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EFFECT OF FREEZING ON THE HARDENING OF STEAM-CURED CONCRETE

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Abstract

In the article the hardening circumstances of steam-cured concrete exposed to frost effect is discussed. The 90 days strength of steam-cured concretes which were post-cured under water later at ambient air, or after steam curing were post-cured alternately at −10 °C then at +20 °C under water was higher than those of hardening under natural circumstances. The reason is the following: the water cracks the hydrated cover formed during steam curing and so helps the process of hydration.

Keywords: steam-curing, hardening after steam curing.

1. Introduction

In Hungary, plant precast concrete and reinforced concrete products are hardened by steam-curing. They reach about 50% of the final strength at the end of the steam curing. The hardening of these units must continue at the storage area.

In our country, steam-cured units are exposed to frost effect at the storage area for a period of 3 to 5 months. Already in the early period of prefabrication (RILEM Symposia in Copenhagen, 1956, and in Prague, 1961) the problem of post-hardening of steam-cured concrete emerged. There had been instances where steam-cured concrete favourably hardened under frost effect, but the regularities of post-hardening were not suggested.

2. Preliminary Experiments

Table 1
Steam-curing and curing of concretes

Test mark	Steam curing diagram mark	Concrete steam-cured	Post-curing	Frost effect applied
1	3	in mould	—	In a freezing chamber at 20 °C for 28 days
2	4	in mould	—	
3	3	stripped	—	
4	4	stripped	—	
9	1	in mould	In water for a day	
10	2	in mould		
11	1	stripped		
12	2	stripped		
24	4	in mould		Alternating 20 times a day in freezing chamber at −5 to −10 °C, then in water at +20 °C
26	3	in mould		
28	2	in mould		
30	1	in mould		
25	4	stripped		
27	3	stripped		
29	2	stripped		
31	1	stripped		

Steam curing marks

Mark	Heating	Steam curing	Cooling
1	slow	80 °C	slow
2	fast	80 °C	slow
3	slow	60 °C	fast
4	fast	60 °C	fast

Cubes of 7.07 cm side length were steam-cured according to each of the four diagrams in *Fig. 1*, with the following results:

a) Not even the steam-cured concrete did harden in an air at −20 °C.

b) Steam-cured concretes, kept alternately in a freezing chamber at −20 °C and in water +20 °C until the period of 28 days, the post-hardening was undisturbed.

c) The best results were achieved by keeping steam-cured cubes alternately in a freezing chamber at −5 to −10 °C and in water at +20 °C until the period of 28 days.

d) Strength of concretes steam-cured after demoulding was much lower all along than that of those steam-cured in mould. Hardening after steam curing had, however, a similar tendency.

