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SELF HEALING OF HIGH STRENGTH CONCRETE AFTER DETERIORATION BY FREEZE/THAW

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ABSTRACT

Some experiments have been performed to investigate the self healing of concretes deteriorated by internal cracking in the ASTM C666 procedure A rapid freeze/thaw test. Six different well cured concretes were deteriorated to various degrees. Then the specimens (concrete beams) were stored in water for 2-3 months. Resonance frequency, weight, volume and compressive strength were measured during deterioration and self healing. Concretes that lost as much as 50% of their initial relative dynamic modulus during freeze/thaw could recover almost completely during subsequent storage in water, somewhat varying with concrete composition and degree of deterioration. Compressive strength showed reductions of 22-29% on deterioration, but only 4-5% recovery on self healing. Freeze/thaw tests on deteriorated and self-healed specimens in partly sealed condition showed clearly that the deterioration was governed by the ability to take up water; the more water that leaked through the plastic foil during freeze/thaw, the larger the deterioration. Self healing may be an important factor giving concrete better frost durability in field than when submitting specimens to freeze/thaw cycles in water.

Introduction and Previous Research

In a previous investigation of freeze/thaw resistance of concrete (1) it was observed that deteriorated concretes that were kept frozen due to problems with the equipment regained some of the loss of resonance frequency. It was therefore decided to investigate this observation further. Several earlier investigations of self healing have been performed. McHenry and Brewer (2) pointed to the positive effects of autogeneous self healing on frost deteriorated concrete, and its importance for frost testing. Abrams (3) was the first to study autogeneous healing of concrete. Abrams observed that cracked compressive strength specimens stored outdoors, exposed to the weather for eight years after testing at 28 days, healed. More than twice of the 28 day strength was measured after 8 years. Munday et al (4) conducted a large test on the self healing of the compressive strength of concrete specimens tested to maximum load using constant strain rate at loading and thus controlling the maximum load more accurately than in normal compressive strength testing (constant stress rate). They investigated concrete, mortar and paste with four different types of cement cured to various ages (1, 7, 14, 28 days) and temperatures, and self healed at different conditions (dry, humid, submerged). They compared healed strengths with "fresh" and fractured strength values (i.e. immediately after the first loading), and found that self healing always took place. The amount of self healing seemed to decrease with the age of the concrete at test. The healing conditions were more important than the curing conditions. High humidity gave more healing than submersion. Also the type of cement influenced the results.

Fagerlund (5) discussed the effect of continued hydration on degree of saturation. He calculated that very little extra hydration could reduce the degree of saturation from critically saturated to frost resistant. Continued hydration will both reduce the amount of freezeable water and provide additional strength, i.e. appear as self healing.

Self healing of cracks with respect to water ingress/permeability has been studied by several researchers. Clear (6) made a study of water flow and healing in cracks both in field and laboratory. In the laboratory he studied the flow of water through concrete cracks of 0.1, 0.2 and 0.3 mm width on different concretes. He found that the smaller the initial effective width of a crack was, the faster the sealing of the crack. Chemical analysis on water before and after passing a crack and inspection of thin sections before and after healing were performed. The results showed $CaCO_3$ in the cracks. The healing observed during the first days of water flow was however not accounted for by these mechanisms, but rather due to blocking of the flow path by loose particles already in the crack. Even though the cracks studied in (6) were rather large (0.1-0.3 mm range) and water was flowing through the cracks during healing, it was found that the healing was large in terms of reducing water flow. Flow reductions of several orders of magnitude were observed during 2-6 days, somewhat varying with crack width, concrete composition and flow rate. Also Meichsner (7) and Ripphausen (8) studied self healing of cracks during water leakage. Meichsner discussed typical reductions in water flow through cracks with time, effect of crack geometry, crack width and water quality and possible reasons for crack healing. Ripphausen (8) performed an extensive study of self healing of cracks related to water transport. He used a different test set-up than Clear (6), and also found large reductions in water flow. The reductions were dependent on various test parameters (e.g. initial crack width). Ripphausen also discussed possible causes for self healing, such as continued hydration, calcium carbonates and loose particles of various origins. Arnold and Johnson (9) measured reduced seepage of water through cracks in roller compacted concrete dams, and attributed this to the healing of cracks. Fidjestøl and Nilsen (10) found marked crack healing in concrete in sea water. Bakker (11) discussed the significance of crack healing for the corrosion of steel in concrete due to carbonation. Self healing in cracks and reduction of crack permeability was explained by deposits of various cement components and hydration products from the interior of the concrete.

