1. Understanding concrete sewer pipe corrosion

1.1 Brief history

Concrete sewer pipe corrosion was first observed towards the end of the 19th century when it was rightly concluded that sulphuric acid was the corrosive agent however it wasn't until the 1940's that the biological nature of the concrete corrosion process was established through work undertaken in Australia and the USA when the bacterium "Thiobacillus concretivorous", (later renamed Acidithiobacillus Thiooxidans) was identified amongst the acidic corrosion products. Today we know that there are many bacterial and fungal species involved in the concrete sewer pipe corrosion cycle.

Microbial induced corrosion (MIC) of concrete sewers was not regarded as a significant issue until the 1980's when corrosion rates in sewers increased significantly in the USA, Europe and Australia. At this time tighter controls placed on industrial wastewaters to be discharged to the sewer system (e.g. the US Clean Water Act) led to significantly lower levels of biologically toxic metals such as lead, mercury and arsenic in the sewer system and as a consequence bacterial levels (and consequently MIC) increased dramatically.

Modern day increases in corrosion activity are also linked to:

- increased sewage temperature, (due to increasing use of hot water in domestic situations)
- increased use of sulphate containing detergents
- increase in sewer line lengths (and hence sewage residence times)

MIC of reinforced concrete sewer pipe is currently considered one of the most serious and costly problems currently affecting the world's sewer infrastructure with the global repair bill for MIC corrosion of sewer piping estimated to be in the order of billions of dollars per year.

1.2 Overview

Concrete sewer pipe is corroded by acids produced in the sewer from chemical and microbial processes. Microbial induced corrosion (MIC) however is responsible for most of the corrosion that takes place.

The basic sewer processes that drive concrete corrosion activity are illustrated in Figure 1. The corrosion cycle begins in the wastewater stream. Colonies of anaerobic sulphate reducing bacteria (SRB) active in biofilm layers that line the submerged sewer walls reduce sulphates and oxidise biodegradable organic carbon producing hydrogen sulphide and carbon dioxide:

$$\text{Organic matter} + SO_4^{2-} \xrightarrow{SRB} H_2S + CO_2$$

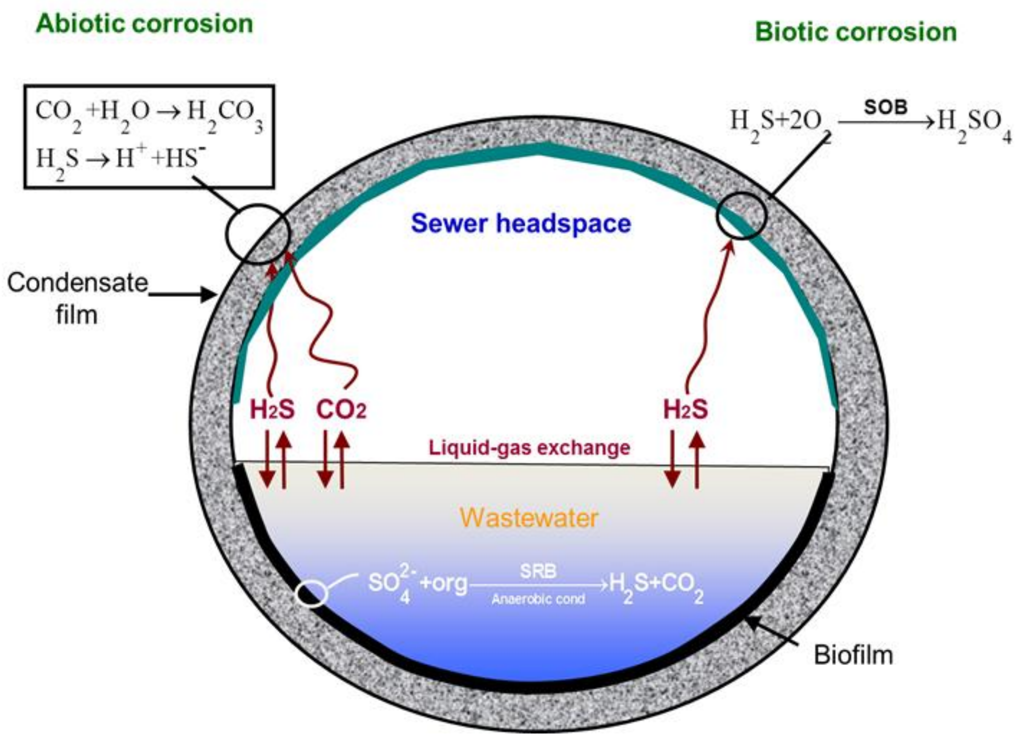

Figure 1. Schematic of sewer processes driving corrosion.

