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Effect of coupled deterioration by freeze–thaw, carbonation and chlorides on concrete service life

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ABSTRACT

Concrete performance is traditionally based on assessing the effect of a single degradation mechanism. In the field, however, concrete is simultaneously affected by degradation mechanisms, possibly with a synergetic effect on deterioration. This paper presents the results of a Finnish research project assessing coupled deterioration mechanisms including frost attack, carbonation and chloride penetration.

Research was composed of an extensive laboratory testing regime, in parallel to the exposure of several concrete specimens at field stations. Testing took into account the effects of ageing and repeated exposure cycles to different conditions. More than 60 concrete mixtures were evaluated with varying binder types and air contents. Testing results together with local weather data serve as a basis for modelling and development of service life assessment tools.

The results show the synergetic effect on concrete deterioration of coupled deterioration and quantitatively support that a holistic approach should be adopted for predicting deterioration.

1. Introduction

Service life assessment of concrete structures is typically based on one main driving force of deterioration, such as scaling due to de-icer salt with freeze–thaw exposure or cracking caused by reinforcement corrosion due to chloride ingress. To test these individual deterioration mechanisms and correlate the results to real-time performance of structures accelerated laboratory tests are used. 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 mechanisms, when modelling service life.

A three year Finnish research project DuraInt – Deterioration Mechanisms on Service Life of Concrete Structures in Cold Environments (2008–2011), investigated the deterioration of concrete when subjected to coupled deterioration mechanisms [1]. The research project was undertaken by VTT Technical Research Centre of Finland in cooperation with the University of Aalto. The overall objective of the project was to evaluate the effect of interacted deterioration mechanisms on the service life of concrete structures [2–9].

The concrete studies were divided into two main categories: field and laboratory assessments. Section 2 in this paper addresses the research performed in field testing, where concrete specimens subject to outdoor environmental loading were evaluated for interacted deterioration being subject to freeze–thaw, carbonation and chloride ingress. The intensive field testing resulted in an extensive amount of data collected, analysed and reported [3]. Only selected results are presented in this paper, in an attempt to show the different aspects of the work performed related to different mechanisms. The HW7 field station was established less than 10 years ago (in 2007) and thus is still relatively young, revealing no extensive deterioration of concrete samples yet. Section 3 addresses 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 ageing of the concrete surface prior to testing was also addressed, which is a key issue to study when using mineral by-products as binders.

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2. Field testing for concrete durability

Field testing provides relevant information on concrete durability in real environmental conditions. In most cases, direct comparison of field testing results with standardized laboratory test results is not possible due to the interaction of different deterioration mechanics in the field. There is a need for modifying laboratory test methods for quality control purposes to represent adequately field deterioration of concrete.

In Finland, VTT has three concrete durability field exposure site (FES) in operation that have been established from year 2001–2007 [3,7]. Two of these are located in southern Finland in Espoo and along highway number 7 (HW7) near Kotka (Fig. 1a), and the other is above the Arctic Circle in Sodankylä. The FES in Espoo and Sodankylä include concretes where freeze–thaw and carbonation are evaluated. The HW7 FES includes concrete samples for assessing freeze–thaw scaling resistance, carbonation and chloride penetration. Sheltered carbonation studies are also performed at the Espoo site (Fig. 1b). In the autumn of 2009 some additional concrete specimens were delivered to a similar highway testing field in Borås, Sweden.

With new concretes being constantly added to the FES on an annual basis to serve the Finnish concrete industry's and their customers' needs, it is expected that all the concretes at the FES will continue to be monitored for at least 20 years.

For a correct interpretation of the deterioration mechanism affecting concrete, a quantification of the environmental loading is necessary. A detailed record of weather conditions and road salting practices has been kept [3].

During the first winter (2007/08) the concrete samples were subject to mild weather conditions, with 83 fluctuations around 0 °C. The second winter (2008/09) was closer to the average winter in southern Finland, with 80 freeze thaw cycles below 0 °C, but including also approximately 25 cycles below −5 °C and 9 cycles below −10 °C. The third winter (2009/10) was colder than normal in southern Finland. There were only 59 freeze–thaw cycles below 0 °C, but included four long periods below −20 °C and one below −25 °C.

