



Corrosion rate of carbon steel in carbonated concrete – A critical review

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ABSTRACT

Reinforced concrete with lower environmental footprint (lower CO₂ emission) can be obtained by reducing the clinker content in the cements. As the carbonation of concrete is faster, corrosion of steel in carbonated concrete during the propagation phase is becoming important both for science and practice. The present literature review summarizes the state of the art, reporting corrosion rate data for a broad range of cement types, w/b ratios and environmental conditions. Correlations between corrosion rate and the main influencing parameters are elaborated and discussed. It confirms that the corrosion rate of steel in carbonated concrete is not under ohmic control. More important are the degree of pore saturation and the effective steel area in contact with water filled pores. It also emerges that the new blended cements have to be systematically studied with respect to the corrosion behavior of steel in carbonated concrete in order to make reliable service life prediction.

1. Introduction

1.1. Background

Carbonation means the progressive neutralization of the alkaline constituents of concrete by carbon dioxide in the air forming mainly calcium carbonate. In this neutralized environment reinforcing steel is no more protected by the alkaline pore solution of fresh concrete. When the carbonated surface zone reaches the depth of reinforcing steel, significant corrosion may be initiated [1]. Indeed, corrosion of steel in carbonated concrete was a major concern of research and practice in the years from 1950 to 1990, a review of the published literature on carbonation and its effects was published by Parrot in 1987 [2]. The research findings led to the requirement of dense concrete (lower w/c ratio), the control of concrete properties and to a marked increase in the cover depth (from 20 mm to 35 mm) in the codes of practice. The European standard on concrete EN 206-1 published in the year 2000 classified the risk of carbonation-induced corrosion depending on the severity of the environment (XC1 to XC4). With the minimum requirements given in the recommendations (maximum w/c ratio, minimum cement content, minimum cover depth) the codes of practice since then give guidance for reinforced concrete made with Portland cement (CEM I) on how to avoid carbonation induced corrosion for structures with expected service life of 50 or 100 years.

1.2. Carbonation of concrete

The role of carbonation as a factor that contributes to the degradation of reinforced concrete is becoming increasingly important again for two reasons: first many old reinforced concrete structures that were built before modern standards were applied are ageing and have to be maintained. Secondly, the need to reduce CO₂ emission [3] and to obtain materials having a reduced environmental footprint, is leading to a reduction of the clinker content in the cements. Clinker (CEM I) is substituted with supplementary cementitious materials (SCM) such as limestone, fly-ash (FA), ground granulated blast-furnace slag (GGBS) etc. In the future, blended cements with increasingly lower clinker content and a huge variety of supplementary cementitious materials (SCM) will be used [4]. The future potential for application of blended cements depends on the current application level, on the availability of blending materials, and on standards and legislative requirements. The global potential for carbon dioxide emission reduction through producing blended cement is estimated to be at least 5% of total carbon dioxide emissions from cement making, but may be as high as 20%, the potential savings would vary by country, and even by region, according to local availability [5–8].

The introduction of low clinker binders has strongly reduced the pH buffer capacity as a result of the reduction (or elimination) of the calcium hydroxide reserve, considered one of the main reasons for the corrosion inhibiting nature of Portland cement systems [9]. Comprehensive reviews have summarized the effect of ground granulated blast-furnace slag (GGBS) [10] and fly ash (FA) [11] on the carbonation

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resistance of concrete. It is shown that FA and GBBS increase the carbonation rate of concrete. The influence of the cement type on carbonation rate was proposed to be contained in a single parameter termed “the effective buffering capacity of the cementitious binder expressed as an equivalent Portland cement content” [12]. This has been demonstrated by a recent work of Lehmann et al. [13] where the different blended cements could be rationalized by the CaO content. The carbonation rate of blended cements has been found to be a factor of 2–4 higher than for Portland cement [14,15], thus the recommendations in the standards based on the experience with Portland cement are no more applicable. For service life prediction of concrete structures with new, blended cements, corrosion rate data are urgently needed because the so-called “corrosion propagation stage” might be a significant part of the total service life.

1.3. Corrosion of steel in carbonated concrete

Maximum rates of carbonation are observed when the concrete is exposed to atmospheres with relative humidity in the range from 55 to 75%. The corrosion rate of embedded steel in carbonated concrete in this humidity range is not of practical concern [1]. At conditions of high RH and especially by periodic wetting and drying the risk of corrosion increases markedly. The understanding of corrosion rates in carbonated concrete, in dependence of binder composition and mix design, is of major importance to provide adequate codes for ensuring long, maintenance free service life.

