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Corrosion of reinforcing steel in concrete sewers

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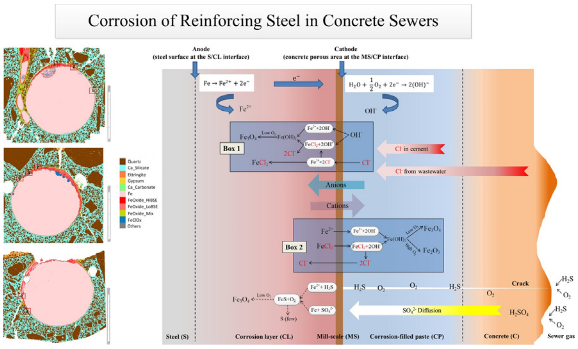
HIGHLIGHTS

- A first thorough investigation of rebar corrosion in sewers
- Rusts at steel/concrete interface characterized by mineral analytical techniques
- H_2S and sulfuric acid are not directly involved in sewer rebar corrosion.
- Chloride initiates rebar corrosion in sewers and forms a chloride-enriched layer.
- A conceptual model about corrosion processes of sewer rebar is established.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydrogen sulfide is a controlling factor for concrete corrosion in sewers, although its impact on sewer rebar corrosion has not been investigated to date. This study determined the corrosion mechanism of rebar in sewers by elucidating the roles of chloride ions, apart from the effects of hydrogen sulfide and biogenic sulfuric acid. The nature and distribution of rusts at the steel/concrete interface were delineated using the advanced mineral analytical techniques, including mineral liberation analysis and micro X-ray diffraction which is the first-ever use in such studies. The corrosion products were found to be mainly iron oxides or oxy-hydroxides. H_2S and biogenic sulfuric acid did not directly participate in the product formation of steel partly covered by concrete or directly exposed to sewer atmosphere. Instead, chloride ions played an important role in initiating steel corrosion in sewers, supported by a thin chloride-enriched layer at the steel/rust interface. Away from the chloride-enriched layer, iron oxides accumulated on both sides of the mill-scale to form a corrosion layer and corrosion-filled paste respectively. The corrosion layer around rebar circumference was non-uniform and the rust thickness with respect to polar coordinates followed a Gaussian model. These findings support predictions of sewer service lifetime and developments of corrosion prevention strategies.

1. Introduction

Sewer networks are essential urban infrastructures for collecting and safely transporting wastewater to treatment facilities. Hydrogen sulfide (H_2S), which is produced in sewers especially under anaerobic

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conditions, is well recognized for shortening the service lifetime of these installations due to the microbial-induced concrete corrosion (Lin et al., 2017; Parker, 1947; Pikaar et al., 2014). The corrosion causes loss of concrete mass, cracking of concrete cover and ultimately, the structural collapse. The rehabilitation and replacement of corroded sewers is estimated to cost several billion dollars annually worldwide (Sterling et al., 2010), and the cost is expected to increase as the aging sewers continue to fail (EPA, 1991).

Concrete pipes used in wastewater systems can be of plain concrete or steel reinforced. Usually, for pipes with diameters larger than 0.60 m, it is common to have a sufficient number of steel bars designed to withstand a combination of internal pressure and external loads (Nnadi and Lizarazo-Marriaga, 2012; Grengg et al., 2018; Joshi, 2015). A recent study commented that reinforced concrete pipes, with wider ranges of sizes (12–72 in) and relatively low corrosion rates compared to metallic pipes, are prevalent among ductile iron, vitrified clay, polyvinylchloride (PVC), composite fiber reinforced polymer (FRP) and high density polyethylene (HDPE) pipes (Vahidi et al., 2016). Corrosion of concrete sewers involves a range of abiotic and biotic processes. The process proceed by initial acidification by carbonate and sulfide and then progress to more damaging chemical reactions between the biogenic produced sulfuric acid and the cementitious materials (Noeiaghaei et al., 2017; Parker, 1945a, b; Parker, 1947). As the concrete corrosion develops, the reinforcing steel that is originally protected by concrete matrix also suffers from possible corrosion. Factors contributing to steel corrosion could be summarized as follows: the reduced alkalinity of surrounding concrete, of which the pH could reach 2–4 due to the biogenic sulfuric acid produced in the corrosion process (Jahani et al., 2001; Jiang et al., 2014b); the ingress of H_2S, CO_2, oxygen and wastewater through concrete cracks to rebar surface (Parande et al., 2006); the direct exposure of rebar by regional concrete scaling or spalling that may occur in the later stages of service life (Fandrich et al., 2007). These factors can enhance steel corrosion in a short time period. However, most studies on sewer deterioration to date concentrate only on the concrete corrosion (Islander et al., 1991; Joseph et al., 2012; Parker, 1945a, b). There is poor understanding of the fundamental aspects of reinforcing steel bar corrosion in the sewer environment. The corrosion mechanism, i.e. the detailed reactions involved, and the nature and distribution of corrosion products, remains to be elucidated.

