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Modelling of Carbonation and Chloride Penetration Interacted by Frost Damage in Concrete

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ABSTRACT

The main objective of this research was to analyse the results of laboratory and field tests on frost attack and the effects of frost attack on the rate of carbonation and chloride penetration. Both internal frost attack and frost scaling were studied. Differential equations for interacted degradation were developed. The results of carbonation and chloride penetration tests with internally damaged concrete samples were utilised in quantification of carbonation and chloride penetration rate. The process of simultaneously proceeding frost attack, carbonation and chloride penetration could be reproduced by computer simulation.

Key words: carbonation, chloride penetration, frost attack, interaction.

1. INTRODUCTION

The main focus in the project was laid on the field test results of frost attack (both internal and surface scaling) and the effects of frost attack on the rate carbonation and chloride penetration. As it was desired to apply these findings to practical service life design, a special effort was made to produce "interaction factors" for service life models based on the "factor approach". By the interaction factors the accelerating effect of frost attack on carbonation and chloride penetration is taken into account.

The research consisted of the following parts: (1) theoretical study, (2) analysis of laboratory test results, (3) determination of service life factors, and, (4) computer simulation.

2. RESEARCH AND RESULTS

2.1 Theoretical study

This study was an attempt to develop a theoretical basis for practical service life models with respect to carbonation and chloride penetration in concrete with the interaction of frost attack.

In the case of concrete exposed to frost attack, the carbonation coefficient is increasing with the increased internal damage in concrete. In that case the total carbonation depth is determined as the sum of incremental carbonation depths which are determined from Equation 1. The carbonation coefficient $k_{ca;IntFr}$ increases with time with increased frost deterioration in concrete. Likewise the depth of frost scaling increases with time [1]:

$$x_{ca;Fr} = \sum \Delta x_{ca;Fr} \tag{1}$$

$$\Delta x_{ca;Fr}(t+\Delta t) = \frac{k^2_{ca;IntFr}(t)}{2} \cdot \frac{1}{x_{ca;Fr}(t) - x_{FrSc}(t)} \cdot \Delta t$$

where $k_{ca;IntFr}$ is the carbonation coefficient of concrete exposed to internal frost action,
x_{ca} depth of carbonation as interacted by frost attack, and,
x_{FrSc} depth of frost scaling.

Using the analogy with carbonation the depth of critical chloride content (with respect to corrosion initiation) can be determined from the Equation 2 [1].

$$x_{cl;Fr} = \sum \Delta x_{cl;Fr} \tag{2}$$

$$\Delta x_{cl;Fr}(t+\Delta t) = \frac{k^2_{cl;IntFr}(t)}{2} \cdot \frac{1}{x_{cl;Fr}(t) - x_{FrSc}(t)} \cdot \Delta t$$

where $k_{cl;IntFr}$ is the coefficient of chloride penetration in concrete exposed to frost action , and
x_{cl} depth of critical chloride content.

2.2 Analysis of test results

To evaluate how the carbonation coefficient and the coefficient of chloride penetration ($k_{ca;IntFr}$ and $k_{cl;IntFr}$) depend on the of internal damage in concrete carbonation and chloride penetration tests with internally cracked concrete specimens were made. The residual dynamic modulus (RDM) was adjusted by freeze-thaw tests and ultrasonic measurements to predefined values, ranging between 0 – 100%, before starting the carbonation and a chloride penetration tests. The carbonation test was an accelerated test in a carbonation chamber with 1% CO_2. The chloride migration test was made using the standard NT Build 492.

According to the test results the depth of carbonation increases with increased internal frost damage (RDM) as presented in Figure 1a. In Figure 1b the increase of chloride migration coefficient with internal frost damage is presented [2].

