MICROBIAL CORROSION OF SEWER PIPE IN AUSTRALIA- INITIAL FIELD RESULTS.

PA (Tony) Wells¹ and Robert E. Melchers¹
¹ Centre for Infrastructure Performance and Reliability,
The University of Newcastle, Australia

SUMMARY: Microbial induced corrosion (MIC) of concrete sewers pipes is a significant global problem incurring losses in the order of billions of dollars per year. While the basic theory of the MIC process is understood management of sewer corrosion is hindered by a limited understanding of several key in-sewer processes. This paper describes the initial findings of a program of fieldwork in which newly cast and pre-corroded concrete samples have been installed in sewers around Australia and allowed to corrode for a period of up to 12 months under a range of environmental conditions. The first 12 months exposure to the sewer environment has produced noticeable changes in virtually all coupons recovered. Surface pH has been lowered from a starting level of 10.3 down to as low as pH=6 over the year on new coupons and from pH=8.1 down to as low as 3.5 for pre-corroded coupons. Generally the rate of acidification has been a strong function of H₂S concentration in the sewer headspace with pre-corroded coupons experiencing more rapid decreases for a given H₂S concentration. Extensive corrosion of sound concrete has also been observed on pre-corroded samples over this period while minor losses are becoming apparent on new coupons. The combination of pH change, concrete losses and appearance of biological activity on the coupon surface all point to a rapid transition through an initial abiotic corrosion phase to the next stage in which corrosion is the result of neutrophilic microbial activity. A comparison of the early corrosion activity of new and pre-corroded coupons and anomalous readings at one high H₂S location also indicate that the corrosion rate will most likely vary in a complex fashion over time and will be influenced by a variety of environmental factors in addition to H₂S levels. As more field data is collected and complementary laboratory and biological data become available a realistic, phenomenological model of this process will be developed allowing the service life of sewer pipes in Australia to be realistically predicted.

Keywords: Concrete corrosion, hydrogen sulphide, sewers, microbial, model.

1. INTRODUCTION

Sulphuric acid corrosion of concrete sewer pipes was observed as long ago as 1900 (Olmstead and Hamlin 1900) but it wasn’t until the 1940’s that the biological nature of the corrosion process was established when the bacterium “Thiobacillus concretivoros” was identified among the acidic corrosion products (Parker 1945a; 1945b and Pomeroy and Bowlus 1946). Microbial induced corrosion (MIC) of concrete sewer pipes however was not regarded as a significant issue until the 1980’s when corrosion rates were observed to increase significantly in the USA (Tator 2003) and Europe (Gu et al., 1998). This increase was later linked to the introduction of tighter limits on the nature and toxicity of industrial wastewater that could be discharged into the sewer system which had the unintended consequence of allowing bacterial (and consequently MIC) levels to rise significantly. Increases in MIC in recent decades have also been linked to increased sewage temperatures and sewer line lengths (and hence sewage residence times) that have accompanied the growth of suburban populations (Sand et al., 1992). Currently the global cost of repairing MIC damage to sewage infrastructure is estimated to be many billions of dollars per year (Hewayde et al., 2007). In the USA alone a recent review of corrosion put the cost of sewage infrastructure corrosion at US$13.75 billion/annum (Appendix K, Koch et al., 2001). In Germany repair of MIC degraded sewer pipe is estimated to cost in excess of $50 billion (Hewayde et al., 2006) and the cost of repairing MIC of sewer pipe in Australia is estimated to be in the order of one hundred million dollars per annum (http://www.score.org.au/ ).
MIC of the concrete sewer pipe comprises four (not necessarily discrete) stages (Antony et al., 2010, Melchers and Wells 2009, Wells and Melchers 2009):

1. **Abiotic neutralisation of the (highly alkaline) concrete surface.**
   The initial high surface pH of freshly cast and installed concrete sewer pipe, (pH=12-13), is too alkaline to allow bacterial colonisation to take place. Initially alkali species in the concrete react with H₂S and CO₂ gases produced by sulphur reducing bacteria in the wastewater biofilm layers that have diffused into the sewer atmosphere. As a consequence the pH of the pipe surface is lowered over time to levels more suitable for bacterial colonisation.

