FINDINGS OF A 4 YEAR STUDY OF CONCRETE SEWER PIPE CORROSION

P.A. (Tony) Wells¹ & R.E. Melchers²

¹, ² Centre for Infrastructure Performance and Reliability, The University of Newcastle, Callaghan, NSW 2308, Australia

SUMMARY: Microbial induced corrosion (MIC) of reinforced concrete sewer piping and manholes is a significant issue in Australia and overseas costing water authorities hundreds of millions of dollars annually. It is anticipated that as the country’s sewer infrastructure ages the problem will become more severe. Over the last 4 years an ARC and industry funded research project has been undertaken with the aim of building a mathematical model to predict the corrosion of concrete as a function of exposure time and environmental and operational conditions. After almost 4 years of field trials in Sydney, Melbourne and Perth sewers a detailed understanding of the evolution of the corrosion process has emerged and a phenomenological model has been developed. The present paper describes the study findings and their implication for pipe service life prediction.

Keywords: Concrete corrosion, sewers, microbial, model.

1. INTRODUCTION

Microbiologically induced corrosion (MIC) inside reinforced concrete sewer pipe was first observed over a century ago by Olmstead and Hamlin (1900). However it was not until the mid-1940s that the corrosion process was linked to the presence of *Thiobacillus* bacteria (Parker, 1945a; Parker, 1945b; Parker, 1951; Pomeroy and Bowlus, 1946). More recent studies have also implicated other bacterial and fungal species (for example see Cho and Mori, 1995; Gu et al., 1998; Nica et al., 2000). For many years MIC corrosion of concrete sewer pipe was not a major concern as corrosion rates were generally low particularly in cold climate countries. However in recent decades MIC rates have increased significantly in many countries to the point where it is currently estimated that repair and maintenance costs of MIC affected wastewater infrastructure are of the order of billions of dollars per year (Kaempfer and Berndt, 1999; Hewayde et al., 2007). In the USA alone, a recent review 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 some one hundred million dollars per annum (http://www.score.org.au/, 2014).

The increase in MIC activity in recent decades has been attributed to a number of factors, including: (1) high sulphur content of modern detergents and increased protein content of sewage (Milde et al., 1983), (2) a reduction of biologically toxic metals in wastewater following the introduction of clean water legislation (Mansfeld et al., 1991; Tator, 2003); and (3) increased residence times as sewer line lengths increase with increases in suburban areas serviced and population (Sand et al., 1992).

The challenges posed by the increasing severity of MIC has resulted in a renewed research push to improve understanding and quantification of the underlying mechanisms of the sewer corrosion processes (for example see Jensen, 2009; Joseph et al., 2012; Vollertsen et al., 2008) as well as the bacterial population dynamics and kinetics involved (Bielefeldt et al., 2010; Okabe et al., 2007; Satoh et al., 2009). Most of the research has involved laboratory experimentation focussing on individual facets of the corrosion process. However, despite much research progress, practical management of sewer corrosion is still hindered by a limited understanding of the overall in-sewer corrosion process and how it evolves over time.

