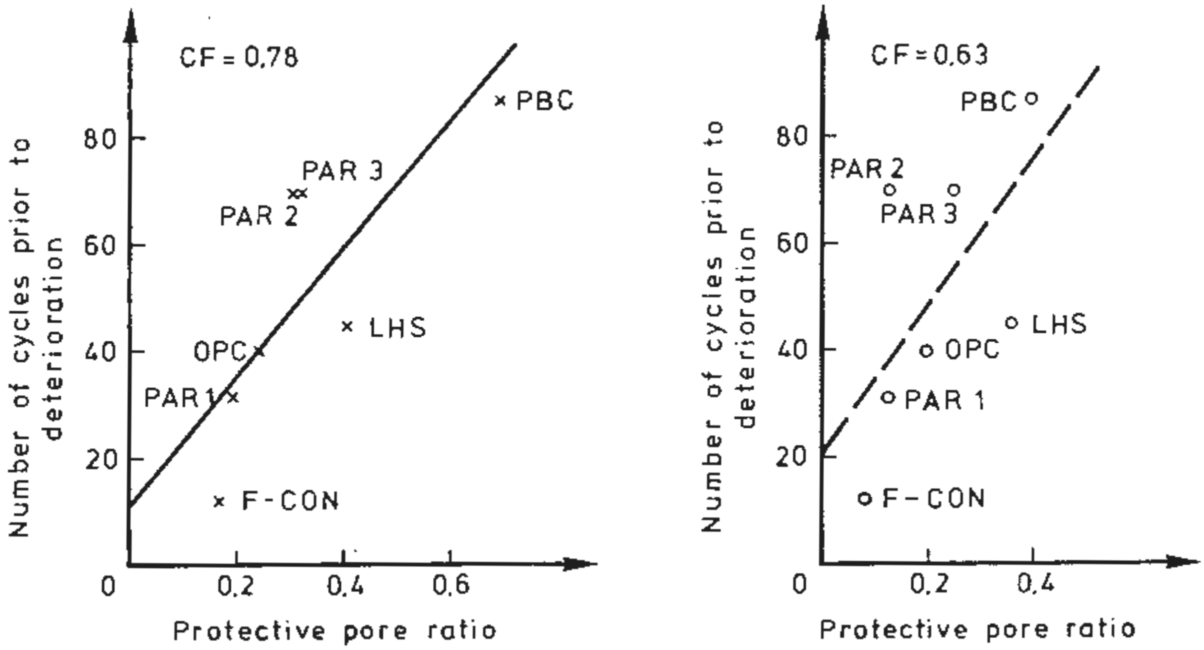

Fig. 5. Relation between protective pore ratios measured using the pressure method (—x—) and capillary water absorption method (--o--) and durability in the freeze-thaw test.

In the abrasion tests and water impermeability tests the results of different concretes differed very little from each other. All of the concretes can be regarded as hard and water-impermeable. The test methods used were not very suitable for testing concretes for use in arctic offshore structures.

Heat generation results are shown in figure 6. The heat development of the mix made with Portland blast furnace slag cement can be regarded as the most favourable in spite of the highest total amount of heat generated, due to the very slow generation. This results in lower temperature stresses where the structures are not very thick.

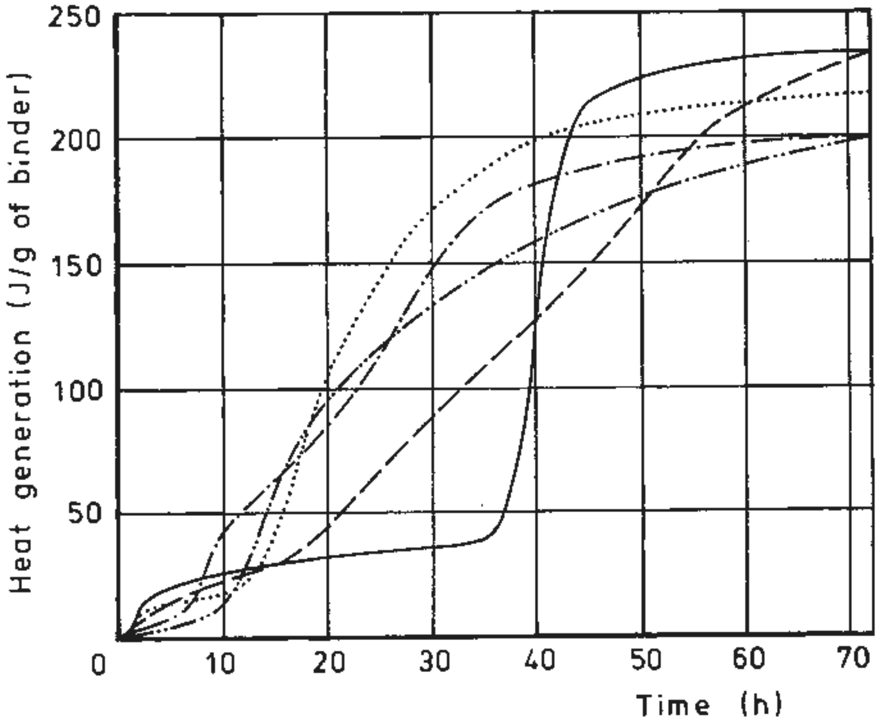

Fig. 6. Heat generation of concrete mixes. ——— OPC, ---- BPC, ——·· —— ·· F-CON, —·——· LWA, ... LHS

4.4 Conclusions and future research

With the developed test method the durability of different concretes can be compared fairly rapidly.

In spite of the fact that all concretes were superplasticized and impermeable, higher air content and protective pore ratio were found to result in better durability. Based on these results there seems to be a need for air-entrainment in the concrete used for arctic offshore structures. How high the requirements for air content and protective pore ratio should be is still unclear, because the amount of concrete mixes tested so far is small.

In this test series the highest air content was 4,2 %. Another test series is already under way in order to study the effect of higher air contents and the effect of silica fume on durability. In that test series the amount of variables between different concrete mixes will be minimized so that they will be better comparable to each other. The results will be analyzed with the same multicorrelation method used in this test series. The aim is to be able to give recommendations of the air content, spacing factor and protective pore ratio of hardened concrete for use in arctic offshore structures.

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