2. **Colonisation of the concrete surface by neutrophilic bacteria.**
   Once surface pH falls to ~9 neutrophilic sulphur oxidising microorganisms (NSOM) will, if sufficient O₂, nutrients and moisture are available, begin colonising the concrete surface. NSOM oxidize H₂S diffusing into the water filled pores of the exposed concrete producing H₂SO₄ which further lowers the pH of the concrete surface.

3. **Colonisation of the concrete surface by acidophilic bacteria.**
   When the surface pH of the sewer pipe falls to ~4 acidophilic sulphur oxidising microorganisms (ASOM) colonisation of the concrete surface begins. ASOM also act to oxidise H₂S to sulphuric acid but can also oxidise thiosulphate and elemental sulphur deposited on the sewer walls after the direct oxidation of gaseous H₂S by oxygen present in the sewer headspace. The activity of the acidophilic bacteria further lowers the concrete pH to ~1-2.

4. **Loss of concrete mass.**
   At this stage of the corrosion process concrete mass loss begins. Sulphuric acid produced by NSOM and ASOM reacts with silicate and carbonate compounds within the cement component of the concrete to form gypsum and the mineral ettringite via the following reactions:

   \[
   \begin{align*}
   H_2SO_4 + CaO.SiO_2.2H_2O & \rightarrow CaSO_4 + Si(OH)_4 + H_2O \\
   H_2SO_4 + CaCO_3 & \rightarrow CaSO_4 + H_2CO_3 \\
   H_2SO_4 + Ca(OH)_2 & \rightarrow CaSO_4 + 2H_2O \\
   CaSO_4 + 3CaO.Al_2O_3.6H_2O + 25H_2O & \rightarrow 3CaO.Al_2O_3.3CaSO_4.31H_2O
   \end{align*}
   \]

   The expansive nature of the gypsum and ettringite formed results in weakening of the cement structure and internal cracking and pitting of the concrete.

The basics of the corrosion process are understood however management of sewer corrosion is hindered by a limited understanding of several key in-sewer processes (Wells and Melchers 2009). In 2008 an Australian Research Council linkage project involving research teams from the Universities of Newcastle and Queensland as well as industry personnel from a large number of Australian water authorities was initiated to investigate odour and corrosion issues in Australian sewer systems (see http://www.score.org.au/). The subproject dealing with the study of MIC of concrete sewer pipes involves 5 year long field work and a paired laboratory study (Antony et al., 2010). The aims of the study are:

a. Determine the relationship between the corrosion rate and various environmental parameters such as H₂S concentration, humidity, temperature and thereby identify the factors controlling the corrosion process;

b. Use insights and data gathered from the laboratory and field work to develop a mathematical model predicting the corrosion rate of concrete sewer pipe as a function of time and environmental/operating conditions. This model will be used by industry personnel to estimate the reliability and expected remaining physical life of concrete sewers under given conditions.

In this paper the outcomes for the initial 12 months of field trials will be discussed.

### 2. METHODOLOGY

#### 2.1 Environmental monitoring at the field sites.

Ongoing monitoring of key environmental parameters at each of the field sites is being undertaken by the project’s industry partners. The parameters monitored are those expected to have the most impact on bacterial growth and include H₂S concentration in the sewer atmosphere as well as air temperature and relative humidity. Conditions at each field site are monitored for a minimum of 2 weeks every 3 months. This data enables the diurnal, seasonal and annual variations in the sewer environment to be determined over the course of the project. The data not only allows a site to site comparison of environmental conditions but also allows valid comparisons between field results and the laboratory outcomes to be made.
2.2 Field coupon installation, recovery and analysis.

