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Carbonation-induced corrosion: Investigation of the corrosion onset

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HIGHLIGHTS

- Apparent early carbonation-induced corrosion onset is reported in the literature.
- Conditions for corrosion are met once the mortar-steel interface is carbonated.
- The spatial variation of the carbonation depth is influenced by the reinforcement.
- The apparent early corrosion onset was due to the influence of reinforcement.
- The influence of reinforcement should be considered in service life prediction.

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ABSTRACT

There are different views in the literature on the relationship between the location of the carbonation front and the onset of reinforcement corrosion. Theoretically, corrosion starts when the carbonation front reaches the reinforcement, but some authors have observed an apparent earlier start of corrosion. In the present study, mortar samples with and without reinforcement were exposed for up to 22 weeks to 20 °C, 60% RH and 1.5% CO_2. The state of the reinforcement was monitored by potential measurements. The carbonation of the bulk and the mortar-steel interface was detected by spraying a pH indicator on a freshly split or cut surface. Good agreement was found between low potential values (compared to reinforcement in the passive state) and the carbonation of the mortar-steel interface. A difference in the spatial variation of the carbonation depth was observed between plain and reinforced samples. The differences found in the literature between the location of the carbonation front and the corrosion onset can probably be explained by the spatial variation of the carbonation depth in the vicinity of the reinforcement.

1. Introduction

Corrosion is one of the major causes of deterioration in reinforced concrete structures [1]. Chloride ingress and carbonation are the most common causes of initiation of reinforcement corrosion. Reinforcement embedded in concrete is prevented from corrosion by a thin layer of iron oxides, which is stable in the high-alkaline environment of sound concrete [2]. Upon carbonation, the pH of the pore solution is reduced to values below 7 [3]. The oxide layer is no longer stable in such a low pH and reinforcement embedded in carbonated concrete can corrode depending on the exposure. Differences are found in the literature on the location of the carbonation front and the onset of the reinforcement corrosion. Some authors have observed that reinforcement corrosion can start before the carbonation depth compares to the concrete cover. Table 1 presents a summary of published experimental investigations on carbonation-induced corrosion onset.

Parrott detected corrosion when the difference between the average carbonation depth in plain concrete and the concrete cover (in reinforced samples), the "unneutralized remainder", was 10–15 mm, i.e. he observed corrosion before the apparent carbonation front reached the reinforcement [4,5]. He determined ongoing corrosion by gravimetric analysis of the reinforcement, and the unneutralized remainder from the carbonation depth measurements in plain samples. For further description of materials and exposure conditions, see Table 1. Carbonation development in

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Abbreviations: CO_2, carbon dioxide concentration in the air (volume); D_{max}, maximum aggregate size; FA, fly ash; GGBFS, ground-granulated blast-furnace slag; L, limestone; OCP, open circuit potential; pH, pH indicator; RH, relative humidity; SCE, saturated calomel reference electrode; t, time; T, temperature; w/b, water-to-binder ratio; w_x, width of the carbonation front; $x_{c,i}$, carbonation depth measurement "i"; δ_x, spatial variation of the carbonation depth; Ø, reinforcement diameter.

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Table 1
Summary of the experimental investigations on carbonation-induced corrosion onset.

Authors		Parrot [4,5]	Yoon et al. [6]	Hussain et al. [7,8]
Materials	Type	Concrete	Concrete	Concrete
	SCMs	FA, GGBFS, L	–	–
	w/b	0.35, 0.47, 0.59, 0.71, 0.83	0.45, 0.5, 0.55	0.45
Geometry	Samples [mm]	Cubes, 100	Prims, length 200	Prims, 200 × 100 × 100
	Cover [mm]	4, 8, 12 and 20	12	13
	D_{max} [mm]	10	25	20
	Ø [mm]	6.4	8	13
Curing	T [°C]	not reported	20	20
	Moisture conditions	Wet cured	Wet cured	Sealed
	t [days]	1, 3, 28	28	28
Exposure	T [°C]	Indoors	20	20
	RH [%]	45–58% outdoors sheltered or exposed	65	55
	CO_2 [%]	0.04%	3, 5, 10	10
Characterization	Carbonation	pH in plain samples	pH in plain samples	pH in plain samples
	Corrosion onset	Gravimetric analysis	Gravimetric analysis, LPR	Corrosion potential
	Criteria for corrosion onset	Weight loss [not reported]	Weight loss 0.2–0.5 g	Potential drop ≈200 mV

FA: fly ash, GGBFS: ground granulated-blast furnace slag, L: limestone, D_{max}: maximum aggregate size, Ø: reinforcement diameter, pH: pH indicator.

the plain samples and corrosion in the reinforced samples were measured after 6, 18 and 48 months of exposure.

