SUMMARY: Microbial induced corrosion (MIC) of reinforced concrete sewers and manholes is a significant problem in sewage systems with global repair costs estimated to be in the order of billions of dollars per year. When the corrosion is sufficiently advanced it can lead to structural failures with potentially serious longer-term operational consequences. While the fundamentals involved in concrete sewer deterioration are reasonably well-understood, the prediction of the rate of deterioration and the quantitative effects of various influencing factors are not well developed. This paper outlines the basic mechanisms involved in deterioration of concrete sewers and the likely effects of various influencing factors, based on currently available information. A brief description of the current knowledge gaps is also provided. A new ARC and industry funded research project is discussed that combines industry and multi-disciplinary university research with the aim of determining the relationship between sewer environmental parameters such as $\text{H}_2\text{S}$ level, temperature and humidity and the instantaneous corrosion rate of concrete using in situ field observations and extensive laboratory testing. Investigations into the molecular, chemical and material dynamics of the corrosion process will enable an accurate picture of the various underlying processes to be constructed. This data along with historical records and the experience of the industry participants will enable a phenomenological model of the corrosion process to be constructed. It will enable industry to estimate the reliability and the expected remaining physical life of concrete sewers.

KEYWORDS: Concrete corrosion, hydrogen sulphide, thiobacillus, sewers, microbial, model

1. INTRODUCTION

Microbial induced corrosion (MIC) of reinforced concrete sewer pipe is one of the most serious and costly problems currently affecting the world’s sewerage infrastructure. Globally, the losses due to MIC breakdown of sewer piping are estimated to be in the order of billions of dollars per year (Hewayde, Nehdi et al. 2007). In Germany alone the estimated cost for the repair of MIC degraded sewer pipe is in excess of $50 billion (Hewayde, Nehdi et al. 2006). In Flanders, Belgium, biogenic corrosion of sewers represents approximately 10% of the total sewage treatment cost (Zhang, De Schryver et al. 2008). Throughout the Los Angeles county district an estimated 200km of corroded pipe needs to be replaced at a cost of more than $500 million dollars (Sydney, Esfandi et al. 1996). In Australia the total value of wastewater assets is approximately $40 billion of which 70% is tied up in ~110,000 km of sewer piping and channel that service the residential and industrial sectors of the community. The annual repair cost to redress MIC damage to this system is tens to hundreds of millions of dollars per year. Moreover, advanced corrosion can lead to unexpected catastrophic failure resulting in significant system interruption and extensive damage to surrounding roads and pavements. While not related to MIC the recent landslide incident in Bellevue Hill, Sydney (Brown 2009) which produced a 25m wide crater and swallowed up cars, trees and a telegraph pole is a good example of the additional costs that sewer main failure can incur.

The incidence of corrosion of concrete sewer pipe was first studied towards the end of the 19th century in the USA by Olmsted and Hamlin (1900). They noted that a white pasty material formed on corroded sections of concrete sewer pipe. They concluded that sulphuric acid was the corrosive agent but the link between the occurrence of the acid and the presence of $\text{H}_2\text{S}$ in the sewer system was not recognized until some decades later (Bowlus and Banta 1932). At this time it was believed that the oxidation of $\text{H}_2\text{S}$ to form $\text{H}_2\text{SO}_4$ was a purely chemical process which occurred in the presence of oxygen in the sewer headspace (Lea and Desch 1936). In the 1940’s a conceptual understanding of the biological nature of the concrete corrosion process was established through systematic work undertaken in Australia and the USA (Parker 1945a;
Parker 1945b, Pomeroy and Bowlus 1946) when the bacterium “Thiobacillus concretivorous”, (later renamed Acidithiobacillus Thiooxidans, (Kelly and Wood (2000)), was identified amongst the acidic corrosion products.

