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STRENGTH DEVELOPMENT AND FROST RESISTANCE OF CONCRETE AT LOW TEMPERATURES

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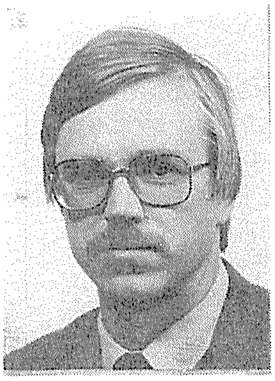

SYNOPSIS

The use of concrete in the very cold arctic climate gives new challenges to concrete technology. When shelters are used during concreting operations, use is made of ordinary or winter concreting technology. In joints and minor castings the use of anti-freezing admixtures gives the possibility of using concrete without heating at temperatures below 0 ^{o}C. The freeze-thaw effect on concrete is intensified when the minimum temperature is low, but air-entrainment acts beneficially. On the other hand, the strength necessary for the avoidance of damage during the first freezing period does not seem to depend on the minimum temperature during freezing.

Key words: Arctic, strength development, frost resistance

1. INTRODUCTION

Concrete is widely used in winter construction operations, and the technology of winter concreting is far advanced. Several studies on the strength development of concrete at temperatures down to -15 ^{o}C have been published. The principles of the resistance of concrete to freezing and thawing have also been studied. The increasing use of natural resources in the arctic regions has created a need to know e.g. the influence of very low temperatures on concrete and concrete structures in the Arctic. In a series of studies carried out at the Technical Research Centre of Finland, material tests have been conducted for examining the effect of the age at freezing to -65 ^{o}C on the final strength of concrete and that of freeze-thaw cycles -65 $^{o}C < T < +20\ ^{o}$C on the strength of concrete as well as on the strength development of concrete at -10 ^{o}C when anti-freezing admixtures are used. In the following, the results of the tests made up till the fall 1983 are discussed. The first two parts of the study concerned with the arctic concrete technology are presented in references /1/ and /2/.

2. STRENGTH DEVELOPMENT OF CONCRETE

2.1 General

The strength development at temperatures customary for concrete under winter concreting conditions, i.e. ranging between 0 and -20 °C, has been studied e.g. in reference /3/. When the temperature on the building site is lower, down to -20...-30 °C, the concreted structure is heated usually so that its temperature is above +20 °C by electrical or infra-red heaters or using hot air. At very low temperatures below -20 and -30°C on the building site the use of heated shelters is usually necessary, where concreting can be carried out by ordinary concreting methods. The use of shelters is also necessary under arctic conditions because of working conditions. When shelters are used, concreting technology does not differ very much from that of ordinary concreting or winter concreting operations, depending on the temperature of the shelter.

2.2 Anti-freeze admixtures

In concreting small structures and joints it is seldom advisable to heat the structure and its adjoining parts. Therefore in the experimental study it was concentrated on the possibility of ensuring the strength development of concrete with anti-freeze admixtures at temperatures down to -25 °C. The first tests were made with admixtures mentioned in Table 1. Finnish ordinary Portland cement was used in the mixes with a maximum particle size of 8 mm and the mix proportions cement/aggregate/water were 1:7:0.65. The 160 x 40 x 40 mm^3 test specimens were cast at a normal room temperature and the test specimens were stored at a temperature of -10 °C immediately after casting.

In Table 1 the chemicals used and the strength results are given. As shown in the table, the combinations $NaNO_2 + Na_2SO_4$, $Ca(NO_3)_2 + Na_2SO_4$ and K_2CO_3 + a retarder gave most promising results. A lignosulphonate-based retarding plasticizer was used as the retarder. The retarding and plasticizing admixture is necessary because of the accelerating and stiffening effect of K_2CO_3.

The second tests were made with the most promising admixtures in the first tests and with different precuring times at +20 °C before freezing to -10 °C. Finnish rapid hardening portland cement was used in the mixes, but otherwise the mixes and the test specimens were similar to those used in the first test The results are shown in table 2.

Table 3 gives some results of tests on concrete with a maximum particle size of 16 mm. It also includes results of tests on the same mixes cured at 20 °C and of the 28-day combined curing both at -10 °C and +20 °C. As is shown in the table, the curing at -10 °C produces strength losses part of which are also permanent after additional curing at 20 °C.

These series of tests will be completed in the tests to be made with different admixture dosages and at different temperatures.

