Service life with regard to frost attack : a probabalistic approach

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A probabalistic approach

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SERVICE LIFE WITH REGARD TO FROST ATTACK. A PROBABALISTIC APPROACH

A general service life model

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Abstract

Significant frost damage will not occur until a certain critical moisture level is transgressed over a sufficiently big portion of the structure. The critical moisture level is a "fracture value" which can be compared with the load carrying capacity in structural design. It is a materials property that seems to be rather uninfluenced by normal variations in environmental properties, such as number of freeze-thaw cycles and minimum freezing temperature. The moisture content inside the structure depends on the outer moisture conditions; the more moist the environment, the bigger the inner moisture content, and the bigger the risk of frost damage. The actual moisture content in the structure can be compared with the actual load in structural design. The risk of frost damage can be calculated when the frequency functions of the two parameters, critical moisture content and actual moisture content are known. Some hypothetical cases are treated in the paper showing that the probability of frost damage might actually decrease with increasing exposure time in moderately moist environments, but that it normally increases with increasing exposure time in continuously moist environments where the structure has no possibility to dry.

Keywords: Frost resistance, service life

1 Frost attack generally - "the critical moisture content"

Consider a small but representative materials volume inside a structure, Fig. 1(a). For most building materials the size of a representative volume (unit volume) is less than 1 cm^3. The material is supposed to be porous with the porosity P, m^3/m^3. The structure is exposed to moisture from outside so that a certain moisture profile occurs over the cross-section of the structure, Fig. 1(a). The size of the representative (unit) volume is so small that its moisture content can be assumed to be constant, w_e, kg/m^3. Thus a degree of saturation S, m^3/m^3 of the unit volume can be defined

$$S = w_e/(1000 \cdot P) \qquad (1)$$

where 1000 kg/m^3 is the density of pore water.

All neighbouring unit volumes have almost the same degree of saturation under such natural situations where the outer environment is very moist and, therefore, the risk of frost damage is imminent. As a first approximation, this means that each unit volume can be treated as an isolated materials volume which is not affected by its "neighbours" when frost action occurs. No more water is transferred to the unit volume during freeze/thaw than transferred from the volume.

If the material is exposed to frost, some pore water is transformed into ice. This causes stresses inside the unit volume considered. Theoretically, all principal damage mechanisms proposed (e.g. Powers 1949, Powers and Helmuth 1953) will lead to the occurrence of a critical, or maximum, allowable moisture content inside the unit volume, (Fagerlund 1979, 1996). In the following this moisture content is expressed in terms of a critical degree of saturation, S_{cr}. The theoretical prediction of the existence of a critical moisture content has been verified by numerous experiments, (e.g. Fagerlund, 1972, Klamrowski and Neustupny, 1984).

Theoretically, and also experimentally, it can be shown that the value of S_{cr} is hardly influenced at all by changes in the freezing rate (Fagerlund 1992, Klamrowski and Neustupny, 1984). It has also been shown experimentally that it is almost unaffected by an increased number of freeze-thaw cycles (Fagerlund, 1973, Rombén 1974, Klamrowski and Neustupny, 1984). On the other hand, since the amount of freezable water increases with decreasing temperature, the S_{cr}-value ought to be somewhat influenced by the lowest temperature reached during each freeze-thaw cycle. It seems safe to state, however, that the value of the critical moisture content is a true materials property that is almost constant when the material is used during normal, natural variations in the outer climate.

Thus, S_{cr} can be compared with the strength, or fracture stress, used in structural design.

Examples of experimental determinations of the critical moisture content by freeze-thaw tests are shown in Fig. 2. The critical value is indicated by the rather drastic change-over from undamaged to damaged material within a narrow range of degree of saturation. It should be noted that the specimens in Fig. 2 have only been exposed to 3 freeze-thaw cycles with constant degree of saturation. Therefore, it is evident that few freezings cause considerable damage when the material is more than critically saturated.

