CONCRETE SEWER PIPE CORROSION – FINDINGS FROM AN AUSTRALIA FIELD STUDY

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ABSTRACT

Samples of new and 70 year old pre-corroded OPC concrete were exposed for up to 5 years in sewers throughout Australia. Corrosion losses at each site followed a bi-linear trend. During an initial phase (lasting <3 years) negligible loss of material occurs, however, once the surface reaches pH=6 losses commence and accumulate linearly at a rate that appears to remain constant with time. Two strategies for lowering the rate of corrosion are (i) maintain surface pH>6 and/or (ii) lower the sewer gas humidity. A model developed to predict the rate of corrosion using local environmental conditions is described.

INTRODUCTION

The management of long-term corrosion of concrete sewer pipelines represents a major challenge facing water authorities around the world. Replacement and repair of corroded concrete sewer pipe is estimated to cost billions of dollars per year in the USA (Koch et al., 2001) and in Germany (Hewayde et al., 2006). In Australia the cost is estimated to be hundreds of millions of dollars per year (http://www.score.org.au).

It has long been known that the internal corrosion of concrete sewer pipe is caused by acid secreted by a range of microbes (Parker, 1945a; Parker, 1945b). Until recently, however, development of a sound understanding of the link between sewer conditions and corrosion rates and the manner in which the corrosion process evolves over extended periods of time in actual sewers has hampered the development of operational procedures that aim to minimise corrosion rates and thereby prolong the serviceable life of the existing concrete sewer pipe network (Roberts et al., 2002; Wells and Melchers, 2009).

To gain a better understanding of the corrosion process inside actual sewers, an in-situ study of sewer pipe corrosion was recently undertaken by the authors. The results of this study, reported here, suggest a number of strategies for minimisation of corrosion in concrete gravity sewers. A first pass model enabling corrosion prediction has also been developed. The findings, model and strategies for corrosion minimisation are discussed in this paper.

FIELD AND LABORATORY WORK

In situ corrosion of sewer pipe was examined for 5 years during 2010-2015 in working gravity sewers located in Sydney, Melbourne and Perth (Figure 1). The Melbourne and Sydney sewers are naturally ventilated. The Perth sewers are part of a sealed system. Samples cut from newly manufactured standard concrete sewer pipe ('new' samples) and from sewer covers exposed for 70 years ('old' samples) were installed in pairs along or near the crowns of a number of working sewers (Figure 2). The test locations were chosen to encompass a wide range of sewer environments, ranging from relatively benign to very aggressive.

Several differences in the new and old coupon concretes were noted. Aggregate in the new coupon concrete was generally smaller in size (typically 10-15 mm compared to 15-30 mm in the old coupon concrete). Both concretes were of a similar mineralogical makeup, although XRF/XRD analysis revealed that a significant portion of the portlandite originally present in the old coupon concrete had been converted to carbonate minerals (calcite and vaterite) during the 70 years previous exposure period. The alkalinity of the old coupons (as determined by the method of Snell and Ettre (1972)) was consequently lower (0.15g $CaCO_3$/g concrete compared to 0.22g $CaCO_3$/g concrete for new coupons). The permeable pore space fraction of the old coupon concrete, however, was higher (11.4% versus 6% for new coupon concrete).

During the study samples were recovered (in pairs) every 6 to 8 months initially and annually after 3 years. Care was taken to leave the corrosion product layer intact. Coupons were numbered individually to enable accurate 'before' and 'after' comparisons. Also, comparison of the corrosion behaviour of the new and old sewer pipe coupons enabled both short and long term corrosion behaviour to be determined. Immediately after recovery the coupons were inspected under a low power microscope for changes in surface morphology. Thereafter the average surface pH of the exposed coupon surface was determined from a minimum of 4 spot measurements. Finally, the depth of the corrosion product layer that had formed and the depth of sound concrete removed during the time of exposure were determined. This was done by comparing the average height of the exposed surface prior to installation, with that of the surface after recovery, with the corrosion product layer intact and, after removal of the corrosion product layer using a high pressure water wash. In all cases photogrammetric analysis was used to determine the position of the exposed surface relative to a fixed reference plane (for details see Wells and Melchers, 2014).

