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Monitoring reinforcement corrosion and corrosion-induced cracking using non-destructive x-ray attenuation measurements

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ABSTRACT

To test the applicability of the x-ray attenuation method to monitor corrosion products as well as the formation and propagation of cracks in cementitious materials, reinforced mortar samples were tested under accelerated corrosion conditions. Experimental results demonstrate x-ray attenuation measurements can track time-dependent development of corrosion products and the subsequent initiation and propagation of corrosion-induced cracks. Also, x-ray attenuation measurements allowed determination of the actual concentration of the corrosion products averaged through the specimen thickness. The total mass loss of steel, obtained by the x-ray attenuation method, was found to be in very good agreement with the mass loss obtained by gravimetric method as well as Faraday's law. Results of the presented experimental approach provide pertinent information for the further development and verification of numerical tools simulating corrosion-induced damage in reinforced concrete.

1. Introduction

Corrosion of reinforcement in reinforced concrete structures is a major deterioration problem causing considerable costs due to durability design, maintenance, and repair needs. Therefore, the development of models to predict the (residual) service life of reinforced concrete structures subjected to corrosion has gained momentum in the past decades. Service life models attempt to describe the initiation and propagation phases of reinforcement corrosion (e.g., Refs. [1–3]) and numerous mechanical models have been developed to describe the subsequent consequences of reinforcement corrosion (i.e., corrosion-induced concrete cracking or spalling) (e.g., Refs. [4–6]). The proposed models can be broadly divided into empirical [4], analytical, [5,7–11], and numerical [6,12–16] models. An initial model to simulate corrosion-induced concrete cracking in Ref. [5] considered only expansion of reinforcement, inducing an internal pressure on the surrounding concrete. This model significantly underestimated the time-to-crack initiation. The initial model was extended and the concept of the “porous” or “diffusion” zone was introduced (e.g., Ref. [8]) to adjust the model to fit experimental data. Later, additional parameters were included in the various models to describe different phenomena related to corrosion-induced concrete cracking, e.g., debonding [12] and creep/shrinkage [14].

The commonly called “diffusion” or “porous” zone is a vital parameter in the proposed corrosion-induced concrete cracking models. The zone describes a region of concrete around the reinforcement which can accommodate expansive corrosion products, delaying stress development in the concrete. This region has a major influence on the predicted time-to-crack initiation and the crack propagation behavior [8,10,15]. These commonly used terms (“diffusion” or “porous” zone) are however potentially misleading and/or confusing. The entire concrete surrounding is porous, not just a certain region in close proximity to the reinforcement. Also, development of solid corrosion products is likely not governed by diffusion alone. Diffusion (i.e., transport of matter due to concentration gradients) may describe the movement of ions present in the concrete pore solution (e.g., Cl^-, Ca^+, K^+) or formed during the corrosion process (e.g., Fe^{2+}, Fe^{3+}) through the concrete pore system. However, solid corrosion products (e.g., Fe_2O_3, Fe_3O_4), which actually induce the internal pressures, precipitate. Therefore, the “diffusion” or “porous” zone is referred to as the corrosion accommodating region (CAR) throughout this paper and is suggested as an alternative term to more accurately describe this region.

Inconsistent values are cited for the CAR, ranging from 0.002 to approximately 0.12 mm in thickness [7]. In some cases, the size of the CAR is “determined” by adjusting the value to provide model outputs in line with experimental results [8,9,15,16]. Other experimental methods (e.g., image correlation [10], acoustic emission [17], ultrasound and thermography [18], etc.) are capable of detecting corrosion-induced damages; however, to date these techniques are not capable of providing simultaneous real-time measurements on the amount and/or location(s) of corrosion products. Experimental

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