The S_{cr}-value can also be determined theoretically assuming the existence of a maximum distance inside the material for moisture flow during freezing, (Fagerlund 1979). Other factors besides the maximum distance determining the S_{cr}-value are:

1: The total content of coarse pores (radius bigger than about 5 μm)
2: The size distribution of such coarse pores
3: The manner by which the coarse, initially air-filled, pore system is inactivated by water absorption when the material is more or less continuously exposed to water from an outside source

The S_{cr}-value of the unit cell is of course not precisely defined. It has a certain variation depending on variations in the materials properties. To some extent it is also influenced by natural variations in the outer climate, such as the number of freeze-thaw cycles and the minimum freezing temperature. Therefore, S_{cr} can be described by a frequency function $f(S_{cr})$ or a distribution function $F(S_{cr})$. Under ideal conditions these are normal distributed.

For many materials S_{cr} can be assumed to be independent of time, simply because the material itself does not change with time. For other materials, such as concrete, there is a gradual hydration changing the properties that are determining the value of S_{cr}. Therefore, one can assume that there is a certain time dependency also in S_{cr}, so that the frequency and distribution functions can be described by $f(S_{cr})=f[S_{cr}(t)]$, and $F(S_{cr})=F[S_{cr}(t)]$. These principles are illustrated in Fig. 1(b).

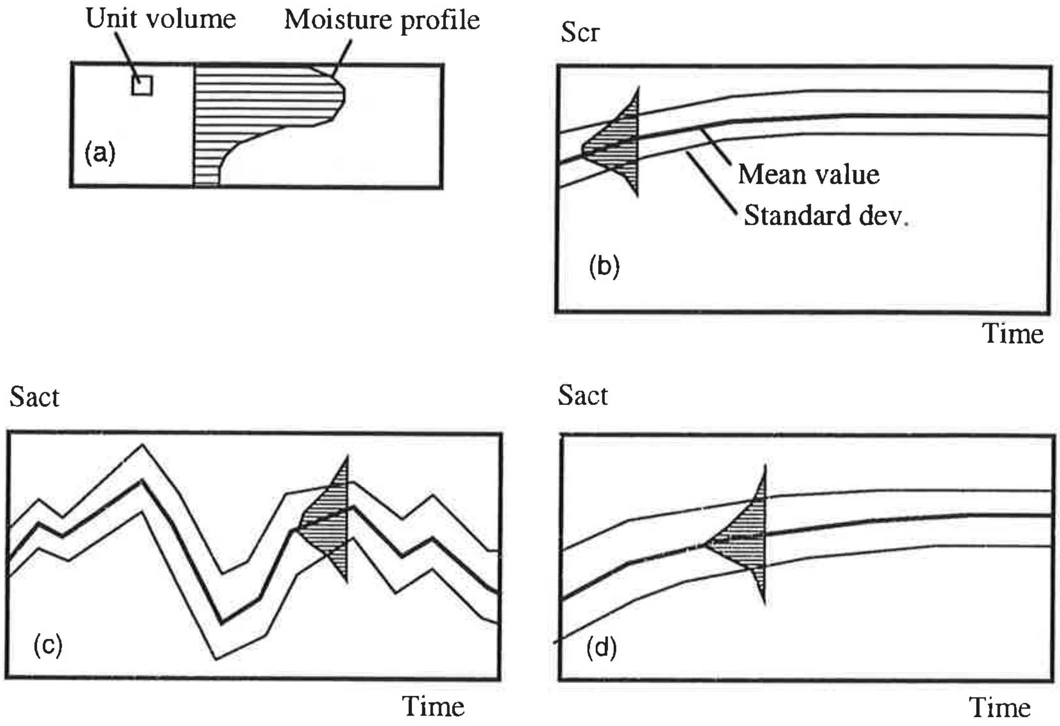

Fig. 1: (a) A representative unit volume inside a structure and the moisture profile across the structure.
(b) The critical degree of saturation of the unit volume, and its distribution, as function of time.
(c) The actual degree of saturation of the unit volume, and its variation, as function of time. Varying outer moisture conditions.
(d) The actual degree of saturation of the unit volume, and its variation, as function of time. Permanent exposure to moisture at the surface.

The frequency function $f(S_{cr})$ can be determined experimentally by freeze-thaw tests of a representative number of specimens. The freeze-thaw cycle used can either be a standard cycle representing the most severe cycle likely to occur in practice, or a spectrum of freeze-thaw cycles representing the real spectrum occurring in practice. However, the effect of the shape of the freeze-thaw cycles on $f(S_{cr})$ will probably not be so big. An experimental technique for determination of S_{cr} has been developed (RILEM 1977).

