MECHANICAL DAMAGE AND FATIGUE EFFECTS ASSOCIATED WITH FREEZE-THAW OF MATERIALS

Göran Fagerlund
Division of Building Materials, Lund Institute of Technology, Sweden

Abstract

In a traditional freeze-thaw test, in which the specimen is exposed to water during freezing and/or thawing, it is often observed that damage increases progressively with increasing number of freeze-thaw cycles. Sometimes a certain "incubation" number of cycles is required before frost damage occurs. This behaviour is often believed to be an effect of fatigue. In the paper it is shown that the progression of damage observed probably is caused by a gradual water absorption during the test. Therefore, each new freeze-thaw cycle is performed with a somewhat higher moisture content in the specimen than in the cycle before. This means that progressive destruction is not an effect of fatigue of traditional type, but is caused by gradually increased internal stresses due to the increased inner moisture level. No damage occurs until the number of cycles has become big enough to cause damage which explains the existence of "incubation" cycles.

It is shown that a certain low-cycle fatigue exists and that this has an influence on the progression of damage. But, this effect is limited to rather few freeze-thaw cycles following the the one that caused the first damage. Experiments with different materials indicate that an upper limit for low-cycle frost damage fatigue exists and that this limit is a function of the moisture content.

Results of an investigation of concrete on the effect of frost and high moisture levels on compressive strength, tensile strength, bond strength, and E-modulus are presented.

1. Evolution of damage in traditional open freeze-thaw tests

There are two types of freeze-thaw damage:

1: *Internal damage* caused by a transgression of a certain maximum tolerable, critical, moisture condition inside the material.

2: *Surface scaling* mostly occurring when the surface of the material is exposed to a salt solution -de-icing salts or sea water- during freeze-thaw.

This paper only deals with internal freeze-thaw damage.

It is often believed that frost damage -at least during a freeze-thaw test- is caused by fatigue as a result of repeated freeze-thaw cycles. Each new cycle is supposed to add to cumulative internal damage similar to what occurs in normal mechanical fatigue. Since the number of freeze-thaw cycles in a test nomally is below 1000 the fatigue should, however, be more of type low-cycle fatigue than high-cycle fatigue. Besides, in the practical use of the material, the total number of severe freeze-thaw cycles during its lifetime seldom exceeds some thousend. Therefore, also in practice, frost damage should be of type low-cycle fatigue, provided there is any fatigue at all.

The reason behind the fatigue hypothesis is that one often notices a development of damage of the type shown in figure 1 when the material is tested in so-called "open" freeze-thaw, i.e. in a test where the specimen has access to water during freezing and/or during thawing, (1). In some cases -curves D, P, C in figure 1- damage increases progressively with the number of freeze-thaw cycles already form the first cycle. In other cases -all other curves in figure 1- a certain number of freeze-thaw cycles are needed in order to initiate damage. Thereafter, damage increases progressively with increasing number of cycles. It will be shown in this paper that this behaviour can be explained by a different phenomenon than ordinary fatigue, namely by a gradual water absorption during the test, causing bigger and bigger stresses during continued freeze-thaw. After a certain critical water content has been reached, damage begins and is increased by a low-cycle fatigue effect lasting for a limited number of cycles until the material is more or less totally destructed. This critical water content can be described as a *fatigue limit*.

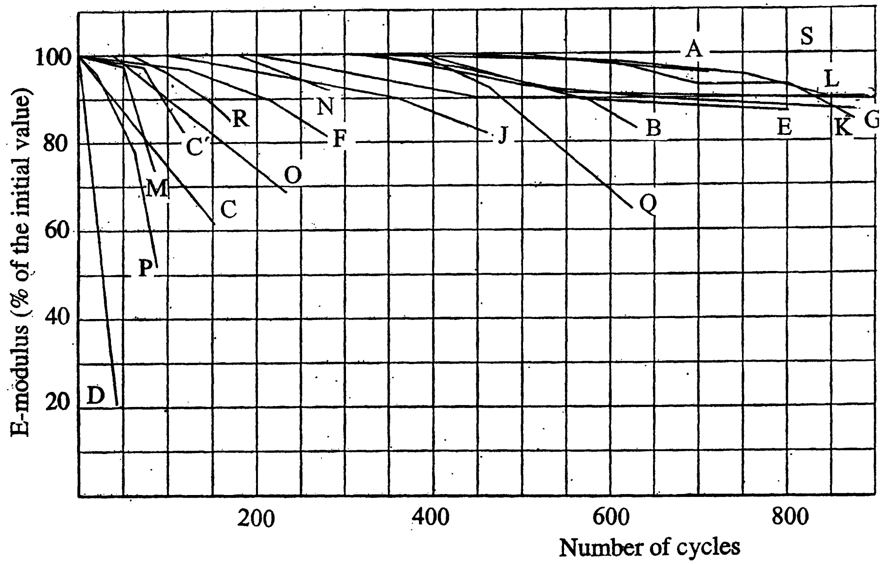


Figure 1: Reduction in E-modulus of cement mortar specimens repeatedly frozen in air to -15°C and thawed in water at +5°C. 2 cycles per day; (1).