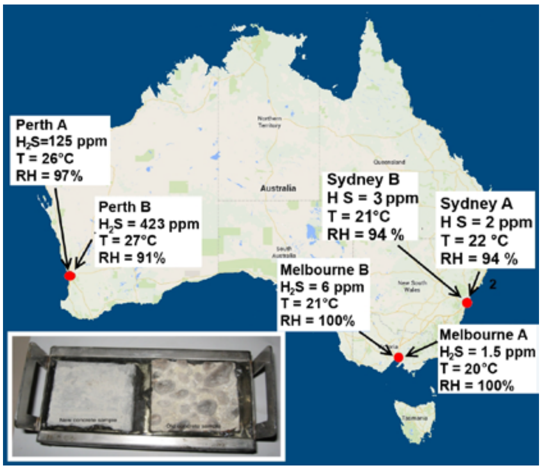

Figure 1: Location of field sites used in the study and conditions present at those site. Inset: coupon pair in sample holder.

Figure 2: Samples being mounted along the crown of the Melbourne A sewer.

At each field site extensive environmental monitoring was undertaken to determine both the average conditions and the range of diurnal and seasonal variations in sewer gas temperature, humidity and H_2S concentration. H_2S gas phase concentrations and sewer gas temperatures were logged every 5 minutes over a 2 week period every 3 months throughout the study period. Sewer humidities were recorded at the same frequency at the two Perth sites. At the Melbourne and Sydney sites humidity measurement proved problematic due to repeated sensor failure. For this reason the values reported for humidity at the two Melbourne sites are based on a limited pool of data (2 days observations) while humidity observations at the Sydney sites are restricted to four records each 2 weeks long for the entire study period.

Observations made during the field study were used subsequently in conjunction with the known behaviour of bacteria on sewer walls to develop: (1) a better quantitative understanding of the corrosion process, (2) strategies for reducing corrosion rates of concrete sewer pipe and (3) a first pass quantitative model relating concrete corrosion loss in sewer pipes to local average sewer gas temperature, humidity and H_2S concentration.

RESULTS

Coupons were installed in sewers between September 2009 and June 2010. Melbourne A and B coupons were recovered after 7, 13, 18, 24, 32, 39 and 63 months exposure; Perth A and B coupons after approximately 6, 14, 19, 26, 31, 37, 48 and 58 months (Perth B only); and Sydney A and B coupons after 9, 12, 24, and 36 months exposure. The trial at the Sydney sites was abandoned after 36 months as a result of inadvertent contamination of the coupons during sewer maintenance operations. All results reported here are the average values for each set of 2-3 coupons retrieved at each recovery.

Environmental conditions

The average environmental conditions over the study period at each field site are summarized in Figure 1. Average H_2S concentrations ranged from >400 ppm (Perth B) to approximately 1.5 ppm (Melbourne A). H_2S concentrations recorded in the Perth (sealed) sewers were many time greater than those observed at the Sydney and Melbourne sites where pipes were naturally ventilated. Average Perth sewer gas temperatures (26-27°C) were also higher (~6°C) than observed at the Melbourne and Sydney locations. Average humidity in the Melbourne and Perth A sewers were close to saturation (RH>97%). Perth B and the Sydney A and B sites, however, were drier (RH<95%).

The diurnal variation in sewer gas temperatures typically was less than +/-1°C. However larger variations were observed at sites (such as Sydney) where the sewer is positioned above ground, in which cases the internal conditions can be expected to be influenced by external (atmospheric) temperature fluctuations. In all cases, humidity remained relatively constant over the diurnal cycle, typically varying by only 1-2%. Concentrations of H_2S in the sewer gas, however, varied much more, - by as much as 100% over the diurnal cycle.

Seasonally averaged sewer gas temperatures generally fell within a 6-8°C band at all locations with the exception of Perth B where season to season variations of up to 14 °C were observed.

Considerable variations in average H_2S concentrations also were observed from season to season at all sites, with higher concentrations experienced throughout the summer and autumnal months. Seasonal average humidities generally were steady, however, there was a small increase in humidity at the Perth B site towards the end of the field trials.

Coupon surface pH

Over time, the abiotic and the biotic processes in sewers lower the surface pH of the exposed sewer pipe surface from an initial highly alkaline state, (pH=12-13), to levels more suitable for microbial colonisation (Parker, 1951). As the surface pH falls, the composition of the bacterial and fungal communities colonising the pipe surface changes and this tends to alter the dynamics of the corrosion process (Islander et al., 1991; Davis et al., 1998). It follows that surface pH can serve as an indicator of the changing corrosivity of the local sewer environment. It is also an indicator for the changing activity of the bacterial and fungal species present on sewer walls.