An example of a determination of the time effect on the S_{cr}-value of concrete is shown in Fig. 2. In this case the S_{cr}-value is increasing with time.

A special type of frost attack is salt scaling ocurring when the material is exposed to combined frost and salt solution at the surface. Typical solutions are sea water and de-icing agents. Under such conditions, surface spalling often occurs. This type of frost attack is caused by moisture ingress during the freeze/thaw cycle. The theory presented in this paper does not cover this type of attack.

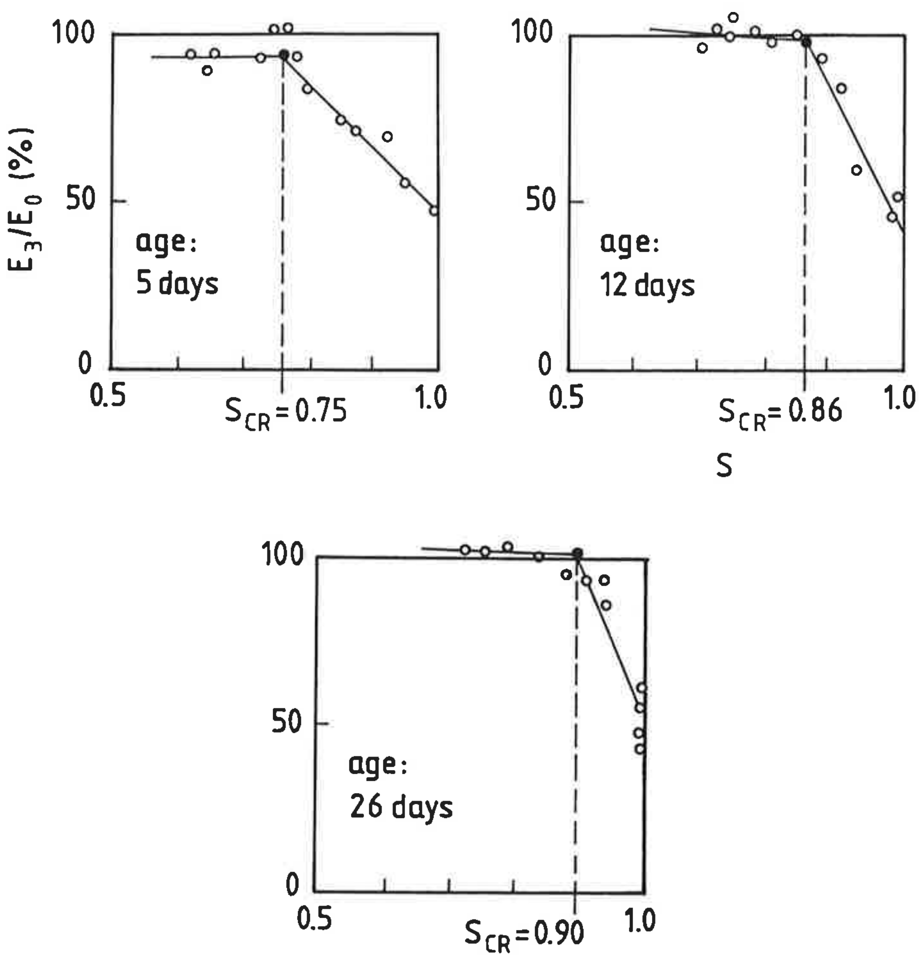

Fig. 2: The critical degree of saturation of a certain concrete as function of the concrete age. The parameter E_3/E_0 is the relative dynamic E-modulus after 3 freeze-thaw cycles and before freeze-thaw.

2 The water content in practice - "the actual moisture content"

In practice, the unit volume will take up moisture. Its moisture content can be expressed in terms of an actual degree of saturation, S_{act} where S is defined by Eqn 1. S_{act} will depend on the pore size distribution and on the "wetness" of the environment. One can theoretically show that pores that are smaller than about 1 μm will become completely saturated after a rather short time of exposure to free water, while it takes a much longer time to fill the coarse pore system, (Fagerlund 1996). But, for most materials, the S_{cr}-value corresponds to a certain water-filling of the coarse pore system. Therefore, frost damage will not occur until the unit volume has had time to fill itself by water to a more than critically saturated condition. This takes time, and it means that the risk of frost damage increases with increased possibility for the material to take up water, and decreased possibility to dry. Therefore, the longer the exposure to free water present at the material surface, the bigger the risk of frost damage.

