SERVICE LIFE DESIGN OF CONCRETE STRUCTURES WITH REGARD TO THE FROST RESISTANCE OF CONCRETE

Erkki Vesikari
Technical Research Centre of Finland
Concrete and Silicate Laboratory
MSc Tech, Research Scientist

SYNOPSIS

This paper presents a model for evaluating the service life of concrete structures with regard to frost resistance. The model is based on a direct accelerated laboratory test but an indirect method for service life evaluation has also been developed. The possibilities of applying the model to practical design and quality control are described, and the need for its further development is discussed.

Key words: service life, frost resistance, durability design.

1. INTRODUCTION

Over the past few years the concept of service life has repeatedly been discussed in the literature pertaining to building materials and components. Many authors are of the opinion that service life is in fact the most natural basis for the durability design of structures /3/. Therefore, both research scientists and designers must seek new methods of analysing expected service life expressed in years rather than blindly following the old rules of design which often lead to mistakes. A structural designer should in principle possess tools for designing a structure with regard to service life, in the same way he now does with regard to bearing capacity.

Service life is defined as the period of time during which a building or a structure or material preserves the functional, aesthetic and other requirements established for it. In mathematical models service life is considered as the time required before a predetermined grade of damage is reached as expressed in measurable physical properties.

In practice, many factors limit the service life of structures. In Nordic countries the most common factors causing deterioration are frost attack, frost-salt attack and abrasion of concrete as well as corrosion of reinforcement. In addition, the chemical attack of concrete and the alkali reactivity of aggregates in concrete are severe local problems. In spite of deterioration in the material due to ageing and environmental factors, service life can also be limited by excessive cracking or deformation of structures as a result of overloading or mistakes in structural design.

Regarding the corrosion of reinforcement, a large number of service life models have been established during the last decade. Although there may be room for additional research into, and development of, the models they can already be applied to the design of structures. The same is not true of frost resistance or other durability problems in concrete. Very few serious efforts have been made to develop service life models with regard to deterioration in concrete /2/.

In evaluating a particular durability property of concrete in the laboratory, so-called accelerated tests are normally used with all their variations. We know that the degree of validity of accelerated tests is not always high since conditions in a laboratory can never correspond exactly to those in nature /7/. Nevertheless, accelerated tests are those most often accepted for official assessment of durability properties. It is the author's opinion that many of the accelerated tests can also be approved as a basis for service life models. As to the validity of a test, much depends on the details of the test procedure itself.

In an ideal situation a linear correlation exists between the 'lifetime' of a specimen in an accelerated test, t', and the service life of a structure, t_1:

$$t_1 = k \cdot t' \quad (1)$$

where k is a constant.

The only difference between the deterioration process under natural conditions and that in an ideal laboratory test is the 'shrinkage' of the time scale in the laboratory. The deterioration mechanism and physical property in terms of which the degree of damage is evaluated are the same both in the laboratory and in nature.

In an accelerated frost-resistance test the lifetime of the specimen can usually be expressed in terms of the number of freeze-thaw cycles, since it is the cycles rather than the testing time itself which cause damage to the concrete. If we now assume the number of freeze-thaw cycles to which the structure is subjected annually to be constant, the service life of the structure can be evaluated using Formula 2:

$$t_1 = k_e \cdot N \quad (2)$$

where k_e is a coefficient related to environmental conditions
N is the number of freeze-thaw cycles required to cause a specified degree of damage to a specimen.

The environmental coefficient, k_e, expresses the aggressiveness of the natural environment. The value of k_e is of course also dependent on the type of testing method used.

2. FREEZE-THAW TESTS

A great variety of freeze-thaw tests has been used in the evaluation of concrete frost resistance. The tests differ in many respects, such as the preconditioning of specimens, the testing procedure itself and the way in which damage is detected. Differences in test procedure may have a significant effect on the results.

Freeze-thaw tests fall roughly into two categories. The first of these, 'ordinary freeze-thaw tests', consists of tests which measure the frost resistance of concrete in pure, freezing water. The second group includes the 'frost-salt tests', and incorporates the effect of chloride salts in the frost action.

In ordinary freeze-thaw tests the specimens are subjected to successive freeze-thaw cycles in pure water. The freezing of test specimens can take place either in air or in water. The thawing phase is also possible either in air or in water. The quickest way of performing a freeze-thaw cycle is to allow the specimens to freeze in air and thaw in water.

