Field and Laboratory Testing and Service Life Modelling in Finland

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ABSTRACT

Extensive data on the true weathering rate of concrete is needed to determine the correlation between field tests, laboratory tests and concrete mix designs. A wide range of concretes with different cements and binding materials are needed for these studies. Studies on integrated degradation must be included. All this data together with local weather data serves as a basis for thorough modelling, computer simulation and development of comprehensive and calibrated service life models. These all-out models can be used as tools in the development of more practical tools for engineering purposes. The current ongoing DuraInt-project aims at serving this objective.

Key words: Concrete, durability, field testing, frost-salt, frost, chloride penetration, carbonation, ageing, interacted deterioration, models, service life.

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1 INTRODUCTION

In Finland there are today a total of three concrete durability field testing areas under evaluation. The first two field stations include concretes where frost and carbonation are evaluation, while the third station includes concrete samples for assessing frost-salt deterioration, carbonation and chloride penetration. The first station was established within the EU 5th Framework project "CONLIFE: Life-time Prediction of High-Performance Concrete with Respect to Durability" (2001-2004) and is located in northern Finland in the town of Sodankylä. In the parallel national project (YMPBETONI 2002 - 2004) with Finnish ecological binding materials, an additional station was established in southern Finland in the neighbourhood of Otaniemi, in the town of Espoo [1]. The most recent Finnish project (2008-2011) is entitled "Effect of Interacted Deterioration Parameters on Service Life of Concrete Structures in Cold Environments (DuraInt)". In the DuraInt project, one more testing area has been established in southern Finland, beside Highway 7 near the town of Kotka. The former so called Durafield-project [2, 3] is today included as one task in this more versatile DuraInt-project.

In addition to field and laboratory testing, DuraInt includes laboratory testing, theoretical studies and also service life modelling on the effect of interacted deterioration parameters. [4] In the DuraInt-project VTT works in co-operation with TKK (Helsinki University of Technology) and with foreign partners from Norway, U.S.A, Canada and Portugal. DuraInt is a public project funded by TEKES (the Finnish Funding Agency for Technology and Innovation) and also by several participants including organizations, companies, and cities.

The main strategy in Finland is to use modelling and computer simulation to treat such complex phenomena. This means accounting for simultaneous frost or salt-frost deterioration, chloride penetration and carbonation of different concrete structures. The simulations also need to consider different binding materials, concrete mix designs and different or constantly changing climatic conditions. Computer simulation is calibrated with field and laboratory testing. By the use of calibrated simulation, service life models for engineering purposes can be developed, i.e. most of the parameters in the factor method design formulas of the Finnish national codes can be defined. 'Interaction parameters' will be included in updated models developed in the project to take into account the effect of interacted deterioration.

2 FIELD AND LABORATORY TESTING

2.1 Testing field information

There are a total of three different concrete durability field testing areas in Finland. Two of these are in southern Finland and one in northern Finland. The main information on these field stations and the testing extent is summarized in Table 1. Some field station photos are presented in Figure 1. An example of temperature and relative humidity variation (Otaniemi field station, Espoo, autumn 2007 – autumn 2008) is presented in Figure 2.

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Table 1 – Basic field testing area information.

Information, research field	Highway 7, Kotka	Otaniemi, Espoo	Sodankylä
Frost - XF3	-	X	X
Frost-salt (de-icing) – XF4	X	-	-
Carbonation:			
- sheltered outdoors – XC3	-	X	-
- not sheltered outdoors – XC4	(X)[1)]	X	(X) [1)]
Chloride penetration, road environment - XD3 (mainly 4.5 m from road line)	X	-	-
Projects and mix designs to date:			
- DuraInt (2007…)	27	27	-
- CONLIFE (2001…)	-	-	22
- YMPBETONI (2001…)	-	19	19
Own meteorological station	X	X	-
Concrete temperature and humidity/RH measurements	X	-	-
Location	N 67^{o}22´ E26^{o}39´	N60^{o}11´ 24^{o}48´	N67^{o}24´ E26^{o}35´
Elevation from sea level [m]	about 20	about 20	179

Temperature information (1971-2000):	for Helsinki, Kaisaniemi (elevation 4 m):	Sodankylä:
-Year average [^{o}C]	+6	-1
- January average[^{o}C]	-4	-14
- June average [^{o}C]	+15	+12
Days in a year, when minimum temperature is below 0^{o}C	169	230
Days in a year, when minimum temperature is below -10 ^{o}C	40	111
Relative humidity, year average [%]	79	62
Precipitation, year average [mm]	642	507

1) No specific specimen for monitoring, but can be measured later on.

Figure 1 – Field testing areas in southern Finland beside Highway 7 near Kotka and in Otaniemi, Espoo.

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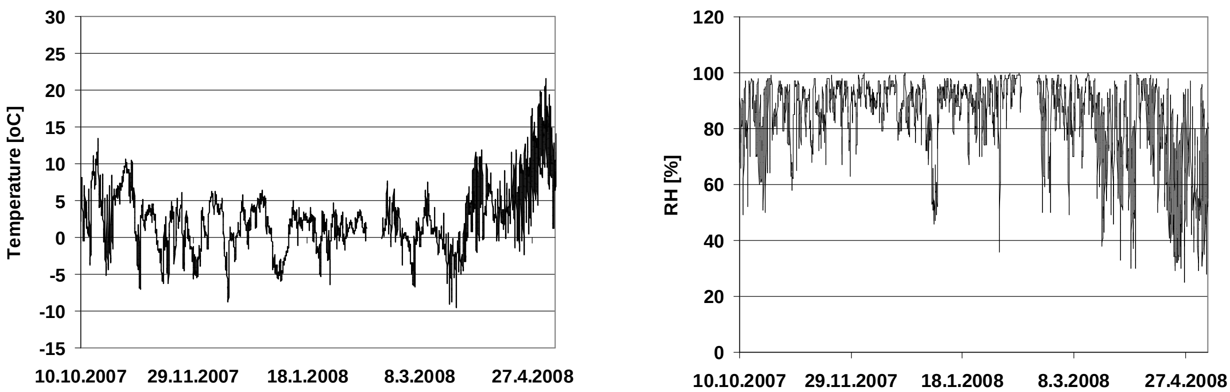

Figure 2 - Temperature and relative humidity variation at Otaniemi testing field in southern Finland autumn 2007 – spring 2008.

2.1 Concrete mixes and general testing plans

DuraInt – Basic series

The mix designs of the first series ("Basic") of the DuraInt-project were performed with the Finnish concrete industry and represent mainly prevailing common industrial mixes (Table 2). About half of the castings were done in a ready-mixed concrete plant or in a pre-cast element factory. Of the 27 mixes, 23 were produced in autumn 2007 and then four additional mixes were made with a slight adjustment to the air entrainment dosage in spring 2008. Common Finnish cements (manufactured by Finnsementti Oy), blast furnace slag (BFS) and fly ash (FA) were used. The effective water-to-binder ratio, as defined in Table 2, was about 0.42, 0.50 or 0.60 and the compressive strengths were up to 60 MPa. Field testing concentrates on air entrained bridge concretes. Some concretes were intentionally produced with no or only inadequate air entrainment. In addition, 6 air entrained façade or balcony concretes are included. The DuraInt project includes a wide laboratory testing program, i.e. basic properties as well as salt-frost, frost, carbonation and chloride diffusion testing and thin section studies (Table 5). The suitable testing field and testing extent for each concrete mix was defined according to the range of use, e.g. façade concretes are not tested for chloride penetration. All the results in the future will be publicly available for anyone interested and the results will be preserved in a documentation database for decades.

DuraInt – Interacted deterioration

In autumn 2008 further laboratory test series will be cast for interacted deterioration studies. General information on the testing plan is presented in Table 5 as well as more general mix design information. Some mixes in this research are the same as in the DuraInt Basic series (Table 2). This also means that there will be field testing data for these mixes, and comparison of the results and verification of the models will be possible. E.g. results for the interaction of carbonation and salt-frost resistance can be compared with field testing results. Studies on the interacted deterioration are in the early phase. General mix design information and testing plans are presented in Table 6.

CONLIFE

In the CONLIFE-project all 22 mix designs were >60 MPa high performance concretes (HPC) with water-binder ratios of 0.30 – 0.42. The cement was Danish Type CEM I 52.5R cement from Aalborg Portland. Air entrained and non-air entrained high strength concretes with silica fume (SF), normal or fine blast furnace slag (BFS) or fly ash (FA) were included. Mixtures for

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lab and field testing were cast and exposed in autumn 2001. Besides the Finnish field station in Sodankylä, CONLIFE-mixtures have also been exposed in 8 other marine and frost testing fields in Germany, Italy, Sweden and Iceland. The CONLIFE-project also included studies on acid attack, cyclic temperature attack, shrinkage and fire resistance, but these themes are not considered within this paper. Only the laboratory testing results corresponding to Finnish field test observations are presented here. The CONLIFE mix design information is presented in Table 3 and general information on testing in Table 5. [5]

YMPBETONI

The YMPBETONI-project concretes were made with Finnish cements 'Yleis' (CEM II/A-M(S-LL) 42.5) and 'Rapid' (CEM II/A-LL 42.5 R) and they included up to 60 % fly ash (FA) or 70 % blast furnace slag (BFS). These ecological 30 – 45 MPa air entrained concretes were cured with or without heat treatment. The mix designs were based on the target strength for precast and ready mix concrete. Mixes were cast in autumn 2003 and were exposed at both southern and northern Finland field stations. The YMPBETONI mix design information for all 19 mixes is presented in Table 4 and general information on testing in Table 5. The results have been reported in Finnish literature through 2005 testing but will be further assessed within the DuraInt project.