The corrosion field trials involve the exposure of several hundred concrete coupons for 4 years in pairs of sewers in Sydney, Melbourne and Perth. The field sites were chosen to allow the corrosion process to be studied under a variety of humidity, temperature and H₂S conditions (see Table 1 for typical summer conditions at the field sites). The field samples comprise coupons cut from newly manufactured pipe (“new coupons”) and sewer main covers that had been in service for 70 years (“pre-corroded coupons”). Coupon pairs (one “new” plus one “pre-corroded”) are embedded in resin in specially designed stainless steel containers. The exposure of new and pre-corroded coupons enables the study of corrosion processes present at the beginning of the pipe service life and after corrosion is well established to be undertaken. Samples are mounted in an inverted position at the crowns of the sewers in the Sydney and Melbourne locations and in stainless steel racks fitted in manholes at the two Perth sites. An additional set of samples are mounted on the sewer wall at one Sydney site immediately above the (normal) wastewater level to allow the effect of circumferential position on corrosion rate to be determined (Figure 1). Coupons were installed in the Sydney (a) and (b) locations in September 2009, in Melbourne (a) and (b) in February 2010 and finally in the two Perth sites between May and June 2011. All coupons are individually numbered to allow before and after comparison to be correctly determined. Coupons exposed for 6 and 12 months have so far been recovered from the Melbourne and Sydney sites and samples exposed for 6 months have been recovered from the Perth sites. Future sampling will occur after 18, 24, 36 and 48 months exposure at each site. On each sampling occasion three new and three pre-corroded coupons are recovered from each field site. Recovered coupons are analysed for changes in surface pH, the level of corrosion layer buildup and the loss of sound concrete material.

Table 1. Daily average environmental conditions at the corrosion field sites (summer months).

<table>
<thead>
<tr>
<th>Field site location</th>
<th>Daily average Temperature (°C)</th>
<th>Daily average Relative Humidity (%)</th>
<th>Daily average H₂S concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sydney (a)</td>
<td>25.2</td>
<td>94</td>
<td>3</td>
</tr>
<tr>
<td>Sydney (b)</td>
<td>26.1</td>
<td>90</td>
<td>3</td>
</tr>
<tr>
<td>Melbourne (a)</td>
<td>18.6</td>
<td>(unknown)</td>
<td>1</td>
</tr>
<tr>
<td>Melbourne (b)</td>
<td>20.9</td>
<td>(unknown)</td>
<td>5</td>
</tr>
<tr>
<td>Perth (a)</td>
<td>26.5</td>
<td>100</td>
<td>68</td>
</tr>
<tr>
<td>Perth (b)</td>
<td>26.8</td>
<td>92</td>
<td>650</td>
</tr>
</tbody>
</table>

Figure 1. Arrangement of field coupons on the sewer crown and wall at the Sydney (a) site (left) and a stainless steel sample holder with coupon pair (right)
Upon recovery the surface pH of each coupon is determined at up to nine points on the exposed surface using a calibrated, flat faced pH probe. A drop of deionised, distilled water is placed on the coupon surface and allowed to come to equilibrium with the concrete surface before the pH reading is recorded. The pH value assigned to the coupon is the average of the readings taken. The surface pH of 6 control samples (3 new and 3 pre-corroded) which are kept in a dry, dark location at the University of Newcastle Civil Engineering Laboratory are also undertaken regularly.

The buildup of the corrosion layer and the depth of sound concrete removed from each coupon are determined using a photogrammetric technique. A set of stereo images of each coupon is taken prior to the installation of the coupon in the sewer and then again immediately after the sample is recovered (with the corrosion product still coating the coupon surface). Finally a third set of images is taken after a high pressure water jet has removed the corroded material from the exposed coupon surface. Each set of images includes a stainless steel frame covered in coded targets that is placed over the sample holder to act as a fixed reference plane against which the coupon height is determined at each stage (Figure 2). A commercial imaging software package (Photomodeler Scanner ®) then creates 3D representations of the coupon surface from the stereo images. By comparing the movement of the 3D surfaces relative to the fixed reference plane it is then possible to determine the thickness of the corrosion layer and the amount of sound concrete corroded away during the time the coupon was exposed to the sewer conditions (Figure 2).