The corrosion of concrete sewer pipe varies in a complex fashion over time. Conditions on the exposed internal surface of the pipe change as chemical (abiotic) and biotic processes alter the surface chemistry. In turn these changing conditions alter the nature and magnitude of corrosive activities taking place. This was recognized in a three-stage model of sewer pipe corrosion proposed by Islander (1991). The corrosion process proceeds initially mainly by chemical (i.e. abiotic) acidification of the pipe surface, followed by MIC, driven by a succession of evolving microbial communities (Figure 1).
During the initial stage of the life of the pipe, calcium hydroxide present in the concrete matrix dissolves in the concrete pore water producing a highly alkaline environment (pH of ~12 to 13. Lea, 1970). Under these conditions bacterial activity (and hence biologically driven corrosion) is minimal, however acidic gases such as CO$_2$ and H$_2$S present in the sewer atmosphere can dissolve into the condensate film and react with the alkali species. As a result of this abiotic activity the surface pH is lowered towards more neutral levels. Once the surface pH falls below pH=9, conditions become favourable for the colonisation of the surface by neutrophilic sulphur oxidising organisms (NSOM) (Islander et al., 1991; Okabe et al., 2007) and the corrosion process enters a second stage. As the pH falls to near neutral, surface biological oxidation of sulphur species occurs, dominated by the oxidation of thiosulfates to polythionates and sulphates (Islander et al., 1991; Okabe et al., 2007) and the formation of organic acids by bacteria and fungi all of which act to further lower the surface pH. When the surface pH reaches ~4 the corrosion process enters a final stage during which the pipe surface is colonised by acidophilic sulphur oxidising microorganisms (ASOM). At these acidic conditions abiotic and biological processes convert H$_2$S to elemental sulphur which in turn is readily oxidized to sulphates by the ASOM present. The acids produced by the ASOM and to a lesser extent the NSOM attack the alkaline components (portlandite, calcium silicates and calcium aluminates) within the cement binder to form gypsum, CaSO$_4$.2H$_2$O, and the mineral ettringite, 3CaO.Al$_2$.O$_3$.3CaSO$_4$.32H$_2$O (Mori et al., 1992). The accompanying increase in volume (124% and 227% respectively, Parande et al., 2006) causes cracks and the formation of internal voids, reducing the structural integrity of the pipe wall and facilitating permeation of moisture, acids and biota into the concrete structure, thereby propagating the corrosion cycle.

As noted by Roberts et al. (2002) and Wells and Melchers (2009) there has been little quantitative assessment of the overall corrosion process (such as presented by Islander above) under real sewer conditions and consequently management of sewer corrosion is still hindered by a limited understanding of several key in-sewer processes. As part of a larger study (Rootsey and Yuan, 2011), the opportunity arose to study the corrosion of sewer pipe samples (both new and 70 year old previously corroded) in a number of working sewer mains throughout Australia over an extended period of time. This paper describes the findings of almost 4 years of these field trials at six sewer locations. The general form of the corrosion loss curve determined from these observations is discussed as well as the insights gained on the impact of different environmental factors on the extent of the corrosion losses.

2. METHODOLOGY

2.1 Field sites used in the study

In consultation with the industry partners involved in the research project, six gravity sewers were selected for detailed study, two sites each in Sydney, Melbourne and Perth (Figure 2). Unfortunately, samples in the two Sydney sewers were contaminated when mistakenly coated with a magnesium hydroxide gel before significant corrosion losses were observed. At the four remaining sites observations were made over approximately four years of exposure and under a wide range of environmental conditions. This was sufficient to enable a reasonably comprehensive picture of the corrosion process to be obtained. To characterise the sewer environment at each site H$_2$S gas concentrations, sewer gas temperatures and humidities were logged every 5 minutes over a 2 weeks period at 3 monthly intervals throughout the course of the study. The pattern of monitoring enabled average conditions to be determined and also permitted an understanding of the diurnal and seasonal variations in conditions to be obtained. Humidity monitoring at the Melbourne sites proved problematic as sensors failed after only a few days operation. Consequently the average values reported for humidity at the two Melbourne sites are based on a limited set of data.
2.2 Field coupons installation, recovery and analysis

Two sets of concrete coupons were exposed at each of the field sites. One set, (‘new’ coupons) were cut from newly manufactured 1.2m ID spun cast standard Class 2 reinforced concrete sewer pipe with a minimum 400kg/m³ cementitious content and an aggregate content of 45-50% by volume. These were used to obtain information about the corrosion behaviour during the early years of exposure of a concrete sewer pipe. A second set, (‘old’ coupons) were used to establish the nature of longer term corrosion behaviour (once corrosion was well established). These were cut from reinforced concrete slabs that had served for 70 years as covers for a concrete sewer pit that was part of a typical operating sewer system carrying domestic, industrial and trade waste. Aggregate content was similar to the new coupon material (~45% by volume) however average aggregate size was larger (average 20mm versus 14mm for the new concrete). Pairs of coupons (one “new” plus one “old” were embedded in resin in especially designed stainless steel containers (Figure 3A). Twenty four pairs of samples were then mounted in an inverted position at the crowns of gravity sewers at the Sydney and Melbourne sites (for example see Figure 3B) and in racks fitted in manholes at the two Perth sites (Figure 3C). Coupons were installed at the Sydney sites in Sept 2009, at the Melbourne sites in February 2010 and at the two Perth sites between May and June 2010. The gravity sewers ranged in size from 1 to 2m in Sydney and Perth to approximately 4m in Melbourne. In each location the samples were well above the normal ‘tidal range’ of the wastewater stream and were only immersed at times of high (i.e. storm water assisted) sewage flow.