In the real case, with given environmental conditions as regards wetness, the S_{act}-value will evidently be a function of time. It is quite clear that the S_{act}-value will be a stochastic variable that can be expressed in terms of a frequency function, $f(S_{act})$ and a distribution function, $F(S_{act})$. These principles are shown in Fig. 1(c). The variation in S_{act} will depend on variations in the pore structure, but above all on variations in the outer climate. It is safe to assume that the variation in S_{act} is considerably bigger than the variation in S_{cr} simply because the normally occurring big variations in the outer climate is fundamental for S_{act} but of marginal importance for S_{cr}.

For many types of environment the functions $f(S_{act})$ and $F(S_{act})$ are independent of time, seen over a given constant time interval, e.g. one year. Each year gives about the same spectrum of S_{act}. The two functions only depend on natural climatic conditions. Typical environments giving this type of behaviour are:

- A façade exposed to normal variations in rain and outer RH. The outer climate generates an internal climate expressed in terms of a variation in the S_{act}-value of the unit volume. This variation is about the same each year.
- A road surface exposed to normal variations in rain, melting snow and RH. Each new winter will give about the same variation in the internal S_{act}-value as the previous winter, or the winters to come.

Other types of environment will give a steadily increasing value of S_{act} with increasing exposure time, Fig. 1(d). Typical examples are:

- A concrete dam wall constantly exposed to free water, which will cause a gradual increase in the S_{act}-value of each unit volume inside the wall.
- A concrete pier standing in water, in the splash zone.
- A ground-wall founded below the ground water level and, therefore, constantly sucking ground water.

In these cases, the functions $f(S_{act})$ and $F(S_{act})$ will be time dependent, $f(S_{act})= f[S_{act}(t)]$ and $F(S_{act})=F[S_{act}(t)]$. In the simpliest case, the standard deviation of S_{act} can be assumed to be constant while the mean value of S_{act} increases with increasing time.

It is a very difficult task to determine the exact shape of the function $f(S_{act})$ since it involves a calculation or measurement of the relation between the outer climate (frequency of rain and snow, frequency of RH, sequence of rain and RH, etc) and the internal moisture content in all parts of the structure. It is not possible to have all the required information concerning the outer climate. Therefore, one has to use a standard environment representing the real environment as closely as possible. Such an environment could be a cyclic variation composed of fixed periods of free water at the surface and fixed periods of a certain constant RH at the surface. Then, by using computer simulations, or by measurements on the structure, one can estimate the moisture variation inside the structure. A technique for calculating the moisture content in concrete at such cyclic variations of the outer environment has been developed (Fagerlund and Hedenblad 1993).

Other complications in estimating the function $f(S_{act})$ are:

- Frost damage almost always occurs when the moisture content is above the so-called hygroscopic range. It is very difficult to calculate moisture transport at these very high moisture levels. Ordinary transport equations, transport data and moisture fixation data used in the hygroscopic range cannot be used. A technique for determination of the relevant material properties at these high moisture contents, together with a calculation method, has been developed (Janz 1997).
- There are no good methods for determination of the moisture content above the hygroscopic range. Therefore, it is difficult to verify calculation methods. Methods such as NMR can be used, but they are limited to laboratory use and are very expensive. Weight measurements are fairly precise, but they are destructive. One

theoretical possibility is to use an osmotic cell by which it ought to be possible to measure the capillary under-pressure, and thereby indirectly the moisture content, but so far no cells have been developed. Electrical methods (resistive or capacitive) might be used, but they are very sensitive to salt migration in the material, or to other disturbances.