2. Open freeze-thaw versus closed freeze-thaw

2.1 Open freeze-thaw. Gradual water uptake

In a traditional open freeze-thaw test the specimen is frozen in air or in water, and it is almost always thawed in water. This means that the specimen is free to absorb water during the test. Normally, thawing in water causes bigger absorption than freezing in air causes drying. Therefore, normally the water content increases with increasing number of freeze-thaw cycles irrespectively of how the open test is performed. Examples of the gradual water absorption during a test is seen in figure 2, (2). In open freeze-thaw the internal stresses during freeze-thaw will gradually increase due to this water absorption.

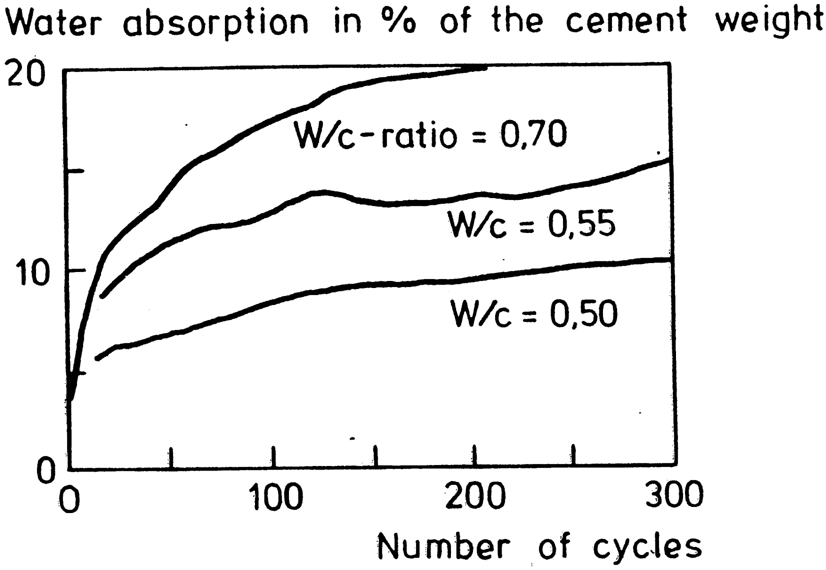


Figure 2: Water absorption in three types of concrete during freeze-thaw in water; (2).

The mechanism behind the water absorption is not fully clarified. One plausible explanation, based on a thermodynamic analyses of the energy state of ice, air, and water phases during the freezing-melting process, the "micro lens pump", has been proposed by Setzer, (3); Another mechanism has been suggested by Kaufmann (4); when a specimen warms from its lowest temperature the thermal contraction of the ice phase is bigger than the thermal contraction of the solid material. Therefore, theoretically at least, there is a possibility of a certain absorption, provided the specimen is thawed in water. Also other water uptake mechanisms during freeze-thaw tests have been suggested; e.g. (5, 6). At constant temperature, above zero temperature, water absorption can also be caused by a dissolution of air enclosed in "air-pores". The mechanism is described in (7).

A salt scaling test is a special case of open freeze-thaw. In this, the material surface is exposed to a salt solution, normally NaCl. Then, ice bodies formed close to the surface will absorb water from the outer solution and grow. The driving force for water absorption is the free energy differential between solution and ice, (8). The mechanism is in a way identical to frost heave in the ground, which, however, involves moisture transport on a macroscopic scale.

When, after a number of cycles, the material becomes damaged, the cracks formed will be rapidly filled by water. Therefore, one can assume that the absorption rate is somewhat bigger in the frost damaged material than it was before frost damage occurred.

2.2 Closed freeze-thaw. No water uptake

In closed freeze-thaw the material is protected from moisture uptake or loss. Thus, the moisture present before the first freeze-thaw cycle is unchanged during all consecutive freeze-thaw cycles. Either the material is damaged directly during the first cycle, which is the case when the moisture content is above a certain critical level, or it is undamaged also after numerous cycles, which is the case when the moisture content is below the critical value. It will be shown below that the number of freeze-thaw cycles -the fatigue effect- is of significant importance only when the moisture content is above the critical.

3. The effect of moisture at closed freeze-thaw

In closed freeze-thaw there is no moisture change in the material during the entire test. A test can be performed in the following manner: a series of specimens of the same material is adjusted to different individual moisture conditions, either by drying from saturated condition, or by absorption from dried condition. After that, they are sealed in order to hinder moisture exchange with the surroundings. Hysteresis effects might cause a certain moisture gradient across the specimen volume during the moisture adjustment phase, especially when the adjustment is made by drying. This effect can be diminished by a conditioning procedure where the specimen is cyclically warmed and cooled in its sealed condition. Another possibility is to adjust the specimens by using a pressure plate apparatus in which water is either forced out by an external air pressure, or in which water is sucked in by a gradually lowering of the outer air pressure. The procedure is described in (9). At such moisture adjustment, water leaves or enters the specimen homogeneously over the entire volume.