MIC of concrete sewers was not regarded as a significant issue until the 1980’s when a manifold increases in the corrosion rates in sewers in the USA (Tator 2003) and Europe (Gu, Ford et al. 1998) were observed. At this time government authorities were imposing tighter limits on the nature and toxicity of industrial wastewaters to be discharged to the sewer system (via the US Clean Water Act and EPA pre-treatment programs). This led to significantly lower levels of biologically toxic metals such as lead, chromium, mercury, arsenic and cadmium in the sewer system and as a consequence bacterial levels (and consequent MIC) increased dramatically (Sydney, Esfandi et al. 1996). Increases in MIC were also linked to increased sewage temperature, (due to increasing use of hot water in domestic situations) and increased use of sulphate containing detergents. Increases in bacterial activity also accompanied the general increase in sewer line lengths (and hence sewage residence times) that have accompanied the growth of suburban populations (Sand, Dumas et al. 1992). The increase in the severity of the MIC problem has led to a renewed interest in the processes involved. This has revealed its complexity and the involvement of many species of bacteria (Nica, Davis et al. 2000; Okabe, Odagiri et al. 2007) as well as some fungal species (Cho and Mori 1995; Gu, Ford et al. 1998; Nica, Davis et al. 2000).

2. FUNDAMENTALS OF SEWER CORROSION

A schematic representation of microbial corrosion of concrete sewer pipe is shown in Figure 1.

Stage 1. Abiotic neutralization of concrete surface

Newly installed concrete pipe has a surface pH of approximately 12-13 which is too high for microbial activity to take place. In the wastewater stream however colonies of anaerobic sulphate reducing bacteria (SRB) are active in biofilm layers that line the submerged sewer walls (Figure 2). In these films SRB reduce sulphates and oxidise biodegradable organic carbon and in doing so produce hydrogen sulphide and carbon dioxide (Eqn (1)).

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

Figure 1. Progression of microbial corrosion of sewer pipe.
The hydrogen sulphide formed is transported through the biofilm into the wastewater where the molecular form of the sulphide co-exists in equilibrium with its dissociated ions, $H^+$ and $HS^-$. At normal domestic sewage pH 25-35% of the dissolved sulphide exists as molecular $H_2S$. Carbon dioxide is also transported into the liquid phase where a portion is dissolved as carbonate and bicarbonate ions. At the liquid-gas interface $H_2S$ and $CO_2$ are volatilised into the sewer headspace. The gases diffuse through the headspace atmosphere and dissolve into the condensate film that forms on the roof and walls of the sewer. Once back in a liquid phase a proportion of the $H_2S$ re-dissociates to form $HS^-$ and $H^+$ while $CO_2$ dissolves to form carbonic acid in its various forms ($H_2CO_3 ⇌ HCO_3^- + H^+$, $HCO_3^- + H^+ ⇌ CO_2 + H_2O$). The weak acids that form in the condensate layer react with alkali species in the concrete such as calcium hydroxide lowering the pH of the concrete surface over time (pH ≈ 9). The duration of this essentially abiotic process is not well defined. Estimates range from a few months to several years.

**Stage 2. Colonization by neutrophilic bacteria**

If sufficient oxygen, nutrients and moisture are present neutrophilic sulphur oxidizing microorganisms (NSOM) such as Thiothrix spp can colonize the concrete surface once the pH falls to 9. During stage 2 of the corrosion process these organisms produce $H_2SO_4$ through the oxidation of $H_2S$ diffusing into the condensate film. The acid produced reacts with the concrete surface to further lower the pH. A variety of microorganisms can colonize the concrete under these conditions and in practice it is most likely that there will be a succession of waves of growth of the different organisms as the pH gradually decreases.

**Stage 3. Colonization by Acidophilic bacteria**

When the pH of the concrete falls to 4 acidophilic sulphur oxidizing microorganisms (ASOM) can begin colonising the concrete surface. They too will act to oxidise $H_2S$ to sulphuric acid but can also oxidise thiosulphate and elemental sulphur that is deposited on sewer walls after gaseous $H_2S$ is directly oxidized by oxygen present in the headspace. The activity of the acidophilic bacteria further lowers the concrete pH to values around 1-2.
Stage 4. Loss of concrete mass

At this stage of the corrosion process concrete mass losses begin. The sulphuric acid produced by ASOM reacts with the silicate and carbonate compounds within the cement component of the concrete to form gypsum via the following reactions:

\[
H_2SO_4 + CaO\cdot SiO_2 \cdot 2H_2O \rightarrow CaSO_4 + Si(OH)_4 + H_2O \quad (2)
\]

\[
H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2CO_3 \quad (3)
\]

\[
H_2SO_4 + Ca(OH)_2 \rightarrow CaSO_4 + 2H_2O \quad (4)
\]