Table 2. Mortar tests with anti-freeze admixtures and different precuring times using rapid hardening portland cement.

Admixture combination	Without admixt.	$NaNO_2$+Na_2SO_4 6 + 3 %					$Ca(NO_3)_2$+Na_2SO_4 5 + 3 %					K_2CO_3+ret.(Plastiment V) 7 + 0,75 %					$NaNO_2$+$CaCl_2$ 6 + 1,5 %	
Temperature (°C)	+20	+20	-10				+20	-10				+20	-10				+20	-10
Precuring at +20 °C(h)	-	-	0	3	9	24	-	0	3	9	24	-	0	3	9	24	-	0
Compressive strength																		
0 d	-	-	-	-	5,9	15,0	-	-	-	4,5	17,9	-	-	-	1,3	17,1	-	-
1 d	14,7	15,0	0,5	2,1	9,8	17,1	17,8	3,8	2,8	9,4	18,7	17,1	1,6	1,7	2,9	8,7	19,4	1,0
3 d	26,9	17,8	4,2	6,8	14,2	17,8	21,3	4,1	7,6	14,4	19,0	23,8	2,9	3,4	5,1	19,4	25,5	6,9
7 d	32,9	21,0	13,7	19,5	18,3	18,8	23,5	9,6	8,4	16,3	20,0	25,0	10,8	7,2	9,5	21,2	28,2	12,9
28 d	38,4	30,7	21,4	22,4	21,7	22,0	29,5	12,6	15,2	23,7	22,4	32,6	15,6	19,2	26,4	26,7	32,9	20,7
28+28 d	-	-	29,4	36,4	32,8	34,5	-	20,3	25,0	31,0	32,7	-	25,7	28,0	30,3	31,1	-	33,2
Flexural strength																		
0 d	-	-	-	-	1,6	4,0	-	-	-	1,1	3,8	-	-	-	0,3	3,2	-	-
1 d	2,9	4,0	0,1	0,3	2,3	3,6	4,0	0,9	0,7	2,0	3,7	3,2	0,3	0,3	0,5	3,8	3,9	0,2
3 d	5,4	4,6	0,1	1,5	3,2	3,7	4,6	1,0	1,6	3,0	4,0	4,2	0,5	0,6	1,1	3,8	5,4	1,5
7 d	5,9	5,3	2,6	3,0	3,9	4,3	4,5	2,1	1,8	3,3	3,9	4,2	1,8	1,2	1,8	3,7	5,6	2,9
28 d	6,5	6,0	4,3	4,2	4,2	4,2	6,7	2,8	2,6	3,8	3,9	6,0	1,8	2,3	4,0	4,2	6,0	4,1
28+28 d	-	-	5,8	6,2	6,5	7,2	-	5,7	6,3	6,5	6,7	-	4,2	5,1	5,5	5,8	-	5,8

Table 1. Mortar tests with anti-freeze admixtures using ordinary portland cement

Admixture combination	Without admixture	$NaNO_2$ 7 %		$NaNo_2$+ $Ca(NO_3)_2$+ $CaCl_2$ 4,9+2,4 + 4,9 %		$NaNO_2$+ $CaCl_2$ 4,9+4,9 %		$NaNO_2$+ Na_2SO_4 6+3 %		$Ca(NO_3)_2$+ $CO(NH_2)_2$ 5,2+5,2 %		$Ca(NO_3)_2$+ Na_2SO_4 5,2+3 %		K_2CO_3 7 %		K_2CO_3+RET 10+3 %	
Temperature (°C)	+20	+20	-10	+20	-10	+20	-10	+20	-10	+20	-10	+20	-10	+20	-10	+20	-10
Compressive strength																	
1 d	8,3	-	0,1	8,1	0,2	9,0	0,3	12,6	2,2	3,8	0,1	12,0	0,8	3,4	0,6	0,7	0,4
3 d	20,9	13,9	2,0	16,5	0,4	17,4	0,3	15,2	6,2	12,3	0,5	16,0	4,8	5,4	0,7	8,3	1,6
7 d	26,8	15,5	5,2	19,7	0,9	19,0	3,5	16,2	9,3	17,8	1,9	16,0	11,9	5,6	1,0	12,0	4,1
28 d	29,3	20,1	16,3	19,7	10,5	24,2	15,3	21,5	18,2	23,4	8,5	21,6	16,3	7,5	4,1	19,0	17,8
28+28 d	-	-	20,6	-	14,6	-	20,4	-	23,8	-	14,7	-	20,6	-	7,3	-	19,2
Flexural strength																	
1 d	1,8	-	0,0	2,2	0,1	2,2	0,1	3,2	0,5	1,1	0,1	3,0	0,3	1,0	0,1	0,2	0,2
3 d	4,1	3,0	0,5	3,1	0,1	3,5	0,1	4,0	1,6	3,1	0,2	4,0	1,5	1,3	0,2	2,3	0,7
7 d	4,7	3,5	1,3	3,2	0,2	3,5	0,7	4,1	-	3,5	0,6	4,0	2,9	1,6	0,2	3,1	1,2
28 d	5,2	4,0	3,6	3,3	2,8	4,0	3,3	4,7	3,3	3,9	2,6	4,4	3,4	1,6	0,6	3,5	2,8
28+28 d	-	-	3,6	-	2,7	-	3,7	-	3,3	-	3,5	-	4,9	-	1,2	-	3,1