In ordinary freeze-thaw tests gradual scaling of specimen surfaces is not expected. Local disintegration or delamination may take place but the amount of disintegrated concrete is not a suitable criterion for damage, the loss of strength or reducduction of the E modulus often being used instead. Ultrasonic pulse velocity has also been applied in detecting inner defects of concrete.

The frost-salt tests differ from ordinary freeze-thaw tests in that the specimens are exposed to chloride salts during freezing, and different criteria are used in the evaluation of damage. As the typical form of damage seen in frost-salt tests is gradual scaling of specimen surfaces, the reduction in weight or volume of specimens is normally selected as the necessary criterion.

Three of the most common frost-salt tests are 1) immersed-freezing test, 2) thin-layer-freezing test, 3) dip-freezing test.

In immersed-freezing tests the specimens are frozen and thawed in a vessel containing a relatively large amount of unsaturated chloride solution. The chloride content of the solution is about 3 %. The main problem encountered with immersed-freezing tests is the slow rate of freezing and thawing which prolongs the testing time. The slow rate of freezing is also responsible for the fact that gradual disintegration of specimen surfaces sometimes fails to occur. Instead the specimen is either totally destroyed or remains intact.

In thin-layer-freezing tests a thin layer of unsaturated chloride solution is applied to the upper surface of a specimen. Since the thickness of the layer is only about 3 mm, rapid freezing takes place, resulting in gradual scaling. However, thin-layer-freezing tests have been found very sensitive to minor variations in the test set-up. Small differences in the freeze-thaw cabins or in the environment surrounding the specimens during freezing may lead to a completely different set of results /6/. Unless a great deal of effort is given to the preparation and control of specimens, wide scattering of the test results is to be expected.

In dip-freezing tests freezing is accomplished by placing the specimens in a precooled liquid usually consisting of saturated NaCl solution. Thawing is achieved in the same way in pure water. In dip-freezing tests the rate of scaling of specimens is regular. This is due to the very rapid freezing of the specimen surfaces. The penetration of chlorides close to the surfaces affects the scaling process.

The results of the dip-freezing tests have been found to correlate closely with those of the thin-layer-freezing tests /1/. Accordingly, the validity of the dip-freezing tests is not significantly lower than that of the thin-layer-freezing tests in spite of the seemingly unnatural method of freezing. However, the reliability of the dip-freezing tests is higher than that of the thin-layer-freezing tests owing to the smaller scatter of the test results.

3. EVALUATION OF SERVICE LIFE BASED ON THE DBV FROST-SALT TEST

3.1 The DBV frost-salt test

In the DBV (Deutsche Beton Verein) frost-salt test 100 mm cubes are used as specimens. Three specimens of each concrete are usually reserved for each test /8/.

After removing from the moulds, the specimens are stored for 7 d in water. Subsequently they are suspended in air (70 % RH) up to the age of 28 d. Prior to testing the specimens are once again immersed in water for a period of 7 d. The test normally begins no sooner than 35 d after casting the specimens. Freeze-thaw cycles consist of transferring the specimens from a warm tap water bath (+20 °C) to a cold saturated NaCl solution (-15 °C) and back again. Each freeze-thaw cycle involves 8 hours of freezing in the cold bath and 16 hours of thawing in the warm bath. Normally 25 cycles are performed but the test may be prolonged if desired. After a given number of cycles the reduction in volume of specimens is determined by weighing in water and in air.

A typical feature of the results of the DBV frost-salt test is a regular rate of scaling. Following each freeze-thaw cycle a thin layer of concrete is loosened from the surface while the rest of the concrete remains whole. Figure 1 illustrates the scaling process in Portland cement concrete.