Gray (12) reported self healing of interfacial bond between steel fibres and mortar. Pullout- and compression tests were performed at different test ages and reloading of fractured and healed specimens were performed after several test ages. Significant self healing properties were recorded. It was found that up to 90 days of water curing, the increase in pullout resistance due to self healing can be larger than the increase due to curing of virgin specimens. For compressive strength tests the self healing was much lower. Kukko (13) found increased flexural strength of concrete beams deteriorated in freeze/thaw testing after some time of storage, compared to testing the flexural strength immediately after freeze/thaw testing.

From the above cited investigations it is clear that self healing has been observed in a variety of concrete properties, and appears to be caused by a variety of mechanisms, i.e. hydration in areas exposed by cracks, filling/blocking of cracks by loose particles, cement compounds or

TABLE 1 Concretes used in the experiments

Mix	w/c+s	s/c+s	Cement		$f_{c,start}$	Slump	Air (vol-%)		Aggregate	
			kg/m^3	type	MPa	cm	fresh	hard. 1)	kg/m^3	Type
030-08QD	0.30	0.08	469	HS	141	16	2.0	2.2	1650	quartzdiorite
030-08 LS	0.30	0.08	469	HS	111	16	2.1	1.4	1738	limestone
035-00	0.35	0	387	OP1	73	8	2.7	2.4	1921	granitic
040-00	0.40	0	432	OP2	74	20	1.6	2.0	1799	granitic
040-05	0.40	0.05	409	OP2	83	19	2.0	2.3	1782	granitic
040-05A	0.40	0.05	411	OP2	73	21	5.1	4.2	1703	granitic

1) Measured by pressure saturation with 10 MPa after drying and saturation by capillary suction

reaction products. It seems that both mechanical strength and durability properties may be improved by self healing.

Concretes Investigated

Six different concretes were investigated. In Table 1 concrete mixes and some data of the concretes are given. The effects of cracking and self healing on these concretes have also been investigated by other means, and are published (14, 15).

Concrete beams 10 by 10 by 34.5 cm were investigated. Three parallel specimens of each concrete mix were exposed to rapid freeze/thaw according to ASTM C666 procedure A. The concretes were water cured 3 months (040-series and 035-00) and more than a year (030-08). One beam for each mix was investigated in self healing except for mix 035-00, for which all 3 beams were self healed.

Freeze/Thaw Testing and Healing

All concretes were exposed to rapid freeze/thaw cycles in water (ASTM C666 procedure A). After freeze/thaw exposure the deteriorated concrete beams were stored in water at 20°C, see Table 2. During freeze/thaw exposure and subsequent self healing, measurements were made of fundamental transverse resonance frequency, weight and volume. In addition to the compressive strengths on 10 cm moulded cubes, also compressive strengths on 10 cm cubes sawn from the beams were tested for three of the six concretes (040-00, 040-05, 040-05A). Two or three cubes were tested at start of freeze/thaw exposure, immediately after deterioration and after three months of self healing in water for each concrete. The three other self healed concretes (030-08 QD, 030-08 LS, 035-00) were wrapped in thick (0.2 mm) plastic foil after self healing, taped and freeze/thaw tested again in a condition that was intended to be sealed. The freeze/thaw cabinet was adjusted to produce the same amount of cycles pr. day and between the same temperature limits as in the submerged freeze/thaw test (5 cycles pr. day between + 5 and - 18°C). The temperature was measured by a thermocouple moulded in the centre of a dummy specimen and on the surface of the concrete. The cycle obtained differed slightly from that obtained in water, see figure 1 (freezing rate sealed: 10°C/h, freezing rate in water: 12°C/h).