3. OBSERVATIONS

3.1 Changes in coupon pH.

Abiotic and biotic processes operating within the sewer act to lower the surface pH of the concrete sewer pipe. The rate at which the change in pH takes place is therefore an indicator of the corrosivity of the sewer atmosphere and the relative activity of the acid producing bacteria present. The pH value also serves as a guide allowing us to track the progress of the coupon as it passes through the four stages of the corrosion process discussed above.

Average surface pH values for recovered coupons and control samples are plotted in Figures 3 and 4. Prior to placement in the field the surface pH of new coupons was 10.3, a value slightly lower than that expected for freshly cast concrete pipe (pH = 12-13). This indicates that the exposed surfaces of new concrete coupons experienced a degree of carbonation prior to installation in the sewer. Microscopic inspection of a cross sectional slice of a new coupon treated with universal indicator revealed that the depth of carbonation was approximately 0.1-0.2 mm. The pH surveys of the recovered new coupons revealed that the 6, 12 months exposure to the sewer environment had produced a significant decrease in surface pH for all coupons. Generally the sites with higher H2S concentrations in the sewer headspace produced the most rapid acidification. For example new coupons recovered from the Perth (a) site (H2S = ~70ppm) experienced the most rapid surface acidification (5.5pH units/yr) while a more modest decline of ~3.5 pH units/yr was observed on samples retrieved from locations with moderate H2S levels, (Melbourne (b) - 5ppm H2S; Sydney (a) and (b) - 3ppm H2S). By comparison new coupons recovered from the Melbourne (a) site and Perth (b) sites recorded small rates of change (2-2.5 pH units/yr). While this was expected for the relatively benign conditions (Figure 2).
Melbourne (a) site (H₂S=1ppm) the modest change in samples exposed at the potentially very aggressive Bibra lake site (H₂S=680ppm) was surprising.

Change in surface pH for the pre-corroded samples is complicated by the fact that a layer of crystalline material produced during the original exposure of the concrete to the sewer environment was present on the samples prior to their installation in the various sewers. The presence of this layer reduces the starting pH of the coupon to a more neutral value of pH=8.1. The surface pH of the recovered pre-corroded coupon is therefore not only a function of the biotic and abiotic corrosion activity taking place, (as is the case for new coupons), but is also influenced by any erosion of the crystalline layer which exposes sub-layers with potentially different characteristic pH values. Eventually when the crystalline layer is totally stripped away the exposure of relatively “fresh” concrete underneath is expected to further impact on the observed surface pH.

Evidence of this complicated response can be seen in Figure 4. After 6 months exposure significant decreases in the surface pH of pre-corroded coupons were observed at all sites with samples retrieved from the Perth (a) site again experiencing the most rapid decrease (8.5 pH units/yr) closely followed by the Perth (b) and Melbourne (b) samples (7.5 pH units/yr). Samples retrieved from less aggressive sites, (Sydney (a), (b) and Melbourne (a) sites) experienced lower rates of acidification (3.5-5 pH units/yr). Analysis of pre-corroded samples recovered after 12 months exposure from Sydney and Melbourne however indicate that the surface pH is stabilising at a pH of ~3.5. This may be the result of a buffering action taking place within the crystalline pre-corroded layer or due to complex interaction between the level of abiotic/biotic reactions taking place and the uncovering of previously unexposed material in the existing crystalline layer.