Sets of new and old coupons were recovered after approximately 6, 12, 18, 24, 30 and 36-40 months of exposure. All coupons were individually numbered to allow before and after comparison of individual coupons to be correctly determined. On each sampling occasion three new and three old (pre-corroded) coupons were recovered from each site. Recovered coupons were analysed for changes in surface pH, the level of corrosion layer buildup, and the loss of sound concrete material.

Figure 3. A: sample holder with new coupon (left) and old (pre-corroded) coupon (right). B: Samples mounted at the Melbourne A site (samples in the centre). C: Samples mounted at the Perth B site (samples at rear).
Directly after being recovered samples were examined under a low power optical microscope to assess the general condition and morphology of the exposed sample surface. Following this, the average surface pH of each coupon was calculated from a flat faced pH probe determination. This used 4 to 9 drops of deionised, distilled water placed on the coupon surface which was then allowed to come to equilibrium with the concrete surface pH. To assess the extent of any background changes in concrete surface pH, six control samples (3 unexposed new and 3 unexposed old) were kept in a dry, dark location at the University of Newcastle Civil Engineering Laboratory and their surface pH monitored regularly.

The build-up of the corrosion product layer and the extent to which sound concrete had been corroded from each coupon were determined using a photogrammetric technique detailed elsewhere (Wells and Melchers, 2014) and is only described briefly here (Figure 4). Prior to installation in the sewer multiple images of each coupon together with a coded stainless steel reference frame mounted on the rim of the sample holder were taken. A commercial imaging software package (Photomodeler Scanner ®) was then used to generate a 3D representation of the coupon surface from the images from which the average height of the surface, \( Z_a \), relative to the reference plane was then calculated. Upon recovering the coupon from the sewer the imaging procedure was repeated for the coupon with corrosion product layer intact and also after the corrosion product had been stripped away with a high pressure water jet allowing the average surface height with and without corrosion product (\( Z_b \) and \( Z_c \), respectively), to be determined. The depth of the corrosion product layer (= \( Z_b - Z_c \)) and the quantity of sound concrete that had been lost due to corrosion (= \( Z_a - Z_c \)) were then calculated.

![Figure 4. Determination of corrosion layer depth and corrosion losses. Photogrammetric imaging is used to generate 3D representations of the coupon surface. The average height of the surface relative to a fixed reference plane is then determined for the coupon prior to exposure (\( Z_a \)), immediately upon recovery (\( Z_b \)) and after stripping of the corrosion product (\( Z_c \)).](image)

3. RESULTS

In the following, the findings regarding changes in the surface pH, the corrosion losses and the development of the corrosion layer are reported. As noted, contamination of the Sydney coupons occurred before any significant corrosion losses could be observed although some observations of surface pH trends for these samples can be reported.

3.1 Changes in the surface pH of coupons

Surface pH of the concrete coupons is of interest because it has long been recognized that the biotic and abiotic processes operating in sewers lower the surface pH of the concrete sewer pipe over time (Parker, 1951). The surface pH in turn is known to influence both the species of fungi and bacteria present on the surface and their respective level of activity. This in turn will dictate the rate of corrosion (Davis et al., 1998; Islander et al., 1991). The surface pH also serves as a guide to the stage of corrosion process that has been reached on the surface of the coupon (as discussed above). Further, the rate at which pH decreases serves as an indication of the relative aggressiveness of the corrosion conditions at a site.

