Construction and Building Materials 167 (2018) 15–19

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A novel link of the time scale in accelerated chloride-induced corrosion test in reinforced SHCC

Gideon P.A.G. van Zijl [a], Suvash Chandra Paul [b,*]

[a] Department of Civil Engineering, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
[b] Civil Engineering, School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, 46150 Bandar Sunway, Malaysia

HIGHLIGHTS

- Steel corrosion in R/SHCC is induced by applying a high amount of external voltage.
- A novel method of determining the corrosion acceleration factor (AF) is presented.
- AF enables durability design of structures when the corrosion steel mass loss is known.

ARTICLE INFO

Article history:
Received 30 October 2017
Received in revised form 28 January 2018
Accepted 4 February 2018

Keywords:
Corrosion
Mass loss
Acceleration factor
SHCC

ABSTRACT

It has become common to use accelerated corrosion tests (ACT) in research programs to evaluate the durability performance of reinforced concrete (RC), and more lately, also fibre reinforced concrete (FRC) structures. One corrosion accelerating condition is the application of high voltage to RC elements, found in literature to be in the range 3 V–60 V. Such ACT tests are typically comparative, for instance to demonstrate reduced corrosion rates of embedded steel bars in advanced cement-based composites, for instance strain-hardening cement-based composites (R/SHCC) in comparison with reference RC elements. However, deterioration models are not yet refined to the point that actual deterioration rates can be derived from such ACT, as the mechanisms that accelerate the degradation are not well understood, and the link with natural exposure is not yet clear. In this paper, ACT of R/SHCC elements is performed under various potentials (10, 20 and 30 V), and at various cover depths (15, 25, 35 mm) of the steel bars. A novel approach is proposed and demonstrated to determine the acceleration factor of these conditions.

1. Introduction

The structural stability of existing reinforced concrete (RC) structures becomes a concern with aging as long-term deterioration causes loss of structural integrity. Corrosion of the reinforcement is the most common deterioration mechanism in existing RC infrastructures causing large economic losses in terms of maintenance and repair costs. In general, corrosion of steel reinforcement in concrete structures is a techno-economic problem for several reasons. Technically it poses challenges in research and development of methods and materials either to control or prevent corrosion. Corrosion in RC or other cement-based composites like fiber reinforced concrete (R/FRC), or strain-hardening cement-based composites (R/SHCC) may initiate by processes of carbonation or chloride ingress to the level of the embedded steel. In the former, carbon dioxide from the environment penetrates the cover concrete, and in the latter water containing dissolved salts penetrate the concrete cover or reach the steel via a crack [1,2]. In both cases the passive layer is destroyed, leading to corrosion initiation. Subsequently, corrosion product of lower density than the original metal develops, and this volume growth builds internal pressure and may induce cracking. This physical effect together with sectional loss of reinforcing steel affect the load carrying capacity, serviceability, and the service life of a reinforced concrete (RC) structures [2]. Repair and rehabilitation of corrosion damaged structures is often cumbersome requiring high technical expertise, competence and cost. Therefore, measurement of steel reinforcement corrosion in concrete is essential to assess the remaining strength and durability of the structure or structural element [3,4].

The corrosion process in RC and R/SHCC is an electrochemical process that generates an electrical current. Hence, measurement of concrete electrical properties such as resistivity and potential enable assessment of the probability and even rate of corrosion of the reinforcing steel. There are various methods and commercial

---

* Corresponding author.
E-mail addresses: gvanzijl@sun.ac.za (G.P.A.G. van Zijl), suvash.chandra@monash.edu (S.C. Paul).

https://doi.org/10.1016/j.conbuildmat.2018.02.019

equipment available to measure and monitor corrosion rate [1,3,4]. Similarly, there are existing models such as a lattice model and stochastic modelling procedures for the prediction of corrosion induced cracking behaviour and spalling in RC [5,6], which ultimately enable structural integrity assessment of RC infrastructure under corrosion attack.

Typically, corrosion is a slow process and it may take a long time, possibly several years, to see visible effects in RC structures. Therefore, accelerated corrosion tests (ACT), also known as aging tests, are used in the laboratory experiments to study corrosion phenomena, and to develop understanding of the degradation process. It should be noted that there may be differences between ACT and natural corrosion in terms of the corrosion product, corrosion mechanism, corrosion-induced internal pressure and corrosion morphology [7]. Hence, it is recommended that these differences are systematically studied to improve the accuracy and application of the ACT method. However, it is beyond the scope of this research paper. In order to accelerate corrosion, the exposure can be intensified by providing a higher temperature, a higher saline concentration, or a higher applied voltage [8–12]. The steel degrades by loss of cross-section due to corrosion mass loss, whereby strength and/or stiffness of the RC or R/SHCC member is reduced. The relationship between the accelerated decay, and the decay under long-term testing under natural exposure in regions where such deterioration occurs, is expressed through an *acceleration factor k*. The acceleration factor is the ratio between time exposures under natural and accelerated aging to a similar level of deterioration. For example, in corrosion testing, an *acceleration factor* $k = 100$ means that the degradation that occurs in RC in the period of one day under accelerated laboratory corrosion test conditions represents the deterioration in such a RC element or structure over a period of 100 days under the normal environmental conditions in coastal regions or practice of salt-based de-icing.

