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Concrete performance subject to coupled deterioration in cold environments

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ABSTRACT

The design of concrete durability is normally based on the assessment of its performance when subject to a single deterioration mechanism. In reality, concrete structures are subject to varying environmental exposure conditions which often results in multi-deterioration mechanisms occurring. The Nordic climate, with cold harsh winters, poses a severe challenge to the long-term durability of concrete. The most common deterioration mechanisms are freeze-thaw damage, carbonation and chloride induced corrosion. Research is now more focused on the assessment of coupled deterioration mechanisms. For instance, evaluating how cracks resulting from freeze-thaw influence chloride ingress, or how carbonation changes the surface properties and thereby influencing freeze-thaw scaling and chloride penetration.

This paper presents the results of research projects at VTT focusing on coupling deterioration mechanisms. These research projects have built on several decades of concrete durability research at VTT, including 15 years of field station studies. The durability of the concretes has been assessed using both accelerated laboratory testing and also from in situ exposure results from field stations. This research has contributed to the development of concrete performance models and service life tools, supporting a holistic approach for deterioration assessment.

1. Introduction

The design tools available for predicting the lifetime of concrete materials are typically based on a single driving force for deterioration, such as freeze-thaw induced scaling due to de-icing salts or concrete cracking due to chloride ingress induced reinforcement corrosion. Accelerated laboratory tests are used to characterise the individual deterioration mechanisms and correlate the results with in-situ performance of structures. In reality, existing structures are subjected to numerous and simultaneous forms of deterioration. Thus laboratory simulations and deterioration predictions should take into account these multiple, interacted deterioration parameters when modelling service life.

The effect of binding material must be considered when studying the interacted deterioration of concrete. Multi-deterioration mechanisms are complicated and there is little knowledge on the real performance of concrete subject to such complex deterioration mechanisms. There are no widely accepted rules or service life models to take this into account, for instance the effect of surface carbonation and drying on the scaling caused by freeze-thaw with de-icing salt. Still it is already well known that concrete surface properties will vary according to the binding materials and cement types when exposed to e.g. atmospheric carbon dioxide and drying at dry microclimate. Recent research in Finland on multi-deterioration mechanisms of concrete included also the effect of the binding material when reasonable or possible. In the future the effect of binding materials will be a subject for the further studies.

Recent research at VTT has been undertaken with the overall objective to evaluate the effect of interacted deterioration mechanisms on the service life of concrete structures – DuraInt (Deterioration Parameters on Service Life of Concrete Structures in Cold Environments, 2007–11) and CSLA (Concrete Service Life Assessment, 2012–2015) (Leivo et al., 2011a; Ferreira et al., 2012). Typically, concrete research has focused on both field and laboratory studies. This paper presents aspect of the research performed in the laboratory using natural and accelerated testing procedures and looking at the interacted deterioration of freeze-thaw, carbonation and chloride ingress. The effect of concrete mix design, including the binding material type, is also included in some of the studies.

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2. Laboratory studies on the multi-deterioration mechanisms

2.1. Materials

Table 1 presents the basic information on the cements, additions and admixtures used in the laboratory studies on multi-deterioration mechanism. Acronyms used for labelling mixes are presented. Cements, blast furnace slag (BFS) and fly ash (FA) were provided by Finnsementti Oy. The aggregates were good quality Finnish granitic aggregates with water absorption <0.5%. The effective water/binder content (w/b_{eff}) was used for the w/b calculation, i.e. water absorbed by the aggregate particles was not included. (Leivo et al., 2011b; Holt and Leivo, 2011; Ferreira et al., 2014a).

2.2. Concrete mix design

Water-binder ratios (w/b) varied between 0.42 and 0.60. The effective w/b ratio was calculated by:

$$w/b_{eff} = w/(\text{Cement} + 2 \times \text{SF} + 0.8 \times \text{BFS} + 0.4 \times \text{FA}) \tag{1}$$

The binder factors given in the above equation are provided in the SFS 7002 (2011), which describes the application of SFS-EN 206-1 (2005) in Finland. The number of concrete mixtures was altogether about 40. Table 2 presents the concrete mix design ranges for the different multi-deterioration studies covered. Table 3 presents the concrete mix design. The concretes were air entrained bridge concretes representing Finnish practice, or concretes with relatively high w/b, and in some cases also with inadequate air entrainment, to make the deterioration faster. In some cases, mortars were prepared for the studies. Air content varied from 2% (no air entrainment) to 6%. When BFS was use, the content was 50% of the binding material. For FA the content considered was 24%.

