EFFECT OF THE FREEZING RATE ON THE FROST RESISTANCE OF CONCRETE

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ABSTRACT

A limited literature survey shows that there is no univocal relation between the freezing rate in an <u>unsealed</u> test and the amount of frost damage.
A theoretical analysis shows that the effect of the freezing rate on the destructive forces occuring during a <u>sealed</u> test is very limited, if any. This is also confirmed experimentally by tests in which the effect of the freezing rate on the critical degree of saturation is studied and found to be negligible.
Therefore, the different and opposing effects of the freezing rate that have been observed in <u>unsealed</u> tests are no doubt mainly caused by the effect that the shape of the freeze/thaw cycle has on the maximum water content that is reached in the specimen during the test.

Key words: Frost resistance, freeze/thaw testing, freezing rate, air pore distribution, destruction mechanism.

1. THE FREEZING RATE

In this report rate of freezing is defined as the rate by which the <u>temperature of the specimen</u> is lowered; i. e. the <u>rate of cooling of</u> the specimen. This is roughly proportional to the rate by which the air or water surrounding the specimen is cooled. However, due to the latent heat of fusion of the pore-water the proportionality constant at a given temperature is a function of that temperature. For a coarse-porous material containing a large amount of water that freezes somewhat below $0^{\circ}C$, the specimen temperature stays constant at that temperature for a considerable length of time despite the fact that the outer temperature decreases continuously, more or less rapidly. However, the duration of the time of constant temperature is inversely proportional to the rate of cooling of the outer air or water. Therefore, considering a certain given temperature interval - e.g. from 0°C to -20°C -, the average rate of cooling of the specimen is roughly directly proportional to the average rate of cooling of the outer air or water at that same interval; see Fig. 1.

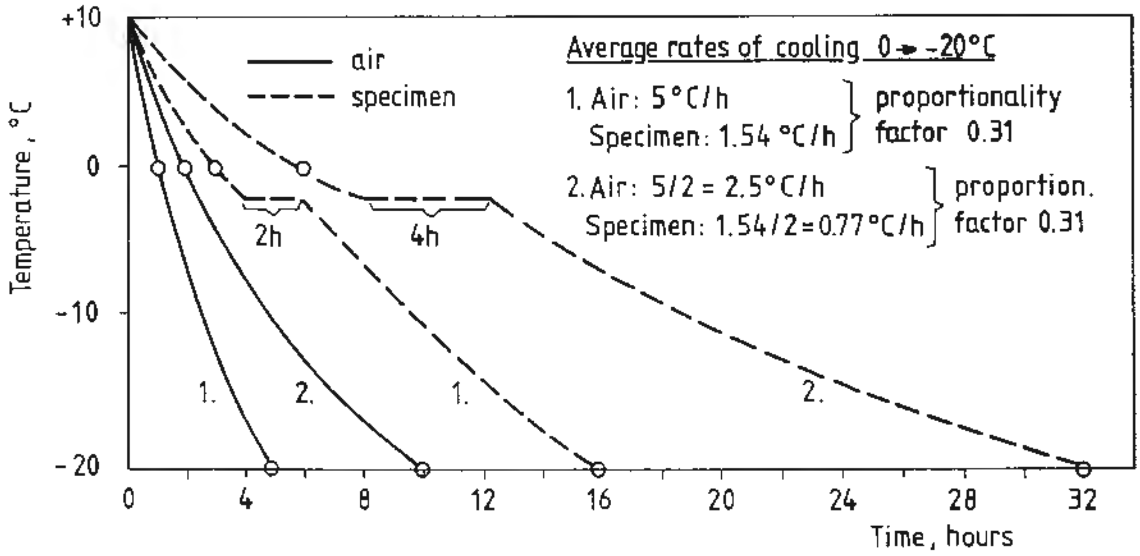

Fig. 1 Over a given temperature interval the average rate of cooling of the specimen is roughly proportional to the rate of lowering of the outer temperature.

There is, however, not necessarily a direct relationship between the freezing (or cooling) rate as it is defined above and the rate by which ice inside the specimen is formed. Neither is there always a direct relationship between the rate of cooling and the total amount of ice formed. Those facts will be discussed below in section 3.

The maximum rate of cooling of outdoor air in central and northern Europe is about 6°C/h /1/. Normal values are below 3°C/h. The rate of cooling of the concrete is somewhat lower than that of air, especially in more massive structures. Maximum values of about 3°C/h have been observed in a Norwegian wharf /2/. Under special conditions - e.g. radiation towards a clear dark sky during a winter night - considerably more rapid temperature drops of the concrete surface can occur; results of calculations presented in /3/ indicate that under such conditions surface cooling rates of about 12°C/h might occur when the cooling rate of the air is "only" 6°C/h. Cooling rates on this order have also been observed in practice in brick walls /4/.

2. EFFECT OF THE FREEZING RATE - TEST RESULTS

It is generally believed that the severity of a frost cycle increases with increasing freezing or cooling rate. Thus, increasing the cooling rate is often utilized as a supposed means of accelerating a freeze/thaw test. The common opinion is strengthened by many experiments, some of which will now be presented.