Results and Discussion

Table 2 gives the results of freeze/thaw testing according to ASTM C666 procedure A: number of freeze/thaw cycles, Durability Factor (DF), days in water during self healing and further testing. Table 3 gives the resonance frequencies before and after deterioration, after self healing

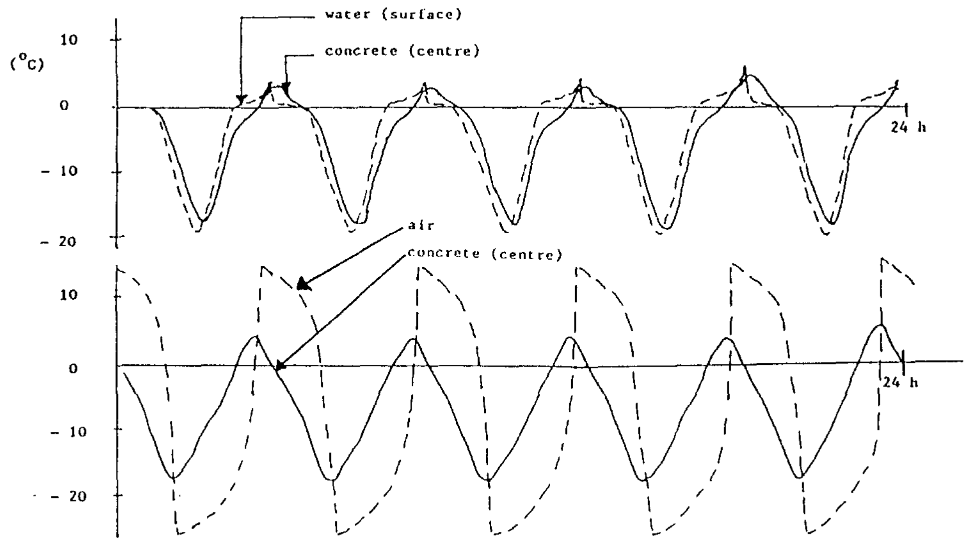

FIG. 1.
Freeze/thaw cycles used in the experiments. Top: standard ASTM C666, bottom: sealed test.

and after sealed freeze/thaw. Table 4 gives the results of compressive strength from beams before and after freeze/thaw deterioration and after self healing. Table 5 gives changes in weight and volume during freeze/thaw and healing. Figure 2 shows a plot of resonance frequency during ASTM C666 procedure A, self healing and subsequent sealed freeze/thaw.

From Table 2 and Figure 2 it is seen that all concretes were more or less deteriorated due to internal cracking with Durability Factors in the range 9-79. From table 3 we see that after deterioration the resonance frequencies were 47-87% of the initial values, and after self healing they went back to 85-99%. By comparing the concretes that had equal reductions in resonance frequency after freeze/thaw (030-08 LS and 040-00: 71-72%, and 035-00 and 040-05: 47-48%) it is seen that they do not always regain resonance frequency to the same level. It therefore appears that the concrete composition influences the self healing. Since the concretes 040-00 and 040-05 were deteriorated to different degrees it is not possible to deduce the effect of silica fume on self healing. From tables 3 and 4 we see that for 040-00, 040-05 and 040-05A the frost deterioration leads to reductions in compressive strength of 22-29%. The resonance frequencies are reduced 28-52%. Self healing brought the resonance frequencies back to 85 to 98% of the original values, but only 4-5% increase of the compressive strength. The resonance frequency does therefore not correlate with compressive strength measurements in the case of self healing. This was also observed by Abdel-Jawad et al. (16) by comparing healing using ultrasonic pulse velocity and compressive strength of concrete specimens loaded and healed at various ages and degrees of cracking. This is a very important aspect of the non-destructive test methods: that they fail to measure the permanent loss in material strength. This is probably due to the low stress levels involved in the non-destructive test.