Figure 5 shows the rate of change in surface pH over the first 6 months exposure against average H₂S concentration recorded at each site. (Note that the data for Perth (b) has been omitted for reasons discussed later). Figure 5 indicates that a linear relationship exists between the rate of change in surface pH and the log of the H₂S concentration over this initial period for both new and pre-corroded coupons. It is also clear that for a given H₂S concentration the rate of acidification, at least initially, is substantially greater for the pre-corroded coupons than the new coupons, a finding that will have implications for the modelling of the corrosion process as the pipe ages. Also included in Figure 5 is some data presented by Roberts (Roberts et al., 2002) for a laboratory study of the acidification of Portland cement samples exposed to a range of H₂S atmospheres. While the data presented by Roberts is for more aggressive conditions than generally observed in this study the data appears to follow similar trends to those observed in our field data.

3.2 The development of a layer of corrosion product.

As the acidic species produced abiotically and from NSOM and ASOM react with the alkaline compounds within the concrete sewer pipe a layer of corrosion product consisting of gypsum, ettringite and other sulphated compounds is expected to form on the concrete surface. The thickness of the corrosion layer is a function of the rate at which the corrosion product is formed (and its density) and the rate at which it is eroded away (either by wastewater spray or the flow of the wastewater itself). The resultant thickness of the corrosion layer is an important factor to be considered when modelling the corrosion process as the rate of diffusion of species such as O₂, H₂S, nutrients, H₂O and H₂SO₄ across this layer will influence the rate at which the corrosion takes place.
The buildup of corrosion product on new and pre-corroded coupons resulting from 6-12 months exposure at the various field sites is illustrated in Figures 6 and 7. The thickness of the corrosion product was determined by calculating the distance that the surface of the recovered coupon receded after the corrosion product was removed via a high pressure water jet. The same washing procedure was applied to “blank” new and pre-corroded coupons (i.e. those not placed in a sewer) to estimate the depth of removable material present on new and pre-corroded coupons prior to installation in the sewer. Washing of 3 new and 3 pre-corroded blanks resulted in the removal of an average 0.04mm of material from new coupons (consisting of fine scale and carbonated concrete) and 2.05mm from the pre-corroded samples (pre-existing consolidated crystalline corrosion material). Consequently these values were assigned as the corrosion layer depth at zero exposure time.

The level of corrosion product built up on new coupons placed in the sewers for up to 12 months (Figure 6) was quite small, ranging from no additional product to approximately 0.75mm of corroded material added over that period of time. A layer of corroded material was evident on new concrete coupons recovered from the two Perth sites after 6 months (Perth (a) 0.48mm and Perth (b) 0.2mm). Samples recovered from the more moderate sites in Melbourne and Sydney however only showed signs of a development of a corrosion layer after 12 months exposure ranging in thickness from 0.1mm at the benign Melbourne (a)
site up to 0.78mm for new coupons retrieved from the Melbourne (b) site. Closer inspection of the corrosion material found on the new coupons under optical and scanning electron microscopes, (Figure 8), revealed the presence of numerous regularly shaped crystals which energy dispersive spectrometry (EDS) analysis (spectra shown in bottom left hand corner of Figure 8) suggests consisted primarily of gypsum.

As was the case for the new coupons, pre-corroded samples recovered from sites with higher H₂S concentrations (Perth (a), (b) and Melbourne (b)) exhibited a better developed corrosion layer than those recovered from the less aggressive sites (Figure 7). In all cases the depth of corrosion product created after 12 months exposure to the sewer environment was approximately an order of magnitude greater than that observed for the corresponding new coupons (even when the higher initial value was taken into account). This was likely due to a combination of factors including the lower starting surface pH and the existence of a more porous surface that was more easily wettable making the surface of these coupons more suitable for both abiotic and biotic activity.