In Fig. 2 some results from the famous cooperative test of the four previous ASTM-tests for frost-testing concrete are shown. Many laboratories participated in the test /5/. Three concretes of different quality (HG,LG, HP) were tested with the test methods "Slow air" and "Rapid air". The major difference between the methods is the rate by which freezing (and thawing) took place. The average cooling rate in the interval +3°C to -16°C was 3.8°C/h (stand. dev. 0.2°C/h) for the slow test and 14°C/h (stand. dev. 7°C/h) for the rapid test. In both cases freezing took place in air and thawing in water. The more rapid method gave the most severe destruction during the 300 cycles that the test lasted.

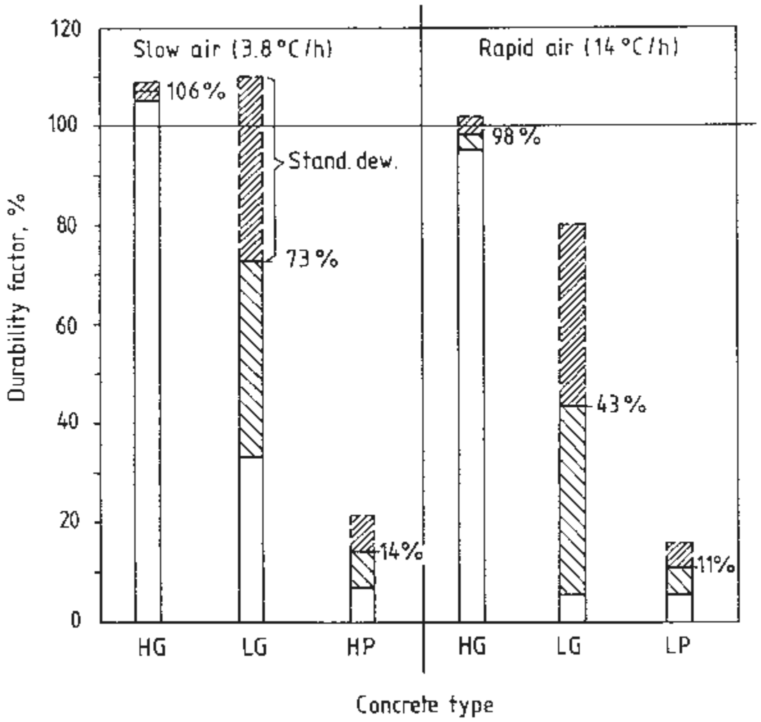

Fig. 2 Results of a cooperative test of the effect of the freeze/thaw cycle on the durability factor of three types of concrete /5/.

Fig. 3 shows the results of a traditional salt scaling test in which two different concrete cooling rates in the interval 0°C to -20% were used: a slow rate A, 2.4°C/h, and a rapid rate B, 4.2°C/h /6/. In both cases, the total cycle lasted for

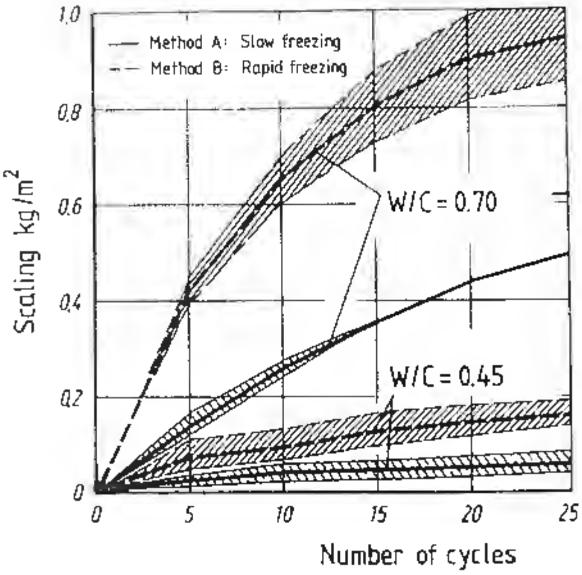

Fig. 3 The salt scaling process for two air-entrained concretes as function of the freezing rate /6/.

24 hours (16 hours of freezing to about -22°C and 8 hours of thawing to +18°C). The top surface of the specimen was covered with 3% NaCl-solution (unprotected from evaporation). The results indicate a more severe scaling for the more rapid test. This is the case for both concretes tested.