The formation of gypsum leads to an increase in volume of approximately 124% (Parande, Ramsamy et al. 2006) which weakens the cement structure. More destructive, however, is the subsequent reaction (Eqn (5)) between gypsum and tricalcium aluminates within the cement matrix to form the mineral Ettringite. The formation of Ettringite produces a significantly higher volume expansion with estimates ranging from 227% (Parande, Ramsamy et al. 2006) to 700% (Monteny, Vincke et al. 2000). Ettringite formation leads to internal cracking and pitting of the concrete which in turn increases the surface reaction area and facilitates easier penetration of moisture, acid and microorganisms into the concrete structure.

\[
CaSO_4 + 3CaO\cdot Al_2O_3 \cdot 6H_2O + 25H_2O \rightarrow 3CaO\cdot Al_2O_3\cdot 3CaSO_4 \cdot 3H_2O \quad (5)
\]

Throughout the corrosion process a soft white layer of corrosion product (primarily gypsum) forms on the concrete surface and gradually thickens over time. Ettringite is more commonly observed in cracks penetrating into the sound concrete material (Mori, Koga et al. 1991; Mori, Nonaka et al. 1992). The effect of the thickening corrosion layer on the corrosion process is unclear. It has been suggested that the layer provides an excellent medium for bacterial growth and hence accelerates the corrosion process (Monteny, Vincke et al. 2000). However, a recent analysis of the oxygen, pH and microbial activity within the corrosion layer (Okabe, Odagiri et al. 2007) suggests that the bulk of the biogenic acid production occurs on the exposed surface of the corrosion layer indicating that the sulphuric acid produced must percolate down through the corroded layer before reacting with the sound concrete. If this is the case the increasing thickness of the corrosion layer may serve to hinder the corrosion process.

3. FACTORS IN SEWER CORROSION

There are many environmental and material factors that affect the corrosion of concrete. NSOM and ASOM utilise H$_2$S (and other forms of sulphur) dissolved into the condensate film to form corrosive acids. Consequently environmental and sewer design features which alter the H$_2$S concentration in the sewer wastewater or headspace are important. For example, it is well known that sewer system configurations that result in hydraulic energy loss and increased residence times and/or feature high BOD concentrations produce a greater degree of microbial activity, increased H$_2$S concentrations in the liquid (and hence gas) phase, and consequently increased MIC levels (Tator 2003).

Factors which help in the transfer of H$_2$S from wastewater to the gas phase also increase MIC rates. Thus, the pH of the wastewater can have a considerable influence on the level of H$_2$S in the sewer headspace. Sulphides generated in the wastewater by sulphate reducing bacteria exist either as discrete molecules or in a dissociated form (Eqn (6)).

\[
[H_2S]_{\text{molec}} \rightarrow HS^- + H^+ \quad (6)
\]

The equilibrium position in Eqn (6) is a strong function of pH (Figure 3). Low pH values increase the $[H_2S]_{\text{molec}}$ concentration in preference to $H^+$ and $HS^-$ in the liquid phase and as only molecular H$_2$S is transferred to the gas phase gas phase concentrations of H$_2$S will rise when wastewater pH is lowered resulting in increased levels of MIC. Other factors which increase the liquid to gas transfer of H$_2$S such as increased temperature or turbulence in the liquid and gas phases also ultimately lead to higher corrosion rates (Monteny, Vincke et al. 2000; Lahav, Sagiv et al. 2006; Parande, Ramsamy et al. 2006).

For a given level of H$_2$S in the sewer headspace higher temperatures raise corrosion rates by increasing microbial activity levels and accelerating corrosion reaction rates (Saricimen, Maslehuddin et al. 1987; Parande, Ramsamy et al. 2006). Higher levels of humidity which produce more condensate on the roof of the sewer and ensure adequate moisture supply for NSOM and ASOM, have also been observed to increase corrosion rates (Islander, Devinny et al. 1991). Conversely the removal of the corrosion layer by “washing” of the upper sections of the sewer pipe (such as may occur after heavy rain in combined sewer systems) has been found to dampen microbial activity (Nielsen, Vollertsen et al. 2008). Interestingly this effect is usually temporary and activity is completely restored in a matter of a few weeks.