3.3 Loss of sound concrete.

The primary aim of this project is to model the rate of change in the thickness of a concrete sewer pipe wall as a function of time and environmental conditions and thereby predict the service life of the sewer pipe. The loss of sound concrete, (defined in this study as the difference in average surface height between the coupon prior to installation and the surface of the recovered coupon after high pressure washing), is plotted in Figures 9 and 10 for new and pre-corroded coupons as a function of time. As expected the loss of material from the new coupons at this stage of the project is quite minor. The samples recovered from the Perth (a) and Melbourne (b) sites with their relatively high H₂S levels showed the highest rate of concrete loss (0.5 to ~1 mm/yr). The escalation of losses experienced by Melbourne (b) new coupons over the 12 month period points to a marked acceleration in corrosion losses which we anticipate will be replicated in the 12 month Perth (a) samples and in future samples recovered from the less aggressive sites. At the other end of the scale new coupons recovered Melbourne (a) and Perth (b) sites registered little if any loss of sound concrete after 12 months (above that recorded for the blank samples). The lack of corrosion losses at the Perth (b) site (680 ppm H₂S) is again surprising but never the less confirms the low level of corrosion activity indicated by the small shifts observed in surface pH. New coupons retrieved from the Sydney (a) and (b) sites all experienced intermediate level of concrete loss (0.1-0.2mm/yr). No significant differences in losses were observed between samples mounted on the wall of Sydney (a) sewer and those mounted on the sewer crown at the same location.
The losses observed for the pre-corroded coupons were significantly greater than those experienced by the new coupons. Again the samples recovered from the Perth (a) and Melbourne (b) sites suffered the greatest losses (16.5 and 7 mm/yr respectively). The corrosion at the Perth (a) site was so pronounced that the entire pre-existing dense crystalline layer had been converted to the consistency of cottage cheese. Upon washing this entire layer was removed to expose the previously unaffected concrete material. Losses from all other sites fell into the range of 2-4 mm/yr. Early indications from the results at hand (see Melbourne (b) data) suggest that, in contrast to the new coupons corrosion, pre-corroded coupon corrosion rates are relatively constant with respect to time (i.e. the losses are increasing linearly with time).

3.4 Other changes.

Building up a picture of the relative timing, (onset, duration and degree of overlap), of the different stages of the corrosion process discussed in the introduction to this paper is an important step in the development of a realistic model of sewer pipe corrosion. The identification of the biota present on field coupons exposed for differing lengths of time under different environmental conditions is a necessary part of this process. Analysis of the microbial species present on the field coupons is the subject of work being undertaken by the University of Queensland (Cayford et al., 2010) and is very much an ongoing process which won’t be discussed in this paper. Never the less inspection of the coupons via optical and scanning electron microscopes has revealed some interesting biological changes that have taken place over the 6 to 12 months that the coupons have spent in the sewer environment. The three most commonly observed biota are pictured in Figures 11 to 16. These features were not present on the coupons prior to their installation in the sewers.

Black spotting of the coupon surface (hereafter referred to as ‘spores’ although this has yet to be verified – Figure 11) was predominantly observed on the pre-corroded coupons recovered from the more aggressive sites (Perth (a) and Melbourne (b)) after six months exposure and on new and pre-corroded coupons from all sites except Perth (b) after 12 months. The pattern of occurrence indicates that the spores prefer a low pH environment. Spore coverage after 12 months exposure, (based on a pixel count on the images taken), ranged from ~1% (new coupons) up to ~6% of the coupon surface (pre-corroded coupons). Inspection of the spores under SEM (Figure 12) revealed them to be small raised roughly hemispherical protrusions ~10µm wide with a surface texture indistinguishable from the surrounding coupon material. EDS spectra of the protrusions (upper yellow chart in Figure 12) were identical to that of the surrounding (concrete) material indicating that either: (a) the chemical makeup was similar to the surrounding concrete or (b) the material was organic and therefore transparent to the EDS analysis. (The SEM used is not directly capable of identifying elements with atomic weights less than sodium). The presence of organic material (i.e. carbon) is generally inferred by the fraction of “noise” generated at the low energy end of the spectra – the first peak at the zero keV mark on the EDS spectra). Clusters of “organic” appearance were found in among the rougher protrusions (see small cluster of nodules on the left hand side of the lower image Figure 12). EDS analysis of these clusters indicated that they were likely to be of organic origin (in this case the height of “noise” peak was much higher than the peak heights of other material present).