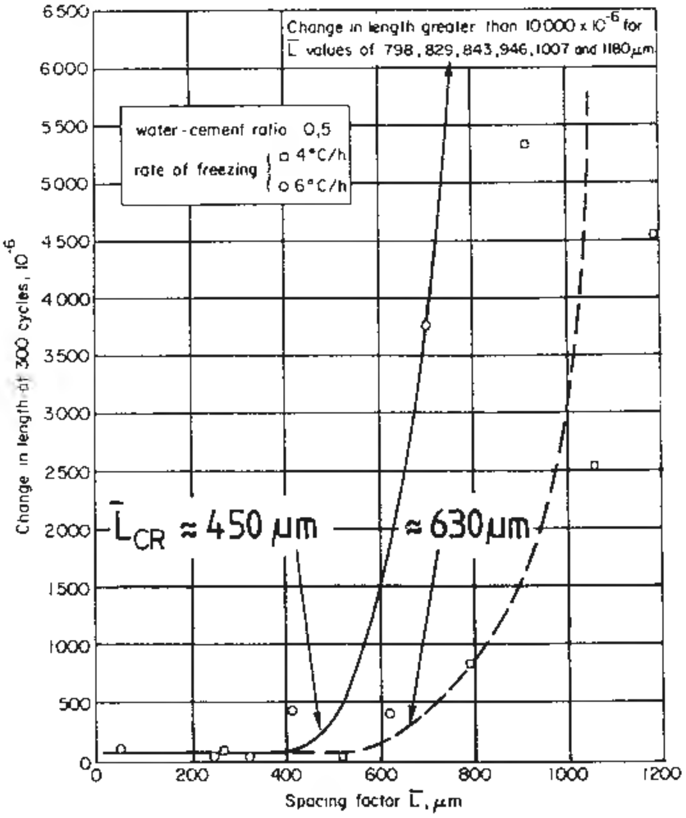

Fig. 4 The length change after 300 freeze/thaw cycles versus the spacing factor for concretes with w/c-ratio 0.50 /7/.

Fig. 4 shows the relation between the critical spacing factor of concrete with w/c=0.50 frozen with two different rates, 4 and 6°C/h /7/. Each specimen was stored in a steel container during the whole test, which lasted for 300 cycles. Freeze/thaw took place in air, but some excess water was added to the container every time the specimen was taken out for inspection. Hence, a certain water uptake of the specimen could take place, which was confirmed by weighing /7/. The more rapid freezing rate seems to reduce the critical spacing factor which indicates that higher internal stresses occur.

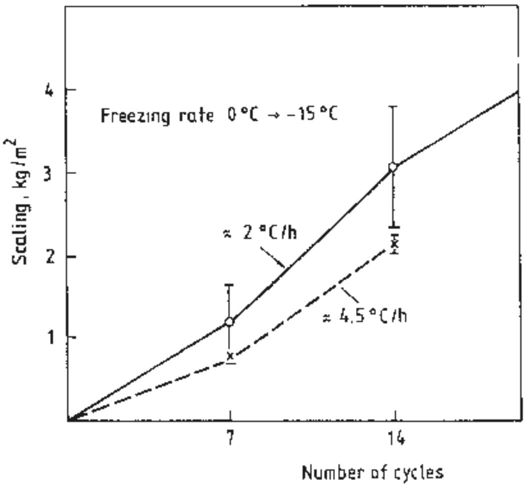

Fig. 5 Studies of the effect of the freezing rate on the salt scaling in the Swedish so-called Borås Method /8/.

There is, however, also some experimental evidence that the freezing rate might have zero or reverse, effect on the destructive forces. Two examples will now be presented.

Fig. 5 shows the results of a study of the effect of the freezing rate on the salt-scaling in the Swedish so-called Borås Method /8/. The freezing rate of the protected salt solution which stays on top of the specimen varies between 2°C/h and 4.5°C/h but the effect of this variation of freezing rate on the scaling is small. There is even a slight tendency toward a reduced scaling when the freezing rate is increased.

This is in opposition to the results by Nischer - Fig. 3 - who used almost the same test method. The major difference between the two tests is that the salt solution is hindered from evaporation in the Swedish test.

Fig. 6 shows results from the same American cooperative test as that described above; see Fig. 2 /5/. In this case both freezing and thawing, however, took place in water. The average cooling rate in the interval +3°C to -16°C was 2.4°C/h (stand. dev. 0.3°C/h) for the "Slow water" test and 23.9°C/h (stand. dev. 13.1°C/h) for the "Rapid water" test. In this case the slow test gave about the same result as the rapid test, which is almost ten times as rapid.

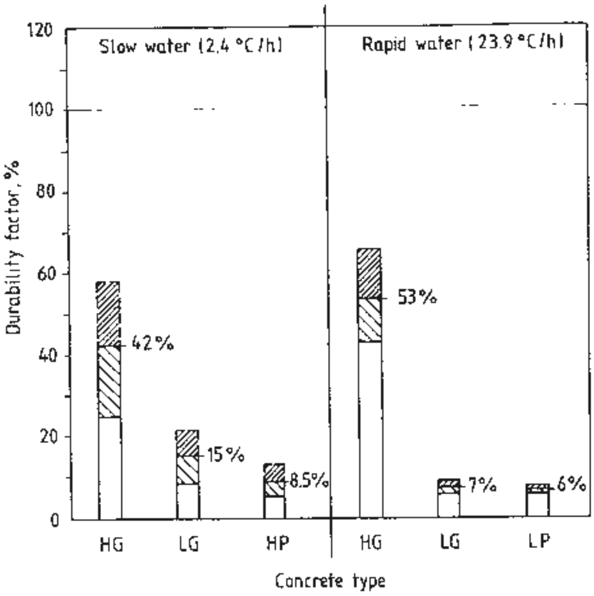

Fig. 6 Results of a cooperative test of the effect of the freeze/thaw cycle on the durability factor of three types of concrete /5/.