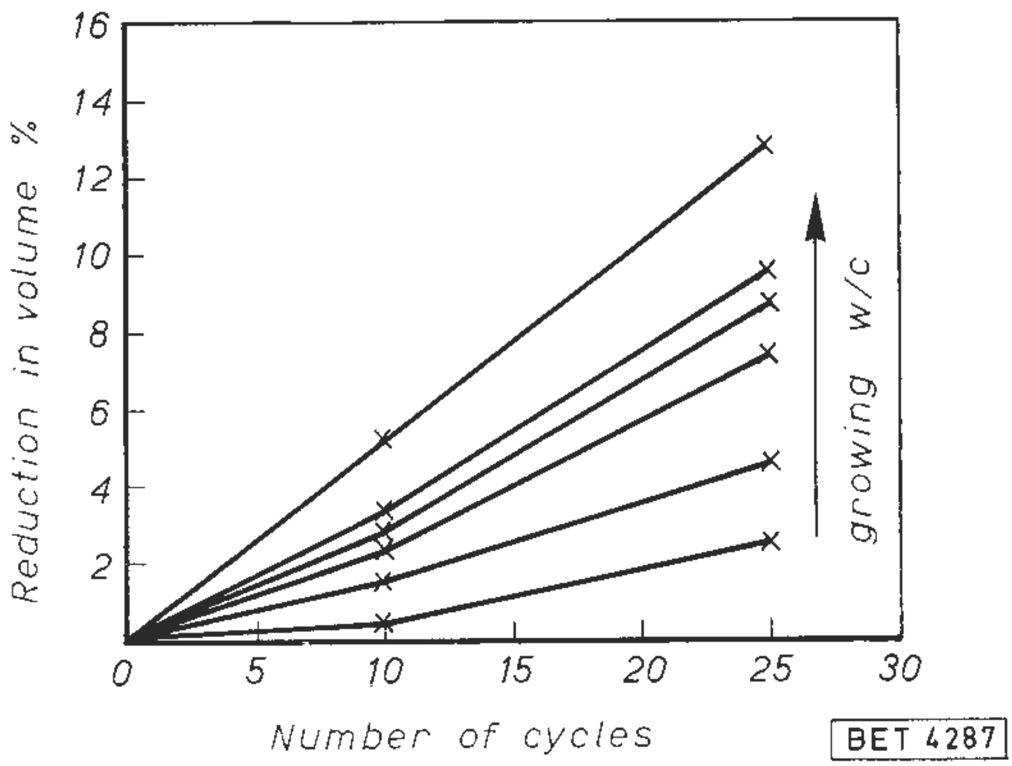


Fig. 1. Reduction in volume as a function of freeze-thaw cycles in Portland cement concrete.

3.2 Frost resistance index

In the DBV frost-salt test the reduction in volume of specimens after 25 cycles, $\Delta V(25)$, is determined. Using the value $\Delta V(25)$, the frost resistance index is determined by linear interpolation or extrapolation to a volume loss of 4 %. In practice this is done by dividing 100 by $\Delta V(25)$ according to Formula 3:

$$P = \frac{100}{\Delta V(25)} \qquad (3)$$

where P is the frost resistance index and
$\Delta V(25)$ is the reduction in volume of specimens after 25 cycles, %.

The calculation method used in the determination of the frost resistance index P for reductions in volume of 8 %, 4 % and 2 % is illustrated in Figure 2. The frost resistance index is in fact defined as the predicted number of cycles needed to bring about a volume loss of 4 % when the rate of scaling remains constant.