An alternative method, used by the author, is to expose at thin slice of the material to continuous moisture uptake from one side. Then, a constantly increasing moisture uptake will occur, which can be detected by weighing the slice at regular intervals. By exposing a number of slices representing the natural variations in materials properties one will obtain a spectrum of S_{act}-values which can be used for calculating the function $f(S_{act})$. This technique will give the maximum values of S_{act} likely to occur in practice. One can only continue the measurements for 1 or 2 months at maximum. Therefore, one has to make an extrapolation of the measurements to longer absorption times. A theoretical analysis indicates that the S_{act} value can be described by the following type of equation (Fagerlund 1996):

$$S_{act} = A+B \cdot t^{C} \tag{2}$$

where A, B and C are coefficients determined by the short-term absorption experiment. t is the absorption time. The coefficient C is smaller than 0,5. Therefore, the water absorption is gradually slowing down with time. It is reasonble to assume that the function $f(S_{act})$ will have the same shape irrespectively of the absorption time. The only effect of time is that the mean value of S_{act} increases with time according to Eqn 2.

3 The probablity of frost damage

The unit volume will be frost damaged if freezing occurs in the more than critically saturated volume. Thus, the condition for frost damage to occur can be defined by

$$S_{act}>S_{cr} \tag{3}$$

The unit volume will be severely damaged also in cases where S_{cr} is transressed by a very small amount. Besides, one single freezing is enough to cause damage. Severe frost damage will not occur in a structure, however, if only one single unit volume is damaged, or only a few unit volumes. For macroscopic frost damage to occur, a considerable volume fraction of the structure must be more than critically saturated. It seems reasonable to assume, however, that this often happens; viz. if one unit volume can be damaged it is reasonable to assume that also adjacent unit volumes can be damaged at the same time, since their moisture contents ought to be about the same. Therefore, the criterion expressed by Eqn 2 can be assumed to be valid also for the material in bulk.

Both S_{act} and S_{cr} are stochastic variables. The probability $P\{S_{cr}<S_{act}\}$ that frost damage occurs can be calculated by:

$$P\{S_{cr}<S_{act}\} = \int_0^1 F(S_{cr}) \cdot f(S_{act}) \cdot dS \qquad 0 \leq P\{S_{cr}<S_{act}\} \leq 1 \tag{4}$$

This equation requires that the lowest S_{act}-value of the function $f(S_{act})$ is lower than the lowest S_{cr}-value of the function $f(S_{cr})$. When the opposite is valid the probability of frost damage can be expressed:

$$P\{S_{cr}<S_{act}\} = 1 - P\{S_{act}<S_{cr}\} = 1 - \int_0^1 F(S_{act})\cdot f(S_{cr})\cdot dS \qquad (5)$$

Thus, the probability of frost damage can be calculated when the two functions $f(S_{cr})$ and $f(S_{act})$ are known. As said above, both functions can be determined experimentally.

4 The service life with regard to frost attack

The service life will depend on the functions $f(S_{cr})$ and $f(S_{act})$. A number of cases can be discerned. Three of these will be treated below. In all three cases the frequency functions $f(S_{cr})$ and $f(S_{act})$ are assumed to be triangular with the mean values $S_{cr,m}$ and $S_{act,m}$ and the standard deviations σ_{cr} and σ_{act} which are both 0.04 (thus, the triangular distributions have the height 10 and the width 0.20).