This small literature survey, therefore, clearly shows that there is no univocal relationship between the rate of freezing during a cyclic freeze/thaw test and the damage occuring. Evidently there are other factors during the test that are just as important as the rate of freezing. The most important factor is probably the water content of the specimen during the test; a slow frost cycle that promotes a large water uptake will probably cause larger destruction than a more "dry" cycle despite the fact that the last cycle is much more rapid /9/. When analyzing the effect of the shape of the freeze/thaw cycle on the frost damage, such as the effect of the freezing rate, one must therefore distinguish between "open" or unsealed tests in which the specimen is free to absorb or desorb moisture, and "closed" or sealed tests in which the initial moisture content is kept unchanged during the whole test. Those two principally different ways of testing will be analyzed below. It will be shown that the effect of the freezing rate is rather small in a sealed test but could be very large in an unsealed test. In a sealed test an increase in the freezing rate will normally create somewhat larger destructive forces. In an unsealed test it can create larger or smaller destructive forces depending on the details in the design of the test.

3. EFFECTS OF THE FREEZING RATE IN A SEALED TEST

3.1 Damage due to hydraulic pressure

If considerable ice formation can take place in situ and excess water is expelled from the freezing site, a hydraulic pressure will appear inside the concrete. In this case there is a direct correlation between the cooling rate and the rate of ice formation. The following relation is valid

$$\frac{dw_f\theta}{dt} = \frac{dw_f(\theta)}{d\theta} \cdot \frac{d\theta}{dt} = f'(\theta)\,\frac{d\theta}{dt} \tag{1}$$

where $w_f(\theta)$ is the equilibrium freezable water as function of the specimen temperature θ (see Fig. 7) and $d\theta/dt$ as the cooling rate of the specimen (the freezing rate). In this case there is also a strict proportionality between the cooling rate of the specimen $d\theta/dt$ and the cooling rate dT/dt of the outer medium (water or air).

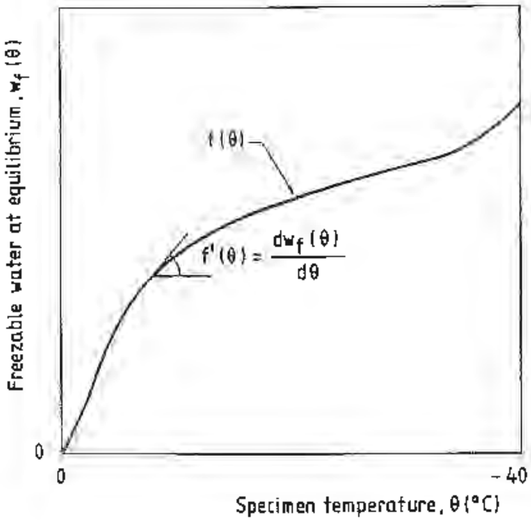

Fig. 7 The freezable water as a function of the temperature for a specimen in which ice formation takes place in situ. (Hypothetical curve).

$$\frac{dw_f\theta}{dt} = \text{const}_1(\theta)\cdot f'(\theta)\cdot \frac{dT}{dt} \tag{2}$$

where T is the outer temperature and the constant is a function of the temperature; see Fig. 1.

The hydraulic pressure $p_h(\theta)$ is a function of the rate of ice formation. For a water-saturated slice of thickness D the following relation is valid /10/.

$$p_h(\theta) = \frac{1}{8} \cdot \frac{0{,}09}{B(\theta)}\, D^2 \cdot \frac{dw_f(\theta)}{dt} \tag{3}$$

where $B(\theta)$ is the permeability of the ice-water mixture at the specimen temperature θ.

The maximum rate of ice formation normally occurs when the specimen temperature is rather high. On the other hand the minimum permeability will probably occur when much ice has been formed, i.e. when the temperature is low. Therefore, the maximum hydraulic pressure does not necessarily occur when the rate of ice formation has its maximum /11/; see Fig. 8.

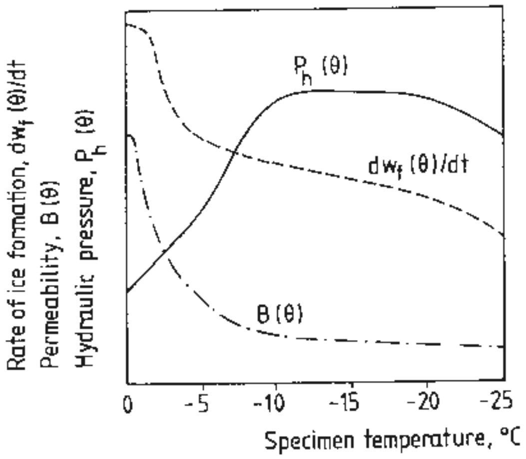

Fig. 8 Hydraulic pressure versus specimen temperature; eq. (3) (Hypothetical curves of freezing rate and permeability).