Table 3. Compressive strength results of concrete with a maximum particle size of 16 mm using anti-freezing admixtures. 150 mm cubes, workability 1 - 2 sVB.

Age (d)	Compressive strength results (MPa)								
	Comparison concrete (no admixtures, + 20 °C)	$NaNO_2$ + Na_2SO_4 (6 % + 3 %)		$Ca(NO_3)_2$ + Na_2SO_4 (5 % + 3 %)		$NaNO_2$ + $CaCl_2$ (5 % + 5 %)		$NaNO_2$ + $CaCl_2$ + plasticizer (5 % + 5 % + 4 %)	
		-10 °C	+20 °C	-10 °C	+20 °C	-10 °C	+20 °C	-10 °C	+20 °C
1	8.3		17.5		15.5		12.7		19.2
2		3.1		3.2		3.1		1.8	
7	28.0	9.6	25.7	6.8	24.0	9.1	32.8	9.3	35.7
28	37.9	13.8	30.7	10.1	31.7	18.2	40.7	22.0	45.7
28 (-10 °C) + 28 (+20 °C)		24.8		14.2	34.8	34.3		39.5	48.2

3. EFFECT OF FREEZING AGE ON THE FINAL STRENGTH OF CONCRETE

At the time of its first freezing period, young concrete should have gained a specific strength (freezing strength) in order to prevent a reduction in its final strength due to freezing. The Finnish Concrete Standards specify the freezing strength of 5 MN/m^2 for concrete. This value is based on tests, in which concrete was frozen only to -20 ^{o}C. In this test it was attempted to find out if a lower freezing temperature has any effect on the freezing strength.

Concrete test specimens corresponding to strength classes K 20, K 30 and K 40 were frozen once to the temperature of -65 ^{o}C at the age of one, two or three days. Both the air-entrained and normal concretes of every strength class were studied and the concrete of strength class K 40 with hollow plastic microspheres was also tested. Before freezing and after thawing the test specimens were stored at the temperature of +20 ^{o}C and in the relative humidity of 95 %. The control specimens were stored under these conditions all the time.

The specimens were let to freeze and thaw in air as follows:

- at the temperature ranging from +20 ^{o}C to -65 ^{o}C for 6 hours,
- at -65 ^{o}C for 8 hours, and
- at the temperature ranging from -65 ^{o}C to 20 ^{o}C for 6 hours.

The effect of freezing on the compressive strength of concrete was studied using 100 x 100 x 100 mm^3 cubes. The control cubes were compressed at the age of one, two, three and 28 days and the test cubes at the age of 28 days.

The effect of freezing on the bending strength of concrete was examined using 100 x 100 x 500 mm^3 beams. All the control beams and test beams were bended to failure at the age of 28 days. The test results, which all are the mean values of three test specimens are shown in Table 4.

Table 4 . The effect of the freezing age on the final strength of concrete. The freezing temperature was -65^{o}C.