In spite of this lacking knowledge of the sewer rebar corrosion, there are many studies reporting rebar corrosion as a major cause of durability problems in other reinforced concrete structures such as concrete buildings, bridge decks, marine structures, slabs and floors (Lu et al., 2018). The electrochemical process causes the dissolution of iron to form various corrosion products, such as iron oxides, hydroxides and hydrated oxides, the nature of the products being dependent on the exposure environment (Bertolini et al., 2013; Lu et al., 2018). In these studies, chloride ions are considered as one of the major causes of the steel corrosion (Sanchez-Silva and Rosowsky, 2008). The dissolved chlorides from the external environment could permeate through sound concrete or cracks to the steel surface thus inducing corrosion of the steel bar (Grengg et al., 2018). In sewers, however, gaseous H_2S and the biogenic sulfuric acid, produced in corrosion biofilms (Parker, 1945a, b), are commonly accepted to be the corrosive substances rather than chlorides (Fernandes et al., 2012). In the active corrosion regions of sewers, such as the pipe crown area (Jiang et al., 2014a; Jiang et al., 2015b), the roles and interactions of chloride, H_2S and sulfuric acid in the rebar corrosion process are unknown.

It is reported that the direct contact with H_2S can encourage steel corrosion to a level of 12.8 mm/year (Tiller, 1990), and sulfides are intensive corrosion stimulators (Heitz et al., 1996). However, steel corrosion in concrete is likely more complicated due to impediment of H_2S diffusion, the protective and heterogeneous concrete layers, which are subjected to degradation themselves. Although a study (Sanchez-Silva and Rosowsky, 2008) proposes that H_2S produced in the sewer could diffuse to the metal surface and form FeS, no rigorous attempts have been made to identify the reactions. Other studies on H_2S-induced steel corrosion usually employ accelerated tests using high voltages or excess H_2S concentrations (Idriss et al., 2001; Parande et al., 2006), of which the conditions would be quite different from those in real sewers, such as H_2S concentrations, relatively humidity, pH, and temperature.

When steel corrosion is initiated, corrosion products at the steel/concrete interface are found to cause expansive stresses on the surrounding concrete by obtaining around 2–6 times the volume of the original steel (EPA, 1991; Lu et al., 2018). Consequently, the main structural damage is not the loss of steel cross-sections, but the concrete cracking. A two-stage model is proposed for the steel corrosion-induced concrete cracking which involves: (1) rust growing, migrating and filling the porous zone around the steel/concrete interface, and (2) rust causing expansive pressure on the surrounding concrete (Wong et al., 2010; Zhao et al., 2013; Zhao et al., 2012b). It was reported that the rust migration is greatly increased in the presence of chloride ions. However, in sewers affluent in H_2S, whether the chloride-facilitated rust migration occurs is largely unknown. To better understand correlations between the steel corrosion and concrete cracking in sewers, a more detailed characterization of rust distribution at the steel/concrete interface is highly required.

In the present study, a long-term exposure experiment (45 months) was conducted to investigate the corrosion mechanism of rebar in sewers when the concrete cover was gradually removed due to the sulfide-induced concrete corrosion. This was performed using the reinforced concrete samples exposed to simulated sewer conditions in a laboratory corrosion chamber with well-controlled conditions of H_2S concentrations, relative humidity and temperature. In particular, the nature and distribution of corrosion products at the steel/concrete interface were delineated using various advanced mineral analytical techniques and modeling. As a first thorough investigation of rebar corrosion in sewers, this study provides significant improvement to the understanding of the corrosion processes in concrete sewer systems.

2. Material and methods

2.1. Reinforced concrete coupons

The concrete coupons were prepared using corroded reinforced concrete obtained from a main trunk sewer of Sydney Water Corporation, Australia. Generally, those pre-corroded concrete consisted of quartz (aggregates and sand particles) and calcium silicate accounting for around 13.1% and 22.2%, respectively. Details of the coupon preparation were described elsewhere (Jiang et al., 2014a; Jiang et al., 2015b; Jiang et al., 2014b). The coupons were cut to a size that was approximately 100 mm (length) × 70 mm (width) × 70 mm (thickness). Each coupon contained a section of plain round steel bars with a nominal diameter of 12 mm, and the concrete cover above the steel bar surface was between 5 and 20 mm. There was no evidence of existing rebar corrosion in the concrete coupons.

After cutting, the coupons were washed in fresh water to remove the existing 2–4 mm corrosion layer of concrete and any surface contamination. Washed coupons were immediately dried in an oven (Thermotec 2000, Contherm) at 60 °C for 3 days to achieve a stable initial water content and then were embedded in stainless steel frames using epoxy (FGI R180 epoxy & H180 hardener). The stainless steel frame had outside dimensions of 230 mm (length) × 110 mm (width) × 60 mm (thickness). After concrete coupons were placed inside the frames, the epoxy resin was injected until the level of the epoxy resin reached the upper rim of the frames. Once the resin was hardened, a flat surface would form at the surface of the epoxy resin and the upper rim of the frames. Because of the thickness difference between the coupon and the stainless steel frame, some blank gaps would appear between the resin and the coupon.