Table 5 gives changes in weight and volume during freeze/thaw and healing of 040-00, 040-05 and 040-05A. Freeze/thaw in water gave a water uptake of 0.5 - 1.9 volume-% and a volume increase of 0.8 - 1.4 volume-%. Earlier data (17) showed that freeze/thaw leads to increased

TABLE 2

Durability Factor (DF), storage time in water and further testing

Mix	ASTM C666 proc.A		Days in water	Further
	DF	No. of cycles	20 °C	
030-08QD	79	300	52	Freeze/thaw
030-08 LS	50	275	52	sealed
035-00	9	60	52	
040-00	11	70	114	Compressive
040-05	10	70	114	strength
040-05A	23	144	99	

absorption of water, even when no deterioration takes place. In the present case the water absorption on deterioration of 040-00, 040-05 and 040-05A was larger than the volume increase, indicating that the absorbed water fills the created space (cracks) as well as some existing empty porespace.

During subsequent self healing in water, the absorption stopped. The volume increase of 0.8 - 1.4% observed upon frost deterioration was also unchanged during healing, i.e. the damage in terms of volume increase was permanent.

During sealed freeze/thaw of 035-00, 035-08 QD and 035-08 LS the absorption of water was restricted since the specimens were taped in plastic foil. However, by weighing the specimens it was observed that some (probably condensed) water was able to leak through the foil during freeze/thaw. During this sealed freeze/thaw testing, the specimens were exposed to more than 300 cycles, but 3 of 5 specimens showed less damage than in the first freeze/thaw in water. After 320 cycles, 035-08 QD and the least deteriorated 035-00 beam absorbed the least: 0.3 vol-%. 03-08 LS absorbed 0.4 vol-%, whereas the last two beams of 035-00 absorbed 0.9 and 1.6%. Therefore the degrees of deterioration of the beams freeze/thaw tested in sealed condition were directly related to the amount of water uptake through the plastic foil.

Figure 2 shows the changes in resonance frequency during freezing and thawing in water, self healing and freezing and thawing of sealed beams. We see that the plot of resonance

TABLE 3

Resonance frequency on freeze/thaw and healing in water

Mix	Start freeze/thaw	End freeze/thaw Hz (%)	Self healed	End sealed fr./th.
030-08QD	3300 (100)	2875 (87)	3275 (99)	3125 (95)
030-08 LS	2875 (100)	2050 (71)	2800 (97)	1725 (62)
035-00	3200 (100)	1500 (47)	2980 (93)	1550 (48) 1)
040-00	2850 (100)	2040 (72)	2800 (98)	(used for
040-05	2830 (100)	1360 (48)	2400 (85)	compressive
040-05A	2780 (100)	1850 (67)	2475 (89)	strength)

1) mean value, individual specimens: 1075, 1425 and 2175 Hz (34, 45 and 68 %)

TABLE 4
Compressive strength 10 cm cubes sawn from beams, MPa (%)

Concrete	1) Before freeze/thaw	2) Immediately after freeze/thaw	3) Self healed in water
040-00	62.4 (100)	49.0 (-22)	51.3 (+ 4)
040-05	73.7 (100)	52.6 (-29)	55.9 (+ 5)
040-05A	59.2 (100)	44.5 (-25)	47.6 (+ 5)

frequency vs. number of cycles in the sealed test has a different character from the first freeze/thaw in water. Apparently the restricted access to water gives a more gradual deterioration than freeze/thaw in water.