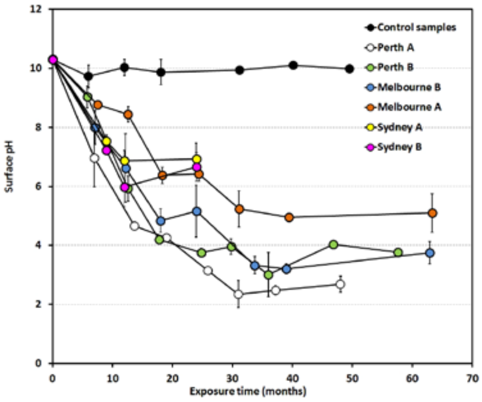

Figure 3. Evolution of surface pH of new coupons.

Surface pH values for the new and old concrete coupons and for the control samples are shown in Figures 3 and 4. The initial new coupon surface pH was ~10.1. This indicates that the surface had undergone some degree of carbonation prior to the beginning of the study. The surface pH declined when the coupon was introduced to the sewer environment (Figure 4). For the first 18 months the rate of this decline was 0.3-0.34 pH units/month at all sites except Melbourne A where the decline was slower (~ 0.2 pH units/month). After 18 months the rate of decline in surface pH slowed to 0.07-0.10 pH units/month at all sites. After 30 months new coupon surface pH levels stabilised at the Perth and Melbourne sites. At the conclusion of the study the pH levels of new coupon surfaces ranged from pH=5 at Melbourne A to pH=2.5 at Perth A. Over the same period the new concrete control coupons showed little variation in surface pH (average 10.0 +/- 0.2). Before the premature termination of the Sydney trials the surface pH appeared to have stabilised at pH=6.

The average old coupon surface pH prior to installation in the sewers was 8.2, a value consistent with the presence of an existing layer of corrosion product, the coupon surface exposure history and the carbonation of the portlandite content of the coupon. The surface pH of the old concrete coupon surfaces declined rapidly immediately after the coupons were installed in the sewers and after 6 to 7 months exposure (i.e. by the time of the first recovery) the average surface pH was pH= 3.5 to 4 at all sites except Melbourne A, where it had fallen to pH=6.1 (Figure 4). After 12 months exposure the surface pH of the old coupons stabilised at all sites except Perth A where surface pH continued to fall until 30 months exposure. The subsequent surface pH readings (i.e. for the remainder of the study period) were in the range pH=2.8 to 4 at all sites except Perth A where they were slightly lower (pH= 2.2-2.6). Over the same period the surface pH of the control samples for the old concrete showed little variation (7.9 +/- 0.3).

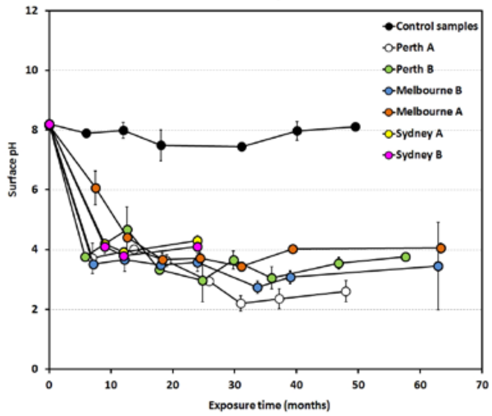

Figure 4. Evolution of surface pH of old coupons.

Coupon corrosion losses

The loss of concrete mass from new coupons at the Melbourne and Perth sites is shown in Figures 5 and 6 respectively. They show the same general trend at all sites. After introduction to the sewer new coupons passed through an "initiation" period during which no losses occurred. This lasted between 9 (Perth A) and 25 months (Melbourne A). At the time the Sydney trails were terminated new coupons at the two Sydney sites had experienced negligible corrosion. It is reasonable to assume, therefore, that for these two sites the initiation period most likely was greater than 36 months.

Subsequent to the initiation period the new concrete coupons at the Melbourne and Perth sites began to show corrosion losses of various degrees. Irrespective of local conditions, corrosion losses at all sites then increased in a linear manner with time (i.e. at a constant rate of corrosion). Concrete losses for the new concrete coupons at the end of each exposure period ranged from 36.4 mm at Perth A (48 months), 28.7 mm (Melbourne B, 63 months), 20.0 mm (Perth B, 58 months), to 3.8 mm at the Melbourne A site (63 months).

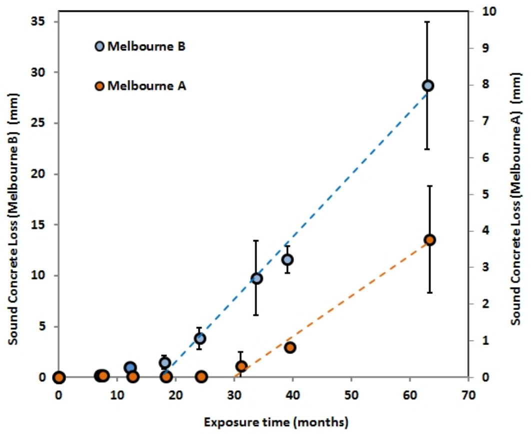

Figure 5. Melbourne new coupon losses.