A considerable variation in corrosion rates across the traverse of the sewer pipe has been observed. However, the spatial variation is not consistent across all studies. In some cases a significantly higher rate was observed at the crown of the
Corrosion of concrete sewers (e.g., Vincke, Boon et al. 2001) while other studies noted more pronounced corrosion immediately above the wastewater level (Mori, Nonaka et al. 1992). The manufacture of the concrete pipe also can have an impact on the corrosion rate. Hewayde, Nehdi et al. (2007), for example, observed higher levels of deterioration in concrete samples with higher cement content and lower water/cement ratios. Sewer pipes with lower porosity and permeability concretes also tend to show lower corrosion rates (Islander, Devinny et al. 1991). Increasing the alkalinity of the sewer pipe by replacing inert aggregate with calcareous material has been found to lower the MIC rate by creating a local buffering environment which protects the cement binder (Hewayde, Nehdi et al. 2007).

Figure 3. The fraction of hydrogen sulphide that exists as the H$_2$S molecule in solution as a function of pH.

4. KNOWLEDGE GAPS

As indicated in Figure 1 the corrosion of concrete sewers is not a linear process with respect to time. Before observable deterioration becomes apparent there is an initial period in which microbial populations come and go and the chemical and physical properties of the concrete alter considerably. Once observable mass loss commences the corrosion rate remains unlikely to be linear as environmental conditions (wastewater chemistry, pH, temperature) and concrete properties (corrosion layer characteristics, microbial populations, concrete chemistry and porosity) continue to evolve. The non-linearity of the corrosion process presents a significant problem for the engineer trying to predict the remaining life of sewer pipes. If, as illustrated in Figure 4, a concrete pipe subject to a complex corrosion process is sampled at time $T_a$ or $T_b$ and the observed mass loss at those times is used to determine the mass loss ($M_a$, $M_b$) at a future time, $T_c$, there is clearly the possibility of under or over prediction of the future mass loss if a constant corrosion rate is assumed. It is desirable, therefore, to develop a more accurate model of the corrosion process, one that can estimate the instantaneous corrosion rate as a function of time over the course of the service life of the sewer.

In 2008 an ARC Industry Linkage project was initiated in which research and industry personnel from a number of water authorities and universities in Australia agreed to examine odour and corrosion issues in Australian sewer systems. The subproject dealing with corrosion has the following overall aims:

a. Determine the relationship between various environmental parameters such as H$_2$S concentration, humidity, temperature and the corrosion rate using laboratory testing and field measurements and hence determine the controlling factors in the process.

b. Use insights and data gathered from laboratory and field work to develop a mathematical model to predict the corrosion rate of concrete pipe as a function of time of exposure 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.

While the basics of the corrosion process (as previously discussed) are understood, numerous knowledge gaps remain. One primary knowledge gap surrounds the dynamics of microbial activity throughout the corrosion process. Until recently, techniques to identify and quantify microbial populations on corroding surfaces were not available. Recent development of microprobe analysis techniques will allow the chemical makeup of the corroding concrete surface to be studied. Through these tests the project will determine:
Figure 4. Possible errors incurred when corrosion rate is not constant over time.

a. The role of the corrosion layer as a growth matrix and provider of moisture and nutrients to bacteria.
b. The vertical distribution of nutrients, O₂, H₂S, and H₂SO₄ within the corrosion layer.
c. The population distribution of NSOM and ASOM within the corrosion layer and nearby concrete and how the distribution (both spatially and by species) changes over time.
d. How microbial H₂SO₄ production rates change over time.
e. How environmental factors such as temperature, humidity and H₂S levels affect the above.
f. The relative roles of the different bacterial species in each stage of the corrosion process.
g. The rate limiting factors for microbial activity at the different stages of the corrosion process.
h. The spatial variability of microbial populations within the sewer.
i. The effect of diurnal variation in H₂S levels on microbial activity.
j. Why there exists a difference between MIC and purely chemical H₂SO₄ corrosion of concrete.

The other major knowledge gap concerns the relationship between microbial activity and the corrosion of the concrete pipe. To address this gap, physical changes to the concrete matrix will be correlated with microbial activity and the level of corrosion. Attention will be given to the following:

a. The changes in mineralogy, permeability and strength of the concrete pipe and corrosion layer throughout the different stages of the corrosion process.
b. The spatial variability of such changes around the sewer circumference.
c. The characteristics (e.g. thickness and permeability) of the corrosion layer and how it changes over time.
d. The extent of chemical and physical changes to concrete properties below the corroded layer.
e. The impact of concrete washing on corrosion rates.
f. The kinetics of concrete loss throughout each stage of the corrosion process.
g. The kinetics of the corrosion reactions (Eqns (2-5)).
h. How environmental factors affect the above.