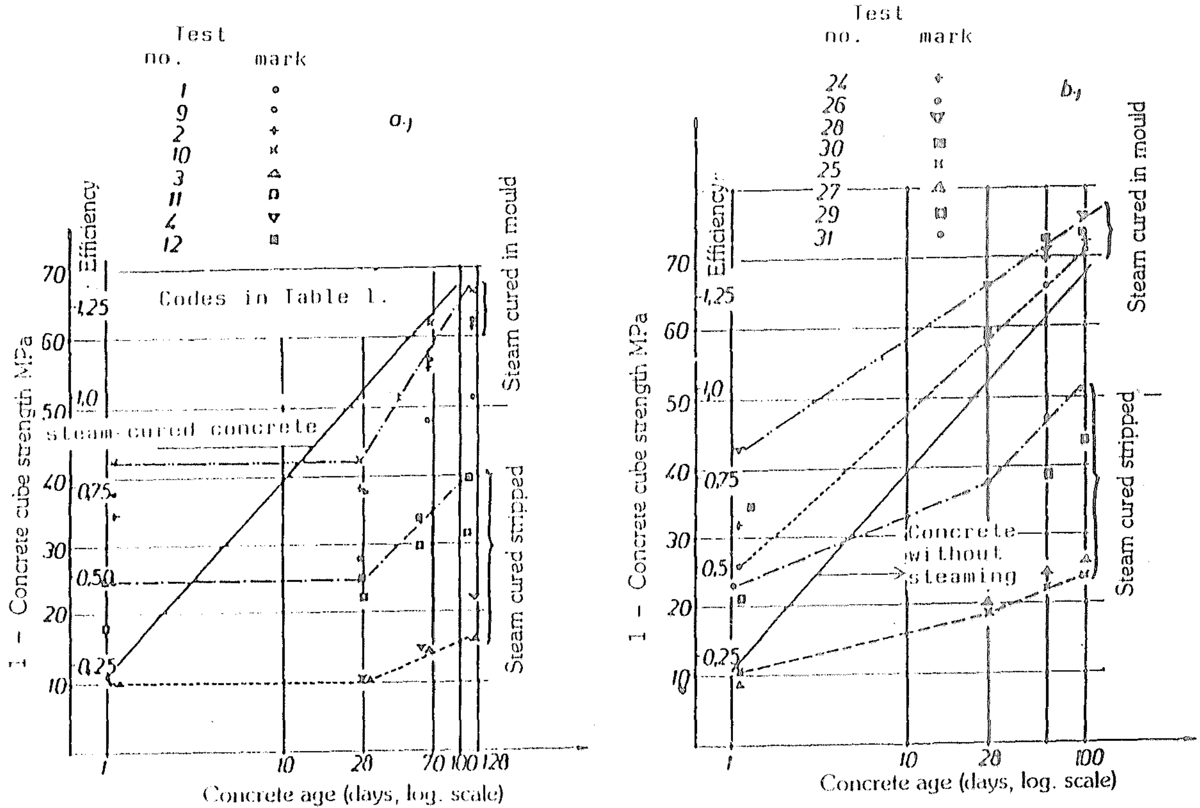

Fig. 1. Hardening of steam-cured concrete when the procedure after steam curing was the next:
a) one day under water and without post curing then for 28 days frozen at −20 °C finally kept at ambient air.
b) alternately kept in +20 °C water and frozen to −5 - −10 °C.

3. Frost Effect on the Hardened Cement Structure

In studying factors of hardening after steam curing, three types of factory made cements have been applied, according to *Table 2*.

Table 2
Mineral compositions of cements

Cement characteristics	Cement type		
	Ordinary with 10 % fly ash	p.c. of high C3S content	Sulfate resistant p.c.
C_3S,%		68.3	60.2
βC_2S,%		5.8	10.1
C_3A,%	incalculable	11.5	0.7
C_4AF%	———	9.0	21.7
$CaSO_4$,%	4.5	4.0	4.6
Free CaO%	—		1.1
Specific surface area according to (Blaine test) sq. m/kg	268	298	245

Cement content of the 7.07 cm side-length concrete cubes was always 400 kg/cu.m, the graded and washed river aggregate had a fineness modulus of 6.0, the concrete was of semiplastic consistence. The 3.0 cm side-length paste cubes were made with a water content required for the standard consistency.

Steam curing diagrams are seen in *Fig 2*. Rapid heating and steam curing at 90 °C were applied to study destruction during steam curing.

Steam curing was followed by five different methods of storage.

a) Daily alternating storage (ten times) in a freezing chamber at −10 °C and in water at 20 °C, then at ambient air.
b) Daily alternating storage (ten times) in a freezing chamber at −10 °C and in a room at +20 °C, then in ambient air.
c) In water at +20 °C until the age of 28 days, then in ambient air until testing.
d) In room at ambient air and 70 to 80% relative r.h. humidity, without moist curing.
d) In water until testing.

The most detailed tests were made on portland cement with 10% fly ash content. Development of strength is shown in *Table 3*.

Table 3
Hardening of concretes and pastes made with cement L 500

Mark of steam curing diagram	Handling	Concrete cube strength MPa at				Paste cube strength MPa at		
		1	28	90	180	1	28	90
		days of age						
Uncured	In water for 8 days, then at ambient air	17.6	58.5	69.4	72.1	28.0	112.5	118.1
I.	Water-frost (a)	43.3	58.6	64.0	73.8	68.3	95.1	141.3
	Ambient air-frost (b)		62.5	68.7	64.5		95.8	102.4
	Water for 28 days (c)	45.5	62.0	79.8	75.2	76.3	98.8	138.0
	Ambient air (d)		63.0	66.0			100.2	113.0
II.	Water-frost	43.0	58.6	72.2	74.5	49.7	83.0	126.9
	Ambient air-frost		59.1	64.2	64.5		82.6	86.3
	Water for 28 days	43.2	63.2	75.5	78.0	71.5	108.8	127.2
	Ambient air		61.4	64.1	59.8		96.3	103.7
III.	Water-frost	43.6	59.6	74.0	72.5	71.1	81.8	113.6
	Ambient air-frost		58.7	65.2	60.0		82.8	101.6
	Water for 28 days	45.9	56.5	73.7	72.3	65.1	80.6	116.0
	Ambient air		55.7	56.8	55.3		83.9	89.1
IV.	Water-frost	32.6	53.9	72.0	74.2	48.7	84.2	121.9
	Ambient air-frost		57.3	65.5	66.2		85.8	103.3

