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Concrete Durability Based on Coupled Laboratory Deterioration by Frost, Carbonation and Chloride

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ABSTRACT

Concrete performance is typically based on deterioration caused by one mechanism alone. The service life of a structure is linked to reaching limit states that are estimated from models based of laboratory data. Accelerated laboratory tests are conducted as independent studies of performance, such as single assessments of frost, frost-salt, chloride ingress or carbonation induced corrosion acting alone. Yet in real field performance, concrete is actually being affected by simultaneous environmental and conditional exposures. This paper presents a new approach to evaluating durability: by coupling deterioration mechanisms within laboratory testing to more accurately predict long-term performance.

Key words: durability, frost, frost-salt, carbonation, chloride, service life, field stations

1. INTRODUCTION

When durability of concrete is evaluated, many types of exposure or attack may be considered to influence the structural performance. Yet tools for predicting the lifetime of concrete materials are typically based on one driving force of the deterioration, such as spalling due to de-icer salt with frost exposure or cracking caused by chloride ingress and subsequent reinforcement corrosion. Accelerated laboratory tests are used to test these individual deterioration mechanisms and correlate the results to real-time performance of structures. In reality, existing structures are subjected to numerous and sometimes simultaneous forms of deterioration in their relative environments. Thus laboratory simulations and deterioration predictions should take into account these multiple, interacted deterioration parameters when modelling service life.

A three year Finnish research project has recently been completed investigating deterioration when concrete is subjected to multiple attacks. For instance, evaluating how cracks resulting from frost attack influence chloride ingress, or how carbonation changes the surface properties and thus may affect frost-salt scaling. The project builds on 30+ years of concrete durability research, including 10 years of field station studies. The latest project's laboratory program has been based on standardized test methods, taking into account the affects of ageing and repeated exposure cycles to different conditions as well as field studies [1]. The final stage of the project addressed improving service life prediction tools based on the laboratory coupled deterioration results [2]. The project results have quantitatively supported the hypothesis that a holistic approach should be taken to predicting deterioration.

2. MIX DESIGN AND TEST PROGRAM

About 30 different normal strength concrete mixtures have been evaluated with coupled deterioration attack with a range of cementitious binders and air contents. The mix designs were chosen to represent prevailing ready-mix and pre-cast production. Common Finnish cements, blast furnace slag (BFS) and fly ash (FA) were used along with Glenium superplasticizer and Ilma-Parmix air entrainment. The compressive strengths were up to 60 MPa and the effective water-to-binder ratio ranged from 0.40 to 0.60. Some concretes were intentionally produced with no or only inadequate air entrainment, to allow for more rapid deterioration and thus modelling a range of behaviours. Full details of the mixture designs are detailed within the project reports and public database. The coupled deterioration testing has included the following combinations:

1) carbonation and frost (effect on water ingress and internal damage),
2) carbonation and frost-salt (effects on scaling),
3) carbonation and chloride (effects on corrosion),
4) frost and chloride (effects of internal cracking on chloride penetration).

In the first two cases of carbonation and frost, testing was done on newer samples as well as ones aged one year and dried at 65% RH, with our without surface carbonation. In the first three of the four series, the reverse order of testing was also done, for instance either carbonation followed by frost, or then first frost followed by carbonation, as shown above. Frost and frost-salt was tested for at least 56 cycles using the Borås slab test (CEN/TC 51 N 722) to assess internal damage and surface scaling. Accelerated carbonation was tested at both 1% and 4% CO_2 compared to normal (non-accelerated) carbonation at 60% RH and 20°C and the field. The chloride diffusion was measured with the CTH method (NT Build 492) at various ages as well as using chloride profiling of field samples by grinding. Carbonation depth was measured using phenolphthalein indicator solution (EN 13295) In some cases, it was possible to subject the samples to repeated cycles of the same two attack types, for instance carbonation and frost attack, followed by additional round(s) of carbonation and frost exposure in lab conditions. Microscopic studies and real-time exposure at field stations have supplemented the lab results.

3. RESULTS

The selected project results reported here are focused on examples of the influence on durability when replacing cement with by-products of fly as or blast furnace slag, for both individual and combined deterioration attack. Investigations of interacted deterioration caused by frost-salt combined with carbonation have shown the influence of the surface layer and pore structure properties when assessing scaling, or vice-versa. These tests were done on reference samples were aged for 1 year, dried and then the sample surface layers were cut away (any possible carbonated layers removed) before exposure to 56 cycles of the slab test with NaCl solution. The second series of combined deterioration had atmospheric exposure to carbonation for one year (65% RH storage), followed by the same frost-salt test.

An example of how the mix design and mineral admixtures affect coupled durability performance is shown in Figure 1. These results are for mixtures with either 50% slag or 24% fly ash (w/b_{eff}=0.42 and 5% air). For single deterioration exposure of frost alone, both mixtures containing by-products had less damage than the reference mix. Yet when exposed to coupled attack of carbonation with frost, the performance of the fly ash mixture was worse than the reference and slag mixtures. This indicates that the pore structure of the fly-ash containing mixtures was detrimentally altered due to carbonation and/or the 1 year of drying at 65% RH, and thus showed worse durability performance. When examining the same test series with respect to internal damage during the frost-salt test, there was no significant damage or variation in the mixtures with or without the carbonation exposure.