Table 2 - DuraInt. Basic series for field and laboratory testing. Mix information and compressive strength 28 d.

DuraInt Short code	Cement type	W_{eff}/(Cement +2*SF+0.6*BFS+ 0.4*FA)	Cement [kg/m^3]	BFS [kg/m^3]	FA [kg/m^3]	Aggregate total [kg/m^3]	Total eff. water [kg/m^3]	Fresh concrete air [%]	Compressive strength 28 d (150 mm cube) [MPa]
1A	CEM II/B-S 42.5 N	0.41	405	0	0	1746	165	6.5	56.3
2A	CEM I 42.5 N - SR	0.42	387	0	0	1796	161	5.9	46.4
3A	CEM II/A-M(S-LL) 42.5 N	0.42	428	0	0	1709	179	5.9	38.0
5A	CEM II/A-LL 42.5 R	0.42	421	0	0	1748	176	5.0	41.2
6A	CEM I 52.5 R	0.42	417	0	0	1737	175	5.5	58.5
7A	CEM II/A-LL 42.5 R & Finnsementti SLG KJ400	0.47 [3)]	217	217	0	1725	163	6.1	46.0
8A	CEM II/A-LL 42.5 R & FA [EN 450-1. 2005] Fineness N. Class A	0.45	344	0	106	1706	173	5.0	54.6
3Ba	CEM II/A-M(S-LL) 42.5 N	0.42	410	0	0	1844	172	2.6 [1) 2)]	50.6
3Bb	CEM II/A-M(S-LL) 42.5 N	0.42	406	0	0	1784	170	4.5 [2)]	46.1
3Bc	CEM II/A-M(S-LL) 42.5 N	0.42	407	0	0	1756	172	5.3 [2)]	48.9
3Bc2	CEM II/A-M(S-LL) 42.5 N	0.42	406	0	0	1715	170	7.0 [2)]	39.0
3Bd-SCC1	CEM II/A-M(S-LL) 42.5 N	0.42	435	0	0	1746	185	3.4 [1)]	51.0
3Be-SCC2	CEM II/A-M(S-LL) 42.5 N	0.42	426	0	0	1709	178	5.7	35.0
1C	CEM II/B-S 42.5 N	0.47	339	0	0	1808	160	6.9	45.5
3C	CEM II/A-M(S-LL) 42.5 N	0.49	333	0	0	1847	163	5.5	40.1
4C	CEM I 52.5 N	0.46	334	0	0	1816	154	5.5	46.3
5C	CEM II/A-LL 42.5 R	0.51	337	0	0	1833	172	5.0	44.9
6C	CEM I 52.5 R	0.40	451	0	0	1722	180	5.4	50.3
3D	CEM II/A-M(S-LL) 42.5 N	0.50	333	0	0	1895	166	3.4	44.5
1E	CEM II/B-S 42.5 N	0.60	273	0	0	1845	163	7.3	32.8
3E	CEM II/A-M(S-LL) 42.5 N	0.58	321	0	0	1828	185	4.3	35.5
4E	CEM I 52.5 N	0.54	300	0	0	1840	162	5.5	39.5
5E	CEM II/A-LL 42.5 R	0.54	322	0	0	1764	174	4.8	41.2
3Bf	CEM II/A-M(S-LL) 42.5 N	0.41	420	0	0	1812	174	1.7	64.0
3Bg	CEM II/A-M(S-LL) 42.5 N	0.41	420	0	0	1745	174	4.2	57.2
3Bh	CEM II/A-M(S-LL) 42.5 N	0.41	420	0	0	1691	174	6.8	46.3
3Bi	CEM II/A-M(S-LL) 42.5 N	0.41	420	0	0	1746	174	4.9	52.8

1) No air entrainment; 2) Presumably extra compaction pores; 3) W_{eff}/(Cement +2*SF+0.8*BFS+ 0.4*FA) = 0.42

Table 3 - CONLIFE mix design information and compressive strength 28 d.

CONLIFE Short code	Code Meaning	Cement type	W_{eff}/(Cement +2*SF +0.8*BFS +0.4*FA)	Cement [kg/m^3]	BFS [kg/m^3]	fine BFS [kg/m^3]	FA [kg/m^3]	SF [kg/m^3]	Water [kg/m^3]	Aggregate total [kg/m^3]	Fresh concrete air [%]	Compressive strength (150 mm cubes) [MPa]
C21	0.30	CEM I 52.5 R	0.29	511	0	0	0	0	146	1859	2.0	81
C22x	0.42	CEM I 52.5 R	0.39	365	0	0	0	0	144	2096	5.5	78
C8	0.30 + 3%SF	CEM I 52.5 R	0.28	491	0	0	0	15	144	1960	2.0	87
C1	0.30 + 7%SF	CEM I 52.5 R	0.27	467	0	0	0	33	144	1960	2.0	98
C9	0.30 + 10%SF	CEM I 52.5 R	0.27	451	0	0	0	45	144	1960	2.5	98
C 2	0.35 + 7%SF	CEM I 52.5 R	0.32	401	0	0	0	28	145	2029	1.7	90
C10x	0.42 + 3%SF+AE	CEM I 52.5 R	0.39	351	0	0	0	11	146	1995	5.1	82
C3	0.42 + 7%SF	CEM I 52.5 R	0.38	334	0	0	0	23	146	2097	1.7	92
C11x	0.42 + 10%SF+AE	CEM I 52.5 R	0.38	322	0	0	0	32	146	1995	5.3	90
C4	0.30 + 7%fineBFS	CEM I 52.5 R	0.27	476	0	33	0	0	144	1960	1.8	90
C 5	0.30 + 7%SF + 30% BFS	CEM I 52.5 R	0.29	361	108	0	0	25	144	1960	2.2	99
C 6	0.42 + 7%fineBFS	CEM I 52.5 R	0.38	340	0	24	0	0	146	1995	1.2	84
C7x	0.42 +7%SF + 30%BFS+AE	CEM I 52.5 R	0.41	258	77	0	0	18	146	1995	5.6	89
C12	0.30 + 7%SF + 10%FA	CEM I 52.5 R	0.29	416	0	0	42	29	144	1960	1.8	97
C13	0.30 + 7%SF + 20%FA	CEM I 52.5 R	0.36	313	0	0	125	22	145	1960	1.8	87
C14	0.30 +7%SF + 40%FA	CEM I 52.5 R	0.32	375	0	0	75	26	145	1960	2.9	89
C15x	0.42 +7%SF + 10%FA + AE	CEM I 52.5 R	0.42	297	0	0	30	21	146	1995	4.5	83
C16x	0.42 +7%SF + 20%FA + AE	CEM I 52.5 R	0.45	268	0	0	54	19	146	1995	5.2	81
C17x	0.42 + 7%SF + 40%FA + AE	CEM I 52.5 R	0.50	223	0	0	89	16	146	1995	4.7	72
C18x	0.30 + 7%SF + AE	CEM I 52.5 R	0.27	467	0	0	0	33	144	1858	6.5	78
C19x	0.35 + 7%SF + AE	CEM I 52.5 R	0.32	401	0	0	0	28	146	1927	4.9	71
C20x	0.42 + 7%SF + AE	CEM I 52.5 R	0.38	334	0	0	0	23	145	1994	4.8	67

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Table 4 - YMPBETONI mix design information.