Highway de-icing is normally applied from October/November to April in Southern Finland. The de-icing salt along HW7 during the project was mainly NaCl spread in crystalline form. In addition, some $CaCl_2$ solution was used as a preventive measure. Approximately 1.3 kg/m^2 of de-icing salt were applied in the 2007/08 and 2008/09 winters and 0.7 kg/m^2 in the 2009/10 winter. Maintenance in the form of snow removal was performed at the HW7 FES to guarantee that salty splash water and water vapour could freely access the exposed concrete specimen surfaces. For the freeze–thaw scaling with salt specimens, it was considered essential that the upper surface was exposed to salt and water. For the chloride penetration specimens, both the vertical surface facing the highway and the upper horizontal surface were considered as exposed surfaces and were kept cleaned from snow accumulation.

2.1. Materials, concretes and characteristics

More than 30 concrete mixes were cast and placed at the FES. Full details concerning the concrete composition and specimen can be found in [3]. The concretes represent mainly prevailing common industrial mixes in Finland (air entrained bridge concretes for the highway testing field), with an effective water-to-binder ratio (w/b) between 0.39 and 0.60. More than half of the mixes had a w/b close to 0.42. Common Finnish cements (manufactured by Finnsementti Oy), blast furnace slag (BFS) and fly ash (FA) were used. Fresh concrete air content varied between 1.7% and 7.3%. Approximately 60% of the concretes had air entrainment content of 4.0–6.0%. All relevant fresh and hardened concrete properties were determined [3]. Table 1 presents the composition for some of these mixes.

2.2. Chloride penetration

The field results presented here are taken from the HW7 exposure site. Chloride profiles were measured after the 1st winter (2007/08) and also the 3rd (2009/10) winter season. The chloride analysis was based on measuring the chloride profile of concrete cores (∅ 100 mm, $h > 100$ mm) taken from the exposed vertical surfaces of the test specimens. Powder samples were obtained by both grinding the surface and by dry slicing and crushing.

Fig. 2 presents the chloride profiles of the vertical concrete surfaces facing the highway for some selected binding materials and w/b after the 1st and 3rd winter season. Table 2 presents the chloride migration coefficients (D_{nssm}) of the same mixes at 3 months of age by the CTH-method [10]. In addition, the apparent diffusion coefficients and surface chloride concentrations based on the curve fitting of the chloride profiles with Fick's 2nd law of diffusion are also presented. The effect of binding material and w/b ratio can be seen clearly in these results, especially with regard to the beneficial effect of incorporating BFS and FA. The effect of time on the evolution of the apparent diffusion coefficient is also noticeable.

Visually comparing the profiles after the first and third winter seasons, it can be seen that there is a shift of the profile inwards from the surface of the concrete (Fig. 2). The average surface layer (0–5 mm) concentration was about 30% higher after the third winter season compared with the 1st winter season, but the difference evened out deeper in the concrete, and disappeared at about 15 mm depth. It can also be seen that the near surface chloride concentration (0–1 mm) was usually lower than the maximum concentration at 1.5 mm. Chloride profile determination was done just before the summer time, and it can be expected that some chlorides may have already been washed away after the winter

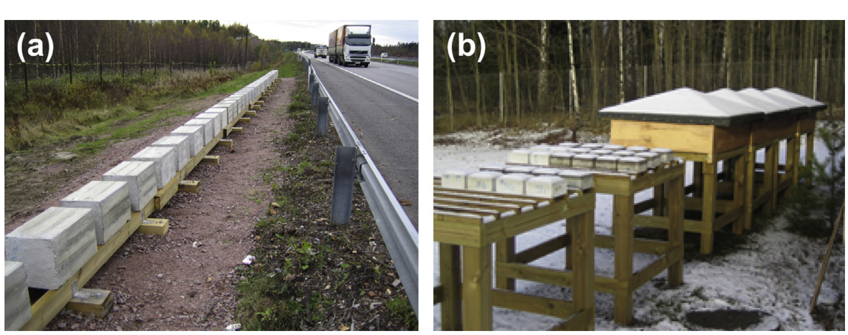

Fig. 1. DuraInt field exposure sites (a) next to Highway 7, Kotka; (b) Suomenoja, Espoo.