A suitable mechanical property for detecting internal damage, like the dynamic E-modulus, is determined for each specimen before freeze-thaw. After that, the specimens are exposed to a number of freeze-thaw cycles in sealed condition. The mechanical property selected is determined after a limited number of cycles. The fatigue effect at moisture contents above the critical can be observed by testing after different number of freeze-thaw cycles. Finally the *damage* -like the residual E-modulus or dilation- is plotted versus the moisture content. Then, diagrams of type figure 3 to 7 are obtained. In these diagrams moisture condition is expressed in terms of a degree of saturation, S (ratio between total water volume and total pore volume). Figure 3 shows results for *cement mortar*, (10). Below S=0.77 there is no frost damage irrespectively of the number of freeze-thaw cycles. Above S=0.77 damage is progressively increasing with increasing value of S. Besides, in this high moisture region, damage increases with increasing number of freeze-thaw cycles.

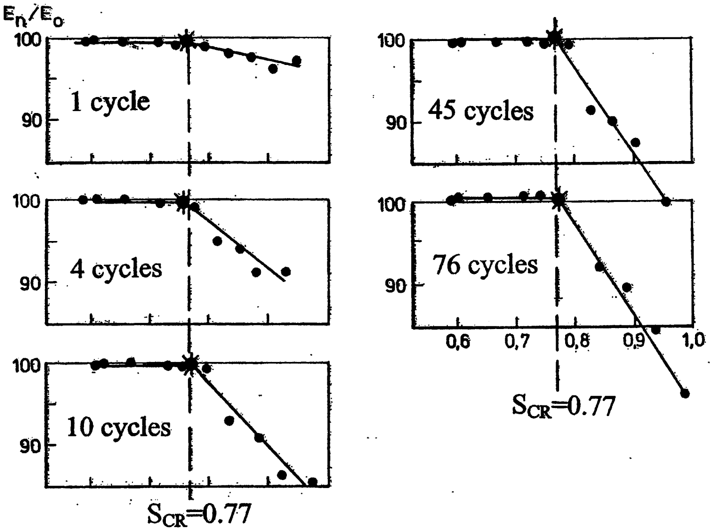


Figure 3: Effect of the degree of saturation and number of freeze-thaw cycles on the E-modulus of a cement mortar tested by closed freeze-thaw; (10).

Figure 4 shows results for a *concrete*, (11). In this case the limit between undamaged and damaged material corresponds to S=0.85. Above this value, damage increases with increasing S. The number of freeze-thaw cycles is of no importance; 78 cycles give about the same damage as 9 cycles. Figure 5 shows results for two *concrete* types, (12). The critical moisture contents are 0.80 and 0.90. Only 6 cycles were used. Despite this, the damage is severe when the critical moisture value is transgressed. The damage is proportional to this transgression. Figure 6 shows results for a *sand-lime brick*, (13). As in the case of cement mortar -figure 3- damage increases with increasing number of cycles, but only provided the degree of saturation is above 0.80. This value is independent of the number of freeze-thaw cycles. Damage is proportional to the transgression of this value. Figure 7 shows the freezing expansion of *concrete* specimens pre-conditioned to different degrees of saturation and freeze-thaw tested in isolated condition for different number of freeze-thaw cycles, (14). There is a clear indication of a critical degree of saturation of 0.90. This value is independent of the number of freeze-thaw cycles. Many more results of similar type can be found in (11, 13, 15).

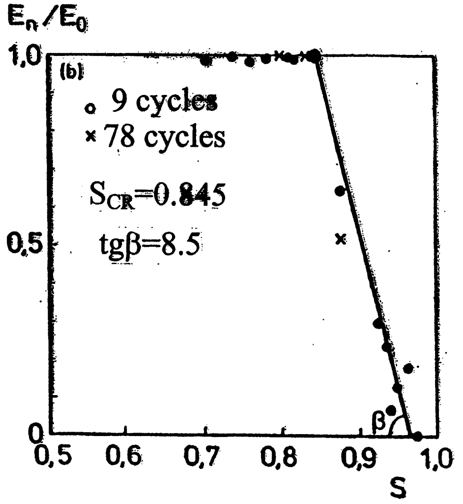


Figure 4: Closed freeze-thaw test of a concrete. Effect of the number of freeze-thaw cycles and degree of saturation on the E-modulus; (11).

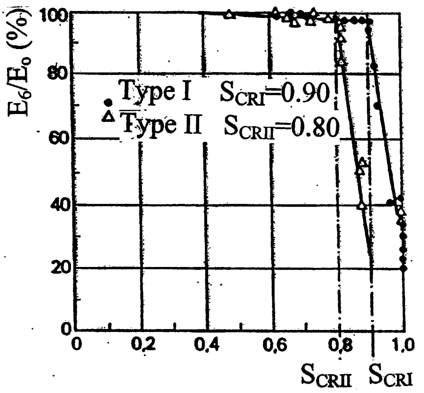


Figure 5: Closed freeze-thaw test of two types of concrete. Effect of degree of saturation on the E-modulus; (12).