YMPBETONI Short code[1)]	Code Meaning	Cement type	W_{eff}/(Cement +2*SF +0.8*BFS +0.4*FA)	Cement [kg/m^3]	BFS [kg/m^3]	FA [kg/m^3]	Water [kg/m^3]	Aggregate total [kg/m^3]	Fresh concrete air [%]	Compressive strength (100 mm cubes/calculated 150 mm cubes) [MPa]
K30	K30 - Reference	CEM II/A-LL 42.5 R	0.58	250	0	0	144	1907	6.0	30/30
L20	K30 - 20% FA	CEM II/A-LL 42.5 R & FA [EN 450-1. 2005] Fineness N. Class A	0.55	231	0	58	139	1839	6.8	37/38
L40	K30 - 40% FA	CEM II/A-LL 42.5 R & FA [EN 450-1. 2005] Fineness N. Class A	0.52	208	0	139	136	1781	6.0	44/47
L60	K30 - 60% FA	CEM II/A-LL 42.5 R & FA [EN 450-1. 2005] Fineness N. Class A	0.47	173	0	259	129	1677	5.7	39/41
K45	K45 - Reference	CEM II/A-M(S-LL) 42.5 N	0.49	343	0	0	167	1786	5.0	43/46
M25	K45 - 25% BFS	CEM II/A-M(S-LL) 42.5 N & Finnsementti SLG KJ400	0.52	253	84	0	165	1748	6.9	37/38
M50	K45 - 50% BFS	CEM II/A-M(S-LL) 42.5 N & Finnsementti SLG KJ400	0.55	170	170	0	167	1755	6.2	36/37
M70	K45 - 70% BFS	CEM II/A-M(S-LL) 42.5 N & Finnsementti SLG KJ400	0.57	102	239	0	168	1761	5.6	33/34
K30U	K30-Ref NEW	CEM II/A-LL 42.5 R	0.60	279	0	0	168	1829	5.6	30/30
L40U	K30-40%FA NEW	CEM II/A-LL 42.5 R & FA [EN 450-1. 2005] Fineness N. Class A	0.62	208	0	139	163	1715	6.3	24/23
L60U	K30-60%FA NEW	CEM II/A-LL 42.5 R & FA [EN 450-1. 2005] Fineness N. Class A	0.57	172	0	257	156	1603	6.5	25/24

1) K means reference (only CEM II) with target strength; L means FA; M means BFS; U means new casting.

Table 5 – Information on field and laboratory testing in DuraInt Basic-, CONLIFE- and YMPBETONI–projects in Finland. (The general scheme for DuraInt Interacted deterioration studies are presented in Table 6).

	Number of mix designs/cases in		
	DuraInt Basic	CONLIFE	YMPBETONI
	Basic series (field + laboratory), Interacted studies see Table 6	(Testing in different countries, different ages and test details as test duration and minimum temperature, see [5])	(Includes mixes with and without heat treatment and 3 re-done mixes)
Testing scheme	(2007...)	(2001...)	(2002…)
Laboratory testing:			
- Fresh concrete basic properties	27	22	19
- Compressive strength (always 28 d, for CONLIFE and YMBETONI more ages)	27	22	19
- Thin section studies, air pore analysis, etc.	27	22	19
- Carbonation: Cabinet: 1% CO_2; RH 60%; T=21°C	23	-	-
- Carbonation: RH 65 %, T=20 °C	23	-	19
- Chloride diffusion coefficient - D_{nssm} (NT Build 492, CTH-method, different ages, e.g. 28 d, 3 months, 6 months)	12 +6[1)]	22	-
- Frost-salt: scaling and internal, slab test	21	-	-
- Frost: scaling and internal, slab test	6	22	19
		-	
Field testing:		-	
- Carbonation sheltered	23	-	-
- Carbonation not sheltered	(27[2)])	-	19
- Chloride penetration profiles	12 +6[1)] + 3[3)]	(22[4)])	
- Frost-salt: volume change and internal deterioration	21	(22[4)])	
- Frost: volume (weight) change and internal deterioration	6	22[5) 6)]	19
- Frost healing at field	5	22	19[7)]
- Optical microstructure (e.g. thin sections) and other further studies, as needed	27	22	19[7)]

1) Effect of impregnation or form lining
2) No specific specimens, can be measured later on
3) Three more distances from road lining
4) Testing not in Finland but in Sweden and Iceland
5) Testing also in Iceland
6) Only weight change is monitored (=scaling+water uptake/drying)
7) Both in southern and northern Finland (Otaniemi and Sodankylä)

Table 6. – Information on mix design and testing in DuraInt Interacted deterioration studies. (2008...)

Laboratory testing on interacted deterioration:	Number of mixes	Mix information	Target
Carbonation – Frost-salt	17	Table 2, mixes:1A, 2A, 3A, 5A, 6A, 7A, 8A, 3Bb-e, 1C, 3C, 5C, 6C	- evaluate the effect of carbonation and ageing (also without carbonation) on salt-frost scaling
Frost-salt – Carbonation	7	Table 2, mixes: 3A, 3Bb, 3Bc2, 3C, 5A, 7A and 8A	- evaluate the effect of salt-frost scaling/deterioration on carbonation depth
Carbonation – Frost	10	Table 2, mixes: 1E, 3E, 4C, 4E, 5C, 5E and 4 new mixes w/c=0.60 and air 2 %, 3 % 5 % & 6 %; CEM II/A-M(S-LL) 42.5 N	- evaluate the effect of carbonation and ageing (without carbonation) on possible frost scaling and internal frost deterioration
Frost – Carbonation (internal)	6	6 mixes with w/c = 0.60 and air 2 %, 3 % & 5%; two binder materials: CEM I 42.5 N + BFS (50 %)	- evaluate the effect of internal cracking on carbonation
Carbonation – Chloride	5	5 mixes with w/c = 0.50 and air 2% and 1 with air 5%; 4 cements/binder materials (CEM I, CEM II, BFS 50 % and FA 24 %)	- evaluate chloride diffusion coefficient in carbonated concrete and the effect of carbonation on chloride distribution, i.e. on chloride profiles
Chloride – Carbonation	5		- evaluate the effect of chlorides on carbonation
Frost – Chloride (internal)	2	2 mixes with w/c = 0.50 and air 2 % & 3 %; CEM II/A-M(S-LL) 42.5 N	- evaluate the effect of cracking (internal) on chloride penetration
Chloride - Frost	2	e.g. 2 mixes with w/c = 0.50 and air 2 % & 3 %; CEM II/A-M(S-LL) 42.5 N	- evaluate the effect of chlorides on frost deterioration

3 RESULTS

3.1 Carbonation - XC3

DuraInt

Carbonation of all the DuraInt basic series mixes (Table 2, not for mixes 3Bf-i)) is studied at the field stations on samples sheltered from rain (XC3). Carbonation has been tested also in the laboratory in an accelerated procedure of - 56 days, 1% CO_2, T= 20 ^oC and RH 60 %. Before testing curing was 7 days in water and 21 days in RH 65 %. Carbonation is also tested in the laboratory in a non-accelerated environment of T=20 ^oC and RH 65 %. The samples have been exposed for 1 year already and exposure is continuing.

Carbonation depth was essentially measured as presented in prEN 13295 (2003) [19]: e.g. for each measurement one or two slices of 15 mm minimum thickness were taken from the prism (originally 100×100×500 mm^3) and sprayed with phenolphthalein indicator solution. The average value for each concrete was calculated based on single measurements (40 measurements for accelerated carbonation and 20 for a preliminary value of not-accelerated carbonation).

The results so far are presented in Table 7. In Figure 3 the calculated k-value (carbonation depth $= k\,t^{½}$) for carbonation at 1 % CO_2 is compared with the values calculated for carbonation at RH 65 % and at the sheltered field location. In this calculation the carbonation time (days) is the time at the actual carbonation circumstance and the k-value is calculated considering the exact carbonation time separately for each concrete.

In the future, carbonation at both the field station and in the laboratory RH 65 % environment will be followed and measured. The next measurement time will be after 2 years of exposure time, in autumn 2009.

Table 7 – DuraInt. Carbonation depth measurement results (1 % CO_2, RH 65 % and field sheltered).

Mix	56 d at 1 % CO_2 [mm]	RH 65 % (7.7…9.0 months; average 8.3 months) [mm]	Field sheltered about 270 d (Sept. 07- May 08) [mm]
1A	3.6	0.7	0.2
2A	3.6	0.7	0.3
3A	5.5	1.3	0.5
5A	5.0	1.1	0.4
6A	2.6	0.4	0.2
7A	5.7	1.9	0.7
8A	4.7	1.3	0.4
3Ba	4.7	1.2	0.3
3Bb	4.8	1.3	0.2
3Bc	4.5	1.2	0.2
3Bc2	5.6	1.5	0.4
3Bd-SCC1	4.5	1.1	0.2
3Be-SCC2	8.0	3.0	0.6
1C	5.9	1.8	0.5
3C	6.1	1.8	0.5
4C	2.7	0.5	0.3
5C	5.4	1.7	0.3
6C	4.0	0.6	0.1
3D	5.2	1.4	0.4
1E	10.5	3.7	2.2
3E	7.1	2.4	1.4
4E	4.3	1.4	0.7
5E	6.4	1.8	0.6

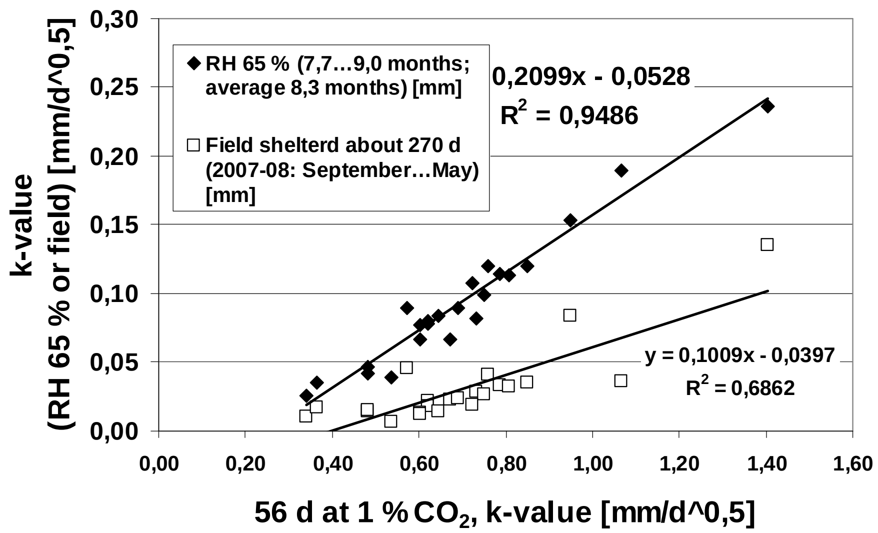

Figure 3 – Correlation between k-values as calculated for carbonation at 1 % CO_2 (x-axle) and at RH 65 % and at field sheltered. Preliminary results after < 1 year.

