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Identification of controlling factors for the initiation of corrosion of fresh concrete sewers

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ARTICLE INFO

Article history:
Received 20 February 2015
Received in revised form
14 April 2015
Accepted 15 April 2015
Available online 6 May 2015

Keywords:
Sewer
Corrosion
Hydrogen sulfide
Humidity
Temperature
Initiation time

ABSTRACT

The development of concrete corrosion in new sewer pipes undergoes an initiation process before reaching an active corrosion stage. This initiation period is assumed to last several months to years but the key factors affecting the process, and its duration, are not well understood. This study is therefore focused on this initial stage of the corrosion process and the effect of key environmental factors. Such knowledge is important for the effective management of corrosion in new sewers, as every year of life extension of such systems has a very high financial benefit. This long-term (4.5 year) study has been conducted in purpose-built corrosion chambers that closely simulated the sewer environment, but with control of three key environmental factors being hydrogen sulfide (H_2S) gas phase concentration, relative humidity and air temperature. Fresh concrete coupons, cut from an industry-standard sewer pipe, were exposed to the corrosive conditions in the chambers, both in the gas phase and partially submerged in wastewater. A total of 36 exposure conditions were investigated to determine the controlling factors by regular retrieval of concrete coupons for detailed analysis of surface pH, sulfur compounds (elemental sulfur and sulfate) and concrete mass loss. Corrosion initiation times were thus determined for different exposure conditions. It was found that the corrosion initiation time of both gas-phase and partially-submerged coupons was positively correlated with the gas phase H_2S concentration, but only at levels of 10 ppm or below, indicating that sulfide oxidation rate rather than the H_2S concentration was the limiting factor during the initiation stage. Relative humidity also played a role for the corrosion initiation of the gas-phase coupons. However, the partially-submerged coupons were not affected by humidity as these coupons were in direct contact with the sewage and hence did have sufficient moisture to enable the microbial processes to proceed. The corrosion initiation time was also shortened by higher gas temperature due to its positive impact on reaction kinetics. These findings provide real opportunities for pro-active sewer asset management with the aim to delay the on-set of the corrosion processes, and hence extend the service life of sewers, through improved prediction and optimization capacity.

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http://dx.doi.org/10.1016/j.watres.2015.04.015

Nomenclature

ANOVA	Analysis of variance
MAM	Minimum adequate model
MIC	Microbially induced corrosion
PLC	Programmable logic controller
SRB	Sulfate-reducing bacteria
SOB	Sulfide-oxidizing bacteria
RH	Relative humidity
RTD	Resistance temperature detector

1. Introduction

Existing sewers are valuable infrastructure and assets that have been established by continuous public investment over the period of more than the past century. These sewers have an estimated asset value of one trillion dollars in the USA (Brongers et al., 2002) and $100 billion in Australia. However, concrete corrosion is a costly deteriorating process affecting sewer systems worldwide. Corrosion causes loss of concrete mass and structural capacity, cracking of the sewer pipes and ultimately structural collapse. The rehabilitation and replacement of damaged sewers involves very high costs. The sewer assets are being lost at an estimated annual economic cost of around $14 billion in USA alone (Brongers et al., 2002) due to corrosion. This cost is expected to increase as the aging infrastructure continues to fail (Sydney et al., 1996; US EPA, 1991).

Population growth and urbanization have led to continuous expansion of existing sewers and replacement of outdated sewers. Fresh concrete sewer pipes and structures are installed worldwide due to many advantages including low costs and flexibility. However, knowledge about the development of corrosion on new concrete surfaces under sewer conditions is limited. Gravity sewers offer favorable conditions for microbially induced corrosion, such as available water (due to elevated relative humidity (RH)), high concentrations of carbon dioxide, and high concentrations of H_2S (Wei et al., 2014). However, the fresh concrete surface after construction is not suitable for microbial growth because of the high alkalinity. Therefore, an initiation period is required to make the surface amenable for sulfide oxidizing microorganisms.