Inserting eq. (1) in eq. (3) gives

$$p_h(\theta)= \frac{1}{8} \cdot \frac{0,09}{B(\theta)} D^2 \cdot \frac{dw_f(\theta)}{d\theta} \cdot \frac{d\theta}{dt} \tag{4}$$

or

$$p_h(\theta)= \text{const}_2(\theta)\cdot D^2 \cdot \frac{d\theta}{dt} \tag{4'}$$

A similar expression can be derived for the more common case of a spherical shell surrounding a spherical air void /10/;

$$p_h(\theta)=\text{const}_3(\theta)\cdot \left[\frac{\bar{L}^3\cdot\alpha}{3} + \frac{3\bar{L}^2}{2} \right] \frac{d\theta}{dt} \tag{5}$$

where $\bar{L}$ is the shell thickness (the spacing factor), and α is the specific surface of the air void.

Theoretically, according to eq. (4) and (5), the hydraulic pressure should disappear when cooling is stopped. For more coarse-porous materials this is also the case; see Fig. 9 showing the length-change temperature curves of a non-air-entrained cement paste with w/c-ratio 0.60 /12/. As long as the temperature drops the specimen expands. When temperature is kept constant at -9 °C the specimen length is constant. When cooling is resumed, after 20 minutes, expansion starts again.

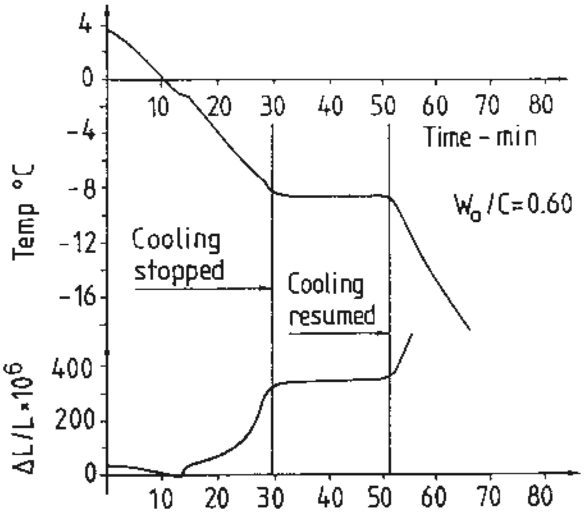

Fig. 9 Temperature and length change curves of a non-air-entrained cement paste with w/c-ratio 0.60 /12/.

The material is fractured when the hydraulic pressure exceeds the tensile strength. Thus, according to eq. (4) and (5) there is a critical slice thickness D_{CR} or a critical shell thickness (critical spacing factor $\bar{L}_{CR}$).

For the slice this is inversely proportional to the squareroot of the cooling rate.

$$D_{CR} = \text{const} \left[\frac{d\theta}{dt} \right]^{-1/2} \tag{6}$$

For the shell the expression is a bit more complicated.

Consequently, when the cooling rate is increased the critical spacing factor is decreased. Therefore, there will also be a decrease in the so-called critical degree of saturation. This effect will be discussed below in section 3.3.

3.2 Damage due to icelens formation

In very fine-porous materials ice formation might also take place by so-called icelens formation, which means that unfrozen water diffuses, from pores that are too narrow to contain ice at the current temperature, to coarse ice-filled pores where it freezes, thereby creating a pressure /12/. In this case the rate of iceformation is only a function of the rate of diffusion and this is not necessarily proportional to the rate of cooling of the specimen. The driving force of diffusion is the free energy differential between unfrozen water and ice. This is, however, only a function of the absolute freezingtemperature and not of the rate of temperature drop.

The diffusion process takes time, however. Therefore, the pressure will increase with increasing length of the cooling part of the freeze/thaw cycle; a rapid cooling which is directly interrupted by warming will therefore create less pressure than a slow cooling to the same temperature just because there is less time for ice to form. On the other hand, the same rapid cooling followed by a very long period of cool temperature could cause much larger destructive forces than a slower cooling directly followed by warming; viz. large ice bodies exerting large pressures have time to develop.

The expansive pressure due to this mechanism must continue even when cooling is stopped. An example of the fact that this actually happens is shown in Fig. 10. The material is a non-air-entrained dense cement paste with w/c=0.45. The behaviour of this dense cement paste is quite different from that of the more coarse-porous cement paste shown in Fig. 9.

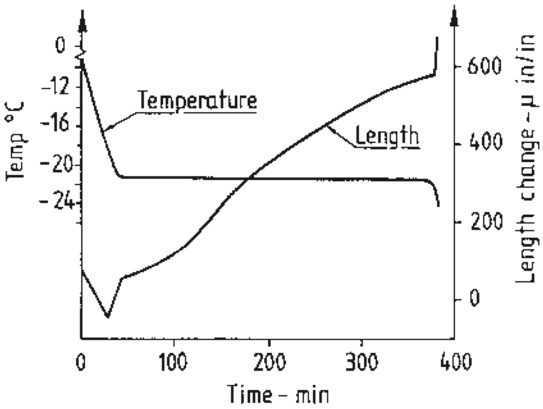

Fig. 10 Temperature and length, change curves of a dense non-air-entrained cement paste with w/c-ratio 0.45/12/.