3.2 Chloride penetration - XD3

DuraInt-project

Chloride penetration studies are made for samples at the DuraInt testing field site beside Highway 7 near Kotka. The results represent surfaces directly affected by de-icing salts or spray containing de-icing salts (XD3).

Only one winter period has passed so far and the results are thus somewhat preliminary. Chloride profiles were made from the surfaces facing the road by the so-called “profile grinding method” (on cores of 100 mm diameter). The main distance from the road lining is 4.5 m. There are also some results from samples placed at distances of 9 m, 11 m and 13 m from the road line. Total chloride content was determined, using one powder sample with one measurement per depth.

In the laboratory the non-steady state diffusion/migration coefficient (D_{nssm}) was measured, with testing at the age of 3 months following the CTH-method, NT Build 492 [20].For these measurements ø98×200 mm cylinders were cast (3 parallel). The actual test specimens were prepared by first cutting the cylinder into two halves, and then cutting a 50 ± 2 mm thick slice from one half. The testing was done by Germann Instruments A/S device called PROOVE’it. An external electrical potential is applied axially across the specimen and forces the chloride ions outside to migrate into the specimen. After a certain test duration (normally after 24 hours), the specimen is axially split and a silver nitrate solution is sprayed on to one of the freshly split sections. The chloride penetration depth can then be measured from the visible white silver chloride precipitation, after which the chloride migration coefficient can be calculated from this penetration depth. Some results are presented in Figures 4 - 6.

From the results in Figure 4, it can be seen that the surface concentration after the first winter season varies between 0.03 – 0.07 w.-% and the maximum concentration is usually higher than the surface concentration. All mixes had a chloride penetration depth of less than 10 mm. These results after only the first year of field testing are not closely analyzed here. It is expected that after a few more years the results will be more stable and then closer analysis will be warranted. As an example of results, for concrete 7A (CEM II/A-LL 42.5 R & 50 % BFS) the surface

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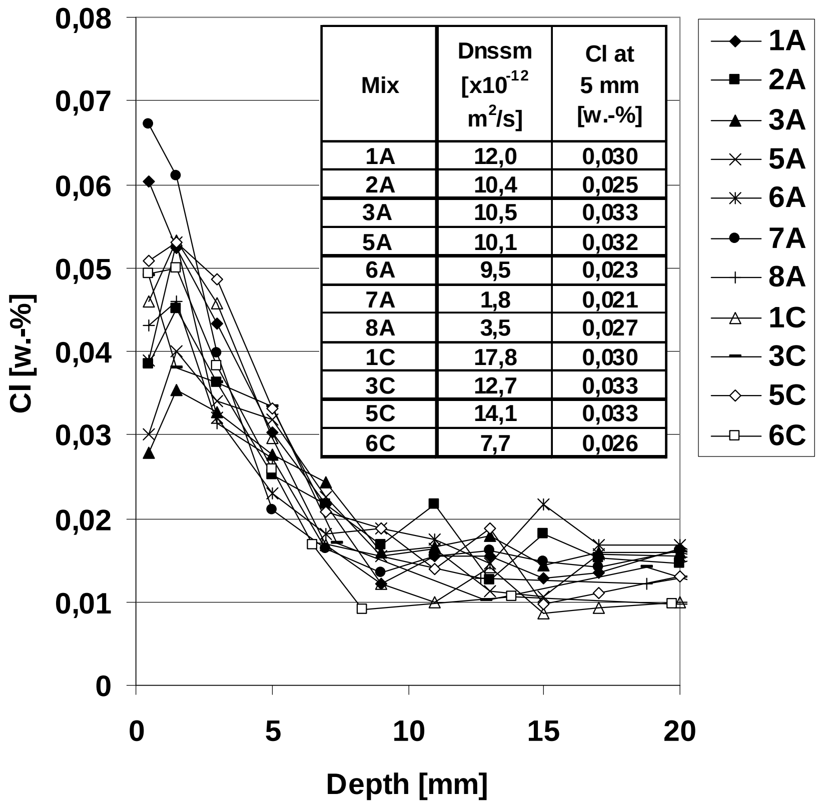
concentration is highest (0.067 w.-%), but the concentration at 5 mm depth is lowest (0.021 w.-%).

In Figure 5 the expected trend could be seen, as the depth of chloride penetration clearly increased as samples were moved closer to the roadway edge.

The study on the effect of hydrophobic impregnation is included in the DuraInt-project as well as the study on the effect of the use of form lining (3 + 3 cases/products, studies with concrete 3D, see Table 2). According to the laboratory tests, i.e. values for D_{nssm} at 3 months with mould surface in the testing by NT Build 492 method [20], and preliminary field testing results, both the use of form lining and hydrophobic impregnation clearly diminished chloride penetration (Figure 6).



Mix	Dnssm [x10^{-12} m^2/s]	Cl at 5 mm [w.-%]
1A	12,0	0,030
2A	10,4	0,025
3A	10,5	0,033
5A	10,1	0,032
6A	9,5	0,023
7A	1,8	0,021
8A	3,5	0,027
1C	17,8	0,030
3C	12,7	0,033
5C	14,1	0,033
6C	7,7	0,026

Figure 4 – Chloride profiles after the first winter period and respective chloride diffusion coefficients measured at 90 day (NT Build 492). See Table 2 for mix information.

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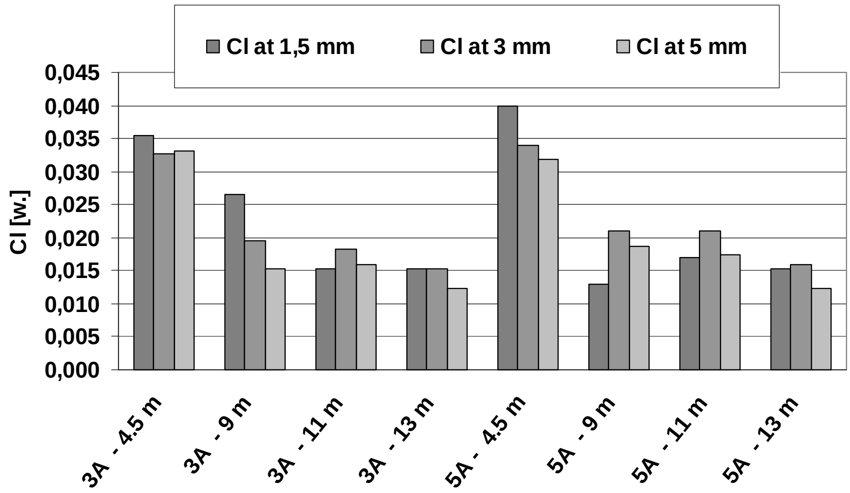

Figure 5 – Chloride contents in concrete specimen (3A and 5A) at different distances from road side (4.5 – 1 3meters). Total chloride content at 1.5 mm, 3 mm and 5 mm depth. of sample.