5. RESEARCH PLAN

The study of concrete corrosion will involve a mix of field and laboratory work (Figure 5) to be carried out by personnel at the Universities of Newcastle and Queensland as well as various water authorities around Australia.

5.1 Field work

It is important for the validity of the corrosion model that as much data as possible be obtained from the corrosion of samples under real sewer conditions as data obtained from the field samples will serve as calibration points for the associated laboratory work. Concrete coupons will be exposed for up to 4 years in sewers in Brisbane, Sydney and Melbourne which possess a variety of temperature and H₂S conditions. A total of over 300 samples will be installed. The majority of coupons will be mounted on the crown of the sewer however an additional set of coupons will be mounted just
above the normal water level in at least one sewer to enable the effect of position within the sewer to be determined. To
determine the effect of concrete age on corrosion rates, coupons cut from newly manufactured reinforced concrete sewer
pipe will be mounted beside coupons cut from 35 year old, partially corroded concrete sewer roof panels provided by the
industry partners. Samples will be mounted in resin in specially designed stainless steel housings that ensure one face only
of each sample is exposed to the sewer environment (see Figure 6).

Multiple coupons will be retrieved after 6, 12, 24, 36, and 48 months of exposure at each site. From each set of retrieved
samples a subset will be sent to the University of Queensland for biological analysis. At the University of Queensland the
microbial activity and functioning of the biofilms present will be determined by microsensors measuring solute (O\textsubscript{2}, H\textsubscript{2}S,
pH) distribution profiles. Denaturing gradient gel electrophoresis (DGGE) will be used to provide profiles of the microbial
communities present. Nutrient levels in the biofilm will be determined by HPLC analysis of the biofilm water content for
oxalic, gluconic and citric acid.

The remaining samples will be sent to the University of Newcastle to determine concrete losses and record any changes
that have occurred to the concrete chemistry or mineralogy. The extent of concrete corrosion will be determined via a
photogrammetric technique in which a 3D image of the exposed surface of each sample will be generated (for example see
Figure 7). The surface height of the corroded sample will be calculated relative to a reference plane and compared to the
surface image recorded for that sample prior to exposure. The surface image will be determined both with and without the
corrosion layer enabling the corrosion layer thickness and the decrease in “sound” concrete thickness to be determined.
This technique not only enables an accurate estimation of average change in coupon thickness to be calculated irrespective
of the surface roughness but also allows a detailed picture of the spatial distribution of losses to be obtained.

The bulk chemistry of the corrosion layer and nearby concrete will also be determined via IC and HPLC analysis of
dissolved material. Surface pH will also be determined. XRD, XRF and SEM/EDS will be used to determined mineralogy,
elemental composition and surface structure of each sample.

5.2 Laboratory work

A series of laboratory experiments will be conducted at the University of Queensland in parallel with the field studies. The
laboratory work will enable the relationships between the environmental variables and the corrosion rate and microbial
activity to be determined under well controlled conditions. New and pre-corroded concrete samples obtained from similar
sources to that used for the field work. Samples will be exposed to a variety of environments in 36 purpose built test
chambers through which waste water is circulated for up to 4 years. Concrete coupons will be exposed to 6 H\textsubscript{2}S levels at a
variety of gas and liquid temperatures ranging from 15 to 30°C. Relative humidity will be kept between 75 and 100%. A
portion of the samples will be partially immersed in the wastewater while the remainder will be mounted above the wastewater stream.

Coupons will be removed at 6 monthly intervals over a 4 year period. Sulphide consumption rates will be determined by measuring the sulphate concentration in the corrosion layer. The coupons will also be examined for biofilm microbial activity and their chemical composition, mineralogy, structure and the rate of corrosion determined using the same techniques as discussed above for the field samples.

5.3 Modelling work
The modelling portion of the project will be undertaken by personnel at the University of Newcastle using the insights and data made available by the field and the laboratory experimental programs in conjunction with fundamental deterioration mechanisms already available in the literature. The aim of the modelling section of the project is to develop a mathematical model which will predict the corrosion of concrete versus time of exposure for a set of given sewer environmental conditions. This may then be used by the industry partners to estimate the reliability and expected remaining physical life of concrete sewers and for the economic assessment of control options versus long-term deterioration expectations.