Another commonly observed feature were small clusters of pale green, fine hyphae centred on mounds of a white powder (Figure 13). These communities were observed on new and pre-corroded coupons extracted from Melbourne (a) and (b) and Perth (b) sites after 6 months exposure but interestingly were absent from the 12 month Melbourne samples suggesting that they
are of a transitory nature. No examples have been observed on Sydney samples or those recovered from the Perth (b) site. EDS analysis of the material present within the “mounds” (Figure 14) suggests that they are mainly comprised of silicon (quite different in composition from nearby surface material as shown by the leftmost spectra in Figure 14). The pale green hyphae present on the 6 month Melbourne samples appear to have been replaced (superseded?) on the new and pre-corroded samples by an extensive network of black webbing (Figure 15). SEM examination of the webbing revealed its braided rope-like nature (Figure 16) suggesting that it was comprised of thick braids of hyphae. Numerous regular shaped nodules observed in amongst the braided hyphae were determined by EDS to be primarily composed of elemental sulphur (Figure 16).

Figure 11. Black spotting on the surface of a 12 month Sydney (a) pre-corroded sample.

Figure 12. SEM images and EDS spectra of two black spots.

Figure 13. Build up of corrosion layer on new coupons.

Figure 14. Build up of corrosion layer on old coupons.
4. DISCUSSION

Traditional models of the corrosion process relate the observed corrosion rate to a limited number of environmental variables (normally just the H$_2$S levels) and tend to assume that the corrosion rate is fixed over time. The aim of this project is to construct a more realistic model of concrete sewer pipe corrosion which is based on a physical picture of the corrosion process built upon observations made in the field and in the laboratory. The phenomenological model will reflect the multistage nature of the corrosion process discussed in the introduction and include the effects of changing microbe populations, the age of the pipe as well as the interplay between temperature, humidity and H$_2$S levels.

The data presented in the paper represents the first findings of the field trials for this project and while the complete picture of the process is still some time away the data collected so far has already given us some insight into the physical nature of the corrosion process. At the outset it was proposed that stage 1 of the corrosion process involved abiotic lowering of the surface pH to pH=9 at which point NSOM colonisation (stage 2) of the process could begin. New coupon surface pH data suggests that stage 1 of the process is considerably more rapid than previously thought as, even under relatively benign conditions (H$_2$S down to 1ppm) the transition to surface pH values necessary for stage 2 to commence was achieved in under 6 months. Certainly the starting pH for the new concrete coupons was lower than for fresh concrete but most probably reflect the reality that carbonation of the outer skin of the concrete pipe is likely to occur before installation. Therefore the conclusion that the first stage of the corrosion process is takes place over a matter of months in Australian sewers is probably valid. This conclusion is further reinforced by the appearance of various forms of biota on new coupons as early as 6 months.

It is also apparent that the corrosive activity experienced by both new and pre-corroded coupons at a given sewer location is a strongly, but not exclusively, linked the concentration of H$_2$S in the sewer atmosphere. We have observed that, (for the most part) as H$_2$S levels climb the rate of acidification of the coupon surface increases and the rate of concrete loss also increases. The lack of corrosion activity observed at the Perth (b) site (H$_2$S=680ppm) however indicates that H$_2$S is not the sole factor influencing corrosion rates. While the Perth (b) results are undergoing additional scrutiny it would appear that either (1) the site with its low humidity is too dry to allow for abiotic/biotic processes to take place, or (2) the extremely high H$_2$S levels may even be toxic to corrosion inducing microorganisms.