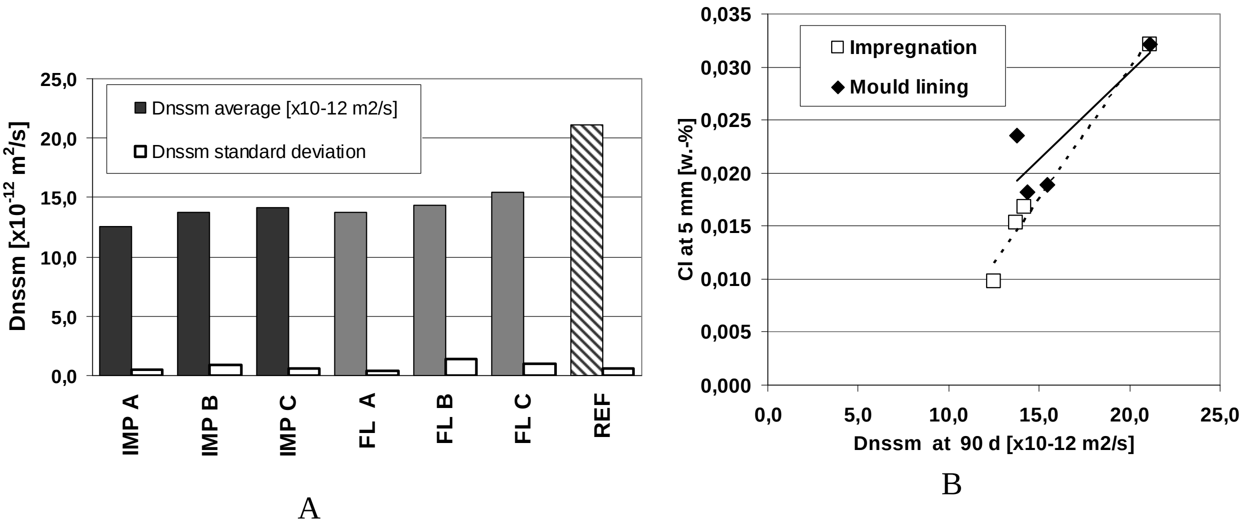

Figure 6 – The effect of hydrophobic impregnation (IMP) and the use of form lining (FL) on chloride penetration and diffusion coefficient (NT Build 492, form surface at test). A) Chloride diffusion coefficient at 90 d. B) Cl-content at field specimen (depth 5 mm) after the first winter period v.s. D_{nssm} at 90 days.

3.3 Freeze-thaw without de-icing salts - XF3

General

Field testing for freeze-thaw in Finland usually corresponds to exposure with high water saturation and horizontal surfaces (XF4). A typical Finnish winter experiences about 50 freeze-thaw cycles. In CONLIFE the testing field in northern Finland also represents a very low minimum temperature (see below), yet the number of actual freeze-thaw cycles is similar to southern Finland.

The so called Slab test is one test method for freeze-thaw and internal damage in CEN/TC 51 N 772 (2003) [21]. This method is mainly used here with the addition of scaling material being measured according to CEN/TS 12390-9 [22]. Internal damage or cracking is measured by ultrasound pulse velocity and a measure of internal damage is calculated as relative dynamic modulus percentage (RDM). Mixtures start with an RDM value of 100% and the concrete is considered deteriorated when the RDM falls below a certain level as defined by acceptance criteria. A typical 'failure' value may be an RDM falling below 85% or 67%, depending on the standard requirements [11].

DuraInt

There are only 6 concretes in DuraInt for freeze-thaw testing with plain water (4C, 5C, 1E, 3E, 4E and 5E). These concretes have been tested in the laboratory using the slab test and they have been in the Otaniemi, Espoo testing field since autumn 2007. Internal deterioration and healing has been followed by ultrasonic transit time and fundamental frequency measurements. Both measurements have been calculated to provide the assessment of internal damage expressed as relative dynamic modulus (RDM %). Measurements of the specimen (75 x 150 x 150 mm^3) are always made after 1 day in water and 7 days in RH 65%. Volume change is also monitored by weighing in water and air and always after 1 day in water immersion. Later on also thin section studies will be made to evaluate the internal structure, e.g. possible cracking.

Laboratory testing results including thin section results on air entrainment and results for the first field testing period 2007 – 08 are presented in Table 8. Compared to an initial RDM value of 100%, only minor changes in RDM can be seen after the first winter period noted as spring 2008. This first winter was considered to be extremely mild for Finland. Some strength gain or healing can bee seen after the first summer period. One concrete (5E) scaled during the lab testing. The next measurements will be done after the winter period 2008 - 09 and again after the summer. These field measurements are planned to continue for 10+ years.

Table 8 - DuraInt-project. Results for frost deterioration, after 1 year. Slab test results and field testing results after the first winter period 2007 – 08 and subsequent summer.

	Laboratory testing				Field testing					
	Thin sections Air pores		Slab test 56 cycles		Internal deterioration				Volume change (+ is grow) [%]	
Mix	Specific surface < 0.800 mm pores [mm^2/mm^3]	Spacing factor (< 0.800 mm pores) [mm]	Scaling [kg/m^2]	RDM $100 (t_0/t_n)^2$ [%]	RDM by ultrasound $100 (t_0/t_n)^2$ [%]		RDM by fundamental frequency $(f_n/f_0)^2$ 100 [%]			
					spring 08	autumn 08	spring 08	autumn 08	spring 08	autumn 08
4C	21	0.29	0.028	110	95.6	97.4	97.0	98.2	0.16	0.37
5C	13	0.51	0.020	107	98.4	101.5	99.7	101.4	-0.03	-0.41
1E	23	0.26	0.013	106	101.0	102.8	98.3	103.3	-0.45	-0.35
3E	25	0.28	0.013	102	98.2	100.8	98.8	100.7	-0.03	0.21
4E	25	0.25	0.023	107	96.5	98.2	97.6	99.2	0.06	0.31
5E	16	0.41	0.259	101	97.6	99.0	99.3	100.7	0.02	0.35

CONLIFE

Field testing of frost deterioration and also healing has been evaluated 8 times so far at the Sodankylä station during from 14.12.2001 – 15.9.2004. The criteria for a freeze-thaw cycle as defined by the project group was an exterior air temperature change, rising over +1 ^{o}C followed by dropping below -1 ^{o}C. There were 42 freeze-thaw cycles measured during the first (2001-02) winter, with the coldest temperature reaching -36°C. During the second (2002-03) season there were an additional 56 cycles and the coldest daily temperature recorded was -39°C.

The internal damage (RDM %, by fundamental frequency) measured on all concretes after two winter seasons is given in Figure 7.

Mixture C3 (w/b=0.42, 7% SF) was the only mixture that had severely deteriorated beyond the acceptance level of 80%. Mixture C6 (w/b=0.42, 7% special slag) also showed some damage but not beyond the unacceptable limit due to summer healing. Note that both of these mixtures had the higher w/b ratios and were non-air entrained. In all 22 concrete mixtures, the most severe deterioration occurred during the first winter (measured in June 2002 after placement in December 2001), followed by summer healing. The healing was significant, as expected, since all of the mixtures contained secondary binder materials that benefit from prolonged curing time to gain strength through further hydration.

The results after two winters of exposure showed heavy surface and internal cracking in both mixtures C3 and C6. The cracking did not show typical frost cracking, which would be cracks running parallel to the outer surface. Upon internal evaluation, it was seen that the cracks mainly ran along the bond areas of aggregate particles and in paste connecting the aggregates. No scaling was detected, but there was a high water uptake. A good correlation was found between the field and laboratory tests in this case (see Table 9). All the results can be found in CONLIFE deliverable reports [5].

Field measurements of the CONLIFE-concretes in Finland will continue and the next measurement time is scheduled for spring 2009. It will be interesting to see the future field performance as there were several mixes that performed poorly and failed during the lab testing; e.g. RDM % after 112 cycles with plain water or after 56 cycles with NaCl-solution (See Table 9).

Table 9 - CONLIFE-project. Laboratory testing results for freeze-thaw (112 cycles) and also frost-salt testing (56 cycles), though there is no field testing for frost-salt.

	Plain water (112 cycles)			NaCl solution (56 cycles)			
Mix	Scaling [kg/m²]	RDM by ultra-sound $100\,(t_0/t_n)^2$ [%]	Moisture Uptake [kg/m²]	Scaling [kg/m²]	RDM by funda-mental frequency $(f_n/f_0)^2$ 100 [%]	RDM by ultra-sound $100\,(t_0/t_n)^2$ [%]	Moisture Uptake [kg/m²]
C21	0.004	51	1.353	0.067	- 1)	130	1.763
C22x	0.010	106	0.163	0.054	-	104	0.657
C8	0.003	64	1.263	0.056	-	131	1.530
C1	0.014	53	1.848	0.138	10	-	1.975
C9	0.012	6	1.723	0.054	-	132	1.607
C2	0.016	38	2.250	0.520	2	-	2.415
C10x	0.006	107	0.140	0.061	-	101	1.113
C3	0.037	14	2.438	1.568	2	-	2.830
C11x	0.012	48	1.380	0.137	-	104	1.340
C4	0.027	29	2.410	0.043	94	-	0.765
C5	0.023	35	2.238	0.075	96	-	0.588
C6	0.032	50	1.883	1.013	2	-	2.343
C7x	0.005	92	1.190	0.165	102	-	0.410
C12	0.008	112	0.558	0.483	4	-	2.503
C13	0.013	113	0.565	0.718	2	-	2.625
C14	0.016	32	2.243	1.000	2	-	2.768
C15x	0.007	106	0.708	0.193	77	-	1.025
C16x	0.010	109	0.830	0.133	94	-	0.735
C17x	0.008	108	1.103	0.293	68	-	1.278
C18x	0.006	99	0.223	0.118	100	-	0.315
C19x	0.015	104	0.448	0.100	95	-	0.620
C20x	0.012	85	1.733	0.255	15	-	1.690

1). Frost-salt measurements of internal damage were by either fundamental frequency or ultrasound. Non-measured specimens are marked with a dash (-).