The approach to be adopted will follow the same general strategy as that developed in the modelling of immersion and atmospheric corrosion of steel in marine environments (Melchers 2006; Melchers and Wells 2006). The approach that will be taken assumes that the instantaneous corrosion rate is not constant but rather is a function of time (such as illustrated in Figure 4). The instantaneous rate is likely to depend on the following factors:

a. The build up of corrosion products.
b. The location, number, type and activity of microbial species present.
c. The magnitude of fluxes and concentrations of various nutrients and other chemical species.
d. The structural and chemical properties of the corrosion layer and nearby sound concrete material.

Figure 6. Sample holder for field samples (top) and several samples mounted on crown of sewer (bottom).
All of the above factors are likely to be complex functions of time and consequently the corrosion rate will also likely be a complex function of time.

Figure 8 illustrates the principal factors involved in the corrosion model. The key to developing the mathematical model is to describe the deterioration process using appropriate mathematical representations (models) for the various biological, chemical and physical processes involved. The relative importance of the different processes is likely to change as corrosion progresses. Initially, for example, the model will focus on the chemical attack on the concrete surface which serves to lower the surface pH from the initial highly alkaline values. With time, biofilm formation and the associated early
corrosion attack on the largely unchanged concrete surface will become a more dominant issue. Once the corrosion attack has been underway for some time the important mechanisms will relate more to the mechanics of concrete component breakdown. As the concrete is attacked the corrosion front moves further away from the outer layer of deteriorated concrete and a layer of corroded product forms which may create new opportunities for bacterial colonization. The corrosion layer also may act to impede the flux of nutrients towards the bacterial mass and/or slow the diffusion of corrosion products created at the corrosion front away from the attack sites. Not only must the biological, chemical and physical processes within each element be represented but also the interfaces between them are important. All of these elements are largely diffusion issues and will be modelled as such. These phases of the model are essentially sequential, although some overlap may occur, since not all parts of the concrete will be undergoing precisely the same phase of corrosion. Similarly, it is expected that only time averages of influencing factors will be required to represent deterioration processes, since it is an integration process.

Initially the various model components describing biological, diffusion and corrosion processes will be assembled from the body of work already available in literature. To avoid over complication of the model the concrete corrosion will, at least initially, be represented as a one dimensional process, i.e. perpendicular to the corroding surface. This approach should capture the essence of the problem sufficiently for engineering purposes. As the model is developed it will be tested for sensitivity to parameters and only those with significant influence will be retained allowing a simple first draft engineering model to be obtained. Data obtained from literature, laboratory and field work as well as historical records obtained from the project’s industry participants will then be used to refine, calibrate and adjust the model until such a time as reasonable convergence between the model predictions and the data is obtained. This may mean re-introduction of elements of the model culled during earlier simplification steps.

6. CONCLUSION

Microbial induced corrosion (MIC) of concrete sewers pipes is a significant global problem incurring losses in the order of billions of dollars per year. This paper has outlined what we currently understand of the corrosion process as well as some areas where basic knowledge is lacking. An ARC Linkage project involving various Australian Water Authorities and Universities has been established to address the problems raised by MIC in Australian sewer systems. The aim of the project is to determine the relationship between sewer environmental parameters such as H₂S level, temperature and humidity and the instantaneous corrosion rate of concrete using in situ field observations, extensive laboratory testing. Not only will simple correlations between the different variables be undertaken but investigations in the molecular, chemical and material dynamics of the corrosion process will enable an accurate picture of the various underlying processes to be constructed. This data along with historical records and the experience of the industry participants will enable a phenomenological model of the corrosion process to be constructed which can be used by industry to estimate the reliability and expected remaining physical life of concrete sewers under a variety of conditions.

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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 10 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.

Dr Phil Bond is Senior Lecturer and a Queensland Smart State Research Fellow at the Advanced Water Management Centre, The University of Queensland, Australia. He has a BSc Hons from the University of Melbourne and PhD from the University of Queensland in 1997. He is interested to understand the complexities of microbial communities and to determine molecular details of microbial functions in their environments. He specialises in the microbiology of wastewater treatment and acid leaching environments. He recently returned to the University of Queensland after some years in the UK.