Average surface pH values for recovered coupons and control samples are plotted in Figures 5 and 6. Prior to placement in the sewers the surface pH of new coupons was approximately 10.3, a value slightly lower than that expected for freshly cast concrete pipe (\( pH = 12-13 \)) indicating that the new concrete coupons had experienced a degree of surface carbonation prior to installation in the sewer. Once new coupons were installed in the sewers the surface pH declined steadily over time at all sites.
Over the first 12 months of exposure the overall rate of decline in new coupon surface pH was similar at all sites (0.3-0.34 pH units/month) with the exception of Melbourne A samples which exhibited a slower acidification (~0.15 pH units/month). After 12 months exposure the rate of decline in new coupon surface pH slowed at all sites to 0.1 - 0.13 pH units/month. By the end of the study the surface pH of new coupons at the Melbourne B and two Perth sites had decreased to between pH = 2.6 and pH = 3.2. The final surface pH of new coupons recovered from the Melbourne A site, however, was significantly higher (pH = 4.9). Over the same period the new concrete control samples showed little variation in surface pH (average 10.0 +/- 0.2).

The trends in old coupon surface pH over time (Figure 6) differed significantly from that observed for new coupons. The starting surface pH of old coupons was lower (pH = 8.2), a value which is consistent with their previous exposure history. Once they were installed in the sewers the surface pH for the old coupons declined rapidly so that by the time of the first extraction, (after ~ 6 months exposure), the average surface pH had declined to pH=3.5 to 4 at all sites, except Melbourne A where a more modest decline to pH=6.1 was observed. After ~ 12 months exposure the surface pH values for the old coupons were similar at all sites (3.7 to 4.5). Surface pH then drifted slowly down at most sites but remained generally in the range of pH = 2.2 to 3.8 for the remainder of the study. Over the whole period the surface pH of old concrete control samples also showed little variation (7.8 +/- 0.3).

3.2 Corrosion losses

The losses of sound concrete experienced by new and old coupons as well as the changing depth of the corrosion product layer as a function of exposure time are shown in Figures 7 and 8 (Melbourne A and B sites) and Figures 9 and 10 (Perth A and B sites). The data points shown represents the average loss (or corrosion layer depth) observed for the 3 samples recovered at that time. Error bars shown represent the standard deviation of the three measured losses (or corrosion layer depths). Larger sample to sample variation was evident for old coupon samples as the aggregate size in these samples was significantly greater and hence the loss of a single piece of aggregate had a greater impact on loss and corrosion layer depth measurements for these samples.

Upon their introduction into the sewers new coupons at all sites experienced an initial period of little or no loss of sound concrete. This was despite the decrease in surface pH that, as noted above, occurs during this time. The duration of this initial period ranged from 10 months at the Perth A site to approximately 25 months at Melbourne A. For the new concrete coupons, once corrosion losses commenced they increased linearly with time for the remainder of the study period. This was the case at all sites. Losses of sound concrete experienced by new coupons by the end of the study ranged from 30.4 mm at Perth A, 11.6 mm (Melbourne B), 7.3 mm (Perth B) to 4.8 mm at the Melbourne A site.

In contrast, the loss of concrete for the old concrete coupons commenced almost immediately upon installation in the sewers. This was the case at all sites, with the possible exception of Melbourne A where the low level of corrosion made loss evaluation problematic. For these old concretes the losses also increased in a linear manner with time for the whole duration of the study. At the end of the study the losses experienced by the sound concrete ranged from a maximum of 30.7 mm at Perth A followed by 19.0 mm (Melbourne B), 15.5 mm (Perth B) to 4.8 mm at the Melbourne A site.
Figure 7. Concrete losses and depth of the corrosion layer for coupons installed at the Melbourne A site.

Figure 8. Concrete losses and depth of the corrosion layer for coupons installed at the Melbourne B site.

Figure 9. Concrete losses and depth of the corrosion layer for coupons installed at the Perth A site.

Figure 10. Concrete losses and depth of the corrosion layer for coupons installed at the Perth B site.
3.3 Corrosion layer development

The build-up of corrosion product on new concrete coupon surfaces during the initial period of minimal corrosion was negligible (< 0.5 mm) as might be expected. The corrosion product comprised a fine layer of crystalline material which XRD analysis revealed was composed primarily of gypsum. For the new concrete coupons, once corrosion losses commenced the depth of the layer of corrosion products increased largely in a non-linear manner with time. The corrosion product was of a white pasty appearance. XRD/XRF analysis of the corrosion product revealed that it was primarily composed of gypsum, (CaSO_4 \cdot 2H_2O), with entrained quartz. The latter are considered to be retained sand particles from the original cement matrix. Optical microscopy of the corrosion product revealed the presence of numerous cracks and voids throughout the layer particularly around the aggregate. By the end of the study corrosion layer depths ranged from ~9 mm on Perth A coupons to 1.4 mm for the Melbourne A new coupons.