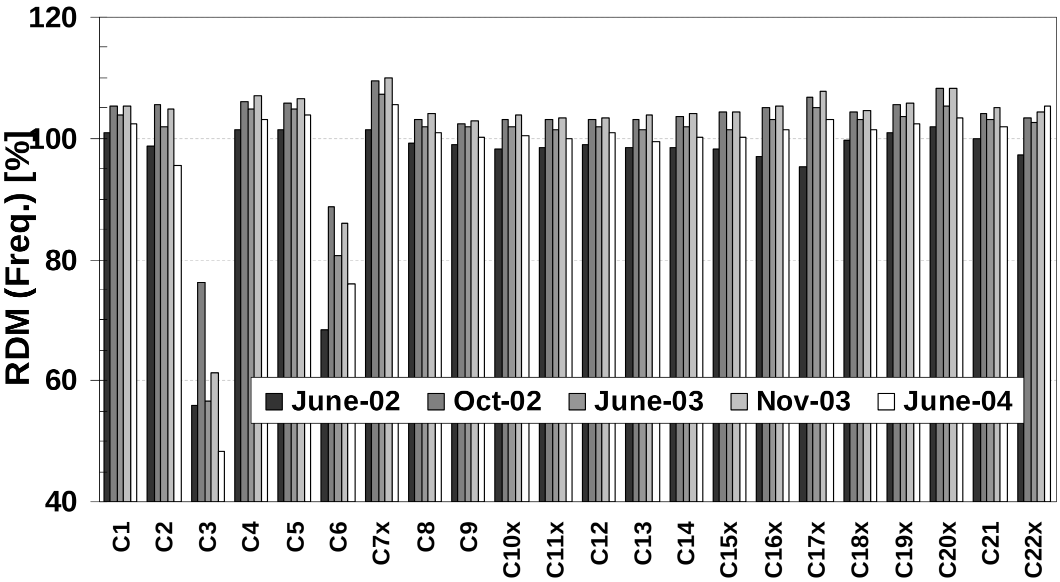

Figure 7 – CONLIFE-project. Internal damage measured by frequency after 2 winters, at Sodankylä field station. Severe damage noticed for C3 (w/b=0.42, 7% SF) and C6 (w/b=0.42, 7% *special slag). [5] See Table 3 for mix information and Table 8 for laboratory testing results.*

YMPBETONI

Almost all the tested concrete grades displayed excellent frost resistance properties in the slab test after 56 cycles, with respect to both surface weathering (0.008 – 0.019 kg/m^2, average 0.013 kg/m^2) and internal damage (RDM = 95.2 – 101.7 %, average 98.6 %). No mixtures came close to the critical acceptance levels for frost damage. This was somewhat as expected, since all the mixtures were air entrained.

The field tests conducted over one winter season showed also very little surface and internal damage in the tested concrete grades. A trend was seen that the more fly ash or slag that was included, the more damage was detected. Heat treatment of samples during initial curing slightly improved the results (Figure 8). The first winter encompassed approximately 50 freeze-thaw cycles (south 52; north 43). Again a cycle was defined in this project as an exterior air temperature change, rising over +1 ^{o}C followed by dropping below -1 ^{o}C. At the southern station in Otaniemi, the weather is moister than in the northern Sodankylä location. At the same time temperature is changing in Otaniemi more frequently around 0 ^{o}C, while in Sodankylä the temperature typically stays clearly below zero during the winter and the cycles are concentrated in late autumn and early spring. Some healing was noticed during the summer, which was detected as an increase in the RDM-value. Field testing results after the first winter and summer (2003-04) are presented in Figures 8 and 9. [1, 6, 7, 8] Field testing will continue and the next measurement is scheduled for spring 2009.

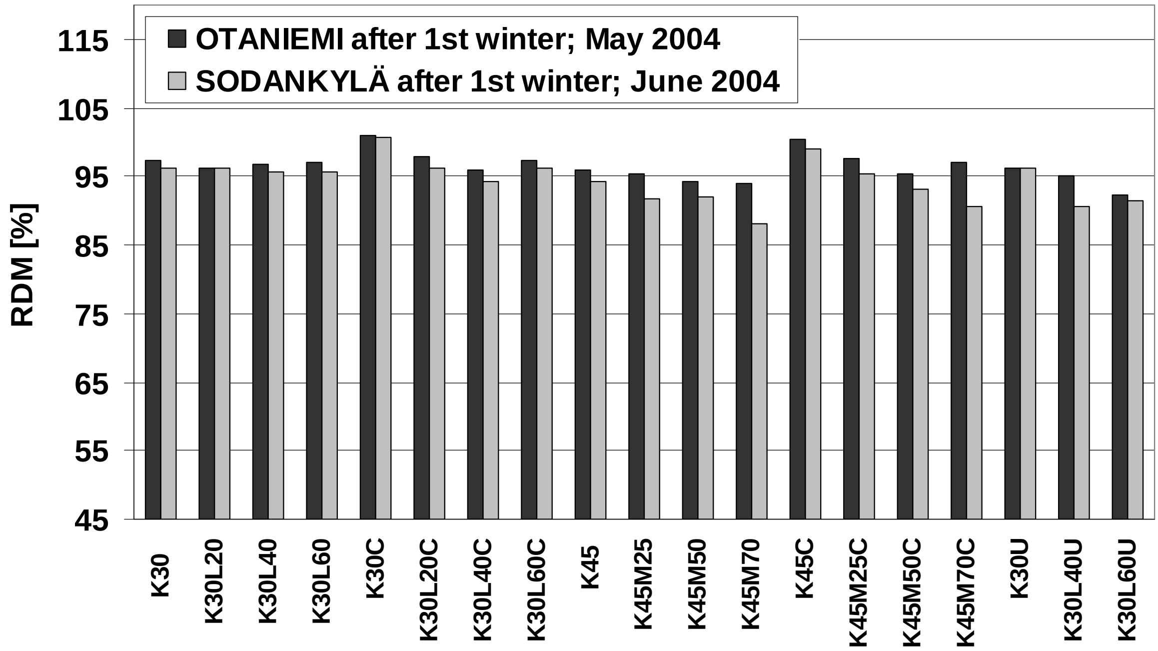

Figure 8 - YMPBETONI. Field testing results for frost deterioration (internal) after 1st winter period at southern (Otaniemi) and northern (Sodankylä) Finland.) K means reference (only CEM II); L means FA; M means BFS; C means heat treatment; U means new casting. [1, 6]

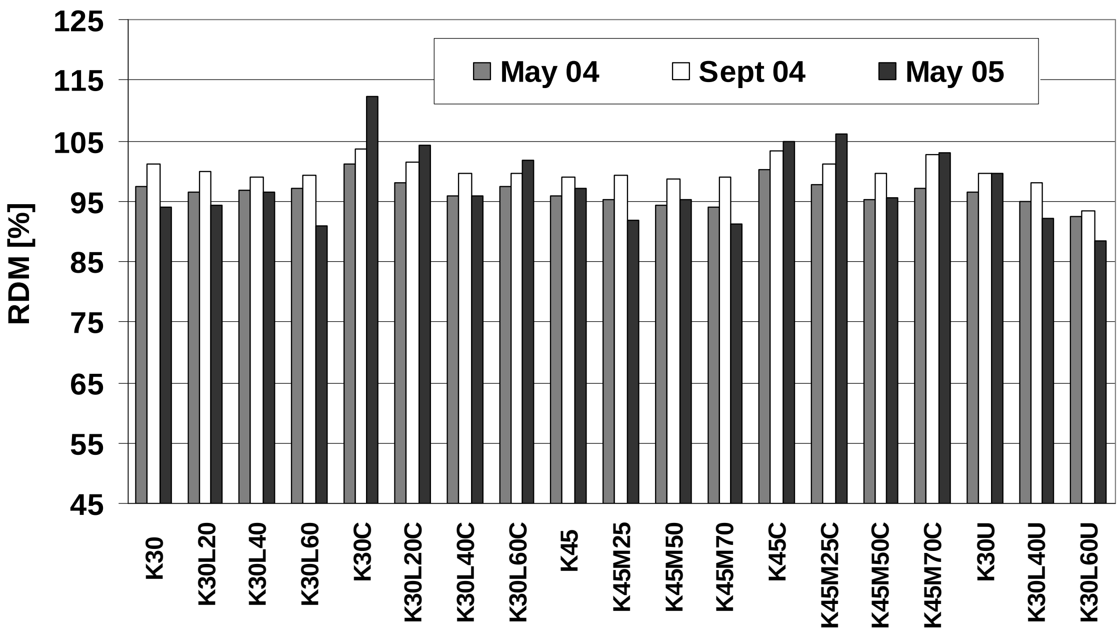

Figure 9 - YMPBETONI. Field testing results for frost deterioration (internal) after 1st winter period, first summer period and 2nd winter period in southern Finland (Otaniemi, Espoo). Healing or strength gain after 1st summer period can be seen (measurement Sept. 04). K means reference (only CEM II); L means FA; M means BFS; C means heat treatment; U means new casting. [1, 6]

3.4 Freeze-thaw with de-icing salts - XF4

General

Field testing for freeze-thaw with salt exposure in Finland corresponds XF4, i.e. high water saturation with de-icing agent. This was only evaluated at a field station in the newest DuraInt project. Evaluation of frost-salt resistance in field tests of the CONLIFE project mixtures were evaluated by other partners in Sweden, Germany and Italy and are therefore not included in the scope of this paper. The test results for CONLIFE are reported in [5].