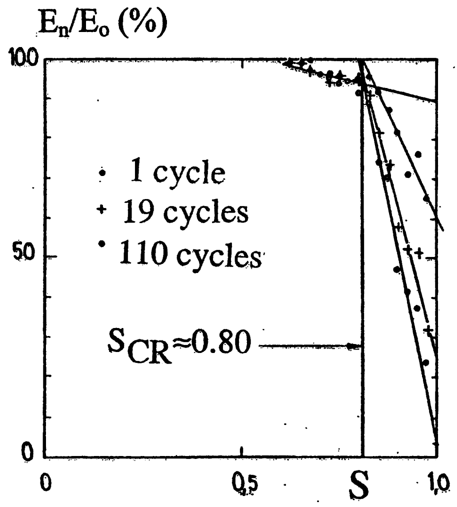


Figure 6: Closed freeze-thaw test of a sand-lime brick. Effect of degree of saturation and number of freeze-thaw cycles on E; (13).

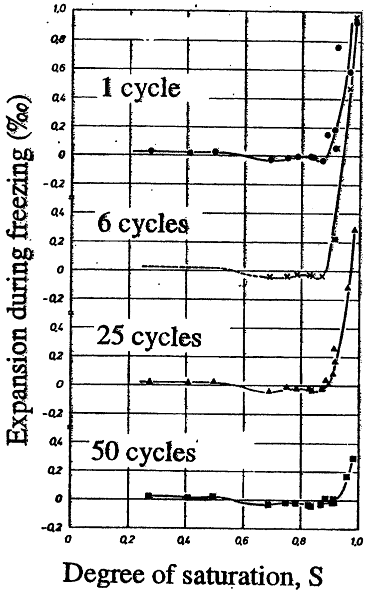


Figure 7: Closed freeze-thaw test of a concrete. Effect of degree of saturation and number of cycles on expansion; (14).

Thus, there is experimental evidence for making the following conclusions:

1: there exists a moisture content that is fairly well-defined, and that marks the border between frost resistance and frost damage. This moisture content seems to be almost uninfluenced by the number of freeze-thaw cycles, at least up to about 100 cycles. The critical moisture content is individual for each material. It is comparable with the *fatigue limit* in normal mechanical fatigue, since moisture contents below the critical moisture content are too low to be able to cause damage.

2: frost damage is directly proportional to the amount by which the critical moisture content is transgressed, indicating that the internal stresses increase in proportion to the amount of frozen water above the critical.

3: the proportionality constant between damage and transgression of the critical moisture content increases with the number of freeze-thaw cycles. Few additional cycles above the first give big additional damage. Thus, frost attack above the critical moisture content can be considered a type of *low-cycle fatigue*. Below the critical moisture content there is no significant fatigue. Should ffatigue in this region exist, it should be of limited practical importance since the number of freeze-thaw cycles in nature is too small to cause high-cycle fatigue.

4: there seems to exist a sort of *maximum possible damage* which is independent of the number of freeze-thaw cycles, and that is proportional to the amount by which the critical degree of saturation is transgressed.

4. The fatigue effect in closed freeze-thaw

The experimental findings described above indicate that damage, D, can be described in the following manner:

$$S \leq S_{CR}: \qquad D=0 \tag{2a}$$

$$S_{CR} < S \leq 1: \qquad D=K_N(S-S_{CR}) \tag{2b}$$

where K_N is a "coefficient of fatigue" that depends on the number of cycles. K_N is the slope of the damage curve in diagrams ot type figure 3 to 6. For the cement mortar in Figure 3 the fatigue coefficient is plotted in figure 8. Evidently, K_N approaches an asymptot when the number of freeze-thaw cycles is increased. For the cement mortar in Figure 3 this happens when the number of cycles is about 80. For freeze-thaw cycles above this value, the fatigue coefficient is almost constant, indicating that no more frost damage occurs when the water content is kept constant, irrespectively of the number of freeze-thaw cycles above 80. For the sand-lime brick in figure 6, the value of K_N is plotted in figure 9. The curve has the same general shape as for the cement mortar.

The coefficient of fatigue both for the cement mortar and the sand-lime brick can be expressed in the following way. A and B are coefficients. A is the level of the asymptot:

$$K_N = A \cdot N/(B+N) \tag{3}$$

The following values of A and B apply to the results in figure 3-6.

Cement mortar; figure 3: $K_N = 1.2 \cdot N/(4+N)$ (3a)
Sand lime brick; figure 6: $K_N = 5.4 \cdot N/(8.3+N)$ (3b)
Concrete; figure 4: $K_N = 13 \cdot N/(4+N)$ (B=4 is assumed) (3c)
Concrete Type I; figure 5: $K_N = 12 \cdot N/(4+N)$ (Ditto) (3d)
Concrete Type II; figure 5: $K_N = 12.5 \cdot N/(4+N)$ (Ditto) (3e)

In all equations (3a) to (3e) it is assumed that "damage" is expressed as a relative loss in E-modulus. E_N is the E-modulus after N cycles, E_o is the E-modulus before freeze-thaw, and ΔE is the change in E-modulus caused by freeze-thaw; see paragraph 5.

$$D=(E_N-E_0)/E_0= \Delta E/Eo \tag{4}$$

If another measure of damage is used, like compressive ot tensile strength, the values of the coefficients A and B should of course be changed.