The old concrete coupons originally had a ~2 mm pre-existing hard crystalline layer of corrosion product at the exposed surface. It was observed that upon exposure to the sewer environment this surface material was rapidly transformed to a soft, pasty consistency similar in appearance, chemistry and morphology to that present on the surface of new coupons. At all sites except Melbourne A the surface appearance of new and old coupons gradually became indistinguishable with time (for example see Figure 11). At all sites the corrosion layer depth of the old concrete coupons increased with time although significant increases in corrosion layer depth were not observed at the Melbourne A site until some 30 months after exposure. At all other sites the depth of the corroded material increased with respect to time in a non-linear fashion. By the end of the study period, average corrosion layer depths had reached 11.4 mm at Perth A (the highest in the study), 9.4 mm at Perth B, 6.6 mm at Melbourne B and 0.8 mm at Melbourne A.

![Figure 11. Changing appearance of surfaces of new and old concrete coupons retrieved from Perth A.](image-url)

4. DISCUSSION

In the present study the corrosion of new concrete coupons was used to examine the corrosion behaviour in the early stages of the life of a concrete sewer pipe (stages 1, 2 and possibly the early part of stage 3 in Figure 1). Also, coupons of old concrete were used to determine the expected corrosion performance of concrete sewer pipe when corrosion was already well advanced (that is, well into stage 3 in Figure 1). By the end of the study it was apparent that the corrosion processes taking place with new and old coupons were becoming indistinguishable. Not only were new and old coupon surface morphology and pH in close agreement but also new and old coupon corrosion rates calculated from the rate of loss accumulation were in close agreement at each site (see Table 1). The merging of the behaviour of the new coupon and old coupons suggests that what has been observed during these two parts of the test program represents a near-complete picture of the corrosion process for concrete sewer pipes, from installation to the point where corrosion has become well-established. The results given here are for the sites examined but there is no reason to suggest that the processes involved are significantly different for other concrete sewers at different locations, provided, of course, that the sewage is approximately similar (and without high loading of biologically toxic materials).
Table 1. Rates of corrosion losses experienced by new and old coupons

<table>
<thead>
<tr>
<th>Site</th>
<th>New Coupons</th>
<th>Old Coupons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corrosion rate, $r$, (mm/yr)</td>
<td>+/- (90% ci)</td>
</tr>
<tr>
<td>Perth (A)</td>
<td>12.7</td>
<td>2.4</td>
</tr>
<tr>
<td>Perth (B)</td>
<td>3.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Melbourne (A)</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Melbourne (B)</td>
<td>6.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

The sewer environments present at the Melbourne and Perth field sites include a wide range of conditions, from relatively benign conditions at Melbourne A (T~20°C, $H_2S=1.5$ ppm) to very aggressive conditions at the Perth sites (T~26°C, $H_2S>80$ ppm). While the scale and timing of losses differed substantially between sites as a consequence of the differing exposure conditions it is clear that the general form of the process, in terms of corrosion losses, is generally the same. When a pipe is newly installed there is a short period of time, (the incubation period, $t_i$), during which corrosion activity does not produce any significant concrete losses. During this period, which in the present study lasted between ~11 to 24 months, acids are produced mainly through abiotic processes since the concrete surface is too alkaline for biological activity. These acids act to lower the surface pH of the concrete. However, during this period the loss of sound concrete is insignificant since the pore water within the concrete matrix is initially rich in alkaline minerals (such as portlandite) and must be neutralised before the structural integrity of the concrete can be degraded and corrosion can commence. The incubation phase of the corrosion process was not observed for old coupons as the surfaces of these pre-exposed coupons are already depleted of alkaline minerals and have a starting pH much more conducive to biological activity. In a sense these samples are pre-conditioned for the immediate biological activity to take place and mass losses to occur.