Strength-class	Air content (%)	Age at the time of freezing (d)	Compressive strength at the time of freezing (MPa)	Coefficient of variation (MPa)	Compressive strength at 28 d (% of control specimens' strength)	Coefficient of variation (%)	Bending strength at 28 d (% of control specimens' strength)	Coefficient of variation (%)
K 20	2.7	1	3.8	0.4	91	4	90	15
		2	9.2	0.3	103	5	-	-
		3	12.2	0.2	102	2	92	13
K 20	7.5	1	2.7	0.1	95	10	101	7
		2	7.5	0.4	101	4	-	-
		3	9.8	0.3	103	3	99	1
K 30	2.2	1	2.8	0.1	95	6	93	9
		2	13.8	0.4	105	2	-	-
		3	18.9	0.4	103	2	107	8
K 30	5.7	1	5.0	0.1	101	5	100	10
		2	13.7	0.5	99	6	-	-
		3	17.3	0.1	101	1	107	4
K 40	2.5	1	14.1	0.3	105	2	103	4
		2	27.3	1.2	102	3	-	-
		3	29.2	0.5	100	3	97	6
K 40	5.6	1	14.6	0.2	100	1	105	12
		2	25.1	0.7	107	3	-	-
		3	31.9	1.2	103	1	102	5
K 40	2.6 + micro-sph.	1	14.9	0.1	96	1	90	6
		2	26.9	0.5	98	5	-	-
		3	29.7	1.7	98	2	101	3

As shown in Table 4, freezing to -65 ^{o}C did not reduce the final strength of those specimens that had at least the compressive strength of 5 MN/m^{2} at the time of freezing. The specimens with a lower strength than 5 MN/m^{2} at the time of freezing suffered from slight loss of final strength. It seems that 5 MN/m^{2} would be a safe requirement for the value of the freezing strength also when concrete is being subjected to freezing down to -65 ^{o}C.

4. EFFECT OF FREEZE-THAW CYCLES RANGING BETWEEN -65 ^{o}C AND 20 ^{o}C ON THE STRENGTH OF CONCRETE

Freeze-thaw tests on concrete are usually performed using temperatures ranging from -20 ^{o}C to +20 ^{o}C. The purpose of this test was to study the effect of a lower freezing temperature on the concrete strength. The lower the temperature drops, the more freezes the water in concrete and thus it can be expected that the strength loss due to the freeze-thaw cycles would be greater than in normal freeze-thaw tests. The effect was studied with ordinary concretes, air-entrained concretes and with a concrete containing hollow plastic microspheres to improve its frost resistance.

The test specimens were 500 x 100 x 100 mm^3 beams, which were made of seven different mixes (Table 5). Ordinary and air-entrained mixes were made in designed strengths of 20, 30 and 40 MN/m^2 and six beams were made of each, respectively. A microsphere mix was made in designed strength of 40 MN/m^2 , as well.

Table 5. Mixes used in freeze-thaw -tests.

Strength class	Compressive strength 28 d (MPa)	Air content (%)	Workability slump cm	sVB	Mo drops	Admixture
K 20	18.8	2.7	3.0	3.3	20	-
K 20	16.8	7.5	5.8	1.3	10	AEA 0.07 %
K 30	27.8	2.2	3.5	2.9	16	-
K 30	26.6	5.7	4.5	1.6	13	AEA 0.07 %
K 40	41.5	2.5	2.5	3.8	20	-
K 40	36.9	5.6	3.5	2.5	17	AEA 0.07 %
K 40	43.7	2.6 + microsph.	3.8	2.7	18	microspheres 0.5 %

From each mix six specimens were cast, of which three were tested and three were used as comparison specimens. The cement used was ordinary Portland cement and aggregates employed natural sand and gravel.

The test specimens were cured for three months in a relative humidity exceeding 95 %. During the last week before testing the specimens were immersed in water. The freezing and thawing took place in air at temperatures as follows:

at +20 ^{o}C to -65 ^{o}C	for 6 hours
at -65 ^{o}C	for 8 hours
at -65 ^{o}C to +20 ^{o}C	for 6 hours.

Between each cycle the specimens were immersed in water for about three days. After eight cycles the beams were moved to the relative humidity of more than 95 % for curing a month (air-entrained concrete) or six months (ordinary concrete and concrete with hollow plastic microspheres) in order to examine the recovery of strength. After this period an additional frost resistance test of seven cycles was made. Subsequent to this phase a curing period of three months followed. During the cycling of the test specimens the comparison specimens were kept in water curing and during the strength recovery phases they too were kept in the humidity of more than 95 %.

The compressive strength was evaluated by the ultrasonic pulse method before and after each test period. The measurements were always made from wet specimens.

At the end of the tests after 15 cycles and a three-month curing the flexural and compressive strengths of the specimens were tested. The age of the test beams was at that time 15 months.