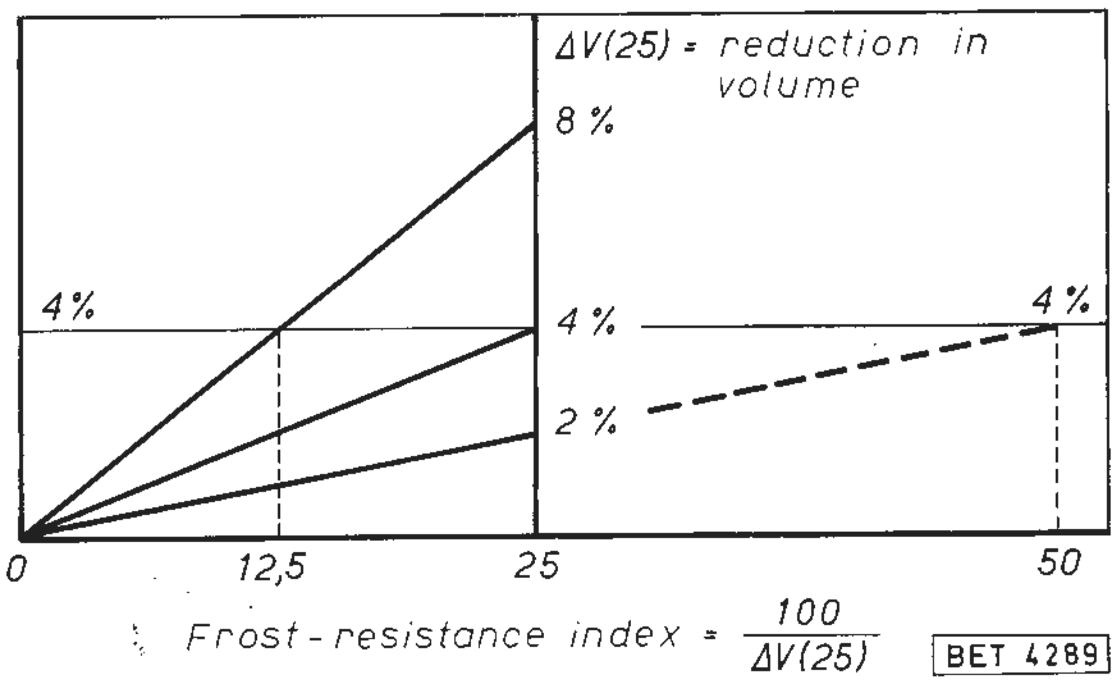


Fig. 2. Determination of the frost resistance index for reductions in volume during the DBV frost-salt test of 8 %, 4 % and 2 %.

3.3 Service life and environmental factors

The service life of a structure can be evaluated using Formula 4:

$$t_l = k_e \cdot P \qquad (4)$$

where t_l is the service life (years) and
k_e is the environmental factor.

Table 10 lists several examples of environmental factors for various types of structure. The values of the environmental factors have been determined by field investigations in which the correlation between the degree of damage, age of the structure and the frost resistance index of concrete have been studied /10, 11/.

Table 1. Examples of environmental factors

Structure	Environmental factor, k_e
Edge beams in bridges	1 - 3
Bridge columns in water	2 - 4
Bridge columns in sea water	1 - 2
Dams, power stations	3 - 6

The validity of the DBV frost-salt test for the prediction of service life of a bridge column or a dam can be questioned owing to differences in the disintegration process. The values of environmental factors in Table 1 have been obtained from correlation analysis disregarding these differences.

Example 1 The edge beam of a bridge is made of concrete with a frost resistance index of 10. If the environmental factor is 1.5, what is the predicted service life?

Answer: Using Formula 3, the service life is

$$t_l = 1.5 \cdot 10 = 15 \text{ years}.$$

3.4 Indirect determination of the frost resistance index

The reduction in volume during the frost-salt test depends on the mechanical and microstructural properties of concrete such as compressive strength, amount of air pores (protection pores) and the quality of cement. In the tests performed at VTT the following relation was found between the amount of scaling and the above material properties /9/:

$$\Delta V(N) = k(N) \cdot \frac{60 - f_c}{P_r - 5} \qquad (5)$$

where $\Delta V(N)$ is the reduction in volume after N cycles, %,
f_c is the compressive strength of concrete at the age of 28 d (mean value, MPa),
P_r is the relative amount of protection pores compared with the total porosity, % (protection pores are those which do not fill with water when the concrete is immersed in water under normal atmospheric pressure),
$k(N)$ is the scaling coefficient (at N cycles).

Table 2 lists the values of the scaling coefficient for concretes containing different binding agents. The values correspond to the average results obtained in a large number of frost-salt tests performed at VTT.

Table 2. Scaling coefficient k(N).

Binding agent	Number of cycles, N				
	10	25	50	75	100
Portland cement	0.9	4.3	10.7	20.9	30.7
Slag cement (70 % slag)	1.5	2.6	3.4	5.6	7.8
Portland cement + silica fume (8 % by weight)	0.6	2.8	7.5	15.0	23.0

The scaling coefficients, k, are also shown in Figure 3.