Compressive strengths (28 days) varied from 27 MPa to 67 MPa. Detailed information on the mixes for the different multi-deterioration studies can be found in (Leivo et al., 2011a,b; Ferreira et al., 2014a,b). Here the mix design short code gives the most basic information on the concrete composition, e.g. "SR-BFS-06-A5" means that the binding material is composed of cement SR and BFS (see Table 1), w/b is 0.60, and air content is 5%.

Table 2
Concrete mix design range for the multi-deterioration studies.

Multi-deterioration study	Mix design range	
	w/b	Binding materials (see Table 1)
Effect of freeze-thaw cracking on carbonation	0.50 and 0.63	Y
Effect of freeze-thaw on chloride penetration: – Effect of freeze-thaw cracking – Effects without cracking	0.50 and 0.63 0.42 and 0.55	Y SR
Effect of varying surface ageing on freeze-thaw scaling with salt	0.40–0.51 (mostly 0.42)	All

3. Multi-deterioration studies, testing methods and results

3.1. Effect of freeze-thaw cracking on carbonation

The aim was to understand how internal freeze–thaw damage and surface cracking affects carbonation. For this study, different degrees of internal damage were achieved with the CEN/TR 15177:2006 slab test method. The amount of freeze–thaw cycles for each specimen was selected so that the different degrees of internal deterioration, as determined by the relative dynamic modulus of elasticity (RDM) by using ultrasonic pulse transit time, was introduced. Two specimens for each concrete were removed from the freeze-thaw test at each of the RDM levels ~95%, 80%, 65%, 50% and 35% and dried at RH65% until constant weight (change in weight < 0.2%/24 h period). At the same time one reference specimen with water on top was also moved to drying. This was followed by carbonation at 1% CO2 for 56 day. Carbonation depths were measured according to EN 13295: 2004. Some thin sections were also prepared to observe the effect of the freeze–thaw deterioration on the near surface cracking and the carbonation.

The results revealed some correlation (R2 = 0.60) between the RDM and carbonation degree, as determined after the freeze–thaw testing for the mixes with high enough w/b concrete (Y-066-A0.8). As the RDM decreased from 80% to 30%, the depth of carbonated concrete increased from 3.5 mm to about 5.5 mm. The cause of this increased penetration can be attributed to surface cracking associated with the increase in internal deterioration due to freeze–thaw, as observed by thin section microscopy. For the concrete Y-050-A1.0 no effect of internal freeze-thaw deterioration on carbonation was detected, as the deterioration degree was determined by RDM. It was concluded that internal freeze-thaw deterioration will have a limited effect on carbonation, and is related to the possible surface cracking degree and type. Cracking parallel to the surface may not have a big effect on the carbonation. It can be expected that the meaning of binding material in multi-deterioration by freeze-thaw and carbonation will be the same as in the case on carbonation only. More studies are needed for reliable service life modelling with this multi-deterioration type. (Leivo et al., 2011b; Kuosa et al., 2014)

3.2. Effect of freeze-thaw on chloride penetration. Effect of freeze-thaw cracking

The aim was to understand the effect of freeze–thaw deterioration on the chloride ingress. Concretes and mortars with little or no air entrainment (Y-050-A1.0, Y-051-A2.7, Y-050-A1.3 and Y-065-A0.8) were prepared for this multi-deterioration study. Freeze–thaw damage was created by using the CEN/TR 15177:2006 slab test method. Different degrees of internal deterioration (RDM)

Table 1
Cements, additions and admixtures.

Acronym	Cement/addition/admixture type	Description	Blaine [m^2/kg]	Other information
SR	CEM I 42,5N–SR3	Sulphate resistant cement	330	Limestone 1%
R	CEM I 52,5 R	High strength cement	440	BFS 1%; Limestone 6%
Y	CEM II/A–M(S–LL) 42.5 N	Ordinary cement	410	BFS 7%; Limestone 6%
PIKA	CEM II/A-LL 42.5 R	Rapid hardening cement	530	Limestone 2%
P	CEM II/B-S 42.5 N	Blended cement	380	BFS 27%; Limestone 2%
BFS	Blast Furnace Slag	BFS KJ400	400	Limestone 2%
FA	Fly Ash	Fineness N, Class A	ca. 250	Complies with the demands in EN 450-1: 2005
G	Glenium G 51	Superplasticizer	–	Modified polycarboxylic ether
IP/AM	Ilma-Parmix/Airmix	Air entraining admixture	–	Fatty acid soap/synthetic tensides