Strength tests showed that freezing of steam cured concrete at the storage area did no harm. Tests unambiguously showed that freezing cycles combined with moist curing is more favourable than with dry curing. This is of importance because of its practical occurrence in winter seasons.

Steam-cured concrete kept in water for a time after curing achieved higher strength at 9-days than that of naturally hardening concrete. This result underlines the importance of moist curing of steam-cured concrete.

Structure changes during hardening were also treated by X-ray diffractometry, derivatography and microscopy. X-ray diffractograms of cement L 500 with 10% fly ash have been plotted in *Fig. 3*. Roman numerals at the diffractograms mark steam curing, letter n marks natural hardening, letters show the mark of the kind of post-curing, numbers show the paste age.

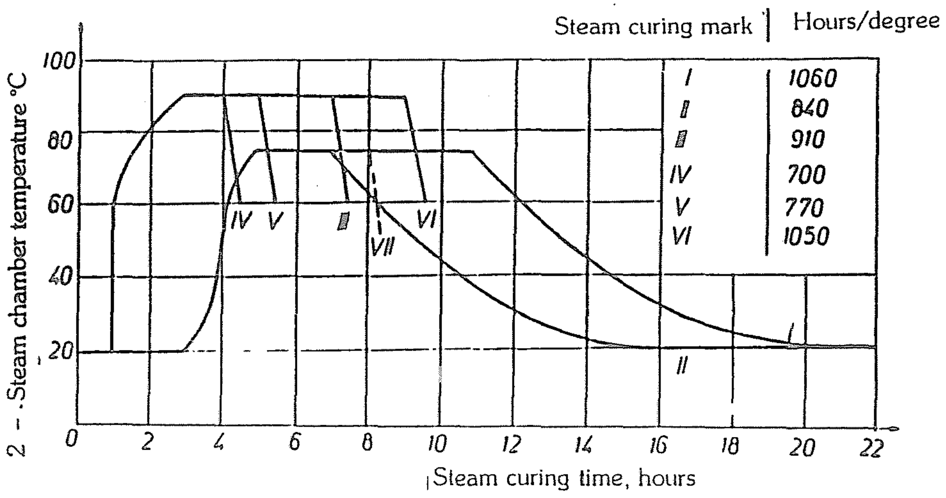

Fig. 2. Types of steam curing diagrams

These diffractograms do not suit for quantitative evaluations but permit to deduce some conclusions.

In case of storage at ambient air after steam curing (d), top value of $Ca(CH)_2$ was 11 (4.9 Å). This corresponds to the case where strengths were about equal and no $Ca(OH)_2$ left the system. Also, for the paste made with cement L 500 stored at ambient air after every freezing cycle (b), in half of the cases the peak value was 11, while in the other two cases it was lower than that. This is again an indication of that the frost effect is irrelevant in itself to hardening after steam-curing. In case of paste specimens stored 10 times alternatively in a freezing chamber, and in water at 20 °C, peak values were about 8 to 9, referring to the dissolution in water of part of the developed $Ca(OH)_2$. 90-day strengths were rather similar concrete and paste specimens stored in water for a time after steam curing, and/or alternatively frozen and stored in water hence it may be concluded that hardening after steam curing is primarily affected by water rather than by frost.

These test results were supported by the freezing-test results of C_3S pastes, and derivatography investigations.

Moist curing and alternating freezing-moist curing have similar effects. On the one hand, water (assisted by frost) disrupts the hydrate coating around the hardened cement, forwarding thereby hydration; on the other hand, water dissolves part of $Ca(OH)_2$, which is again a strength increasing effect.