3.3 Effect of the freezing rate on the critical degree of saturation

As shown above, only hydraulic pressure will be directly related to the freezing rate. When the freezing rate increases, the critical spacing factor decreases. Hence, less water can be accepted in the air-void system. The effect of a change in the critical spacing factor on the "critical air void absorption" can be calculated by a method described in /13/. A simple example is shown below.

The air-void radius frequency curve f(r) is described by the following expression

$$f(r) = \frac{\ln b}{b^r} \tag{7}$$

where r is the poreradius and b is a constant that expresses the shape of the frequency curve. b is defined by

$$b = e^{\alpha_o} \tag{8}$$

where α_o is the specific surface of the empty air void system.

The residual spacing factor $\bar{L}_r$ after a certain water filling of the finest part of the air pore system is

$$\bar{L}_r = \frac{3}{\alpha_r} \{1,4(\frac{P}{a_r} + 1)^{1/3} - 1\} \tag{9}$$

where P is the volume fraction of cement paste exclusive of air. α_r and a_r are the residual specific surface and the residual aircontent after the partial water filling of the air void system. Corresponding values of α_r and a_r can be calculated by inserting different values r of the coarsest airpore, that is water filled into eq. (7). The method is shown in /14/. Thereafter, the residual spacing factor $\bar{L}_r$ can be calculated by eq (9). The critical air void absorption occurs when the critical spacing factor $\bar{L}_{CR}$ equals the residual spacing factor $\bar{L}_r$.

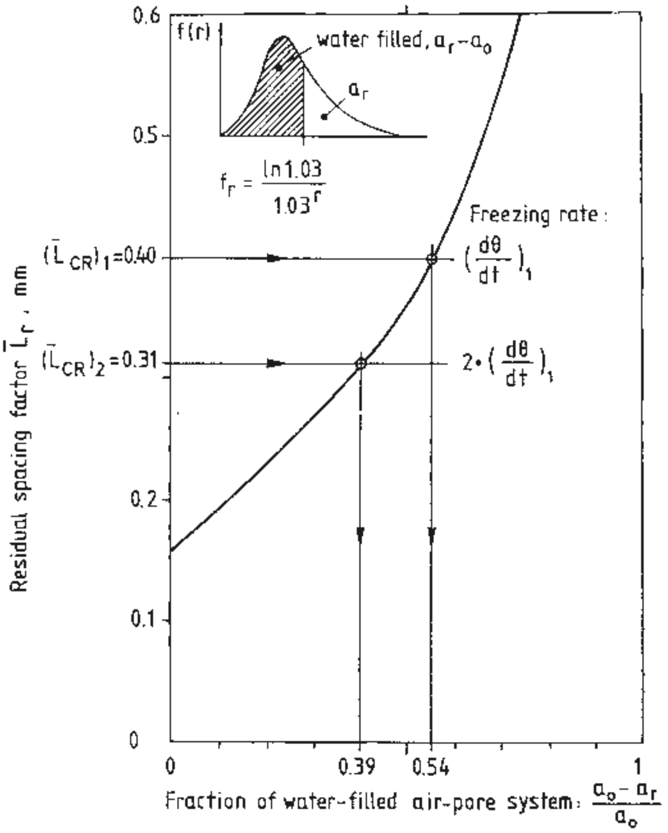

Fig. 11 Relation between the volume fraction of water-filled airpore system and the residual spacing factor of air-filled pores. Total aircontent a_o = 6%, cement paste content P = 30%.

Let us assume a concrete with a cement paste content P = 30%, a total air content a_o = 6% and an airpore system defined by eq (7) with b = 1.03 (i.e. $\alpha_o = 0.030\ \mu m^{-1} \equiv 30\ mm^{-1}$). Then, for such a concrete, a relation according to Fig. 11 between the volume fraction of a water-filled airpore system and the spacing factor $\bar{L}_r$ is valid. Let us assume that a certain freezing rate $(d\theta/dt)_1$ gives a critical spacing factor $(\bar{L}_{CR})_1$ of 0.40 mm. Then, according to eq. (5) a doubling of the freezing rate gives a new spacing factor $(\bar{L}_{CR})_2$, which is 0.31 mm. According to Fig. 11 the effect on the critical water absorption in the airpore system is rather limited; it changes from 54% to 39% of the total air pore volume. Assuming the total porosity of the con-crete to be 16% (160 litres/m^2) this means that the critical degree of saturation changes

$$\text{from:}\ (S_{CR})_1 = \frac{160 - 0.46 \cdot 60}{160} = 0.823$$

$$\text{to:}\ (S_{CR})_2 = \frac{160 - 0.61 \cdot 60}{160} = 0.772$$

For dense concretes in which destruction is due mainly to ice-lens formation, the effect of the freezing rate is smaller still, if any.

The limited effect of the freezing rate on the critical degree of saturation has also been confirmed by direct freezing experiments. In a cooperative test of the so-called S_{CR}-method two different concretes (Type I and II) were tested at 5 laboratories /15/. The cooling rate in the interval 0°C to -10°C varied between 1.9°C/h and 7.1°C/h but the variation in the measured degrees of saturation was very small; see Fig. 12.

