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# Modelling concrete deterioration in sewers using theory and field observations

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ABSTRACT

Samples of new and 70 year old pre-corroded OPC concrete were exposed for up to 48 months in 6 sewers throughout Australia. Corrosion losses at each site followed the bi-linear trend originally proposed by Wells and Melchers [1]. During an initial phase (lasting <2 years) negligible loss of material occurs however once the surface pH = 6 losses commence and accumulate linearly at a rate that is likely to remain constant over time. Corrosion rates were found to be sensitive to humidity but insensitive to concrete alkalinity. A first pass model which predicts the rate of concrete sewer pipe corrosion from a knowledge of local average sewer gas temperature, humidity and $H_2S$ concentrations was also developed. The equation predictions were in good agreement with rates determined from field observation and historical data.



## 1. Introduction

Long-term deterioration is a major challenge for the continued reliable and economic performance of reinforced concrete sewer pipelines in wastewater infrastructure systems used in many major cities worldwide. In many cases the concrete sewer piping currently in use has been in place for many decades. For example Kaempfer and Berndt [2] estimated that 35% of the sewer network in Germany is over 60 years old. This raises serious issues for wastewater utilities of prioritizing remedial and replacement work and of minimizing disruption and other costs, including consequential costs. It follows that predicting the time to failure of existing reinforced concrete sewer systems is an important issue for wastewater utilities. However, reliable prediction requires an adequate understanding of the deterioration process and how this is influenced by operational and environmental conditions. Ideally such understanding is then translated into a quantitative model that builds on actual, quantified, observations of corrosion losses (such as obtained from visual and other inspections of pipes in service) together with quantified information on the most relevant environmental and other influences. Construction of such a model, using in-service data from a variety of sources, is the aim of the present work.

Much of the deterioration of concrete sewer pipes is the result of microbial induced corrosion (MIC) of the internal concrete surfaces under moist acidic conditions. The main mechanisms for such deterioration are well established and involve interactions between the sewage (or wastewater) stream in the lower part of the sewer and the gaseous phase above. A key factor is that biofilms form on the concrete in the part of the sewer submerged in wastewater. The sulphate reducing bacteria (SRB) present in the biofilms convert the sulphates in the wastewater to $H_2S$. Diffusion and turbulence of the wastewater stream then facilitates the release of the $H_2S$ into the sewer atmosphere. There it is absorbed onto the moist upper surfaces of the concrete pipe where both abiotic and biotic processes produce a number of sulfur species including sulfuric acid ($H_2SO_4$) [3]. The acid so produced reacts with the alkaline minerals within the concrete matrix to produce highly expansive minerals such as gypsum and ettringite. These are known to reduce the structural strength of the concrete and this, ultimately, may lead to structural failure of the pipe.

Based on the main features of the deterioration process outlined above, a previous study [1] showed that the long-term corrosion behaviour of concrete sewer pipes under aggressive conditions could be represented by a bi-linear function of exposure time. This was based on in-situ corrosion data obtained for concrete pipe samples exposed for 31 months in a sewer with very high $H_2S$ concentrations at Perth, Australia. The purpose of the present paper is to examine, using other field data and observations, whether the bi-linear functional form is applicable more generally and in particular under less aggressive conditions, as well as to evaluate the effect of such conditions on the quantification of the bi-linear model. As described below, this includes the influence of sewer gas $H_2S$ concentration, humidity and temperature. Developing such quantification will allow the bi-linear model to be compared with theoretical concepts for concrete sewer pipe deterioration that have been developed previously in the literature. It is acknowledged that in-situ field trials of the type used here involve an unavoidable level of inter- and intra-site variation in environmental conditions as well as sampling issues for corrosion coupons. However, provided this is recognized in the analysis and the model-building

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process, the results have a higher chance of representing reality than can be achieved purely with laboratory testing. Similar issues are well-recognized in comparable research activities [4].

In summary, the aims of the present study are:

(1) Assess whether the corrosion trends observed in the previous study under highly corrosive conditions are also relevant under more benign exposure conditions,
(2) Assess the degree to which the bi-linear model can be rationalized against known concrete sewer corrosion mechanisms and in particular examine the links between the onset of corrosion and surface pH, and
(3) Calibrate the bi-linear model for concrete sewer corrosion against local average environmental conditions such as sewer gas $H_2S$ concentration, humidity and temperature.

## 2. Background

Microbiologically induced corrosion (MIC) of reinforced concrete sewer pipe was first observed over a century ago by Olmstead and Hamlin [5] and linked to the activity of Thiobacillus bacteria in the mid-20th century [6–9] and later to other bacterial and fungal species [10–15]. Recently concrete losses in sewers have been observed, mainly anecdotally, to have increased considerably possibly as a result of the reduction in discharge to sewers of biologically toxic metals [16,17], increased discharge to sewers of high sulfur detergents [18] and the increased length of sewer lines (and hence sewage residence times) [19].