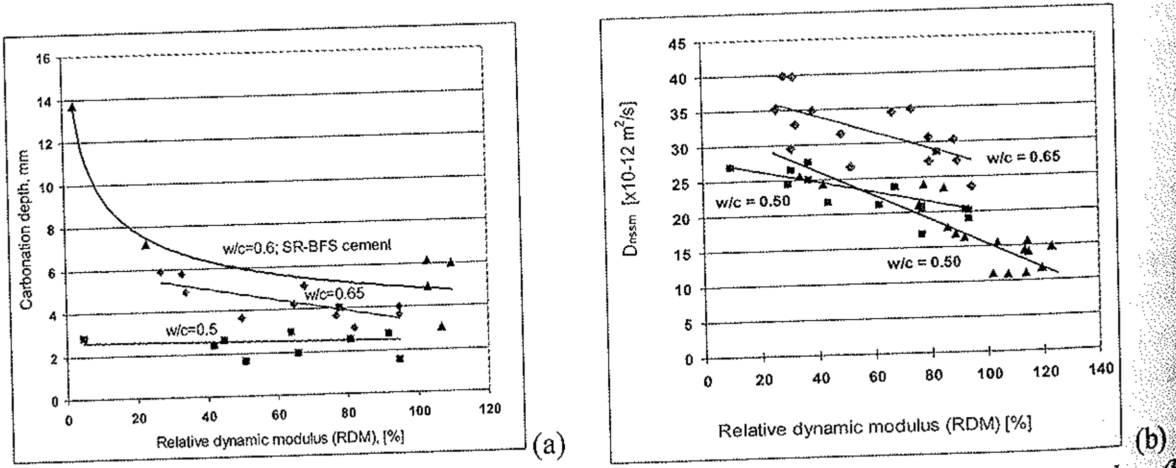

Figure 1 - The effect of internal frost damage (RDM) on (a) the depth of carbonation and on (b) the chloride migration coefficient of concrete.

Using the test results the average trend of the carbonation and chloride penetration coefficients as a function of RDM could be modelled as presented in Equations 3 and 4.

$$\frac{k_{ca;IntFr}(t)}{k_{ca0}} = 1 + 0.64 \cdot \left(1 - \frac{RDM(t)}{100}\right)^{1.32} \qquad (3)$$

$$\frac{k_{cl;IntFr}(t)}{k_{cl0}} = 1 + 0.30 \cdot \left(1 - \frac{RDM(t)}{100}\right)^{0.93} \qquad (4)$$

where k_{ca0} is the carbonation coefficient of undamaged (original) concrete, and
k_{cl0} chloride penetration coefficient of undamaged concrete.

2.3 Determination of the interaction factors for service life

The RDM value 66.7% was assumed to be to the limit state of service life with regard to internal frost damage, $t_{L;IntFr}$. To determine the interaction factors for service life the RDM value was assumed to change linearly with time, as presented in Equation 5.

$$RDM(t) = 100 - 33.3 \cdot \frac{t}{t_{L;IntFr}} \qquad (5)$$

where $t_{L;IntFr}$ is the service life with regard to internal frost damage.

Using the Equations 1, 2, 3, 4 and 5 the interaction coefficients for the initiation time of corrosion could be determined and tabulated as a function of $t_{L;IntFr}$ and the initiation time of corrosion without internal frost attack $t_{0;ca}$ and $t_{0;cl}$ respectively.

The interaction factors of frost scaling for the initiation time of corrosion could also be determined. A linear rate of frost scaling was assumed. The interaction factors in this case are the same for both carbonation and chloride initiated corrosion but they depend on the depth of concrete cover. Table 1 shows the interaction factors for the cover depth of 25 mm [2].

Table 1 - Interaction factors of frost scaling for the initiation time of corrosion (apply to both carbonation and chloride initiation). Concrete cover =25 mm.