The results are shown in Table 6 and Fig. 1. Each concrete without air-entrainment had lost its strength considerably, whereas the air-entrained concrete had maintained its strength. This agrees with what is known of the normal freezing and thawing actions (+20 ^{o}C...-20 ^{o}C) but the strength loss of concretes without air-entrainment is clearly faster than in the normal tests. It is also to be noticed that the strength of a concrete with microspheres decreased.

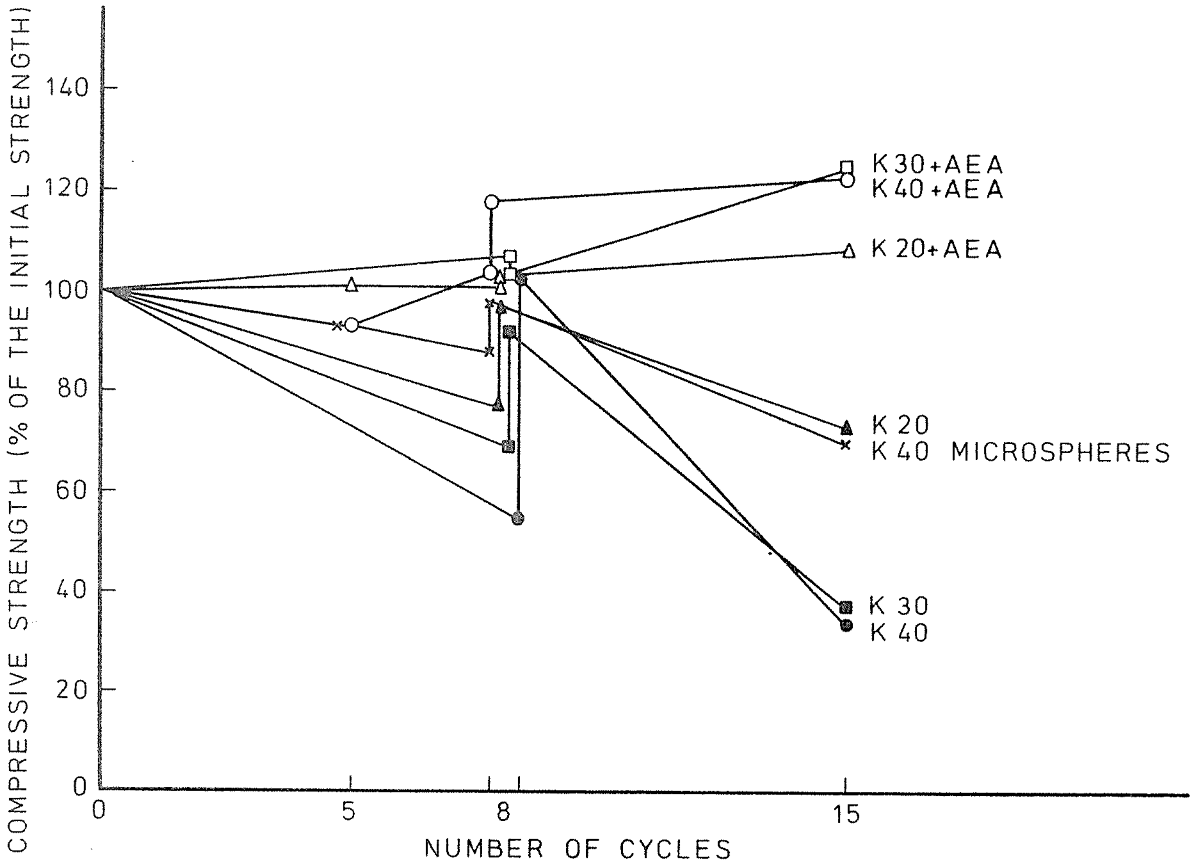

Fig. 1. Changes in the compressive strength of concretes during the test calculated from the results of ultrasonic pulse velocity tests.

After the test of eight cycles and the subsequent curing the strength of the concretes without air-entrainment and with microspheres had almost recovered. After additional seven cycles a decrease in the strength of these concretes was faster than that during the first eight cycles. An exception is the concrete without air-entrainment of strength class K 20, in which the decrease in strength was slower. None of the air-entrained concretes lost its strength during 15 cycles. The strength of their comparison specimens was, however, usually greater than that of the tested specimens.

Table 6. Results of the freezing and thawing test.