Evidently the condition and age of the concrete surface also has an important bearing on the corrosion rate as both the rate of change in surface pH and corrosion losses were found to be significantly higher for the pre-corroded coupons for a given H$_2$S level. This along with early data suggesting that new coupon losses may be accelerating with time (see Melbourne (b) data in Figure 9) strongly suggest that the corrosion rate will not be constant but more likely a complex function of time thereby justifying the approach taken of modelling the corrosion process from a phenomenological point of view.

As more field data is collected the trends will become clearer. Additional work is underway to better understand what is taking place at anomalous sites such as Perth (b). This additional data along with future field results and data generated from a complementary laboratory trial (Antony et al., 2010) and biological analysis of the field and laboratory samples (Cayford et al., 2010) will also add to our understanding of the corrosion process and ultimately allow realistic predictions of sewer pipe service life to be made.

Figure 15. Black webbing found on the surface of old coupons from the Melbourne sites (6 and 12 month samples)

Figure 16. SEM and EDS analysis of the black webbing found on the surface of old coupons from the Melbourne sites (6 and 12 month samples).
5. CONCLUSIONS

Microbial induced corrosion (MIC) of concrete sewers pipes is a significant global problem incurring losses in the order of billions of dollars per year. While the basic theory of the MIC process is understood management of sewer corrosion is hindered by a limited understanding of several key in-sewer processes involved. This paper describes the initial findings of a program of fieldwork in which newly cast and pre-corroded concrete samples have been exposed in sewers around Australia and allowed to corrode for a period of up to 12 months under a range of environmental conditions. The extent of corrosion was examined in terms of changes in the pH of the exposed surface of the coupon; the depth of the layer of corroded products and the loss of sound concrete. The appearance of several varieties of biota on the coupon surface was also noted.

The first 12 months exposure to the sewer environment has produced noticeable changes in virtually all coupons recovered. Surface pH has been lowered from a starting level of 10.3 down to as low as pH=6 over the year on new coupons and from pH=8.1 down to as low as 3.5 for pre-corroded coupons. Generally the rate of acidification has been a strong function of H₂S concentration in the sewer headspace with pre-corroded coupons experiencing more rapid decreases for a given H₂S concentration. Extensive corrosion of sound concrete has also been observed on pre-corroded samples over this period while minor losses are becoming apparent on new coupons.

The combination of pH movement, concrete losses and appearance of biological activity on the coupon surface all point to a rapid transition through stage 1 of the corrosion process (abiotic corrosion only) to stage 2 which involves microbial induced corrosion by neutrophilic species. A comparison of the early corrosion activity of new and pre-corroded coupons and anomalous readings at one high H₂S location also indicate that the corrosion rate will most likely vary in a complex fashion over time and will be influenced by a variety of environmental factors other than simply H₂S levels. As more field data is collected and complementary laboratory and biological data become available a realistic, phenomenological model of this process will be developed allowing the service life of sewer pipes in Australia to be realistically predicted.

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7. REFERENCES


Author details

Dr Tony Wells is a senior research fellow with the Civil, surveying and Environmental Engineering Department at the University of Newcastle, NSW, Australia a position he has held for the last 12 years. He has managed and participated in research projects in areas as diverse as climate change, geomorphology, high pressure physics, and the corrosion of advanced polymeric materials.

Robert E Melchers is Professor of Civil Engineering and Australian Research Council Professorial Fellow at the University of Newcastle, Australia. He has a BE and MEngSc from Monash University and a PhD from the University of Cambridge, UK in 1972. He was awarded the 2004 TP Hoar Prize (Institute of Corrosion, UK), 2007 Guy Bengough Award (Institute of Materials, Minerals and Mining, UK) and the Marshall Fordham prize (Australasian Corrosion Association) in 1999, 2002 and 2007. His research interests include structural reliability and marine corrosion.