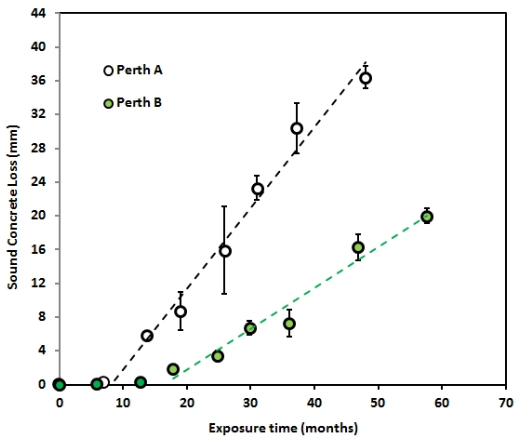

Figure 6. Perth new coupon losses.

Coupons made from old concrete commenced corroding almost immediately on installation in the sewers (Figures 7 and 8). Total corrosion losses for old coupons also were found to be linear functions of time, throughout the study period and at all Perth and Melbourne sites. Average corrosion losses measured on the old concrete coupons at the end of the study ranged from 38.1 mm at Perth A (48 months), 31.8 mm (Melbourne B, 63 months), 23.8 mm (Perth B, 58 months), and as low as 10.1 mm, 2.7 and 2.0 mm at Melbourne A (63 months), Sydney A and B (36 months) respectively.

DISCUSSION

Corrosion of concrete sewer pipe has, for some time, been considered a three stage process (Islander et al., 1991). Stage 1 begins with a newly manufactured pipe that contains calcium hydroxide present in the concrete matrix which has dissolved in the concrete pore water to produce a highly alkaline environment (pH of ~12 to 13, (Lea, 1970)). These conditions are not suited to bacterial activity and consequently biologically driven corrosion is minimal. Acidic gases such as CO_2 and H_2S present in the sewer atmosphere, however, can dissolve into moisture present in or on the pipe wall and subsequently react with the alkali species lowering the surface pH towards more neutral levels.

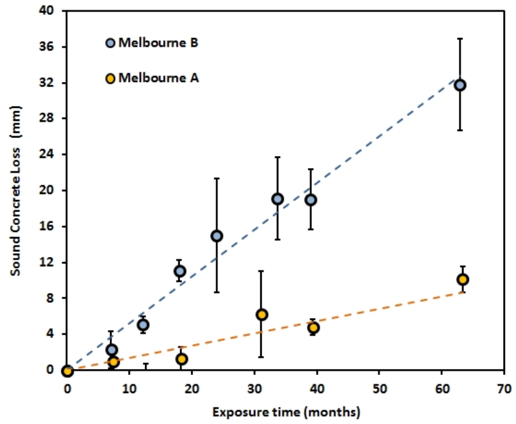

Figure 7. Melbourne old coupon losses.

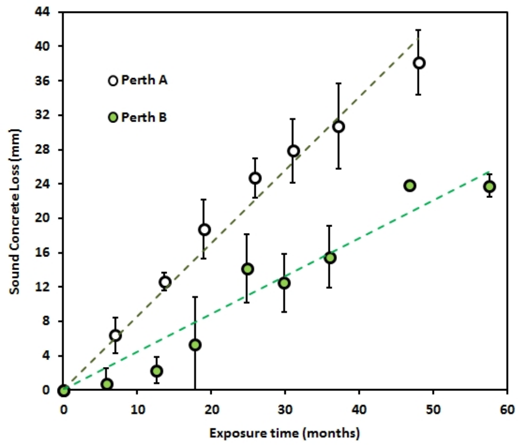

Figure 8. Perth old coupons losses.

Once the surface pH falls below pH=9, conditions become favourable for the colonisation of the concrete sewer wall surface by neutrophilic sulphur oxidising organisms (NSOM) (Islander et al., 1991; Okabe et al., 2007). The corrosion process is then considered to have entered its second stage. During stage 2 bacteria and fungi present secrete limited amounts of organic and inorganic acids which act to further lower the surface pH (Islander et al., 1991; Okabe et al., 2007).