The evolution of concrete sewer pipe corrosion as a function of time is the result of the complex interaction between abiotic and biotic processes, the latter involving many different microbial communities [20]. Islander et al. [20] proposed that this evolution could be represented by a three stage model, dominated in the early stages by abiotic corrosion, followed by two overlapping stages of biotic corrosion governed by neutrophilic species once surface pH fell below 9 and then by more aggressive acidophilic bacteria once the surface pH has fallen below 4. Quantitative assessment of the Islander model has focused primarily on sewer pipes in advanced stages of corrosion (e.g. [12,21,22]) with only a small number of studies concentrating on the initial stages of sewer pipe corrosion [23,24] while very few studies, [1], have managed to assess initial and advanced stages of the corrosion process.

Because of the complexity of the processes involved, the reliable prediction of concrete sewer pipe deterioration has been considered difficult to achieve [25]. Many factors impact on the proliferation and activity of corrosion causing bacteria on the pipe surface and hence have a bearing on the rate at which losses occur. Factors include: pipe wall and sewer atmosphere temperature; pipe wall moisture content (via capillary condensation, contact with aerosols or direct contact with the wastewater stream [20]); surface pH [20]; the physical and chemical nature of the corrosion product layer formed; concrete porosity and the supply of nutrient to the bacteria (sulfur in a number of forms, nitrogen, carbon and mineral salts [26]). Sulfur supply is dictated by the chemistry of the wastewater stream and the rate of transfer between the wastewater and sewer atmosphere (a function of sewage pH, temperature and gas and liquid turbulence [27]) as well as the rate of absorption of $H_2S$ back into the moisture film in the upper pipe [28].

The chemistry of the cementious and aggregate material within the concrete is also believed to impact on the rate or corrosion. The use of high-alumina cements, calcareous aggregates and the inclusion of substances toxic to microorganisms have all been shown to have varying degrees of success in slowing down the rate of corrosion experienced by concrete sewer pipes (for example see [19,26,29,30]). Thistlethwayte [26] however reports that there is little evidence to show that increasing concrete strength or decreasing permeability improves corrosion resistance.

Ideally predictive models should consider all of the above parameters however the above list includes a number of parameters that may not be known, as well as a number of abiotic and biotic processes not all of which are, as yet, fully understood. The traditional approach used to overcome this issue has been to use semi-empirical methods, based primarily on the equations developed by Pomeroy [31]:

$$C = 11.5k\phi_{sw}A^{-1} \quad (1)$$

where $C$ is the average rate of corrosion of concrete by acid (mm year$^{-1}$), $\phi_{sw}$ is the flux of $H_2S$ to the pipe wall (gS m$^{-2}$ hr$^{-1}$) and $A$ is the alkalinity of the sewer pipe wall expressed as $CaCO_3$ equivalent. The factor $k$ accounts for the fraction of acid produced that contacts the sound concrete and takes part in the corrosion process (acknowledging that a fraction of the acid produced is washed back into the wastewater stream). When acid formation is slow $k$ may approach unity but it may be as low as 0.3 to 0.4 in conditions where acid production is rapid. The value assigned to $k$ therefore has a large influence on the corrosion rate predicted by Eq. (1). Despite its importance, there appear to have been no studies to assess the magnitude of $k$, [3].

Attempts to build less empirical models include that of Böhm et al., [32] who used a moving boundary idealization to model the sewer pipe corrosion process and which incorporated the porous structure of the pipe wall. A large number of parameters were required in the formulation and the authors concluded that this rendered the model unlikely to produce reliable predictions for real systems. More recently, Jensen [28], when combining models for $H_2S$ removal rates and oxidation kinetics with an existing model of dissolved oxygen and organic matter transformations in sewers (WATS model, [33]), noted that the concentration of $H_2S$ oxidising biomass on the concrete surface is a key parameter in predicting the rate of corrosion.

The present study follows a semi-empirical approach, by-passing much of the complex and poorly understood microbiological detail. It concentrates, as in the earlier work [1], on the effect of the local sewer environment on the rate at which corrosion losses occur. The next section describes an experimental program conducted over several years to attempt to overcome the acute scarcity of reliable data for sewer corrosion and the relevant environmental parameters. This is followed by the further investigation of the bi-linear model and the effect on it of three key parameters – sewer gas temperature, humidity and $H_2S$ concentration. It includes consideration of the physical and chemical processes involved, the concrete chemistry and how these are reflected in the bi-linear relationship. In addition, historical literature data is considered to test the validity of the model.

## 3. Experimental design

The methodology employed for the experimental work in this study is similar to that previously reported [1]. A summary is as follows.

### 3.1. Materials

Two different OPC concretes cut to 100 mm nominal cubes were exposed in each sewer. One set of samples, ('new' coupons), were cut from newly manufactured 1.2 m ID spun cast standard reinforced concrete sewer pipe. A second set, ('old' coupons), were cut from reinforced concrete slabs that had served for 70 years as covers for a typical operating sewer carrying domestic, industrial and trade waste. Old coupons retained a ~2 mm covering of crystalline corrosion product. The use of the two concretes permitted direct observation of corrosion of realistic concretes at different time intervals - at the commencement of the life of the sewer pipe and at a more advanced stage when corrosion is well established. The aggregates for the new coupons primarily consisted of sub-rounded 10–15 mm dacitic volcanics and chert with lesser amounts of quartzite, quartz and rhyolitic volcanics. Old coupon