Yoon et al. also compared the corrosion onset in reinforced samples with carbonation depth measurements in plain samples. They found that corrosion started before the apparent carbonation front reached the reinforcement, but as long as the unneutralized remainder was more than 5–10 mm in thickness the risk of carbonation-induced corrosion was low [6]. This is in agreement with the findings by Parrott [4,5], although the unneutralized remainder determined is lower. For further description of materials and exposure conditions, see Table 1. Carbonation development was monitored in the plain samples and the corrosion rate in the reinforced samples using linear polarization resistance and gravimetric analysis at the end of the exposure.

In agreement with the above observations, Hussain et al. found that corrosion started when the carbonation depth in plain samples was 80% of the concrete cover [8]. For further description of materials and exposure conditions, see Table 1. The corrosion potential was monitored during the exposure and the corrosion rate was estimated from gravimetric analysis of the reinforcement after exposure. Corrosion onset was identified by a potential drop of 200 mV.

The above observations are also reflected in JSCE Guidelines, which state that corrosion starts before the carbonation front reaches the reinforcement: *"It has been learned from laboratory tests and investigations on actual structures that the corrosion of steel may begin before the carbonation depth actually exceed(s) the cover thickness"* [9]. According to the JSCE, to avoid corrosion onset the unneutralized remainder should be at least 10 mm, and as much as 25 mm if chlorides are present. No references are given to support these statements.

In this study, we investigated three possible hypotheses that could explain the apparent early onset of carbonation-induced reinforcement corrosion:

1. Width of carbonation front (w_x). When detecting carbonation, there will be a volume where the investigated property changes from sound to carbonated concrete. The detected width of this carbonation front depends on the characterisation method used [10]. A large carbonation front width could lead to conditions for corrosion onset before carbonation can be detected at the level of the reinforcement.
2. Spatial variation of carbonation depth:
   2.1. Spatial variation in plain samples (δ_x). The spatial variation in the carbonation depth measured in plain samples could induce corrosion on parts of the reinforcement before the average carbonation depth reaches the level of the reinforcement.
   2.2. Spatial variation in reinforced samples (δ_x). Differences in microstructure between plain and reinforced samples could induce differences in the spatial variation of the carbonation depth and faster carbonation in the vicinity of the reinforcement.

Fig. 1 illustrates the nomenclature used. Moreover, when we refer to the data from the literature, all the authors detected the carbonation in plain samples, so the term "apparent" carbonation front is used.

Mortar samples varying in size and reinforcement position were prepared using 3 different compaction methods. The samples were sealed, cured for 2 weeks, and exposed to accelerated carbonation for up to 22 weeks. The state of the embedded steel was monitored by potential measurements. The carbonation of the bulk and the mortar-steel interface was studied by spraying a pH indicator on a freshly split or cut surface. In addition, thin sections were investigated using optical microscopy. We found that the embedded steel affects the spatial variation of the carbonation depth, possibly due to differences in microstructure between plain and reinforced samples. These differences cannot be attributed to the specific materials or the exposure; similar observations were reported in a field assessment [11]. Based on these observations, monitoring carbonation development in plain samples and assuming similar carbonation development in reinforced samples might give non-conservative prediction of the corrosion onset.

2. Experimental

A set of plain and reinforced mortar samples with different geometries were prepared using various compaction methods:

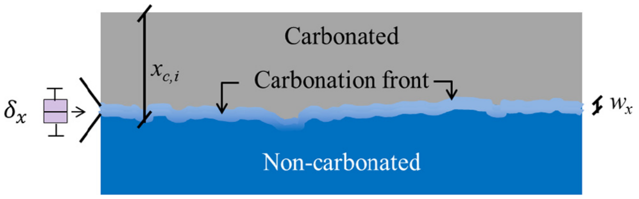

Fig. 1. Nomenclature used: δ_x: spatial variation of the carbonation depth, $x_{c,i}$: carbonation depth measurement "i", w_x: width of the carbonation front. The sketch illustrates carbonation detected using a pH indicator, adapted from previous work [10].