Once the surface pH falls to pH=~4 the corrosion process enters the third and final stage in which NSOM bacteria give way to increasing populations of the more aggressive, acidophilic sulphur oxidising microorganisms (ASOM). The ASOM bacteria rapidly convert H_2S to elemental sulphur and eventually sulphuric acid, resulting in aggressive corrosion of the interior of the concrete sewer pipe.

While conceptually the evolution of the corrosion process of concrete in sewers is well-known, including the microbial aspects, just how this translates quantitatively to measurable corrosion losses and to corrosion rates is not well understood. The influence of external environmental parameters, such as temperature, H_2S concentration and humidity, also has remained uncertain. To address these issues, the present study examined in detail the in-situ corrosion of new and pre-aged concrete coupons from concretes similar to those used in practice, and under realistic practical conditions to determine quantitative relationships between sewer pipe corrosion and its behaviour with time and the environmental conditions. This study included both the early stages and behaviour after corrosion was already well advanced.

The corrosion behaviour experienced by the new coupons in this study revealed that, irrespective of the aggressiveness of the local environmental conditions inside the pipe, a new concrete sewer pipe experiences a period of time in which minimal loss of concrete material takes place. During this time there are changes in surface chemistry as the surface pH is driven down from initially high levels to more neutral values through a combination of (initially) abiotic processes and subsequently by the actions of neutrophilic bacteria and fungi activity. Data obtained in the present project suggest that this period lasts between 9 and 36 months, depending on the aggressiveness of the local sewer conditions. In terms of the 3 stage model originally proposed by Islander (1991) this "initiation" stage encompasses the abiotic stage 1 and a portion of the NSOM-dominated stage 2. The relatively low surface pH and low portlandite content of the old coupons at the commencement of the study resulted in those coupons essentially bypassing the initiation stage. Consequently, mass loss from these coupons was evident from the time of their first exposure to the sewer environment.

Comparison of coupon surface pH and corrosion losses for the coupon made from new concrete (for example, see Figure 9) shows that, irrespective of the aggressiveness of the site, the end of the initiation phase (and the onset of corrosion losses) occurs when the surface pH has declined to pH=~6. The time taken to reach this point, however, depends on the local sewer environment. This dictates the rate of decline of surface pH. The transition to a more active corrosion process at these surface conditions has previously been shown in the experimental work of Morton (1989). Thistlethwayte (1972) also states that concrete surface pH must first be reduced to pH=6 before *Acidithiobacillus thiooxidans* will proliferate fast enough to contribute to corrosion in sewers. However, more recent work, such as that of Okabe et al. (2007) suggests that mass loss does not commence until much lower pH levels (pH=2-4) are reached. In the present work the old concrete coupons reached this transition pH value very quickly after installation in the sewer (Figure 4) and consequently mass loss commenced almost immediately.

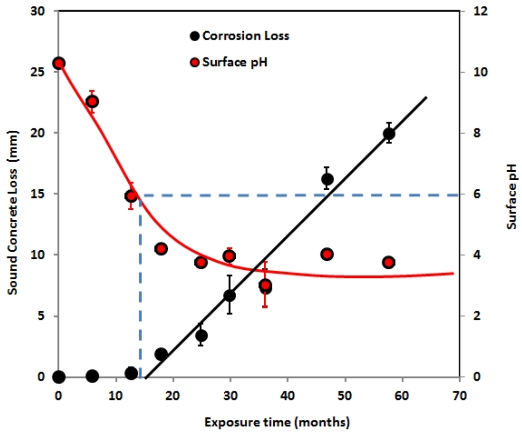

Figure 9. The onset of corrosion losses at ph=6 (Perth B).

Once corrosion losses commence, (immediately for old coupons and after the initiation period for new coupons), it is clear that for both new and old concrete coupons losses accumulated in a linear manner over time at all sites (i.e. all coupons at all sites experienced a constant rate of corrosion). The actual value of the rate of corrosion, however, was site specific, indicating that the rate is in response to the specific local sewer conditions.

In the present study the corrosion rates for coupons made from new concrete were obtained from simultaneous exposures, side by side with coupons made from old concretes (Fig. 1 inset) with significantly lower alkalinity and more open pore structure. The differences in concrete properties suggest that corrosion rates experienced by old coupons should be significantly higher than new coupons at each field site. Based on the generally accepted inverse relationship between the corrosion rate and the level of concrete alkalinity (Thistlethwayte, 1972), the old coupons would be expected to have experienced rates of loss up to 40% faster than the new coupons at each site. A comparison of rates of corrosion experienced by the new and old coupons at each site, however, shows that corrosion rates for the two types of concrete were very similar (Figure 10) and that any differences are well within the level of uncertainty in the measured rate.