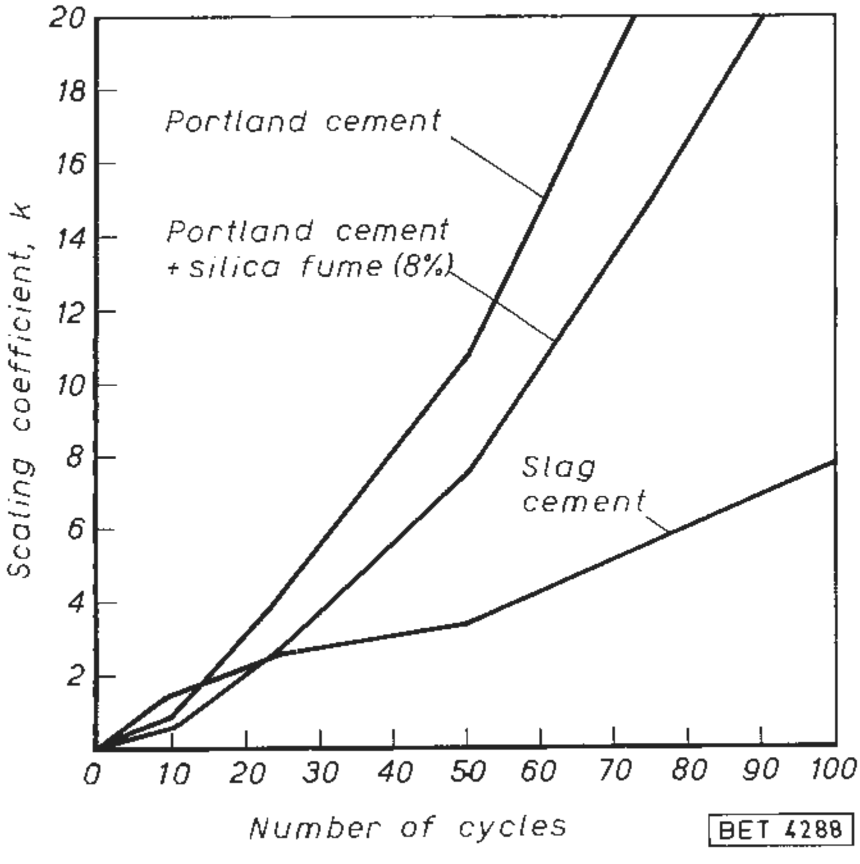


Fig. 3. Scaling coefficients for different binding agents as a function of the number of cycles.

The choice of a binding agent cannot be determined simply on the basis of the scaling coefficients since the contribution of a binding agent to the compressive strength (at 28 d) must also be taken into account. With silica fume, for example, high grades of compressive strength can be obtained. Thus silica fume is more beneficial compared with slag than could be concluded on the basis of scaling coefficients alone.

A very rapid rate of scaling of slag cement concrete has been found to occur during the first ten cycles. Subsequently, the rate of scaling slows down considerably. The reason behind the variable performance of slag cement concrete is probably the carbonation process. This phenomenon is further discussed in Chapter 5.

Applying Formula 5 to Formula 3 (see also Table 2) gives:

$$P = 23 \cdot K_s \cdot \frac{P_r - 5}{60 - f_c} \tag{6}$$

where K_s is the binder factor. Number 23 is according to the results of the portland cement tests.

The values of the binder factor for different binding agents are shown in Table 3.

Table 3. Binder factors, K_s.

Binding agent	Binder factor, K_s
Portland cement	1
Portland cement with S % silica fume by weight of cement	$1 + 0.065 \cdot S$
Portland cement with M % slag (of the total amount of binding agent)	$1 + 0.009 \cdot M$
Slag cement (70 % slag)	1.65

4. DESIGN AND QUALITY CONTROL OF FROST-RESISTANT CONCRETE

4.1 Setting the requirements for frost-resistant concrete

A structural designer sets the requirements for concrete in terms of the frost resistance index, P. Its value depends on the intended service life and on the environmental factor in each case. Formula 4 gives:

$$P_{(required)} = \frac{t_{l(intended)}}{k_e} \tag{7}$$

Use can be made of the environmental factors presented in Table 1. Choosing the mid-point value of the given environmental factor interval gives a probability of reaching the intended service life of about 50 %. Choosing a value below the mid-point gives a higher probability.

Example 2 A structural designer is to set requirements for an an intended service life of 70 years. What is the required frost resistance index if the environmental factor is 3.5?

Answer: Formula 7 gives:

$$P_{(required)} = 70/3.5 = 20$$

4.2 Quality control

The quality control for concrete must always be closely related to the design. As a result, parameters used in service life design must also be suitable for quality control.

Quality control of the frost resistance index can be carried out by either direct or indirect testing. Direct testing serves as a basis for quality control. If there is a contradition between the results of direct and indirect tests the results of the direct tests are decisive.