In the DuraInt project, information on the amount of de-icing salt spread every winter period is collected. The project also includes weather data collection and measurements of concrete temperature, relative humidity and water content at different season periods. Optical fibres are used to measure the concrete temperature and water content profiles. Frost-salt deterioration is followed by measuring volume change of 75x75x150x mm^3 specimen. Internal deterioration is also measured in the same was as or the freeze-thaw specimen without de-icing salts (see above chapter 3.3). Microstructural alteration will be studied in the future as needed to supplement other results.

The so called Slab test is used here for scaling with salt solution (CEN/TS 12390-9) [22]. Internal damage is also measured by ultrasound (CEN/TC 51 N 772 (2003)) [21].

Results

Laboratory and field testing results to date are presented in Table 10. After the first and very mild winter period of 2007-08, no visible scaling or cracking was detected. Perhaps the only possible sign of deterioration was a small volume increase in the poor quality concretes, meaning those with inadequate air entrainment. This volume increase had some correlation with lab testing results, i.e. scaling in the slab test after 56 cycles (see Table 10).

The field specimen for frost-salt damage will be measured again in spring 2009. In the future at least the mixes with inadequate or poor air entrainment are expected to show signs of damage at the field station along Highway 7. One series, mixtures 3Ba – Bi (10 mixes with the same cement, CEM II/A-M(S-LL) 42.5 N,) was specifically designed for studying the effect of air content and air pore quality on salt-frost deterioration and thus interesting and informative results are expected. So far laboratory results demonstrate the importance of proper air entrainment in normal bridge concretes with w/c 0.42 (see Table 10).

Table 10 – DuraInt-project. Results after 1 year for freeze-thaw with de-icing salts. Slab test results and field testing results after the first winter period 2007 – 08.

	Laboratory testing				Field testing		
	Thin sections		Slab test 56 cycles		Internal deterioration		Volume change (+ is grow) [%]
Short code	Air pores. specific surface < 0.800 mm pores [mm^2/mm^3]	Air pores. spacing factor (< 0.800 mm pores) [mm]	Scaling [kg/m^2]	RDM by ultrasound 100 $(t_0/t_n)^2$ [%]	RDM by ultrasound 100 $(t_0/t_n)^2$ [%]	RDM by fundamental frequency 100 $(f_n/f_0)^2$ [%]	Volume change (+ is grow) [%]
					spring 08	spring 08	spring 08
1A	21	0.46	0.195	104	102.5	102.2	0.20
2A	16	0.35	0.045	110	102.3	102.0	0.26
3A	21	0.28	0.202	107	102.0	101.3	0.42
5A	28	0.24	0.205	109	104.2	101.7	0.31
6A	34	0.33	0.075	104	105.5	101.4	0.18
7A	37	0.18	0.320	99	101.6	101.3	0.27
8A	27	0.30	0.158	105	102.5	101.4	0.40
3Ba	14 (no air entr.)	1.15	3.500 1)	<86, no value, too much scaling	101.9	101.9	0.59
3Bb	23	0.51	1.750 1)	no value, too much scaling	102.1	101.6	0.73
3Bc	22	0.38	0.840 1)	no value, too much scaling	102.1	101.9	0.50
3Bc2	19	0.30	0.096	103	103.2	102.0	0.30
3Bd-SCC1	11 (no air entr.)	0.69	1.400 1)	no value, too much scaling	103.1	101.9	0.55
3Be-SCC2	12	0.34	0.128	99	103.9	102.8	0.54
1C	27	0.22	0.039	102	101.9	100.1	0.13
3C	21	0.28	0.084	103	100.8	101.2	0.34
5C	13	0.51	0.636	105	101.8	99.3	0.35
6C	23	0.29	0.390	101	101.0	100.1	0.38
3Bf	12 (no air entr.)	0.98	2.740 1)	<70, no value, too much scaling	to field testing spring 2008, no results so far		
3Bg	23	0.41	0.496	101			
3Bh	24	0.31	0.236	105			
3Bi	16	0.44	0.305	104			

1) This value is an extrapolation. Last measurement was after 42 cycles. The test was interrupted because of too much scaling causing leakage.

4 INTEGRATED DEGRADATION AND SERVICE LIFE MODELS

4.1 Principles

Structures exposed to outdoor climate are usually subject to several types of degradation mechanisms simultaneously. If, for example, a concrete structure is exposed to normal Nordic climate, it is inevitably attacked by both carbonation and frost. The single degradation mechanisms, such as carbonation, chloride penetration and frost attack, are relatively well understood. There are also fairly good models for such degradation when treated separately. However, the interaction of these mechanisms is not well understood and there are hardly any models for such combined effects. However, to be able to evaluate the service life of concrete structures understanding on combined effects of degradation mechanisms is necessary. Laboratory testing is needed to get data and verify deterioration models with interaction. [4]

Figure 10 shows a general scheme for the development of integrated degradation models. The process starts from tests in the laboratory and in the field. Laboratory tests are conducted both as 'single' and as 'coupled'. Based on these laboratory tests and theoretical/analytic reasoning, degradation models for 'single' and 'coupled' degradation mechanisms are developed.

As a first step in the theoretical reasoning process, simple time-related model functions on degradation are developed. As a second step computer simulation can be used for profound understanding of the combined effects of degradation. In computer simulation the 'first step' model functions are used but as differential approximations. That means that the changes in temperature and moisture conditions and the effects of other degradation mechanisms can be re-evaluated in every time step (typically 1 hour) according to the real situation in climatic conditions (local meteorological data) and the real progress of other degradation mechanisms. Computer simulation in this case refers to the following:

1. theoretical emulation of ambient climatic conditions,
2. determination of the temperature and moisture variations in a cross-section of a concrete structure, and
3. application of temperature and moisture sensitive degradation models so that the degradation over time and the service life can be predicted.

Computer simulation must be calibrated with tests results from both the laboratory and field. Calibration means that the simulation results of degradation are made fit with the experimental test results by changing the parameters of simulation models.

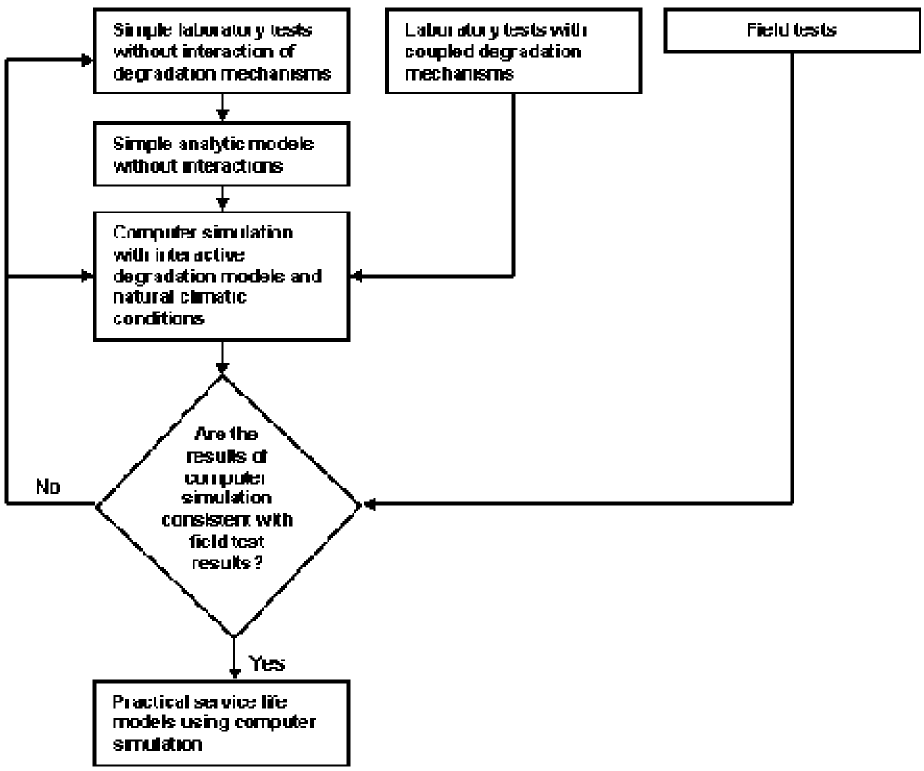

Figure 10 - Development of integrated degradation and service life models. [4]

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4.2 Analytic models

Carbonation

Depth of carbonation is approximately proportional to the square root of time. The theoretical reasoning is not presented here; see [4].

$$X_{Carb} = k_{Carb}\sqrt{t}\ , \tag{1}$$

where k_{Carb} is coefficient of carbonation [$mm/\sqrt{a}$].