According to eqn. (2b) and (3) the maximum possible damage *at a given degree of saturation* and at a very large number of sealed freeze-thaw cycles is:

For $S \leq S_{CR}$: $D_{max,S} = 0$ (5)
For $S_{CR} < S \leq 1$: $D_{max,S} = A(S-S_{CR})$ (6)

The absolute maximum possible damage $D_{max,1}$ occurs when S=1 and the number of freeze-thaw cycles is of the order 100 or more:

$$D_{max,1} = A(1-S_{CR}) \qquad D \leq 1 \tag{7}$$

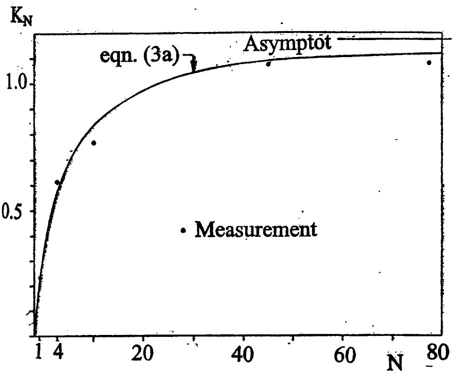
This means that the maximum possible damage for the materials in figures 3 to 6 is:

Cement mortar in figure 3: $D_{max,1} = 0.27$ (27% reduction in E)
Concrete in figure 4 and 5, : $D_{max,1} = 1$ (total destruction in E)
Sand-lime brick in figure 4: $D_{max,1} = 1$ (ditto)

For the three types of concrete it was assumed that the coefficient B is the same as for the cement mortar (B=4). If the value for sand lime brick is used instead, B=8, the value of A would be a bit higher:

For the concrete in figure 4 and Type I in figure 5: A=17 (instead of 13)
For the concrete Type II in figure 5: A=17.5 (instead of 12.5)

Thus, the value of B is not so important for fatigue.



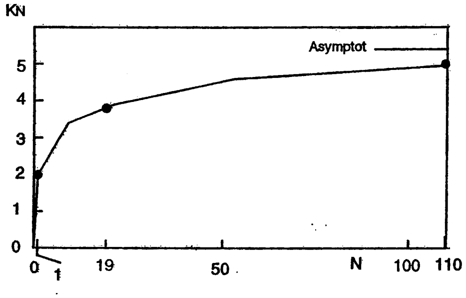


Figure 8: The fatigue coefficient K_N for the cement mortar in figure 3.

Figure 9: The fatigue coefficient K_N for the sand-lime brick in figure 6

The experiments described above and in paragraph 5 show that in almost all cases very severe damage occurs when the material is completely saturated. Besides, also small transgressions of the critical moisture content give big damage; see figure 3, 4, 5, 7. Therefore, the comparably small damage at full saturation in the cement mortar is noteworthy; see figure 6. The reason is not clear. There are at least two possibilities:

1: The real degree of saturation was in fact lower than anticipated due to erroneous determination of the total porosity of the specimens (insufficient vacuum saturation.)

2: The freezable water in the cement mortar is considerably lower than the total water content. Therefore, the "effective" degree of saturation, only considering the freezable water, is smaller than the value based on the total water content. Example: If S is 0.97 and only 30% of the water is freezable S_{eff} is only 0.91. This means that a high value of S might not have as negative effect on frost resistance as might be expected.

4. Interpretation of results of an open freeze-thaw test

The freeze-thaw results shown in Figure 1 for open tests can now be interpreted in the following way, see figure 10.

1: When the test starts, the initial moisture content, S_o, is below the critical value. Consequently no damage occurs during the first cycles; points 1, 2, 3, 4 in figure 10.

2: Due to water uptake during, and between the freeze-thaw cycles, the water content is gradually increasing; figure 10(a). Finally, the critical moisture content is reached in the whole, or parts, of the material, point 5 in figure 10. The time and cycles needed for this to happen depends on the water uptake during each cycle, ΔS, and on the difference between the initial moisture content S_0 and the critical moisture content S_{CR}. Thus, a higher number of cycles are needed for materials which are highly frost resistant than for materials with low degree of frost resistance. This explaions why the different materials in figure 1 start to deteriorate after different number of cycles.

3: Already one cycle after the critical moisture content has been reached, the water content is so high that frost damage occurs; point 6 in figure 10. The amount of frost damage during the first cycle depends on the amount by which the critical water content is transgressed, and is given by the expression $D=K_N(S-S_{CR})=[A\cdot 1/(B+1)]\cdot(S-S_{CR})$.