At this time the reason(s) for the similar corrosion rates are not entirely clear, but may be due to the presence of the corrosion product layer which was generally better developed on the old coupons compared with the coupons made from new concrete (e.g. Figure 11). As the bacteria involved in concrete corrosion tend to colonise the exposed surface of the coupon (i.e. the exposed surface of the corrosion product) it is possible that the thicker product layer present on the old coupons may have hindered the part of the corrosion process resulting from bacterial activity by slowing the transport of acid produced by the bacteria to the concrete interface, thereby slowing old coupon corrosion to rates more in line with the new coupons. This matter remains to be resolved by further research.

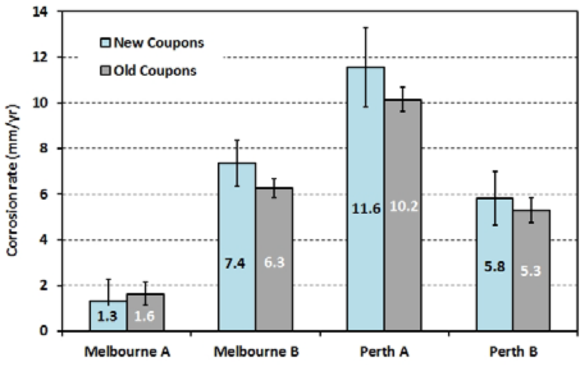

Figure 10. New and old coupon rates of corrosion.

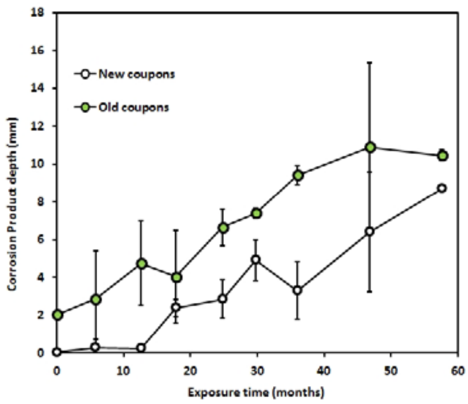

Figure 11. Depth of corrosion product layer on Perth B new and old coupons.

Strategies to reduce corrosion rates

One important finding from this study is that corrosion behaviour is very sensitive to sewer gas humidity. At 85% humidity the pore structure of typical concrete pipes is quite dry and therefore not conducive to microbial activity. Also for such low humidity the effect of gaseous H_2S levels also would be low and consequently the corrosion rate would be low. As humidity increases above 85% the pore structure of the concrete fills with moisture and the corrosion rate climbs. The impact of lower humidity on corrosion rates was particularly evident at the Perth B site which, despite having a H_2S level many times higher than the remaining sites, exhibited only modest rates of corrosion. Its corrosion rates were similar to the Melbourne B site despite having H_2S levels 70× higher. It follows that ventilation of sewers to reduce humidity and produce "dry walls" should significantly reduce corrosion rates.

The results of the present study also show that maintaining the surface pH of the sewer walls above pH=6 (by washing or application of a high pH coating) should prevent the pipe from entering the active corrosion phase of the corrosion cycle and subsequently prevent the proliferation of ASOM bacteria. This would reduce corrosion activity significantly.

A 'first pass' corrosion model

The evolution of the sewer pipe corrosion process can be represented as a bi-linear function with time, as shown in Figure 12. Initially, when a reinforced concrete sewer pipe is put into service there is little or no mass loss for some period of time (months to a few years). Once the surface pH reaches ~6, corrosion of concrete commences and will continue at a uniform rate semi-indefinitely. The bi-linear model can therefore be parameterised using just two parameters - the time, t_i, for corrosion to initiate and the long-term steady state corrosion rate, R. It is evident that the duration of the initiation period and the subsequent rate of corrosion will be functions of the local environmental conditions. In practise it is likely that a number of factors will influence the rate of concrete corrosion, some more than others. Even if these factors were all positively identified, many are likely to be difficult to measure or quantify. To by-pass this issue, the present project identified that a relatively small number of parameters - parameters that also were relatively easy to measure - and that would have the greatest influence. Three such parameters were identified: sewer gas temperature, H_2S concentration and humidity.

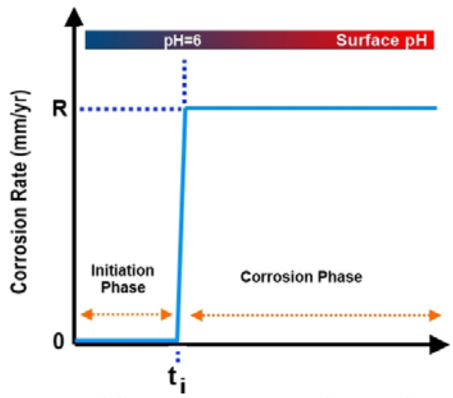

Figure 12. Bi-linear representation of the concrete sewer pipe corrosion process.