When the pH of the surface has been lowered sufficiently MIC can commence and mass loss of concrete can begin to occur. Once it commences, mass loss accumulates linearly over time (i.e. a constant corrosion rate). The close agreement between the eventual corrosion rates for the new and old concretes, as shown above, indicates that once mass loss commences the rate of corrosion will vary little during the service life of a concrete sewer pipe. These observations indicate that concrete sewer pipe corrosion can be modelled as a simple bi-linear process with respect to time (Figure 12, left) characterised by two parameters: an incubation time, $t_i$, and a steady rate of corrosion, $r$, (Figure 12, right).

![Figure 12. Bi-linear loss model for concrete sewer pipe corrosion in terms of losses (left) and corrosion rates (right).](image)

The somewhat surprising observation arising from the present investigation is that a constant rate of loss was observed for new and old coupons at all sites, despite significant increases in the depth of the corrosion product layer (see Figures 7 to 10).
indicates that the presence of the corrosion product has little influence on the rate of corrosion. The reasons for this most likely are twofold: (1) studies such as that conducted by Okabe et al., (2007) indicate that acidophilic bacterial populations are concentrated on or near the exposed surface of the corrosion layer where H2S and oxygen levels are highest thus the development of the corrosion product layer is not likely to impede the access of nutrients to the bacteria; and (2) as noted previously, the corrosion product layer is riddled with cracks and voids (especially in and around exposed aggregate), which aid the transport of acids produced by surface bacteria to the sound concrete interface below.

One question of operational and hence practical interest is whether water blasting of the corroded material from the exposed surface of a partially corroded concrete sewer pipe aids or retards the corrosion process (or has no effect). While the above observations in regard to the lack of impact of the corrosion product layer would at first glance suggest that there is negligible effect in removing the corrosion product layer it must be remembered that water blasting removes not only the corroded product but also is likely to remove (or partially remove) the local microbial community and thus exposing less affected, and therefore more alkaline, concrete. The temporary loss of active microbial colonies and the elevation of surface pH is likely to at least temporarily slowdown corrosion activity. Evidently, the extent and duration of the resulting slowdown will depend on how quickly the optimum corrosion environment can re-establish itself on the concrete pipe surface. The observations herein of the initiation of corrosion on new concrete surfaces suggest that this period of interruption is likely to be only a few months (and most likely much shorter).

The bi-linear model of the corrosion process can be used to make predictions of the likely service life of a concrete sewer pipe. In principle the bilinear model can be parameterized by two parameters, namely the incubation time, ti, and rate of corrosion, r. In practical applications, however, the field data from the present project suggests that in many circumstances the incubation period, ti, can be ignored in estimating the service life, particularly where the expected service life >> ti.

As indicated by the results from the present investigation, both parameters will depend on the local environmental conditions to which the concrete surfaces of the sewer pipes are exposed. As shown, lower average temperatures and less aggressive conditions (lower H2S and lower humidities) will result in longer incubation periods and lower corrosion rates. For example, Figure 13 shows the predicted losses for the Perth B site (ti = 11 months, corrosion rate = 4.4 mm/yr). If the initial cover thickness of concrete over the metal reinforcing is assumed to be 50 mm, the service life predicted for this pipe at this relatively aggressive site is approximately 12 years.

![Figure 13](Image)

Figure 13. Predicted losses and end of service life (EoSL) for an unprotected concrete sewer pipe with an incubation time of 11 months and a corrosion rate of 4.4mm/year. The original pipe is assumed to have a concrete cover depth of 50 mm.

In principle, the corrosion rate and the incubation time characteristic of a given sewer at a given site under known exposure conditions can be determined by repeated measurements of losses at that site. This can be done using the techniques described herein for the present study or it could be done by taking traverses of the remaining concrete at a given location in a sewer and repeating this at several points in time, preferably at reasonably long times apart. Unfortunately, such exercises are technically challenging, costly and have operational implications. The alternative is to estimate the rate of corrosion from knowledge of the local environmental conditions. Traditionally H2S is used by the wastewater industry to characterise the corrosivity of a sewer site. Figure 14 shows a plot of the rate of corrosion observed at the two Perth and Melbourne sites plotted against the log of the average H2S concentration of each site. Perhaps somewhat surprisingly correlation is poor. The rates of corrosion does not rank in the same order as the recorded H2S levels. While increasing H2S levels at the Melbourne A and B and Perth A sites produced the expected attendant increases in the rate of corrosion, rates observed at the Perth B location were significantly lower than...
Perth A and slightly below that observed at Melbourne B despite possessing a significantly higher H$_2$S environment (an average 423 ppm versus 81 ppm at Perth A, for example).