4: Due to frost damage, the water absorption during each cycle probably increases in comparison with the absorption before the critical moisture content was reached. This is visualized by the steeper water uptake curve in figure 10(a).

5: Due to the extra water absorption, and the increasing number of cycles, damage after each number of cycles is determined by different damage lines; point 7 is on the 10-cycle line, point 8 on the 20-cycle line, point 9 on the 50-cycle line, etc.

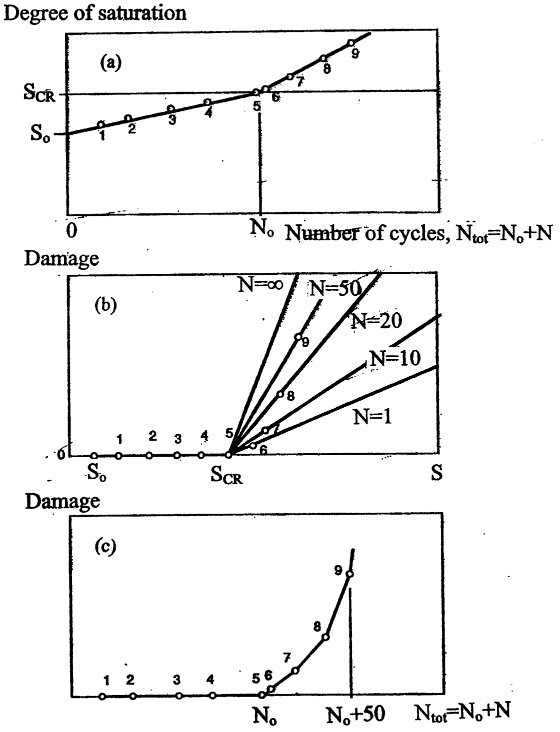


Figure 10: Principles of water absorption and development of damage in an open freeze-thaw test.

Thus, gradual damage observed in open freeze-thaw tests is not a consequence of fatigue, but is due to gradual increase in moisture content. There is a certain low-cycle fatigue, but it is limited to the first cycles with moisture content above the critical.

Frost damage as function of the number of freeze-thaw cycles can be described by:
1: *Before start of damage*, i.e. for $S \leq S_{CR}$ and $N_{tot} \leq N_0$ it is valid:

$$S_0 + N_{tot} \cdot \Delta S_1 \leq S_{CR} \tag{8}$$

That is, the total number of freeze-thaw cycles before frost damage occurs is:

$$N_0 = (S_{CR} - S_0)/\Delta S_1 \tag{9}$$

where ΔS_1 is the water absorption during each freeze thaw cycle *before* frost damage. This means that the total number of freeze-thaw cycles, that a material can sustain, increases with increasing difference between the critical water content and the water content at the start of the freeze-thaw test. This is the reason why a higher air content in concrete gives a higher frost resistance. The higher air content reduces the value of S_0 since only the capillary pore system is filled by water during pre-storage before start of the freeze-thaw test. Similarly, a hard-burnt clay brick is more frost resistant than an under-burnt brick made of the same raw material, because the pore structure of a hard-burnt brick is such that it contains many pores -"impermeable pores"- that cannot become water-filled during ordinary water storage; (13). Normal pre-storage before start of a freeze-thaw test only causes "capillary saturation", while coarser "impermeable" pores stay air-filled. However, during the freeze-thaw test, also these pores might become water-filled.
2: *After start of damage*, i.e. for $S_{CR} \leq S \leq 1$ and $N_{tot} > N_0$ it is valid, eqn. (2b):

$$D = K_N \cdot [(S_{CR} + N \cdot \Delta S_2) - S_{CR}] = K_N \cdot N \cdot \Delta S_2 \tag{10}$$

Or, after inserting eqn. (2b):

$$D = \{A \cdot N^2/(B+N)\} \, \Delta S_2 \tag{11}$$

where ΔS_2 is the water absorption in a *frost damaged* concrete during each freeze-thaw cycle. N is the number of freeze-thaw cycles that can cause frost damage ($N = N_{tot} - N_0$). In eqn. (11) it is assumed that each new freeze-thaw cycle causes the same amount of water absorption irrespectively of the amount of frost damage. Probably, it would be more reasonable to assume that the water absorption is depending on the degree of damage. One possibility is to assume a lineraly increasing water absorption with increasing number of cycles (C is a coefficient):

$$\Delta S_2 = \Delta S_1 + C \cdot N \tag{12}$$

This gives the following development of damage:

$$D = \{A \cdot N^2/(B+N) \cdot\}(\Delta S_1 + C \cdot N) \tag{13}$$

Example:

The following data are supposed to be valid for a certain material tested by open freeze-thaw: $S_0=0.60$, $S_{CR}=0.85$, $\Delta S_1=0.003$, $\Delta S_2=0.007$, $A=1.5$, $B=4$, $C=0$

The development of damage calculated by eqn. (11) is shown in Figure 11. It resembles damage curves observed in a real test; cf. figure 1.