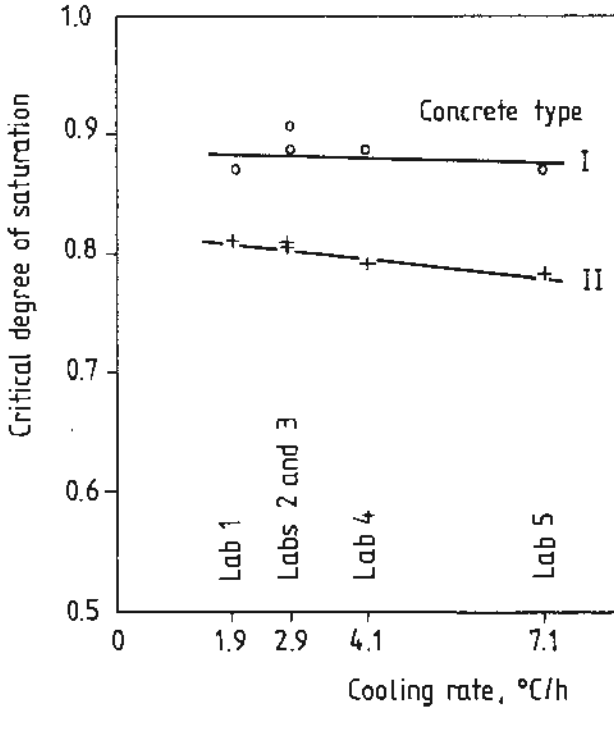

Fig. 12 The international cooperative test of the S_{CR} method. Effect of the freezing rate or S_{CR} of sealed concrete.

At BAM in Berlin a study was made of the effect of the cooling rate on the expansion of sealed concrete specimens containing different amounts of water /16/. The results are shown in Fig. 13. In test B the cooling rate was twice that of test A but the S_{CR} value defined by the abrupt change in the expansion curve is unchanged.

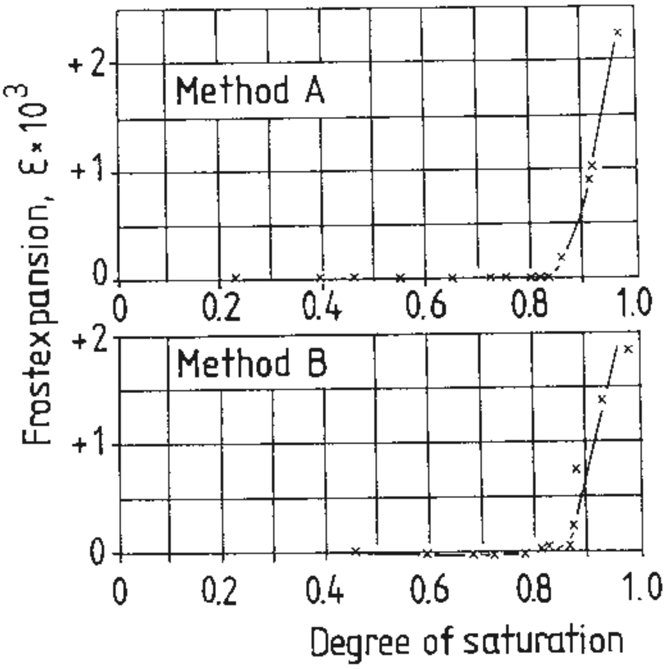

Fig. 13 Effect of the cooling rate on the expansion of sealed concrete containing different amounts of water; w/c-ratio 0.65. Method B is twice as rapid as method A.

4. EFFECTS OF THE FREEZING RATE IN AN UNSEALED TEST

In an unsealed test the specimen can take up or give away water during each cycle. Exactly what happens depends on the design of the cycle. Normally, when thawing, takes place in water, the specimen gradually absorbs water, see Fig. 14. Traditional freeze/thaw cycling is therefore in a way only an accelerated means of filling the concrete with water. Damage occurs when the water content inside the specimen exceeds the critical level. In the vicinity of S_{CR} very small changes in the water content change the behaviour of the specimen dramatically. One example is shown in Fig. 15. Increasing the degree of saturation from 0.88 to 0.90 corresponding to less than 3 l/m^3 causes expansions that are much larger than the fracture strain of the concrete. Freeze/thaw cycles which allow large absorptions in the concrete will therefore be more harmful to the concrete than more "dry" cycles irrespectively of the relative rate of cooling of the cycles. This could explain the test results shown in Fig. 2 and 6. The characteristics of the different cycles are shown in Table 1. There is almost a direct relation between the "wetness" of the test and the damage caused.