In Fig. 14 two possible explanations exist for the suppressed corrosion activity at Perth B relative to the others. The first is that H$_2$S levels at this site are so high that the action(s) of sulphur oxidising bacteria are inhibited (an effect reported, for example, by Nielsen et al., 2014). The second possibility is that the lower than expected corrosivity is linked to the relatively low humidity of the sewer atmosphere at this site (an average 91% compared to close to saturation at the other sites). As noted by Islander and Nielsen (1991) concrete at the crown of the sewer (where the field samples were located) can be wetted by (i) the aerosols generated by sewage turbulence, (ii) occasional rises in wastewater levels and (iii) condensation of water vapour when relative humidities are high. At the field sites employed in the present study wastewater levels infrequently reach the crown of the sewers and aerosol emissions are relatively low. This means that condensation is most likely to be the major mechanism by which the coupons were wetted. It follows that in such cases, sewer gas humidity will play a significant role in determining the moisture content of the concrete pore structure. High moisture content in the pore structure of the sewer pipe wall will favour microbial growth and activity and hence acid production. Of course, it also facilitates the abiotic (ionic) corrosion reactions that are occurring at the same time. Conversely, lower humidities would be expected to suppress corrosion activity. This is an important observation. While H$_2$S monitoring of sewers is common, monitoring of humidity is much less common, in part because in sewers the lifespan of humidity sensors usually is quite limited. The Perth B results indicate that without adequate knowledge of the humidity conditions, accurate prediction of corrosion activity could be problematic. It follows that future work will need to focus not only on expanding understanding of the relationship between the incubation time and the rate of corrosion with the temperature and with H$_2$S concentration but also on the influence of relative humidity conditions inside sewers and the effect this has on corrosion.

![Figure 14. Corrosion rate, $r$, as a function of Average H$_2$S concentration.](image)

5. CONCLUSIONS

The results of the present study of the corrosion of new and 70 year old concretes exposed in a number of operational sewers in Australia have shown that the concrete corrosion process follows a similar trend, irrespective of the aggressiveness of the environmental conditions within the sewer. Initially the pipe experiences a short period (<2 years) during which (principally abiotic) processes drive down the surface pH from the initially alkaline levels to more neutral levels. This is the incubation period, during which time mass loss is minor and little or no corrosion product is generated. Once corrosion commences, however, losses accumulate linearly with time (i.e. the pipe suffers a constant rate of corrosion). Comparison of the corrosion behaviour of new concrete coupons and old, pre-corroded concrete coupons indicates that the rate of corrosion is likely to remain constant for the remainder of the life of the pipe, provided the internal environmental conditions remain unchanged.

A simple, bi-linear model to represent the corrosion process is outlined. For practical purposes with long expected service lives the incubation period can be ignored since it represents only a small fraction of the likely lifespan of the pipe. The rate of corrosion was shown to be a function of the local environmental conditions inside the pipe.

The present study shows that corrosion loss as a function of time is not simply a function of H$_2$S gas concentration as is the current industry standard approach for assessing the relative aggressiveness for concrete corrosion at a given sewer location. It is shown that concrete corrosion also is likely to be dependent on other environmental factors, including relative humidity.
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7. REFERENCES


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8. AUTHOR DETAILS

Dr Tony Wells is a research academic in the Civil, Surveying and Environmental Engineering Department at the University of Newcastle, NSW, Australia a position he has held for the last 15 years. He has a BE (Chem. Eng.) from Newcastle University and a PhD from the University of New South Wales, Australia in 1991. 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, concrete sewer and cast iron water pipes.

Robert E Melchers is Professor of Civil Engineering and ARC DORA Research Fellow at The University of Newcastle, Australia. He holds a BE and MEngSc from Monash University and a PhD from the University of Cambridge, UK. He is a Fellow of the Australian Academy of Technological Sciences and Engineering.

His most recent awards are the 2009 ACA Corrosion Medal, the 2012 Jin S Chung Award (International Society of Offshore and Polar Engineers) and the 2013 John Connell Gold Medal (The Institution of Engineers, Australia).