The field trials have provided information useful for verification of the form of the bi-linear model. However, direct application of the data for model calibration has been complicated by differences in H_2S, temperature and humidity between the various field sites. As a result it was necessary to consider the fundamental physical, chemical and biological processes known to take place in developing a first pass corrosion model and use this information to interpret the field data. This approach was employed to describe the relationship between sewer humidity, temperature and H_2S concentration in the sewer atmosphere and the rate of mass loss experienced by the pipe once the surface pH falls below pH=6.

Temperature influences the rate of corrosion through causing changes in the rates of the chemical, biological and physiochemical processes involved in the corrosion process. To make progress it was assumed that the primary influence of temperature is via its impact on biological activity. This may be represented as an Arrhenius function:

$$C_t \propto e^{-E_a/RT} \qquad (1)$$

where C_t represents the temperature factor in the corrosion model, T is the absolute temperature, R is the universal gas constant and E_a is the activation energy for the process. The value of E_a is set at 45 kJ mol^{-1} for bacterial production of acids (Franzmann et al., 2005; Nielsen et al., 2006).

Humidity influences the corrosion process through its effect on moisture content of the concrete pore structure. As humidity rises in the sewer, pores within the concrete fill with moisture enabling more microbial activity to take place. When the pore filling process is considered (Wells and Melchers, 2015) the following relationship between humidity and corrosion rate is derived:

$$C_{RH} = \left(\frac{0.1602H - 0.1355}{1 - 0.977H}\right) \qquad (2)$$

where C_{RH} represents the humidity factor of the corrosion model and H is the relative humidity (expressed as a fraction of saturated).

The work of Nielsen (2014) suggests that the oxidation of H_2S by corroding surfaces follows a simple nth order kinetics with a process order of n=0.4 to 0.75. Analysis of the corrosion rates observed at the Melbourne A, B and Perth A sites where humidity levels were close to saturation (H>0.97) indicates a value of n=0.5 best describes the influence of H_2S on corrosion rates. A simple square root relationship is therefore proposed:

$$C_{H_2S} = [H_2S]^{0.5} \qquad (3)$$

where C_{H_2S} represents the H_2S factor of the corrosion model and *[H_2S]* is the concentration of H_2S.

From the above considerations the following first pass model is proposed:

$$C = A \times [H_2S]^{0.5} \times \frac{(0.1602H - 0.1355)}{(1 - 0.9770H)} \times e^{\left(-45000/RT\right)} \qquad (4)$$

where C is the rate of corrosion (mm yr^{-1}), *[H_2S]* is the concentration of hydrogen sulphide in the sewer atmosphere (ppm), H is the fractional relative humidity of the sewer atmosphere (-), R is the universal gas constant (=8.314 J mol^{-1} K^{-1}), T is the temperature of the sewer atmosphere (K) and A is a constant (=207,750) determined empirically to obtain the best fit between the model and field data.
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Eqn (4) was used to predict the rate of corrosion at the Perth, Melbourne and Sydney field sites and is compared to observed values in Figure 13. The agreement between predicted and observed rates can be considered excellent and indicates that Eqn. (4) provides a good estimator of the rate of concrete sewer pipe corrosion. This requires the relevant long term average gas phase properties (temperature, humidity and H_2S concentration) to be known or available.

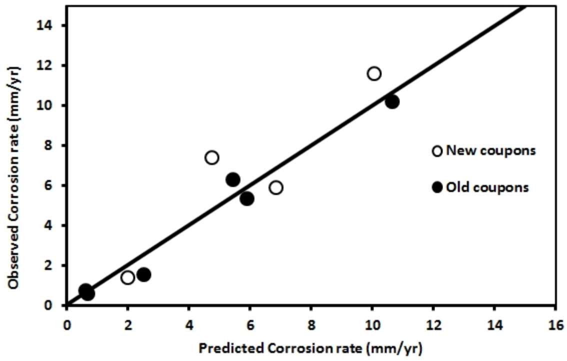

Figure 13. A comparison of predicted and observed corrosion rates. The diagonal lines represents perfect agreement.

