



## Corrosion products of carbonation induced corrosion in existing reinforced concrete facades



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### ABSTRACT

Active corrosion in reinforced concrete structures is controlled by environmental conditions and material properties. These factors determine the corrosion rate and type of corrosion products which govern the total achieved service life. The type and critical amount of corrosion products were studied by electron microscopy and X-ray diffractometry on concrete and reinforcement samples from existing concrete facades on visually damaged locations. The corrosion products in outdoor environment exposed concrete facades are mostly hydroxides (Feroxyhite, Goethite and Lepidocrocite) with a volume ratio to Fe of approximately 3. The results can be used to calibrate calculation of the critical corrosion penetration of concrete facade panels.

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## 1. Introduction

### 1.1. Overview

The effects of reinforcement corrosion have resulted in high maintenance costs in concrete infrastructure around the world in varying climates but also in climates similar to Finland [1–3]. Corrosion is responsible for approximately 11–40% of the repair costs of prefabricated concrete facades in Finland depending on the concrete surface finishing [4]. Regarding concrete facades, corrosion of reinforcement is usually initiated by carbonation [5]. Corrosion damage in concrete structures becomes visible as cracks or spalls. The formation of cracks is usually the first sign of damage thereby making it a suitable limit state in service life considerations that try to take into account both initiation and active corrosion phases of reinforcement service life. When corrosion is far advanced or the spacing of reinforcing bars is small spalling may occur where a piece of the thickness of the concrete cover will be cut off from the surface [6,7]. A method to calculate the critical corrosion penetration exists [8] but it has not been validated especially in the case of carbonation initiated corrosion in slender concrete panel structures.

The concrete cover of reinforcement protects the steel during initiation phase but also determines the amount of corrosion needed to facilitate damage. If the cover is high enough a sufficient stress to generate

damage on concrete surface may never occur [5]. The requirement for sufficient concrete cover is usually specified in national codes of practice such as [9]. In spite of the requirements, a large scatter is associated with the cover depths of existing concrete structures [5,10]. Because the facade panels in Finland are usually very slender (nominal thickness of 40–70 mm) the manufacturing of the panel and the installation of the reinforcement are sensitive in regard of achieving proper cover depth.

### 1.2. Corrosion products

The type of rust formed in corrosion is found to have a significant impact on the cracking behaviour of concrete due to the different volume expansion of corrosion products, see Fig. 1 [6,11,12]. This volume expansion is essential in studies that aim at relating corrosion induced damage and corrosion penetration used in determining the residual service life of corrosion affected structures [8].

The final corrosion products in reinforced concrete have mainly been studied in the case of chloride induced corrosion either in laboratory conditions [14–16], or under marine environment [17]. Zhao et al. [14] concluded that the mechanism of concrete cover cracking due to reinforcement corrosion can be described by two main stages: of stresses caused by the growth of rust thickness and the migration of rust to the pores at the steel/concrete interface. The experiments of Marcotte and Hansson [14] imply that hydroxide types of rusts (in Fig. 1) are formed in high moisture conditions and oxide type rusts in not constantly wet conditions. Characterization studies of corrosion products formed on archaeological ferrous artefacts have been published e.g. in [18,19]. The observed phases in both studies were mainly of goethite, lepidocrocite and magnetite and/or maghemite. Dehoux et al. [19]

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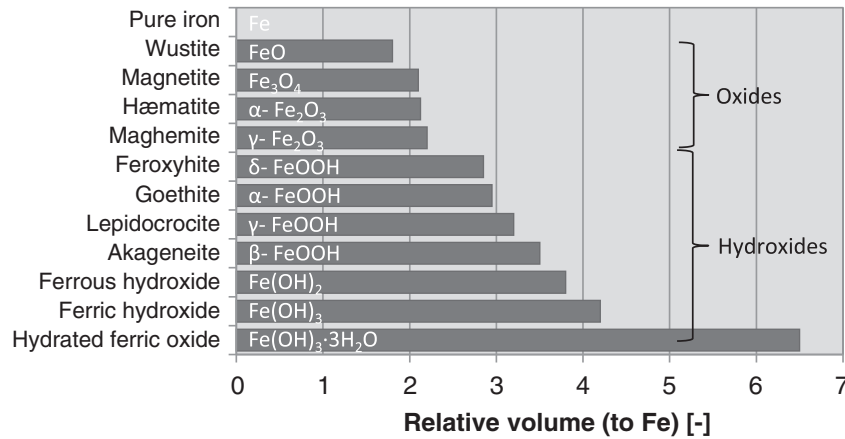