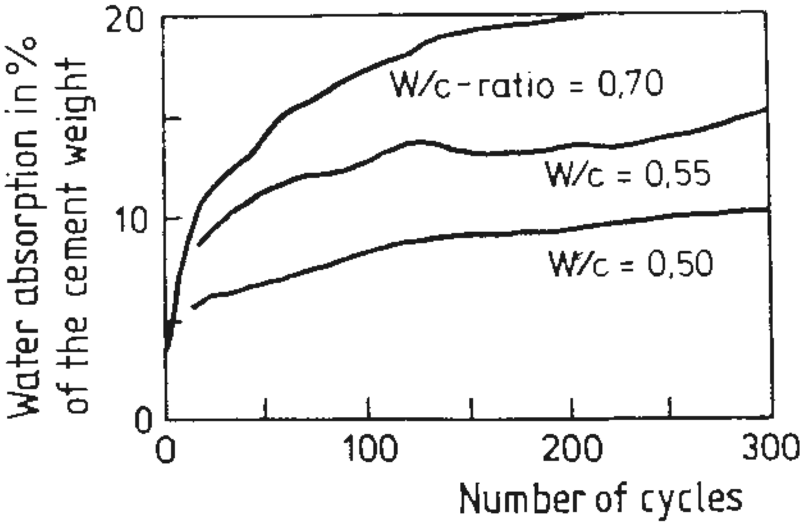

Fig. 14 Example of water absorption in concrete during unsealed freeze/thaw in water /17/.

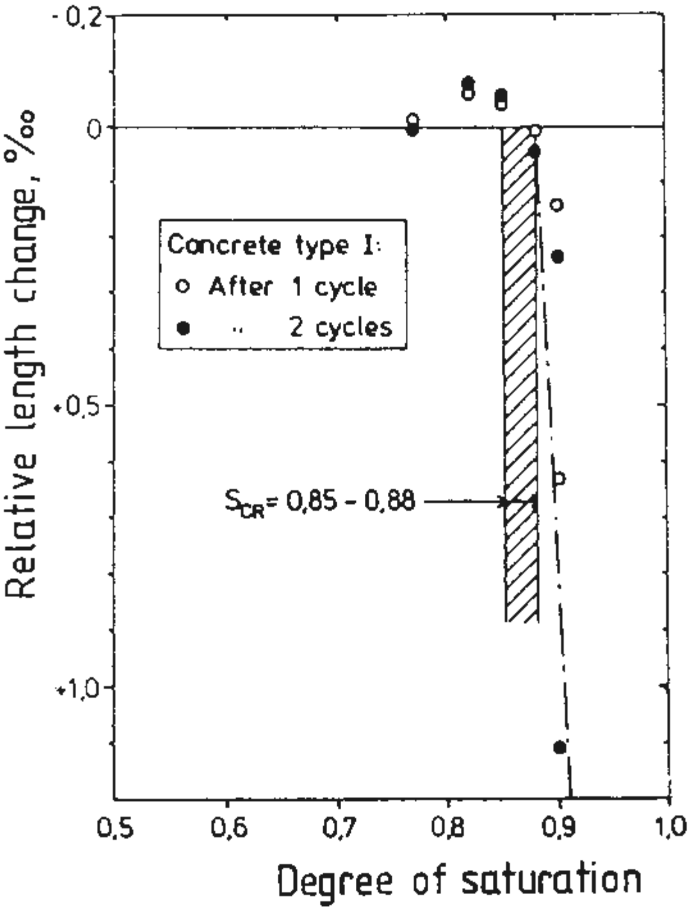

Fig. 15 Example of the small amount of water needed in order to transfer a concrete from being durable to being undurable /9/.

Table 1. Characteristics of the four freeze/thaw cycles used for the specimens in Fig. 2 and 6 /5/ (average values).

Method	Time in air (h)	Time in water1) (h)	Time in air / Time in water	Relative2) wetness	Mean durability factor
Slow water	0	48	0	1	22
Rapid water	0	3	0	2	22
Rapid air	2	1	2	3	51
Slow air	18	6	3	4	64

1) including the time the specimen is frozen
2) 1 is wettest, 4 is driest

5. CONCLUSIONS

The average cooling rate or freezing rate of the specimen is almost directly proportional to the cooling rate of the surrounding medium within the same temperature interval considered. The rate of ice formation is, however, proportional to the cooling rate only when freezing occurs in situ, creating a hydraulic pressure. In this case the destructive forces increase with increasing cooling rate. When freezing occurs as icelens formation in coarser pores by water that has diffused from other, more narrow, pores there is no direct relation between the cooling rate and the rate of ice formation, Fig. 10. Nor is there any direct relation between the rate of cooling and the destructive forces.

In a <u>sealed</u> test with no exchange of moisture between the specimen and its surroundings there is always a rather limited effect of the freezing rate on the destruction. This is proven theoretically - Fig. 11 - but also experimentally - Fig. 12, 13.

In an <u>unsealed</u> test the freezing rate will affect the extent of water exchange between the specimen and its environment. The larger the water content in the specimen, the larger the destructive forces. Therefore, freeze/thaw cycles that introduce much water into the specimen are more harmful than cycles that introduce small amounts of water or even make the specimen dry out during the test. In some cases a cycle with rapid cooling is more harmful than a slower cycle. In other cases the reverse is true. The actual effect depends on all the characteristics of the cycle, especially the length of time the specimen is stored in liquid water during each cycle - Table 1. This could explain all the conflicting results of experiments in which the effect of the freezing rate on frostresistance has been studied - Fig. 2-6.

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