The values of coefficient of carbonation can be found experimentally.

Chloride penetration

The depth of the critical chloride content also approximately complies with the 'square-root-of-time' relationship in the same way as the depth of carbonation [4]:

$$X_{Cl} = k_{cl*}\sqrt{t}\ , \tag{2}$$

where k_{cl*} is coefficient of chloride penetration [$mm/\sqrt{a}$], and
t is time [a].

The Bazant-simplification offers a mathematically easy way to treat the problem of chloride ingress. The coefficient of chloride penetration depends on the type of cement and it can be found experimentally. From Equations (1) and (2) follows that in both cases the following differential equation can be applied (Fagerlund, 1994 [4]):

$$\Delta X_c \approx \frac{1}{2}\cdot k_c \cdot t^{-\frac{1}{2}} \cdot \Delta t = \frac{1}{2}\cdot \frac{k_c^2}{X_c}\cdot \Delta t\ , \tag{3}$$

where X_c is depassivative depth (either carbonation depth or the depth of critical chloride content) [mm], and
k_c is coefficient of depassivation (either carbonation or the chloride penetration) [$mm/\sqrt{a}$], and
t is time [a].

Both the carbonation depth and the depth of critical chloride content can be also modelled with two parameters as follows:

$$X(t) = A \cdot t^B\ , \tag{4}$$

where X is the depth of carbonation or critical chloride content [mm], and
A, B are parameters depending on the climatic conditions, material properties and possible structural measures.

In that case the differential approximation during Δt would be:

$$\Delta X_c \approx B \cdot A \cdot t^{B-1}\Delta t = B \cdot A^{\frac{1}{B}} X^{1-\frac{1}{B}} \cdot \Delta t\ , \tag{5}$$

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Frost attack and frost-salt scaling
Modelling principles for frost attack and salt-frost scaling are presented e.g. in [4] and they are not presented here.

Frost attack is caused by freezing of water inside concrete. To model frost damage, the number of critical freezing events, degree of water saturation in natural weathering conditions and degree of degradation must be specified. The service life is ended when the degree of damage reaches the maximum allowable value (e.g. 30 %).

Frost-salt scaling is caused by freezing on a concrete surface when it is in contact with a chloride solution. The depth of scaling is related to the number of freeze-thaw cycles in the surface of concrete. An accelerating rate of scaling is usually a sign of poor frost resistance of concrete. A retarding scaling rate is a sign of inferior quality of concrete on the surface compared to the quality inside. In homogeneous concrete an even scaling rate is expected.

Service life based on frost-salt scaling
A simple formula was developed for predicting service life based on frost-salt scaling [13] (Vesikari, 1991). It separates the material factors from environmental factors. All material factors are incorporated in the P-value:

$$\mu(t_L) = k_e \cdot P, \tag{6}$$

where $\mu(t_L)$ is the service life [a],
k_e is the circumstantial factor [-], and
P is P-value [-].

According to the Finnish concrete code, service life can be determined using the following values of circumstantial factor [11] (BY50 2004):

$$XF2: \quad k_e = 2$$
$$XF4: \quad k_e = 1.25$$

P-value is determined from the following equations [11, 18]:

$$P = \frac{46 \cdot c_{cur} \cdot c_b}{\frac{10 \cdot (WAB)^{1.2}}{\sqrt{a}} - 1}, \tag{7}$$

$$c_{cur} = 0.85 + 0.17 \cdot LOG_{10}(t_{cur}), \tag{8}$$

$$c_b = 1 - \left(\frac{Q_{h2o}}{Q_b}\right)^{1.5} \cdot (0.05 \cdot SF + 0.02 \cdot BFS + 0.01 \cdot FA), \tag{9}$$

$$Q_b = Q_{cem} + 2.0 \cdot Q_{sf} + 0.8 \cdot Q_{bfs} + 0.4 \cdot Q_{fa}, \tag{10}$$

$$WAB = \frac{Q_{h2o} + 10 \cdot (a-2)}{Q_b}, \tag{11}$$

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where P is P-value [-],
c_{cur} is the curing factor [-],
c_b is the binding factor [-],
WAB is the reduced water-air-binder ratio [-],
a is the air content [%],
t_{cur} is the curing time [d],
Q_{h2o} is the effective water content [kg/m^3],
Q_b is the total amount of effective binding material [kg/m^3],
SF is the silica fume ratio [%],
BFS is the blast-furnace slag ratio [%],
FA is the fly ash ratio [%],
Q_{cem} is the cement content [kg/m^3],
Q_{sf} is the silica fume content [kg/m^3],
Q_{bfs} is the blast-furnace slag content [kg/m^3], and
Q_{fa} is the fly ash content [kg/m^3].

The model is mainly based on empirical results and rests on the above mentioned concrete technological parameters known to affect frost durability. It is also used by the Finnish Road Authorities to predict service life [18] (Finnish Road Administration, 2008).

4.3 Future service life models with 'interaction parameters'

Computer simulation offers a possibility to better manage the effects of constantly changing climatic conditions and simultaneous degradation processes. Computer simulation utilizes theoretical/analytic degradation models. However they are applied as differential approximations in order to take into account the momentary condition and exposure stresses and the momentary progress of various degradation mechanisms in the structure.

There are theoretical methods of coupling degradation mechanisms. Examples of interaction include influences such as frost action likely accelerating the processes of carbonation and chloride penetration in concrete by increasing the permeability of concrete. Also frost-salt attack likely accelerates the penetration of carbonation or critical chloride content by removing material from the surface of concrete. [4]

4.4 Service life models in the Finnish national codes

Simple models
The Finnish national codes presents simple models for service life design of concrete structures based on carbonation and frost attack [11]. The design life span is calculated by Equation (12):

$$t_L = t_{Lr} \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G, \tag{12}$$

where t_L is design life span [a],
t_{Lr} is comparison life span of 50 years [a], and
A to G are coefficients taking into consideration all of the variables affecting the design life span.

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The design parameters affecting the life span with respect to frost attack are presented in Table 11.

Table 11 - Coefficients affecting the freeze-thaw life span of a concrete structure.

Coefficient	Affecting feature	Design parameters
A	Material properties, porosity	Water-cement ratio, air content
B	Design, structural features	Structural member, possible surface treatment
C	Workmanship	Curing measures
D	Internal climate	-
E	External climate	Freeze-thaw class, geographical direction and location
F	Design loads	-
G	Maintenance	Inspection and service sequence

Every coefficient, A to G, can be determined from a respective table. As an example the first coefficient A can be selected as a function of the maximum aggregate size and concrete air content measured from fresh concrete.

In the case of life span assessment for carbonation, a similar formula as Eq. (12) is used and the coefficients A to G are obtained in a similar manner.

The service life design according to the Finnish national codes so far does not present any model for structures in a chloride environment and the interaction between degradation modes is not considered satisfactorily. In DuraInt-project these matters are under development.

Computer simulation in specification of factors of service life

After calibration with field and laboratory tests, computer simulation can be used for quantification of factors in the service life models with respect to various degradation mechanisms. Considering the models in the Finnish national codes (Eq. (12)), the simulation method is especially suitable for quantification of factors A, B, D and E.

The simulation program of VTT allows a possibility for easy quantification of the environmental factor E. The climatic data have been gathered from different observation sites so that the factors for coastal Finland, Middle Finland and Northern Finland can be determined using actual weather parameters in these regions. The weather models are based on the data gathered by the Finnish Meteorological Institute and they consist of data on temperature, relative humidity, velocity and direction of wind, amount of rain and intensity of solar radiation.

The effects of other degradation modes on the service life can be studied using the interaction parameters in the degradation models. As the service life can be determined with and without parallel degradation modes the “interaction factors” can be determined.

The incremental time in the computer simulation is normally one hour. The total calculation may cover some months, some years or even some hundreds of years from the lifetime of the structure although the time of calculation by itself takes only some hours.

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5.0 CONCLUSIONS

Over the past 10 years, two major projects have been completed in Finland and a third is underway where field stations have been established to obtain real-time data on concrete durability. Three field stations exist and have numerous samples under evaluation: two for frost resistance both in southern and northern Finland, one for frost-salt attack and chloride exposure, and all three stations can include carbonation evaluation. The goal of the projects has been to evaluate the correlations between laboratory and field testing, with the aim of improving the service life modelling of concrete.

The tested concretes have included a range of mixture designs and binding materials, including blast furnace slag, fly ash and silica fume. Both air entrained and non-air entrained mixtures have been tested in the lab and exposed in field studies in hopes of seeing a wide range of durability performance. Additional concrete will still be produced in the current DuraInt project, which is scheduled to be completed in 2011.

The results obtained in these projects will be summarized and maintained in a public database, to be used for future durability modelling and improvement of service life prediction codes. The existing Finnish codes for service life account for carbonation and frost attack, yet more data will help improve the models. It is important in future development to account for the interaction of durability factors like frost, carbonation, and chloride, which is the main goal of the newest DuraInt project. The existing Finnish codes do not account for concretes subjected to chloride and therefore need improvement.

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