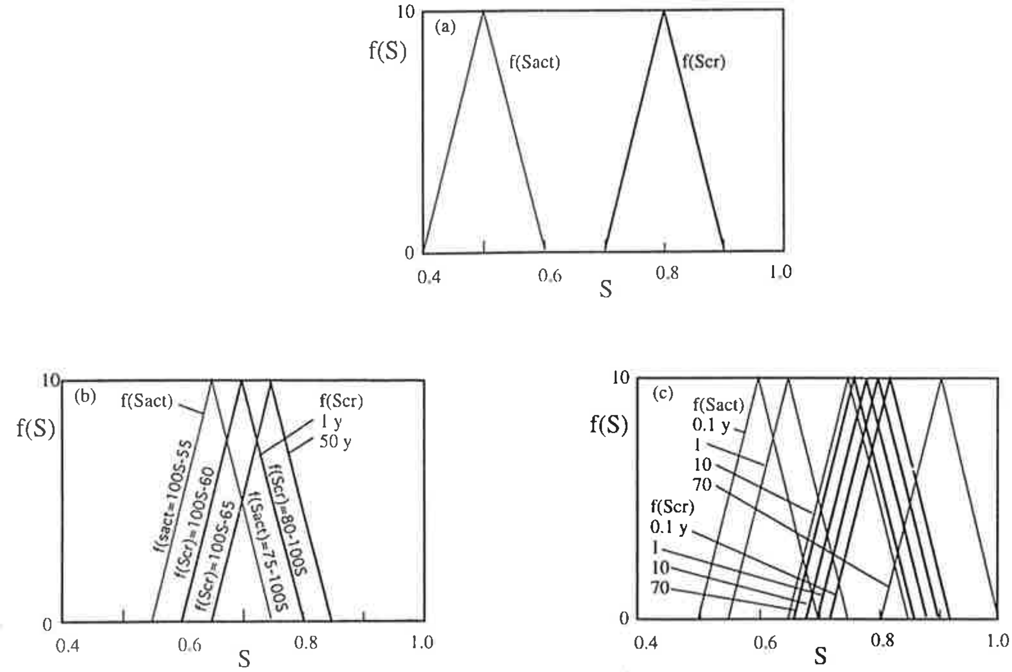

Fig. 3: Frequency functions of S_{cr} and S_{act}.
(a) Case 1: No time dependency of $f(S_{act})$ and $f(S_{cr})$.
(b) Case 2: Time-independent $f(S_{act})$. Time-dependent $f(S_{cr})$.
(c) Case 3: Time-dependent $f(S_{act})$ and $F(S_{cr})$.

Case 1: No time-dependency of the functions $f(S_{cr})$ and $f(S_{act})$; see Fig 3(a):

- S_{cr} is independent of time. The mean value, $S_{cr,m}=0.80$. The lowest value, $S_{cr,min}=0.70$.
- S_{act} over a given period, such as one year, does not change with time. The mean value $S_{act,m}=0.50$. The highest value, $S_{act,max}=0.60$.

This means that all possible values of S_{act} are smaller than the lowest possible value of S_{cr}. Therefore, the probability that frost damage shall occur is zero irrespectively of the exposure time. Therefore, the service life of the structure is not determined by frost damage but by some other destruction mechanism.

A typical example where both S_{cr} and S_{act} can be assumed to be independent of time is a brick façade. Brick is a material that hardly changes with time. Therefore, f(S_{cr}) is constant. Besides, a façade is a structural component that is normally exposed to about the same moisture load each year. Therefore f(S_{act}) is constant.

Case 2: Time-independent function f(S_{act}). Time-dependent function f(S_{cr}); see Fig 3(b):

- S_{cr} is gradually increasing with time. The mean value, $S_{cr,m}$=0.70 after 1 year and $S_{cr,m}$=0.75 after 50 years. Therefore, the distribution functions after 1 and 50 years are:

  1 year:

$$0.60 \leq S \leq 0.70: \quad F(S_{cr}) = \int_{0.60}^{S} (100S-60)dS = 50 \cdot S^2 - 60 \cdot S + 18 \qquad (6)$$

$$0.70 \leq S \leq 0.80: \quad F(S_{cr}) = 0.5 + \int_{0.70}^{S} (80-100)dS = -50 \cdot S^2 + 80 \cdot S - 31 \qquad (7)$$

  50 years:

$$0.65 \leq S \leq 0.75: \quad F(S_{cr}) = \int_{0.65}^{S} (100S-65)dS = 50 \cdot S^2 - 65 \cdot S + 21.125 \qquad (8)$$

- S_{act} does not change with time (the same as Case 1). The mean value, $S_{act,m}$= 0.65. Thus, the frequency function is:

$$0.60 \leq S \leq 0.65: \quad f(S_{act}) = (100S-55) \qquad (9)$$
$$0.65 \leq S \leq 0.75: \quad f(S_{act}) = (75-100S) \qquad (10)$$
$$S > 0.75: \quad f(S_{act}) = 0 \qquad (11)$$

Then, according to Eqn 4 the probability of frost damage after 50 years exposure time is:

$$P\{S_{cr} < S_{act}\} = \int_{0.70}^{0.75} (50 \cdot S^2 - 65 \cdot S + 21.125)(75 - 100 \cdot S)dS = 0.042 \ (\mathbf{4.2\%})$$

For 1 year exposure time the calculation is a bit more laborious and is not shown here. The calculations give a probability of frost damage after 1 year of **20%**.