H_2S and CO_2 are transported through the biofilm into the wastewater stream where some is volatilised into the sewer headspace. The gases diffuse through the headspace atmosphere and dissolve into moisture present in the concrete pores of the upper section of the sewer pipe. The dissolved H_2S and organic material deposited on the sewer pipe surface by washing or condensing aerosols are the nutrients which drive the microbial corrosion process.

Corrosion of a concrete sewer pipe proceeds over a number of stages from the time of installation until pipe failure. As a result the rate at which the pipe is corroded changes with time. The following discussion is a brief summary of that process.

1.2.1 Chemical corrosion during the initial months.

- When a concrete sewer pipe is first manufactured and installed the interior surface of the pipe is too alkaline (pH>10.5) for bacterial or fungal colonisation to take place.
- Under these circumstances only the chemical corrosion of the pipe is possible.
- H_2S and CO_2 dissolve in the concrete pore water to form weak acids:

$$H_2S \text{ Ä } HS^- + H^+$$

$$CO_2 + H_2O \text{ Ä } H_2CO_3 \text{ Ä } HCO_3^- + H^+ \text{ Ä } CO_3^{2-} + 2H^+$$

- The weak acids formed react with strong basic minerals (especially portlandite , $Ca(OH)_2$) present in the cement binder of the concrete

- During this initial stage no concrete is lost but the neutralisation of some of the basic minerals in the concrete does lead to a decrease in the pH of the exposed surface of the sewer pipe.
- This attack is limited to the outer exposed skin of the pipe (<0.5mm deep)
- The purely chemical attack on the sewer pipe only last for a number of months.
- By the end of this stage of the corrosion cycle the surface pH has dropped to the point where biological processes dominate the corrosion process.

1.2.2 Neutrophilic colonisation of the pipe surface.

- When the pH of the surface of the pipe has fallen to pH=9 fungal and bacterial colonies (so called neutrophilic or “neutral loving” bacteria) begin to appear on the pipe surface.
- As the surface of the pipe becomes more acidic successive waves of bacteria more suited to lower pH conditions will dominate the pipe surface.
- Neutrophilic bacteria produce carboxylic acids as well as sulphuric acid from the oxidation of a number of sulphur species present on the pipe surface.
- The production of these acids acts to further lower the pH of the sewer pipe surface but no measurable loss of mass has as yet occurred.

1.2.3 Sound concrete loss begins.

- When the pH of the surface of the sewer pipe falls to pH=6 significant conversion of sound concrete to corroded product (mostly gypsum) begins.
- The time taken to reach this point in the corrosion cycle varies from site to site (depending on the environmental conditions present) but will generally be between 6 months to 2 years from the date of installation.
- Once mass loss begins the rate at which concrete is lost per year remains constant for the remainder of the pipe’s service (if sewer conditions remain constant).
- The rate at which concrete is lost however varies from site to site and is dependent on a number of environmental factors.
- The surface pH will continue to fall after mass loss begins but the rate at which it falls slows.
- As sound concrete loss continues a layer of corroded product builds on the pipe surface however this layer does not affect level of corrosion activity and the rate of corrosion remains constant.
- When the amount of concrete lost over time is plotted the corrosion function takes the following general form:

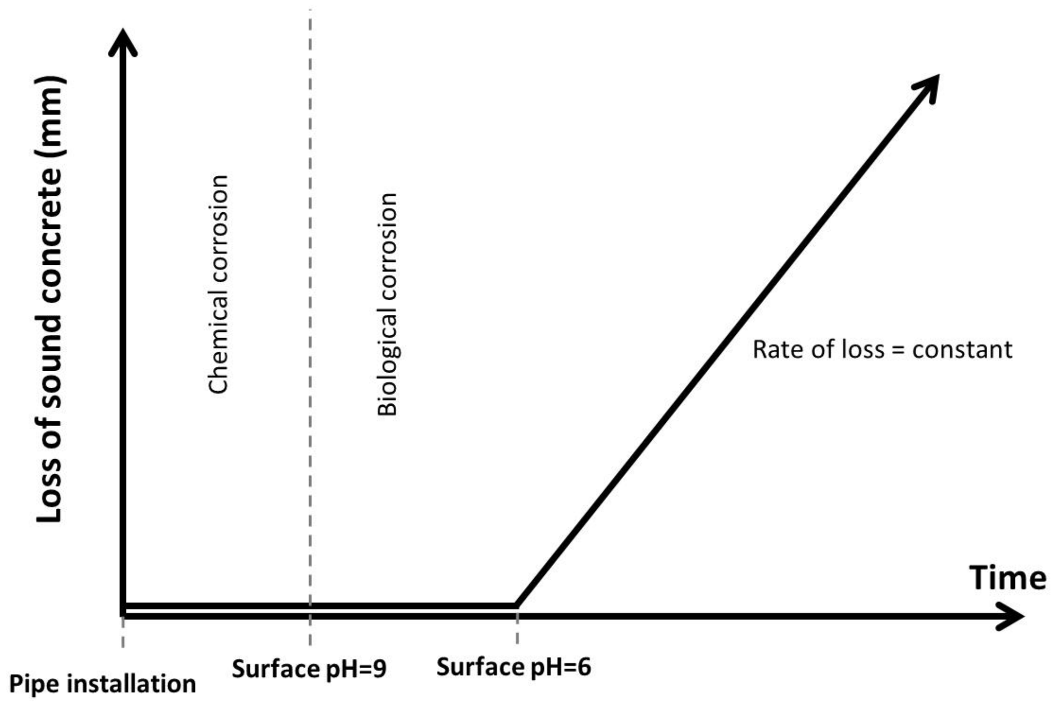

Figure 2. The corrosion of concrete sewer pipe over time.

1.3 Factors affecting the rate of concrete sewer pipe corrosion.

The rate at which sound concrete is corroded (once the surface pH<6) varies from site to site depending on the nature of the local sewer environment.

1.3.1 Impact of H_2S concentration in the sewer headspace.

- As the H_2S concentration in the sewer headspace increases so does the rate of corrosion.
- Field studies and literature data suggest that the rate of corrosion increases with the square root of the H_2S concentration:

$$\textit{rate of corrosion} \propto \left([H_2S]_{gas}\right)^{0.5}$$

1.3.2 Impact of sewer headspace temperature.

- As the sewer temperature increases the rates of biological activity increases as well as the rates of reaction between the acids produced and concrete.
- The impact of sewer gas temperature (averaged over time) on the rate of corrosion can be described by the following expression:

$$\textit{rate of corrosion} \propto e^{\left(-30{,}000/\left(R\times(T+273)\right)\right)}$$

1.3.3 Impact of sewer headspace humidity

Concrete is a porous material. As sewer headspace humidity increases more of the pores within the concrete are filled with water until at 100% humidity all pores are filled. The activity of bacteria responsible for corrosion increases in an aqueous environment. Consequently as concrete moisture content increases the rate of corrosion increases.

- The impact of humidity on the rate of corrosion depends on the distribution of pore sizes within the concrete and thus will be different for different sewer pipes.
- At humidities <85% corrosion is greatly inhibited (the sewer wall feels "dry")
- As humidity increases above 95% the rate of corrosion increases rapidly with increasing humidity
- The impact of humidity can be approximated by the following expression:

$$\textit{rate of corrosion} \propto \frac{(1-0.01245\times RH(\%))}{(0.0955\times RH(\%)-9.8044)}$$

Other factors that can affect the rate of corrosion include:

- The temperature of the sewer pipe relative to the sewer headspace gas.
    - The temperature of the sewer pipe can sometimes be different to the sewer atmosphere inside (especially if the pipe is exposed above ground). This can have a significant impact on the level of moisture condensing within the concrete pore structure which in turn can affect the level of corrosion activity.
- The lining of other sections of the sewer pipe.
    - Lining of sections of the sewer pipe can reduce the ability of the pipe as a whole to absorb H_2S being produced in the wastewater stream increasing H_2S concentrations in the sewer headspace. The outcome is higher corrosion activity at the remaining unlined sections of pipe in the same system.

Further information can be obtained as follows:

<u>Microbial corrosion of sewer pipe:</u>

Microbial Ecology of Crown Corrosion in Sewers, Journal of Environmental Engineering-Asce, 117 , 751-770 by Islander et al. (1991).

Succession of Sulfur-Oxidizing Bacteria in the Microbial Community on Corroding Concrete in Sewer Systems., Applied and Environmental Microbiology, 73, 971-980 by Okabe et al., (2007)

<u>Corrosion in Australian sewers</u>

Microbial corrosion of sewer pipe in australia - initial field results, in: 18th International Corrosion Conference, Perth, W.A., Australia, 2011, pp. Paper no. 183 by Wells and Melchers (2011).

ARC Corrosion Linkage Project Final Report on Identification of controlling factors for the corrosion rate of concrete (Sp1B)