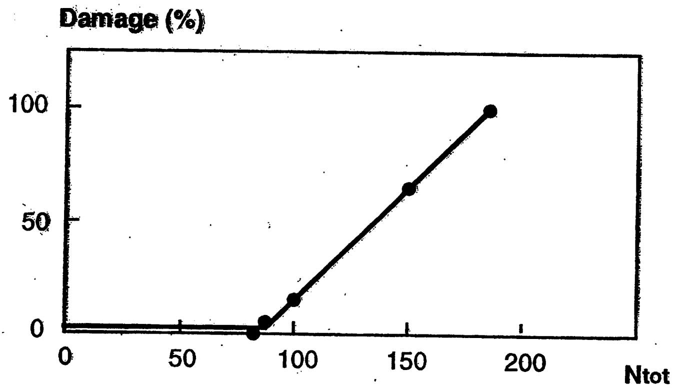


Figure 11: Calculated evolution of frost damage.

5. Investigations of mechanical frost damage at very high moisture level

5.1 Introduction

The maximum possible concrete strength reduction caused by frost has been investigated. Specimens with different w/c-ratio (below 0.80), some with cast-in reinforcement bars (ribbed and plain) using different bond length (130, 100, 72 and 48 mm) were exposed to very severe freeze-thaw. Mechanical properties were determined before and after freeze-thaw. In order to obtain maximum possible frost damage, that might occur in practice, the specimens were pre-saturated using vacuum-treatment. By adjusting the residual air-pressure during the vacuum-treatment, different degrees of saturation in the specimen could be achieved. For each combination of concrete quality, bar type and bond length, 4 specimens were used. One of each specimen was not exposed to frost. The other 3 specimens were freeze-thaw tested with moisture contents well above the critical. The maximum moisture content used corresponds to almost complete saturation. It is hardly possible to obtain more frost damage in a real structure, than that obtained in these saturated specimens. Some results are presented below. The tested material and the test procedure are described in (16)

5.2 Cube compressive strength

The relation between the compressive strength of severely frost damaged concrete and undamaged concrete is shown in figure 12(a). There is a fairly good linear correlation. The biggest strength reduction observed is 35%. A regression analysis gives the following *mean relative* loss in compressive strength:

$$\Delta f_c/f_{c,o} \approx 10/f_{c,o} \qquad \text{(strength in MPa)} \qquad (14)$$

Thus, the reduction in compressive strength is fairly limited.

5.3 Split tensile strength

The relation between the split tensile strength of severely frost damaged concrete and undamaged concrete is shown in figure 12(b). Evidently, frost attack causes much bigger reduction in tensile strength than in compressive strength. The lowest tensile strength observed is 1 MPa valid for a concrete with an initial strength above 3 MPa. The biggest strength reduction observed is 70%. The *mean relative* loss in split tensile strength is :

$$\Delta f_t/f_{t,o} \approx 3/f_{t,o} - 0.2 \qquad \text{(strength in MPa)} \qquad (15)$$

According to this equation the tensile strength might be zero for a severely damaged concrete with an initial tensile strength below 3.7 MPa. Evidently, frost attack causes much bigger reduction in tensile than in compressive strength. A mean relation between the relative loss in tensile strength and compressive strength is:

$$\Delta f_t/f_{t,o} = 1.1\cdot(\Delta f_c/f_{c,o}) + 29 \qquad \text{(relative strength loss in \%)} \qquad (16)$$

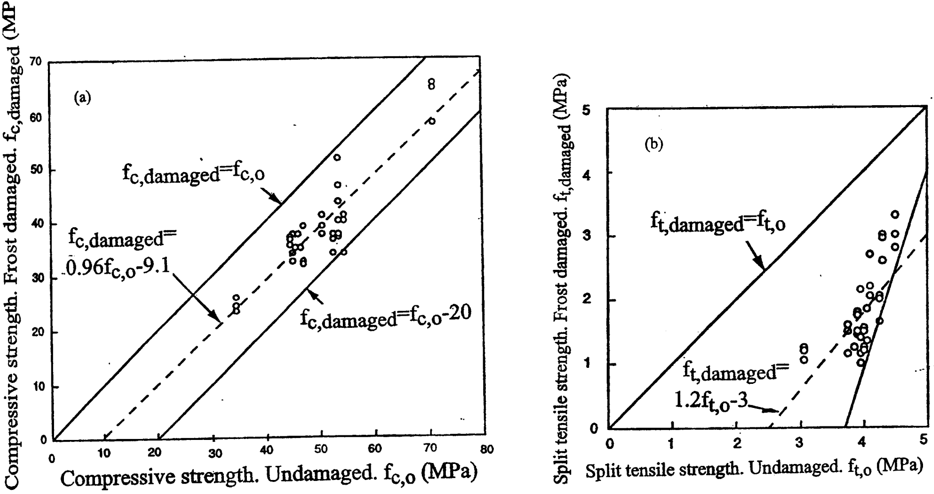


Figure 12: Relation between the strength of frost damaged and undamaged concrete.
(a) Compressive strength. (b) Split tensile strength

5.4 Dynamic E-modulus

The relation between the dynamic E-modulus of frost damaged concrete and E-modulus of undamaged concrete is shown in figure 13. It is not possible to find any well-defined relation. The loss in E-modulus can be very big. In some concrete, the loss in E-modulus is almost total. The lowest E-modulus measured is 5 GPa. Similar big reductions in E at high moisture contents are shown in figure 3-6.