In this case the probability of frost damage decreases with increasing time which depends on the fact that the critical moisture content increases with time. The most crucial years are the first. This behaviour is valid for materials which changes with time in a positive manner. A typical material is concrete which undergoes continued densification by hydration which probably leads to both an increase in S_{cr} and a decrease in S_{act}. One example ot the effect of time on S_{cr} of concrete is shown in Fig. 2.

The opposite result is of course valid when the S_{cr}-value decreases with time, from a mean value of 0.75 to 0.70, or if the S_{act}-value increases with time.

Case 3: Time-dependent functions f(S_{act}) and f(S_{cr}); see Fig 3(c)

- S_{cr} gradually decreases with time. The time function of the mean value is described by:

$$S_{cr,m} = 0.80 - 0.02 \cdot \log t \quad (t \text{ in years}) \qquad (12)$$

Then, the following mean values are valid:
0.1 years: $S_{cr,m}=0.82$
1 year: $S_{cr,m}=0.80$
10 years: $S_{cr,m}=0.78$
70 years: $S_{cr,m}=0.76$

The shape of the function $f(S_{cr})$ is supposed to be unchanged.

- S_{act} increases with time. The following relation is used for the time dependency of the mean value, Eqn 2:

$$S_{act,m}= 0.55+0.10 \cdot t^{0.3} \quad \text{(t in years)} \tag{13}$$

Then, the following mean values are valid:
0.1 years: $S_{act,m}=0.60$
1 year: $S_{act,m}=0.65$
10 years: $S_{act,m}=0.75$
70 years: $S_{act,m}=0.90$

The probability of frost damage is now calculated by Eqn 4 and Eqn 5. The following probabilities are obtained:

0.1 years:	$P\{S_{cr}<S_{act}\}=0$	(0%, frost damage cannot occur)
1 year:	$P\{S_{cr}<S_{act}\}=0.0026$	(0.3%)
10 years:	$P\{S_{cr}<S_{act}\}=0.308$	(31%)
70 years:	$P\{S_{cr}<S_{act}\}=0.984$	(98%)

Thus, the frost damage risk increases with increasing time of water exposure. This case is valid for structures that are constantly exposed to liquid water. Typical examples are concrete dam walls or foundations in water.

In normal cases, the S_{cr}-value will not decrease with time but is kept constant. In such cases a less drastic reduction in the "probability of survival" than that calculated above will occur.

5 Conclusions

The analysis in this paper shows that the frost resistance problem is of a stochastic nature. It also shows that no statement can be made concerning the service life with regard to frost resistance of a given structure in a given environment unless it is possible to transform the outer environment into an internal moisture-time field in all parts of the structure. This moisture field is of a highly stochastic nature.

The analysis also shows that the frost damage problem is of a nature that differs from many other destruction types in the sense that there is normally no well-defined time axis involved. Normally, for most destruction types, an increased exposure time causes increased damage until a certain limit is reached at which service life is ended. In the frost damage problem, an increased exposure time does not necessarily imply an increased risk of damage. Single freezings with a moisture content that is higher than the critical is enough to cause severe damage. But the occurrence of this dangerous situation is not necessarily a function of the exposure time. Frost damage might just as well occur during the first year as during the fiftieth, simply because the risk that the critical moisture content is trangressed is just as high during the first year, or even higher for materials that "mature" in a positive manner, like cement-bound materials. In many respects, the frost damage problem is similar to the problem of structural stability; failure occurs once the load-carrying capacity is transgressed. This might happen when the structure is young as well as when it is old.

The analysis also shows that the uncertainty in a service life prediction with regard to frost attack is very big, which depends on the very big uncertainties in the internal moisture conditions that are reached inside the structure. The only rational way to secure that the service life is high is to design the pore structure of the material in such a way that the probability that the critical moisture level shall be transgressed during the real exposure is very low. This is done by designing the coarse pore-structure in such a way that it cannot absorb water easily (Fagerlund 1996). For a material like concrete this is achived by entrainment of artificial so called air-pores. For brick it is achieved by burning the brick at a sufficiently high temperature. For other materials there are similar possibilities.

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