The service life of concrete structures made with ordinary Portland cement can be predicted from the air permeability and corrosion rate determinations [16–18]. However, mechanistic understanding is still lacking, not allowing us to deduce a quantitative model in the case of blended cements, particularly because we do not know well how these binders age [19]. Another reason for this lack of a quantitative model is that, in most cases, the test results are not comparable due to the enormous variety of local SCMs [20], resulting in dozens of different blended cements, experimental approaches, in terms of sample design and corrosion measuring techniques.

In this paper a number of publications addressing the topic of carbonation-induced corrosion is critically reviewed [21–73] in order to understand the magnitude of the problem, the main influencing parameters and the probable mechanism of the process.

2. Literature data on corrosion rate of steel in carbonated concrete

Compared to the several hundred reports and papers regarding the resistance to carbonation of mortars and concretes made with different (blended) cements, only about 50 publications have been identified that refer to the corrosion rate of reinforcing steel in carbonated concrete in the last 35 years (1980–2016). Table 1 summarizes all the publications considered in the present evaluation. The corrosion rate data were obtained from a variety of experimental setups and the corresponding details are reported in the Table 1. Abbreviations are given in Table 2.

The majority of data (40 out of 53) stems from laboratory studies. Several authors [30,43,45,47,53,55,60,71] report corrosion rate data from carbonated structures, mainly buildings, or from final phase of long-term field tests intended to study carbonation behavior [24,29,45,47]. These papers state “practical exposure conditions” but details on changes of the temperature are given by only one paper [60] and changes in relative humidity are presented only in two publications [47,60], thus the results of these field tests are more difficult to interpret.

From most of the works it was possible to extract a minimum and a maximum value of the corrosion rate (Table 1). From this global perspective, a large overall scatter is apparent: the reported values range from $0.002 \mu\text{A}/\text{cm}^2$ [23] to $20 \mu\text{A}/\text{cm}^2$ [41], thus over four orders of magnitude. Comparing the cumulative distribution of these values (Fig. 1) the average value of the minimum corrosion rate is about

$0.08 \mu\text{A}/\text{cm}^2$, the average of the maximum is about $2 \mu\text{A}/\text{cm}^2$. The large scatter in literature is related to different experimental procedures and to the parameters that affect corrosion rate of steel in carbonated concrete; this will be discussed in the following sections.

2.1. Experimental setups

Most of the works cited in this review refer to laboratory conditions [21–23,25–28,31–44,46,48–54,56–59,61–70,72,73]. The experimental setup was mainly mortar or concrete specimens of different geometries, with a minimum characteristic dimension (smallest side or diameter of the specimen) of 2 cm [21,22,25–27,37,61,64,68] up to 18 cm [32,33] with embedded reinforcing steel with diameter starting from 0.6 cm up to 1 cm. In Table 3 the different geometries and cover depths used are reported. Prisms are the most common geometry and the cover depth spans over a range dictated by the different intentions of the authors: 0.4–0.9 cm were used for fastest carbonation process, 2.0–2.9 cm were used as compromise between fast carbonation and realistic conditions. Few works, in order to have a more ideal system (surface condition and area), used steel sheets, either embedded in mortar layers [28,39] or used as a substrate on which the mortar was applied [53].

2.2. Measurement methods

In most papers (37 out of 53) the corrosion rate of steel in carbonated mortar or concrete was determined from polarization resistance measurements (Table 4). Other methods such as weight loss or impedance were also used; in some works two [61,66,73] or even three [43,72] different methods were used and the results were compared. Two papers compared LPR with weight loss [61,72] and concluded that the corrosion rates calculated from the two methods are in good agreement, within 20% of relative variation. In some works only qualitative evaluation of the surface state was carried out, with no real corrosion rate reported, using either half-cell potential measurements or simple visual inspection of the steel surface (Table 4).

2.3. Relevance

Table 1 summarizes the main experimental parameters and minimum/maximum corrosion rates measured by the respective authors in the reviewed studies. However, when evaluating the literature – i.e. assessing trends, general agreements, and controversial issues (compare the following sections) – we do not consider all studies equally relevant. Many papers cited studied the carbonation process, data on corrosion in carbonated concrete were more a side effect and obtained from visual inspection [24,29] or half cell potential measurements [36,55] and were thus not considered in the further evaluation. Also data on galvanized steel [56] and carbonation in presence of chlorides [44,45] were not included.

3. Influencing parameters

Some of the differences observed in corrosion rates of steel in carbonated concrete reported in the literature may be related to the different experimental procedures regarding curing, carbonation and conditioning of the samples under test. The main parameters that influence the corrosion rate of steel in carbonated mortar and concrete are the exposure conditions, the type of binder and the water/binder ratio [1,2] as will be discussed below.

3.1. Exposure conditions – relative humidity (XC3)

Atmospheric exposure conditions with varying relative humidity are frequently encountered inside buildings or in sheltered conditions outside and are thus of great practical relevance. The relative humidity (RH) studied in the reported publications spans over a wide range from

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