If the constituents and manufacturing methods of concrete are 'normal', the indirect method of testing is usually preferred since it is quicker to use and the results obtained are sufficiently reliable in common practice. In other cases the direct method of testing is preferable unless the scaling coefficients used in indirect testing have been checked in advance under direct testing.

Direct testing determines the reduction in volume of specimens in the DBV frost-salt test after 25 freeze-thaw cycles. The frost resistance index is then determined using Formula 3.

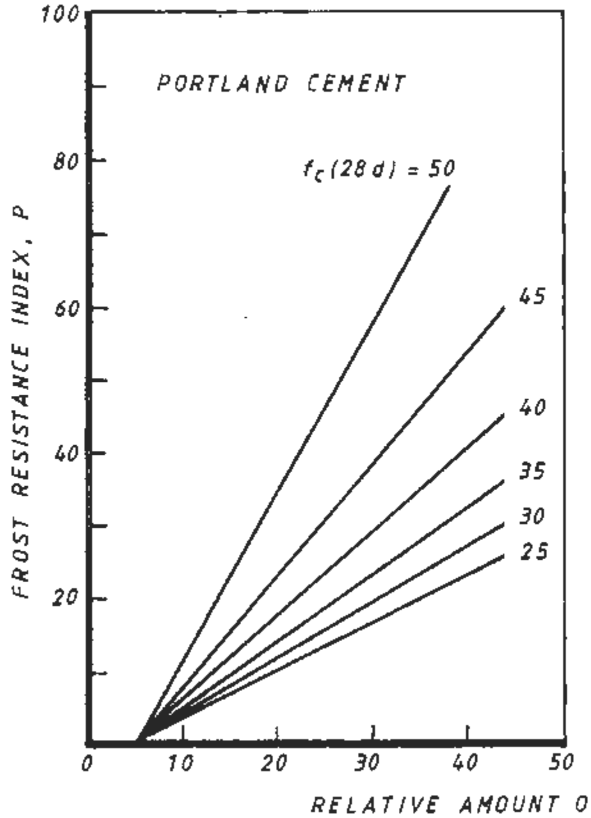
Example 3 What is the frost resistance index of concrete if the reduction in specimen volume under direct testing is 5 %?

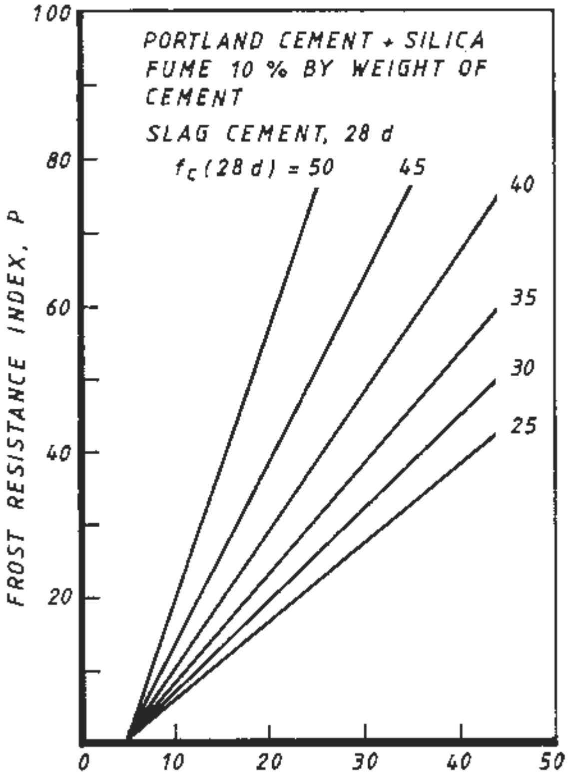
Answer: Formula 3 gives:

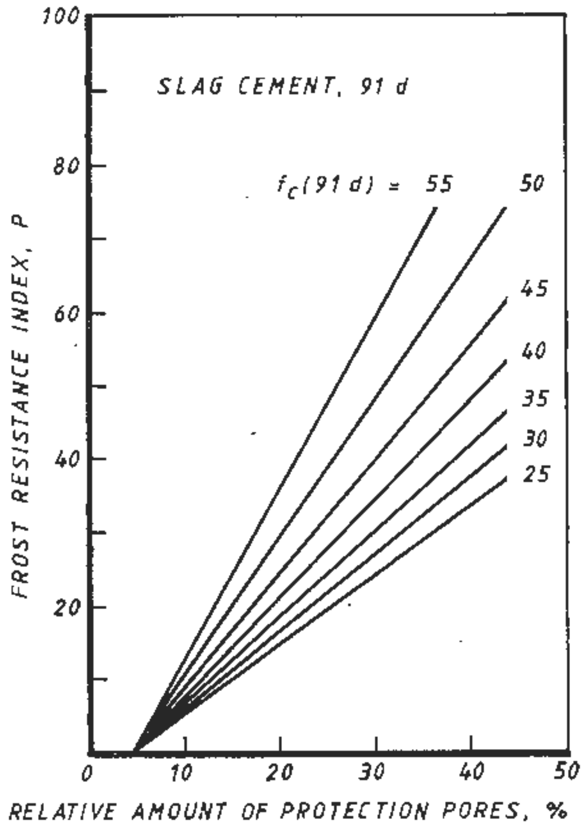
$$P = 100/\Delta V(25) = 100/5 = 20$$

Indirect testing determines the compressive strength of concrete at the age of 28 days and the amount of protection pores in the concrete. The frost resistance index is calculated according to Formula 6.

Figures 4 - 6 illustrate the frost resistance indices as a function of protective porosity and compressive strength (according to Formula 6). Curves corresponding to the compressive strength at 91 days are also drawn for slag cement concrete. Here the compressive strength at 28 d is assumed to be 80 % of that at 91 d.







Figs. 4 - 6. Frost resistance indices as a function of protective porosity and compressive strength.

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<u>Example 4</u> In indirect quality control tests the following results were obtained:
- compressive strength $f_c(28\ d) = 44$ MPa
- protective porosity $P_r = 23$ %

What is the frost resistance index if the concrete contains 8 % silica fume by weight of cement?

Answer: Formula 6 gives:

$$P = 23\ (1 + 0.065 \cdot 8)\ (23 - 5)/(60 - 44) = 39$$

5. DISCUSSION

The above method of designing concrete structures with regard to frost resistance should be considered as a preliminary attempt to find a solution to the very important yet complex problem of service life design. It provides the designer with a basic framework or example of rational service life design and quality control. However, several points still require further research and development. When considering the numerical values of different parameters (Tables 1, 2 and 3), one should bear in mind every detail of the test set-up, the preconditioning of concrete, etc. It is obvious that the use of different testing methods will produce different results.

It is the author's opinion that particular attention should be paid to the following items in the further development of the service life model presented:

1) In practice, tests other than the DBV test may prove necessary. Use of the DBV test is considered well founded in cases in which concrete is exposed to de-icing salts and in which scaling is the main type of disintegration observed. However, it may not prove suitable in cases in which concrete is exposed only to sea water, river water or rain. In such cases other frost resistance indices may be necessary.

   Different test methods will produce varying results. With silica fume concretes the results of ordinary freeze-thaw tests are highly inconsistent with those of the DBV frost-salt test /5, 12/.

2) Particular attention should be given to the preconditioning of concretes prior to testing since the results may totally depend on the duration of the preconditioning period. In this investigation the specimens were stored after casting for 7 d in water, 21 d in air (70 % RH) and 7 d in water. In several frost-salt tests, it has been shown that prolongation of the storage time in air may lead to incongruous test results. In tests performed in West Germany the frost-salt resistance of slag cement concrete was found to be considerably lower upon prolonging the storage time in air /4/. The same phenomenon has been observed in

Finland with alkali-activated slag concretes. The rapid rate of scaling at the edge zones of specimens has been found to result from carbonation. The frost-salt resistance of carbonated slag concrete appears to be much lower than that of non-carbonated parts of the same concrete.

The above phenomenon may be highly significant when evaluating the service life of a structure made of slag cement concrete. Carbonation may be the factor governing the entire deterioration process. Therefore, in the case of slag cement concrete, the service life evaluation method presented here may give misleading results. A longer storage time in air prior to testing would lead to more reliable service life evaluation.

3) The accuracy of service life evaluations could be increased by extensive in-service tests and field investigations. By gathering information concerning the distribution and scatter of such parameters as rate of scaling, strength properties and porosity of concrete as well as environmental factors, stochastic service life models could be developed, leading to more accurate and sophisticated service life analysis. The importance of field investigations is therefore strongly emphasized.

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