Fig. 1. Relative volumes of corrosion products of Fe to the parent metal. Compiled from [6,12,13].

observed differences in the mechanical properties i.e. elastic moduli of the different phases of these corrosion products. Chitty et al. [18] observed that the corrosion products form layers of different composition, density and permeability around the reinforcement. The layered structure was composed of the metallic substrate (M), dense product layer (DPL), transformed medium (TM) of final corrosion products and compounds from the binder and the surrounding binder (B). Since, similar layered structure has been observed also by Jaffer and Hansson [13] in their studies on reinforced concrete specimens produced in the laboratory. Huet et al. [20] used the same structure in mathematical modelling of the corrosion process. Duffö et al. [21] conducted characterization studies on reinforcement embedded in concrete in a 65 year old structure. A layered structure of rust was found, where the inner layer was dense and well adhered to the steel surface and mainly composed of magnetite. The outer layer of rust was mainly composed of goethite and lepidocrocite and was porous. Corrosion was concluded to have been initiated by fast carbonation, but the time taken for the initiation was not known. Analysis on the generated products was presented and a reaction path proposed for the rusts formed.

Hot rolled reinforcing steel is covered with a few micrometre thick mill scale due to the manufacturing process composed of magnetite with a surface layer of haematite and goethite [12]. Zhao et al. [15] measured a thickness of the mill scale of average 34.5 μm. This mill scale does not take part in the corrosion stresses and was therefore not included in corrosion thickness evaluation in their studies. Both hot rolled (typically rebars) and cold formed (typically meshes) reinforcement have been used in the construction of the facade panels currently under study.

### 1.3. Corrosion modelling and the critical corrosion penetration

Studies depicting the propagation phase of reinforcement corrosion in concrete have been presented e.g. in references [11,13,14,22,23]. These studies are based on accelerated laboratory experiments on laboratory specimens. One study on the effect of climatic variations on reinforcement corrosion has been reported in [24] based on observations and measurements on laboratory specimens. The capabilities of models created using laboratory experiments to universally predict time-to-cracking with various reference cases have been under debate [25]. Thus, a new approach is proposed in this paper to contribute to the knowledge on the corrosion propagation phase using investigation methods from condition assessments of concrete facades.

The extent of corrosion is presented as corrosion penetration on the steel circumference. The critical corrosion penetration to form cracking has been studied e.g. in [15,26–29]. The critical penetration values varied in this literature from 15 to 100 μm depending on the experiment, exposure or material.

### 1.4. The objective of this research

This study addresses the determination of the type and thickness of corrosion products formed especially in carbonation induced corrosion in outdoor exposed concrete facade panels. The objective is to produce reliable information on the extent of corrosion that causes visual damage on these structures. The studies are performed on concrete samples taken from visually damaged locations on existing concrete facades that have been in use for 30–43 years.

## 2. Research methods and material

### 2.1. Acquisition and preparing of the research material

The research material for this study was gathered in the period of April–August 2013 in the facade condition assessment of 12 buildings chosen deliberately for this study. The buildings were located in the southern parts of Finland and their construction years ranged from 1971 to 1984. The facades were constructed using prefabricated sandwich panels. Of the studied facades seven were of painted concrete, four of exposed aggregate and one of untreated form surfaced concrete.

In all 27 sample cores of the diameter of 50 mm were drilled from the outer layer of the facade panels directly on visually observable corrosion cracks or spalls, see Fig. 2. The samples contained the corroded rebar and its surrounding concrete. The core samples were sprayed by phenolphthalein solution to measure average and maximum carbonation depth from the freshly cut surface and were then wrapped airtight for transport and storage for further investigations.

Carbonation depth measurements were used to investigate the time of corrosion initiation in these samples and thereby calculate the length of the active corrosion phase by subtracting from the total age of the samples the time of initiation, see Table 1. The initiation time was calculated by the square root model for carbonation [30]. The studied concrete structures were on average 38.8 years old. The average time under active corrosion was for the cracked locations 26.0 years and for spalled locations 33.1 years. This information is further discussed in chapter 5. It should also be noted that for all of the samples corrosion has been initiated quite fast (by average 12.6 years) which indicates that both concrete resistance against carbonation has been poor and the environmental conditions favourable to carbonation.

The concrete core samples were broken in laboratory and the reinforcing bars trapped inside the carbonated layer of concrete were extracted from the core samples. The diameter of reinforcing steel samples varied from 3 to 10 mm. The total number of steel samples was 35 of which 16, ranging from different diameter and corroded surface, were chosen for electron microscopic studies. The properties of the steel samples are shown in Table 1.

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