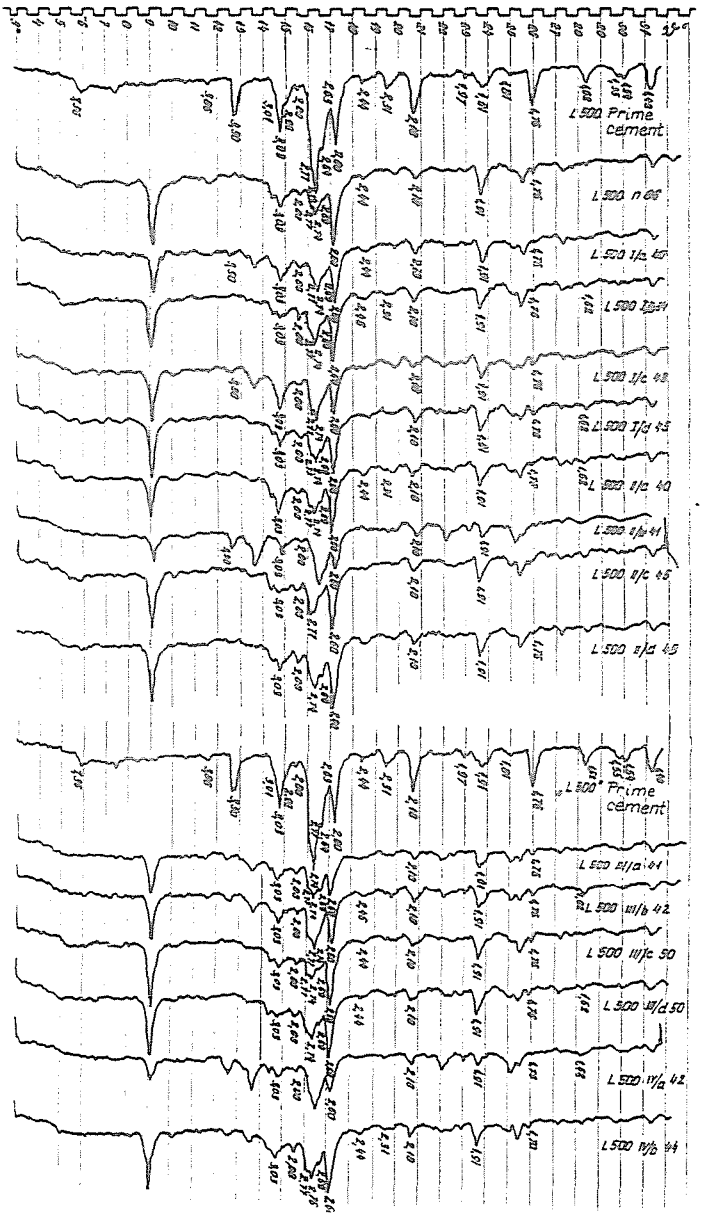

Fig. 3. X-ray diffractograms of cement pastes made with cement L 500

At an about 100 magnification under light microscope it was found that steam curing marked IV–VI caused cracks in the hardened cement, cracks being overgrown with clearly visible regular hexagonal crystals. Heating without a rest coarsely impaired the structure.

4. Summary

Hardening circumstances of steam cured concrete exposed to frost effect have been discussed. Concrete and mortar cubes have been made with normal, high-early-strength, sulfate-resistant cement containing 10% fly ash, with a cement content of 400 kg/cu.m, of low plasticity, steam-cured in different ways, and post-cured differently after steam-curing. Research demonstrated:

a) Steam-cured concrete stored at −20 °C shows no hardening during storage period.
b) Among the cases of storage, about equal strength resulted from storage in water, then at ambient air after steam curing; and by alternate storage after steam curing in a freezing chamber at −10 °C, then in water at +20 °C. The 90-day strengths of these concrete and cement paste specimens exceeded the 90-day strength of naturally hardening concrete. Water is decisively responsible for this favourable result by cracking the hydrate coating deposited in steam-curing, permitting thereby intensive continuation of hydration. Again, dissolution of $Ca(OH)_2$ is of importance.
c) Steam-cured concrete without formwork always exhibits a strength lower than that of concrete steam-cured in mould. In a favourable case, this strength loss may be 20 to 30%.

The tendency of hardening, however, was the same as for concrete steam-cured in mould.