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Review

Non-destructive methods for measuring chloride ingress into concrete: State-of-the-art and future challenges

M. Torres-Luque [a,b,*], E. Bastidas-Arteaga [b], F. Schoefs [b], M. Sánchez-Silva [a], J.F. Osma [c]

[a] Department of Civil and Environmental Engineering, Universidad de los Andes, Carrera 1E N. 19A-40, Edificio ML, Piso 6, Bogotá, Colombia
[b] LUNAM Université, Université de Nantes-Ecole Centrale Nantes, Institute for Research in Civil and Mechanical Engineering (GeM)/Sea and Littoral Research Institute, CNRS UMR 6183/FR 3473, 2 rue de la Houssiniére, BP 92208, 44322 Nantes, France
[c] CMUA, Department of Electrical and Electronics Engineering, Universidad de los Andes, Carrera 1E N. 19A-40, Edificio ML, Piso 7, Bogotá, Colombia

HIGHLIGHTS

- We describe the physical and environmental factors involved in Cl-induced corrosion.
- Non-destructive techniques (NDT) are needed to monitor Cl propagation into concrete.
- NDT are essential for developing optimum maintenance programs.
- We describe the principal advantages and disadvantages of NDT for measuring Cl content.
- We present a critical review of the principal challenges for developing NDT.

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ABSTRACT

Chloride ingress is one of the major causes of reinforced concrete (RC) deterioration. Free chloride induces the corrosion of rebars, reducing the material strength, and therefore, the structural behavior. This paper highlights the importance of chloride content measuring, and also summarizes the state of the art of non-destructive and *in situ* techniques for measuring chloride content into concrete structures. These techniques have been developed over the past twenty years, and they have been shown as good alternatives in durability field. They are based on three methods: electrical resistivity (ER), ion selective electrode (ISE) and optical fiber sensors (OFS).

Contents

* Corresponding author at: Department of Civil and Environmental Engineering, Universidad de los Andes, Carrera 1E N. 19A-40, Edificio ML, Piso 6, Bogotá, Colombia. Tel.: +57 3107659440.
E-mail address: mm.torres118@uniandes.edu.co (M. Torres-Luque).

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1. Introduction

Chloride ingress is one of the major causes of reinforced concrete (RC) deterioration affecting structural serviceability and safety [1,2]. Chloride-induced corrosion begins when the concentration of chloride at the steel bars reaches a threshold value that destroys a thin passive layer of corrosion products (caused by the high alkalinity of concrete at the end of construction), which protects steel bars against corrosion. After corrosion initiation, there is a premature deterioration caused by various mechanisms: loss of reinforcement section, loss of steel–concrete bond, concrete cracking and delamination. After steel corrosion starts, the RC physical and mechanical properties decay at rate that depends on the environmental conditions. This deterioration process generates larger repair and maintenance costs with severe impact on the durability and life-cycle performance.

In 1991, the Federal Highway Administration (FHWA) found that about 39% of highway structures present defects due to reinforcement corrosion. This means that about 134,000 structures are labeled as damaged and require urgent repairs [3]. In 2002 the FHWA and the National Association of Corrosion Engineers International (NACE) stated that approximately 15% of the total bridges in the USA were structurally deficient due to rebar corrosion. They estimated that the replacement and maintenance of these structures cost about USD$8.3 billion [4]. More recently, the ASCE 2009 Report card for America's Infrastructure showed that USD$2.2 trillion are necessary to be invested over 5 years to bring the American structures up to appropriate conditions [5]. In Europe, much of the transport infrastructure in the Atlantic Area is over 50 years old and many structures are in severely deteriorated conditions due to the high aggressiveness of marine environments [6]. For instance, in Denmark the damage costs, due to maintenance programs and traffic delay, vary between 15% and 40% of construction costs [7].

The measurement of chloride content at the concrete cover could be used to estimate the risk of corrosion initiation, and therefore, to optimize repair and maintenance costs. There are many lab techniques and field measurements for measuring chloride content in RC. The most popular techniques are potentiometric and Volhard methods. They measure free and total chlorides in concrete cores extracted from in service structures. However, these techniques are mostly semi-destructive, time-consuming and costly. Furthermore, their destructive nature lead to additional indirect costs such as traffic delay, traffic management, road closures and lost productivity, which increase costs further [8].

Currently, several research groups are working on developing non-destructive techniques (NDT) to survey or measure chloride ingress in concrete. NDT imply methods that do not change the environment and the futures usefulness of the material where the measurement is taken, for example techniques that works with external or embedded equipments [9,10]. The most studied and developed general methods could be classified in: (i) ion selective electrodes (ISE) [11,12,10,13–15], (ii) electrical resistivity (ER) [16–18,7,19,8], and (iii) optical fiber sensor (OFS) [20–24]. Other methods such as grounding penetrating radars (GPR), capacitive methods, or electrochemical impedance spectroscopy (EIS) have been used for corrosion assessment [13,25–27], for detection of chlorides [28], or for chloride diffusion coefficient estimation [29–31] in laboratory concrete specimens; however, until now, there is not NDTs for chloride concentration based on electric capacitance or electrochemical impedance.

ISE, ER and OFS have shown some advantages: ISE shows a good chemical stability in aggressive environments, ER is sensitive to chloride presence, and OFS shows better sensitivity to chlorides than the others. However, there are some problems that have not been solved yet. For instance, most of these methods are very sensitive to changes in the conditions inside the concrete structure (e.g., changes in temperature, relative humidity, pH), and some of them require a careful calibration process. The results derived from these techniques could provide information to improve the understanding and modeling of chloride ingress mechanisms under real exposure conditions. Since non-destructive measurements could be taken at several points and times, the results are useful for uncertainties and spatial variability quantification. This will allow developing probabilistic determination models for determining and predicting structural lifetime and repair/maintenance scheduler [32–35].

The objective of this paper is to present a critical review of the advantages and disadvantages of the main and latest *in situ* non-destructive methods to determine and to assess chloride concentration in RC structures. Moreover, the paper presents an overview of the general critical aspects that influence corrosion risk deepening in chloride ingress and their physical and chemical impact on structures.

The paper is structured as follows. Section 2 presents a summary about corrosion in RC structures; this part takes into account the main causes of the corrosion processes. Section 3 points out the importance of chloride presence in RC durability, the critical chloride content for corrosion initiation and the importance of assessing chloride concentration. Section 4 briefly describes laboratory and field techniques for measuring chloride content. Section 5 explains the physical and chemical principles of non-destructive methods for assessing chloride concentration in concrete structures. Based on the literature review of non-destructive methods/techniques, Section 6 makes a critical comparison between those techniques focus on invasiveness, precision, robustness and fabrication. After, Section 7 remarks the main challenges for the future in non-destructive measuring of chloride concentration. Finally, Section 8 presents the conclusions of this study.

2. Critical issues in corrosion initiation

Corrosion is a natural degradation process of metals, which leads to steel mass loss and dimensional changes [36]. Steel corrosion on steel and RC structures may affect significantly their lifetime. This section presents an overview of corrosion in RC structures including the influencing factors as well as its effects on the durability.