In cement-based composites it is generally accepted (eg. [13,14]) that, increased temperature may lead to accelerated maturity according to an Arrhenius-type relation, due to the thermally activated process of hydration, according to the expression for equivalent time:

$$t_e = \int \beta_T dt \tag{1}$$

with the thermal activation coefficient

$$\beta_T = e^{\frac{E_a}{R}\left(\frac{1}{T_0}-\frac{1}{T}\right)} \tag{2}$$

in which E_a is the activation energy, R the gas constant, and T and T_0 the temperature and reference temperature respectively. This implies an exponential relation between equivalent time and temperature. Inspired by Caceres et al. [15], who studied accelerated stiffness degradation under elevated temperature in fiber reinforced polymers, this paper postulates that accelerated deterioration due to chloride-induced corrosion under elevated electrical potential, and also under reduced cover depth, might follow a similar Arrhenius-type acceleration. The method is demonstrated at the hand of accelerated chloride-induced corrosion tests program and steel bar mass loss measurements, and argued to present a potential link between ACT and durability service life design of R/SHCC structures or structural elements.

For the purpose of the research, corrosion mass loss and applied voltage equivalence principle is used in R/SHCC specimens made with different cover depths. Three different voltages (10, 20 and 30 V) are applied to the specimens for particular periods of time, and the corresponding mass loss is determined by a gravimetric method. Finally, to demonstrate the *acceleration factor* caused by high applied voltages, the corresponding equivalent mass loss without any externally applied voltages (0V) is determined. Based on the accelerated experimental results and with the aid of an Arrhenius relation, an estimated normal deterioration period of time is calculated for R/SHCC specimens. Details of the experimental procedures and outcomes are presented in subsequent sections.

2. Materials and methods

For this research, R/SHCC specimens were prepared with three different cover depths of a single 10 mm diameter embedded steel bar (denoted Y10) as anode, as shown in Fig. 1a–c. A 6 mm stainless steel bar was also embedded as the cathode. Specimen sizes for 15, 25, and 35 mm cover depths are 40 × 40 × 250 mm, 60 × 60 × 250 mm and 80 × 80 × 250 mm respectively. The mix ingredients and proportions per cubic meter of SHCC are 392 kg cement, 674 kg fly-ash, 553 kg fine silica sand of maximum sand size 0.25 mm, 392 kg water, and 26 kg of 12 mm long and 0.04 mm diameter polyvinyl alcohol (PVA) fiber with relative density 1.3 (i.e. 2% by volume). Two days after casting and protection in steel molds, the specimens were stripped and subsequently cured in water at 23 ± 2 °C for another 7 days. Corrosion testing was started at the SHCC age of 9 days. For ACT, three levels of electrical potential (DC power source for 10, 20, and 30 V) were applied to the specimens as shown in Fig. 1d.

Two specimens each for the three different cover depths and applied voltage, thus a total of 18 specimens were prepared and tested. In all specimens, voltages were applied to the anode (Y10 steel bar) and the corrosion current was recorded with a data logger automatically at ten minute intervals up to a maximum test duration of 170 h for the applied potential of 10 V and 20 V, and 105 h for 30 V. For all three the applied voltages, the corrosion current was highest for the 15 mm cover depth and lowest for the 35 mm cover depth.

The average corrosion currents in the specimens were in a range of 0.065 to 0.35 A. Half of the specimen length was submersed into a 5% NaCl aqueous solution (Fig. 1). The Y10 steel bars used in this experiment were not specially treated, except for application of epoxy coating where it protrudes from the concrete (Fig. 1a–c) to avoid any damage in that region. Cracking characteristics were measured in specimens subjected to 20 V. Multiple cracks, with a maximum of 7 cracks in all three cover depths, were observed in the R/SHCC specimens after a period of time under the accelerated corrosion conditions. These cracks are ascribed to the formation of corrosion products, which have relatively low density, and thereby cause pressure build-up in the concrete surrounding the corroding steel bar. Once the tensile strength of the surrounding concrete is reached, corrosion-induced cracking occurs, typically parallel to the corroding bar as shown in Fig. 2. Note that, in this study, the shape of the cracks was not investigated. This could be done for instance by computer tomography (CT) [16], with which images the crack geometry can be visualized. Thereby, it could be determined whether, or to what extent the corrosion led to delamination along the matrix-steel bar interface, and whether possible dissimilarities of the corrosion mechanism and affected regions in the surrounding matrix are caused by the artificially high voltage, as well as the different cover depths. Such investigation was beyond the scope of this study, but is the focus of continued research by the authors, in order to verify the validity of acceleration factors determined in such accelerated tests. The multiple cracking characteristic of SHCC is elaborated in for instance [10–12]. The maximum crack width was larger in the specimens with 15 mm cover (0.50 mm) than those for 25 mm cover (0.36 mm). The actual mass loss of the steel bars was determined by subtracting the mass of the steel bar after the test from its original mass. The mass of all steel bars were determined accurately before they were embedded in the specimens, and again after the corrosion