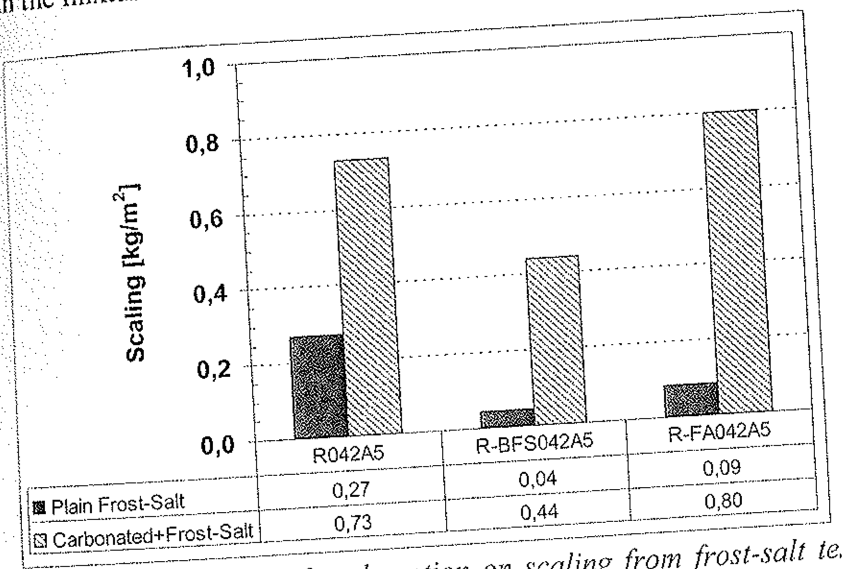
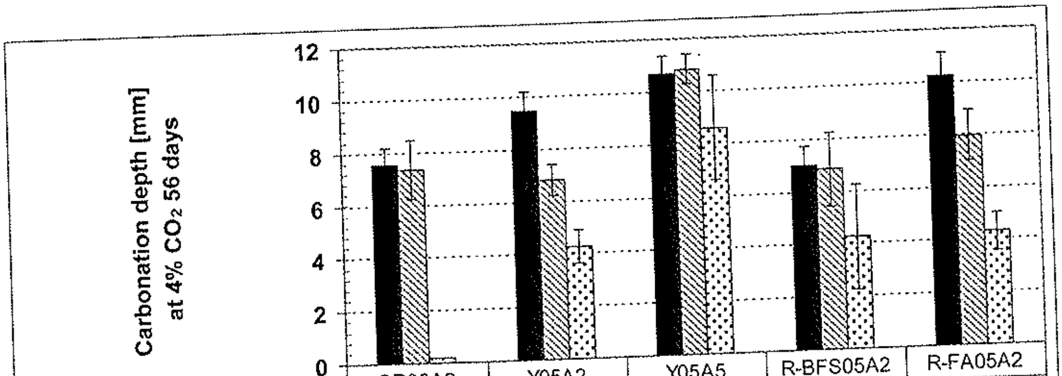


Figure 1 - Influence of carbonation on scaling from frost-salt testing, for reference mix with Rapid cement (R) compared to mixtures with 50% slag (BFS) or 24% fly ash (FA) mixtures.

In another test series of combining chloride attack with carbonation in the interacted durability study, the goal was to see what influence the surface and pore structure properties have on the carbonation. In this series of tests, the pore structure and thus surface layer properties were altered by exposing the samples to a rapid chloride migration test prior to strong carbonation exposure of 4% CO_2 for 56 days. An example of the carbonation test results are shown in Figure 2, with the standard deviation of the measurements indicated by the error bars. The left side solid bar indicates the carbonation measured after CO_2 exposure alone (with no chloride exposure). The other results are from after the chloride plus carbonation exposure, on both the non-chloride side of the sample (exposed to NaOH, indicated by the middle lined bars) and on the chloride exposure side (Cl indicated by the right side dotted bars). The results show a significant drop in the level of carbonation depth for samples that had been exposed to chlorides.

Comparing the effect of cement type, the sulphate resistant cement (mix SR05A2) had the lowest amount of carbonation in both cases of individual or combined influence with chloride ingress. After the combined deterioration exposure, there was extremely low carbonation, showing great durability. The mixture with a higher air content (Y05A5 compared to Y05A2) had the highest level of carbonation in both cases as well. Including blast furnace slag (mix R-BFS05A2) showed the most benefit in reducing carbonation depth alone, though the impact was insignificant in the case of combined deterioration of carbonation and chloride. After chloride exposure, the carbonation levels were nearly equivalent for the reference (mix Y05A2) mixture compared to mixtures containing either fly ash or blast furnace slag.



	SR05A2	Y05A2	Y05A5	R-BFS05A2	R-FA05A2
■ Carbonation only (no Cl)	7,5	9,5	10,7	7,0	10,2
▧ Carb.+Chl. (non-exposed side)	7,3	6,8	10,8	6,8	8,0
⊡ Carb.+Chloride (exposed side)	0,2	4,3	8,6	4,2	4,3

Figure 2 - Influence of chloride ingress on carbonation depth (cements: SR= sulphate resistant, Y=Yleis XX cement, R=Rapid cement; binders: BFS=blast furnace slag, FA= fly ash; air: A2=2% air, A5= 5% air)

Within the scope of the project, new testing procedures have been tried on mortars to evaluation the effects of carbonation on chloride ingress. Additional test results are shared within the scope of the presentation, including further results of chloride-carbonation interaction and the impact of moisture content on chloride ingress.

4. SUMMARY

These results presented here give a small example of the wide range of laboratory investigations that have been a part of the Finnish interacted deterioration project. All of the results of this project as well as two earlier Finnish durability projects in cooperation with Aalto University are available on a public database for evaluation and future cooperative studies. The research has shown that single attacks tested in laboratory conditions yield different results than what may actually be experienced in field applications or in-situ concrete structures, where multiple degradation types are occurring simultaneously. The new interacted durability laboratory results have been combined with field studies to improve durability models and service life prediction tools. The results have had an impact on Finnish concrete practice and durability guidelines.

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