The results again point to the very important role access of water plays during freeze/thaw testing. This was realized already in the American co-operative test in 1959 (18), and also discussed by Fagerlund (19). If water is in direct contact with the concrete during freezing and thawing, there exists a "pumping effect" resulting in increased water uptake compared to freeze/thaw with less access to water, and more water uptake than in concrete submerged at constant temperature. This water uptake appears to be related to the degree of deterioration. Freezing and thawing continuously submerged is a very severe test condition and should be used preferably for concrete to be used in structures or members that will be exposed to water during freezing and thawing.

Self-healing between freeze/thaw cycles of partly deteriorated concrete may be an important factor improving the frost durability of field concretes compared to laboratory freeze/thaw exposure.

Conclusion

Concrete specimens deteriorated by rapid freeze/thaw in water may almost fully recover loss of resonance frequency on subsequent water storage. However, the compressive strength recovered only 4-5% during healing after an initial loss of 22-29% due to freeze/thaw

TABLE 5
Increase in weight and volume of beams during freeze/thaw and healing (vol-%)

Concrete	Absorption fr./th. in water	volume change fr./th. in water	Absorption healing	Absorption fr./th. sealed
030-08 QD	0.5	2)	0	0.3
030-08 LS	0.9	2)	0	0.4
035-00	1.8	2)	- 0.1	0.3 - 0.9 - 1.6 [1)]
040-00	1.2	**0.8**	0	2)
040-05	**1.9**	**1.4**	+ 0.1	2)
040-05A	**1.6**	**1.0**	- 0.1	2)

[1)] variable leakage through plastic foil between three parallel specimens [2)] not tested

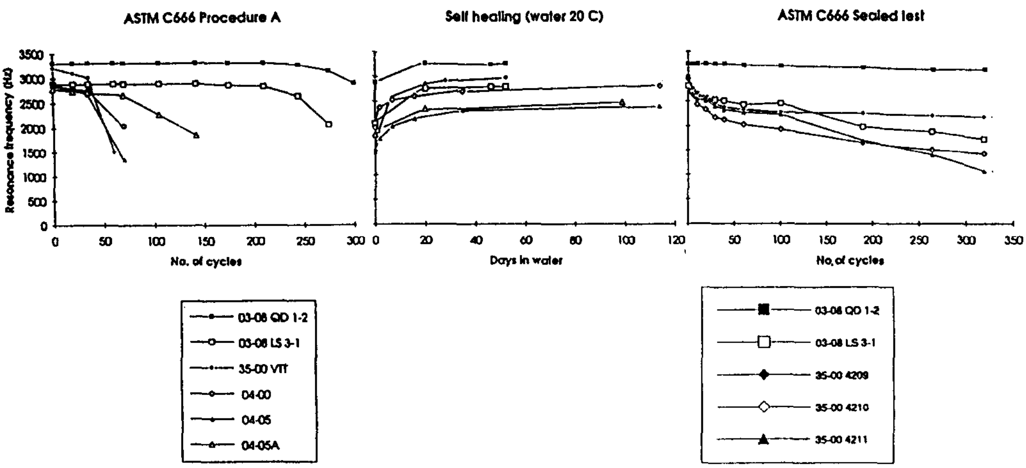

FIG. 2.
Resonance frequency ASTM C666 procedure A, self-healing and freeze/thaw sealed.

deterioration. The resonance frequency does therefore not correlate to concrete strength. The degree of self healing varied with concrete composition and degree of deterioration at stop of freeze/thaw test.

Measurements of volume and weight during freeze/thaw show that the absorption of water is larger than the increased volume due to internal cracking, i.e. some already existing pore space as well as the newly created cracks take up water during freeze/thaw. The amount of water uptake is related to the damage.

Freeze/thaw testing of self healed concrete beams partially sealed show that the deterioration also in this case was related to the possibility of the specimens to take up water during freeze/thaw test. The access of water during freezing and thawing therefore is a decisive parameter for the deterioration and should be considered before choosing test procedure (ASTM C666 proc. A or B) for concrete according to field exposure.

Self healing, in addition to drying, may be an important factor giving concrete better frost resistance in field than in laboratory, since concrete may have more time for healing in field.

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