Strength class	Air content (%)	Test spec./ Comparison spec.	Compressive strength (fc) estimated by ultrasonic pulse method in % of the initial strength, s = coefficient of variation) after 5 cycles fc %	s %	8 cycles fc %	s %	8 cycles + curing fc %	s %	15 cycles fc %	s %	Compressive strength (beam ends) after 15 cycles and curing fc MPa	s %	Flexural strength after 15 cycles and curing fc MPa	s %
K 20	2.7	test comparison	- -	- -	77 115	3 6	97 119	2 2	83 119	7 2	24.5 24.7	3 4	2.6 3.6	9 2
K 20	7.5	test comparison	101 113	5 3	101 111	4 4	103 115	2 2	109 123	3 4	22.2 21.1	7 5	3.8 3.9	4 2
K 30	2.2	test comparison	- -	- -	69 124	7 6	92 136	11 5	37 136	17 5	33.7 41.2	3 7	2.1 4.2	8 15
K 30	5.7	test comparison	- -	- -	107 101	4 1	104 98	2 3	125 118	4 7	33.9 36.6	11 6	4.4 4.5	6 2
K 40	2.5	test comparison	- -	- -	55 114	3 2	103 131	8 4	34 131	4 4	42.0 53.9	2 3	2.8 5.7	14 6
K 40	5.6	test comparison	93 114	2 5	104 117	2 2	118 128	0 5	124 136	2 3	46.5 45.7	4 5	5.7 5.7	6 4
K 40	2.6 microsph.	test comparison	93 132	6 5	88 133	7 5	98 145	5 2	70 153	3 6	42.0 54.1	6 5	3.4 5.3	1 8

The curing in the above 95 % RH after the test of 15 cycles did not recover the strength loss of concretes without air-entrainment and with microspheres as much as after eight cycles. Thus at this stage a considerable part of the strength loss is not recoverable. Exceptions are again the samples of ordinary concrete having strength class K 20, in which the strength had recovered almost entirely. Flexural strength, which in most cases is a more sensitive measure of frost damage, shows, however, that also in this concrete there exist permanent damages. The flexural strength results also show undoubtedly that all the air-entrained concretes proved to be durable in the test, whereas the ordinary concrete and the concrete with microspheres were damaged. The permanent loss of flexural strength varied in the former case from 28 to 51 % and in the latter case it was 36 %.

An interesting and inexplicable matter in the results was the fact that the increased strength did not lessen the frost damages as is usually the case. The very best concrete among the concretes without air-entrainment was the weakest (K 20) and concrete K 30 was slightly better than K 40, but the results were, however, close to each other. Fig. 1 presents graphically the changes in strengths of the various concretes during the tests which are calculated from the results of ultrasonic pulse velocity tests.

5. SUMMARY

A series of studies related to arctic concrete technology has been carried out at the Technical Research Centre of Finland. The paper describes results of three test series: Strength development of concretes with anti-freeze admixtures, effect of freezing (down to -65 °C) age on the final strength of concrete and effect of freeze-thaw cycles ranging between -65 °C and +20 °C on the strength of concrete.

By using anti-freeze admixtures it is possible to lower the freezing point of water in concrete and so ensure the strength development of concrete at negative temperatures. However, significant strength losses can't be avoided, though part of the loss is gained after curing at the temperature of +20 °C. When the hardening temperature of concrete is -10 °C, the most promising admixture combinations are $NaNO_2$ + Na_2SO_4, $Ca(NO_3)_2$ + Na_2SO_4 and K_2CO_3 + a retarder.

Freezing once to -65 °C did not reduce the final strength of concrete that had at least the compressive strength of 5 MN/m^2 at the time of freezing. The specimens with a lower strength than 5 MN/m^2 (from 2.7 to 3.8 MN/m^2 at the test) at the time of freezing did suffer from slight loss (less than 10 %) of final strength. So it seems that 5 MN/m^2 would be a safe requirement for the value of the freezing strength also when concrete is being subjected to freezing down to -65 °C.

In freeze-thaw tests between +20 ^{o}C and -65 ^{o}C the compressive strength of the concretes without air-entrainment decreased faster than in normal freeze-thaw test (+20 ^{o}C...-20 ^{o}C), whereas the concretes with air-entrainment did not suffer from any strength losses even when the freezing temperature was -65 ^{o}C. The compressive strength of the concrete with hollow plastic microspheres also decreased significantly though it is not usually affected by the normal freeze-thaw tests. After eight cycles the compressive strength of non-air-entrained and microsphered concretes recovered almost entirely when cured for six months in humid environment, but after 15 cycles and a three-month curing the recovery was clearly smaller.

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