Note: The E-modulus was calculated from the fundamental frequency of transverse vibration. A concrete which has has lost most of its cohesion, indicated by the low tensile strength, can hardly propagate transverse vibration. Therefore, the static E-modulus at compression might have been somewhat higher than the dynamic.

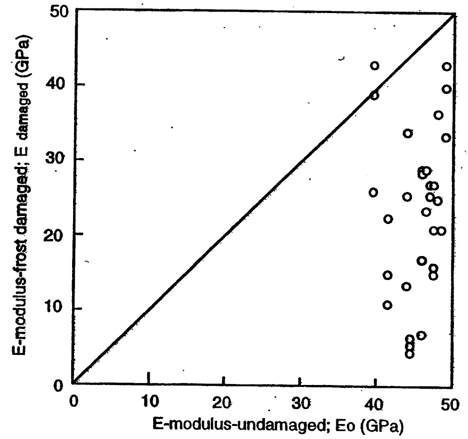


Figure 14: Relation between the E-modulus of undamaged and frost damaged concrete

5.5 Bond strength between reinforcement and concrete

The bond force is here defined as the maximum force in the force-displacement diagram obtained when a centrically cast-in bar in a big specimen is pulled out. Thus, it is an "intrinsic" bond strength with no consideration taken to cover or confinement by stirrups. Relations between the bond force needed to pull a bar out from undamaged concrete and from frost damaged concrete is shown in figure 15(a). The mean relation for ribbed bars (excluding specimens with stirrups) is :

$$F_{b,damaged} \approx 0.5 \cdot F_{b,o} \quad \text{(bond force in N)} \qquad (17)$$

Since the bond length, bar type and diameter is the same for the compared data in figure 14, an equation of type (17) can also be used for the effect of frost on bond strength.

$$f_{b,damaged} \approx 0.5 \cdot f_{b,o} \qquad \text{(bond strength in MPa)} \qquad (18)$$

This means that in average 50% of the bond strength can be lost due to frost action. The maximum reduction in bond observed is about 70%. The lowest absolute bond strength observed is 3.4 MPa.

In figure 15(b) the relative loss in bond strength is plotted versus the relative loss in split tensile strength. The trend is that the two types of destruction follow each other; a big reduction in tensile strength causes a big reduction in bond strength. The *mean* relation is:

$$\Delta f_b/f_{b,o} = \Delta f_t/f_{t,o} - 5 \approx \Delta f_t/f_{t,o} \qquad \text{(relative strength loss in \%)} \qquad (19)$$

Thus, loss in bond strength is about the same as loss in tensile strength. The latter can therefore be used as a measure of the residual bond strength in a frost damaged structure. This is an important observation, since it means that the residual tensile strength can be used as a substitute for bond strength at an assessment of the structural stability of frost damaged strucrtures; (17).

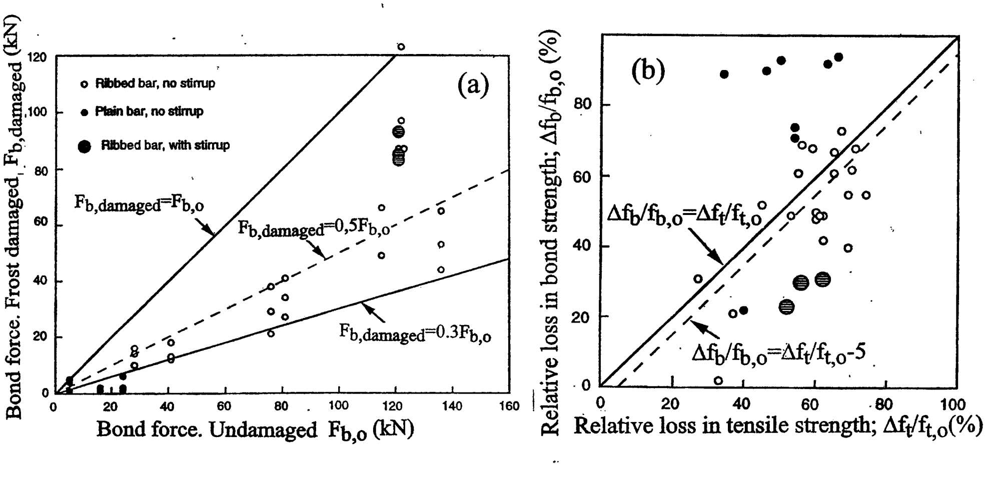


Figure 15: (a) Bond force of frost damaged and undamaged concrete (25 mm ribbed bars anchorage length 100 mm). (b) Relative loss in bond strength and tensile strength.

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