CONCLUSION

A 4 year field study of sewer pipe corrosion has shown that corrosion is a bi-linear process beginning with an initial (short) period involving little or no mass loss. Once the surface falls to pH=6 corrosion losses commence and continue at a constant rate with time for the remainder of the life of the pipe. Two strategies suggested for lowering the rate of corrosion are to maintain surface pH>6 or lower the sewer gas humidity. A model predicting the rate of corrosion using local environmental conditions also has been developed.

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REFERENCES

Davis, J. L., D. Nica, K. Shields and D. J. Roberts (1998). "Analysis of concrete from corroded sewer pipe." International Biodeterioration & Biodegradation **42**(1): 75-84.

Franzmann, P. D., C. M. Haddad, R. B. Hawkes, W. J. Robertson and J. J. Plumb (2005). "Effects of temperature on the rates of iron and sulfur oxidation by selected bioleaching Bacteria and Archaea: Application of the Ratkowsky equation." Minerals Engineering **18**(13–14): 1304-1314.

Hewayde, E., M. Nehdi, E. Allouche and G. Nakhla (2006). "Effect of geopolymer cement on microstructure, compressive strength and sulphuric acid resistance of concrete." Magazine of Concrete Research **58**(5): 321-331.

Islander, R. L., J. S. Devinny, F. Mansfeld, A. Postyn and S. Hong (1991). "Microbial Ecology of Crown Corrosion in Sewers." Journal of Environmental Engineering-Asce **117**(6): 751-770.

Koch, G., M. Brongers, N. Thompson, Y. Virmani and J. Payer (2001). "Report # FHWA-RD-01-156, Corrosion cost and preventive strategies in the United States." Office of Infrastructure Research and Development, Federal Highway Administration, McLean, VA.

Lea, F. M. (1970). "The chemistry of cement and concrete, 3rd edition.". London, Edward Arnold Ltd.

Morton, R., R. Caballero, C.-L. Chen and J. Redner (1989). "Study of sulfide generation and concrete corrosion of sanitary sewers." In-house report; Sanitation Districts of Los Angeles County Carson, California.

Nielsen, A., T. Hvitved-Jacobsen, H. Jensen and J. Vollertsen (2014). "Experimental Evaluation of the Stoichiometry of Sulfide-Related Concrete Sewer Corrosion." Journal of Environmental Engineering **140**(2): 04013009.

Nielsen, A. H., J. Vollertsen and T. Hvitved-Jacobsen (2006). "Kinetics and Stoichiometry of Aerobic Sulfide Oxidation in Wastewater from Sewers: Effects of pH and Temperature." Water Environment Research **78**(3): 275-283.

Okabe, S., M. Odagiri, T. Ito and H. Satoh (2007). "Succession of Sulfur-Oxidizing Bacteria in the Microbial Community on Corroding Concrete in Sewer Systems." Applied and Environmental Microbiology **73**(3): 971-980.

Parker, C. D. (1945a). "The corrosion of concrete 1. The isolation of a species of bacterium associated with the corrosion of concrete exposed to atmospheres containing hydrogen sulphides." The Australian journal of experimental biology and medical science **23**: 81-90.

Parker, C. D. (1945b). "The corrosion of concrete 2. The function of *Thiobacillus concretivorus* (nov. spec.) in the corrosion of concrete exposed to atmospheres containing hydrogen sulphides." The Australian journal of experimental biology and medical science **23**: 91-98.

Parker, C. D. (1951). "Mechanics of Corrosion of Concrete Sewers by Hydrogen Sulfide." Sewage and Industrial Wastes **23**(12): 1477-1485.

Roberts, D. J., D. Nica, G. Zuo and J. L. Davis (2002). "Quantifying microbially induced deterioration of concrete: initial studies." International Biodeterioration & Biodegradation **49**(4): 227-234.

Snell, F. D. and L. S. Ettre (1972). "Encyclopedia of industrial chemical analysis", Interscience Publishers Division, vol 15, New York.

Thistlethwayte, D. K. B. (1972). "The control of sulphides in sewerage systems". Sydney, Australia, Butterworths Pty Ltd, 1972.

Wells, P. A. and R. E. Melchers (2009). "Factors involved in the long term corrosion of concrete sewers (Paper 54)." Conference Proceedings. Corrosion and Prevention 2009: The Management of Infrastructure Deterioration. Coffs Harbour, Australia.

Wells, T. and R. E. Melchers (2014). "An observation-based model for corrosion of concrete sewers under aggressive conditions." Cement and Concrete Research **61–62**(0): 1-10.

Wells, T. and R. E. Melchers (2015). "Modelling concrete deterioration in sewers using theory and field observations." Cement and Concrete Research **77**: 82-96.