The development of corrosion on concrete sewers can be divided into three stages, as shown in Fig. 1. During stage 1, the concrete surface is changed to a more favorable environment for microorganisms due to carbonation and H_2S acidification (Islander et al., 1991; Joseph et al., 2012). On the new concrete surface, owing to the presence of catalytic oxides, hydrogen sulfide is chemically oxidized to sulfur in the form of very small crystals (Bagreev and Bandosz, 2004, 2005). Overall, an important step is the dissociation of hydrogen sulfide to HS^- in the adsorbed film of water on the concrete surface. This dissociation is enhanced by the alkaline surface pH, which is an important factor for the uptake of gaseous hydrogen sulfide during this first stage (Nielsen et al., 2006). Additionally, the chemical sulfide oxidation rate in the sewer is seen to double for a temperature increase of 9 °C by the same study.

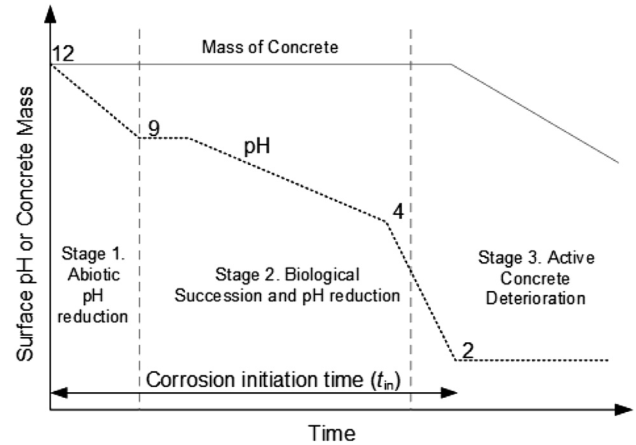

Fig. 1 – The development of microbially induced corrosion on new concrete sewer surfaces, adapted from Islander et al. (1991), with the corrosion initiation time (t_{in}) including stage 1, 2 and a part of stage 3.

Therefore, relative humidity, H_2S concentration and temperature all play a certain role in stage 1 of the corrosion development.

During stages 2 and 3, biological sulfide oxidation by netruophilic and acidiophilic sulfide oxidising-bacteria will contribute to the sulfide oxidation to produce sulfuric acid (Cayford et al., 2012; Okabe et al., 2007). This reacts with the cement material leading to the formation of two important corrosion products: gypsum ($CaSO_4 \cdot 2H_2O$) in the matrix of the corrosion layer and ettringite ($(CaO)_3 \cdot Al_2O_3 \cdot (CaSO_4)_3 \cdot 32H_2O$) near the corrosion front where there is higher pH (Jiang et al., 2014b; O'Connell et al., 2010). Recent studies show that the biological sulfide oxidation rates correlate with H_2S concentration, relative humidity and temperature (Jiang et al., 2014a; Nielsen et al., 2006, 2005).

The total time span starting from fresh concrete surface to observed mass loss of concrete is defined as the initiation time, i.e. t_{in}. It is clear that the length of initiation time depends on many different factors due to the many processes and reactions involved. For a specific sewer environment, it is beneficial to estimate t_{in} for the purpose of evaluating or optimizing current corrosion prevention strategies. Although the well-known Pomeroy model can be used to calculate the deterioration rate of concrete sewer pipes (Pomeroy, 1990), no model exists for the estimation of t_{in} which is mainly due to the limited understanding of the controlling factors for the corrosion initiation. Therefore, a full understanding of the relationship between t_{in} and sewer environmental factors including H_2S concentration, relative humidity and temperature is critical for the overall prediction of sewer corrosion.

This study aims to enhance understanding of the correlation between the initial development of sewer corrosion and the sewer environmental factors including H_2S concentration, relative humidity and temperature. In particular, to determine the controlling factors important for the corrosion initiation time t_{in}. Fresh concrete coupons, either located in the gas-phase or partially submerged in domestic wastewater, were