t_0	$t_{L;FrSc}$									
	20	40	60	80	100	120	140	160	180	200
10	0.90	0.90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20	0.85	0.90	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
30	0.77	0.87	0.90	0.93	0.93	0.93	0.97	0.97	0.97	0.97
40	0.73	0.85	0.88	0.90	0.93	0.93	0.95	0.95	0.95	0.95
50	0.69	0.82	0.88	0.92	0.92	0.94	0.96	0.96	0.96	0.96
60	0.64	0.80	0.85	0.88	0.92	0.93	0.93	0.95	0.95	0.95
70	0.59	0.75	0.83	0.87	0.90	0.91	0.93	0.93	0.94	0.94
80	0.56	0.73	0.81	0.85	0.87	0.90	0.91	0.92	0.94	0.94
90	0.53	0.71	0.79	0.83	0.87	0.89	0.90	0.91	0.92	0.93
100	0.49	0.68	0.77	0.82	0.85	0.87	0.89	0.90	0.91	0.92
110	0.47	0.65	0.74	0.80	0.83	0.86	0.88	0.89	0.91	0.92
120	0.45	0.63	0.73	0.78	0.82	0.85	0.87	0.88	0.90	0.91
130	0.42	0.61	0.71	0.77	0.81	0.84	0.86	0.88	0.88	0.90
140	0.40	0.59	0.69	0.76	0.80	0.83	0.85	0.86	0.88	0.89
150	0.38	0.57	0.68	0.74	0.79	0.81	0.84	0.85	0.87	0.88
160	0.36	0.55	0.66	0.72	0.77	0.81	0.83	0.85	0.86	0.87
170	0.35	0.54	0.64	0.71	0.76	0.79	0.82	0.84	0.85	0.87
180	0.34	0.52	0.63	0.70	0.75	0.78	0.81	0.83	0.84	0.86
190	0.32	0.51	0.62	0.69	0.74	0.77	0.80	0.82	0.84	0.85
200	0.31	0.49	0.60	0.67	0.72	0.76	0.79	0.81	0.83	0.84

The updated initiation time of corrosion is obtained by multiplying the original initiation time by the factor in the table.

2.4 Computer simulation

Computer simulation software (developed in VTT in 1990's) was used to illustrate the interaction of degradation modes. The simulation program was updated with the developed degradation models for frost scaling, internal frost attack, carbonation and chloride penetration. Computer simulation software (1) emulates the real climatic conditions, (2) calculates the temperature and moisture contents in a cross-section of a concrete structure (exposed to weather), and (3) applies temperature and moisture sensitive degradation models so that the degradation over time and the service life can be predicted

The Equations 1, 2, 3 and 4 were inserted to computer simulation. In computer simulation the value of RDM and the depth of frost scaling were evaluated by specific models with the time step of 1 hour. Figure 2 shows an example on how the internal frost attack and the frost scaling effect on the depth of carbonation with time [2].

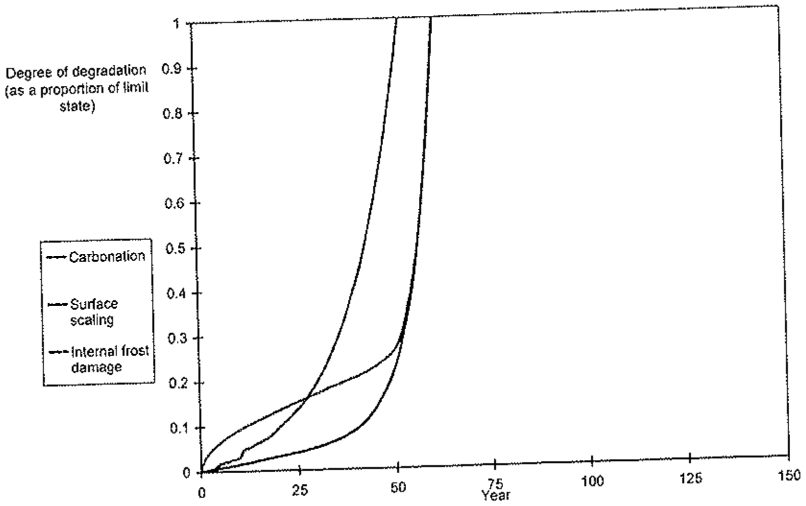

Figure 2 - Computer simulation of carbonation depth together with simultaneous internal frost attack and frost scaling.

3 CONCLUSIONS

The effect of frost attack on carbonation and chloride penetration may be substantial and should be taken into account when evaluating the service life of concrete structures exposed to frost attack. The interaction can be simulated by a special software. Interaction factors for the service life prediction by the factor approach were determined.

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