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Microbiologically Induced Corrosion of Concrete and Protective Coatings in Gravity Sewers

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Abstract Microbiologically induced corrosion of concrete (MICC) and its protective coatings has a high economic impact on sewer maintenance and rehabilitation. A better understanding of the micro-organisms and the biogenic acids that are generated in the sewer is essential in controlling the corrosion of concrete pipes and protective coatings. The role of succession of micro-organisms growth in the corrosion of concrete and protective coatings was evaluated in this study. Examination of various sewer pipe materials exhibiting various extents of degradation, including concrete, cement based and epoxy based coating revealed the presence of both organic and biogenic sulphuric acids. This reflects the activity of fungi and the *thiobacilli* strains. Organism growth and metabolism were strongly related to the substrate pH. Fungi were found to grow and metabolise organic acids at pH from 2.0–8.0. Whilst the *thiobacilli* strains grew and generated sulphuric acids at pH below 3.0. The successive growth of the organisms provides an important bearing in developing improved strategies to better manage sewers.
Keywords concrete, microbiologically induced corrosion, fungi, bacteria

1 INTRODUCTION

Microbial induced corrosion of concrete sewers is a significant problem with global repair costs in the range of billions of dollars per year [1–4]. It is therefore important to determine the mechanisms by which concrete and other protective surfaces corrode. As this may provide insights into corrosion, and methods by which failures can be avoided, to allow the serviceable life of concrete sewers and protective coatings to be predicted for future planning. To begin with, a more accurate identification of the organisms and the metabolic products that contribute to corrosion is essential

The generation of corrosive conditions as a result of biological activity has long been recognised [5–7]. This process has been referred to as 'microbially induced concrete corrosion or MICC'. Parker (1945) first proposed the involvement of *thiobacilli* strains and their sulphuric acid in the corrosion process concrete. Other established bacterium strains known to cause corrosion of concrete include *Thiobacillus thooxidans*, *Thiobacillus neapolitanus*, and *Thiobacillus Intermedius* [8]. Despite the knowledge that complex populations of microorganisms proliferate in sewers, the current view that associates concrete corrosion principally to the action of sulphuric acid, remains widely accepted. Other organisms including nitrifying bacteria and its nitric acid product [9, 10] and fungi and its organic acids [3] are known to grown in sewers, however their activities mainly largely ignored in the analysis of sewer corrosion. In addition their symbiotic relationship [11–13] that paves for the successive growth of various organisms and generation of different acids has hardly been considered.

The aim of this investigation was to establish the involvement of organisms, particularly that of fungi, in corrosion of concrete and protective coatings. To identify the nature of organisms and their acidic metabolic products, samples of sewer pipe surfaces were obtained. Cores of concrete, cement based coatings and polymeric coatings were obtained from existing sewer infrastructures.

2 EXPERIMENTAL

2.1 Materials

In this study, various representative materials of sewer pipes and coatings were obtained from several locations in Sydney. The materials collected for this study are shown in Table 1.

2.2 pH measurement and sulphate and organic anion analysis

The concrete and linings samples were weighed (approximately 2 g) and put into a microwave extraction/digestion cell and 10 ml of deionised water was added to extract the organic acids and sulphate anions. The extraction was conducted in a microwave digester, Milestone Ethos Lab Stations, at 90 °C for 10 min (5 min ramp time plus 10 min at 90 °C). After the microwave extraction, the sub-samples were cooled to room temperature and filtered using a No. 1 Whatman filter paper. The pH of the samples was measured with an Orient pH meter. The concentrations of organic and sulphuric anions were determined using ion chromatography (Dionex ICS 2000) employing standard conditions [14].

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Table 1 Field samples

Sample	Sampling address	Location	Description of sample
A	NSOOS① Manly-Mosman	roof	concrete lining
B	Perry St, Matraville Millpond Rd, Botany	roof and wall	cement based coating
C	Kissing Point Rd, Herbert St, SWSOOS② 2 south cell section 7 Sydney airport	roof and wall	epoxy-mortar coating

① NSOOS: Northern Suburbs Ocean Outfall System.
② SWSOOS: South Western Suburbs Ocean Outfall System.

3 RESULTS AND DISCUSSION

3.1 Bioacid and bulk pH analysis of sample A-concrete lining

Sewer traverses in Sydney Water have focussed on the visual surface integrity of the concrete and typically reported it to be in a good condition. Recent traverses in the NSOOS revealed unexpected sheet failures of the surface of the unreinforced arch roof tunnel lining. The observation of slab failures points to a deterioration occurring well inside the surface face, at least 100 mm and potentially to the full depth (approximately 250 mm) of the concrete lining. A sample of the failed concrete lining was retrieved and is shown in Fig. 1. This un-reinforced concrete lining (referred to as "concrete lining" here) is composed of cement, sand and sandstone aggregates. The minerals in sandstone (quartz, feldspar and clay) can also be subjected to the same acid degradation as cement minerals. This sample was sub-sectioned according to Fig. 2 and Table 2. Bioacid acid analysis of the concrete lining is reported in Table 3.

Analysis of the water soluble components (or water extracts) of the various subsections of the concrete lining revealed pH 2.05–2.75. These are clearly lower in comparison to the natural sandstone pH of 6–6.5 and of cement pH>12. This significant drop in pH confirms biological activity. Analyses of the extract for sulphate and organic anions (citrate and oxalate) in Table 3 confirm activity from fungi and from acidophilic *thiobacillus* strain. The relatively higher sulphate anions in comparison to the organic anions (citrate and oxalate) in the cement lining sub-samples suggests greater activity of *thiobacilli* strain to fungal activity.

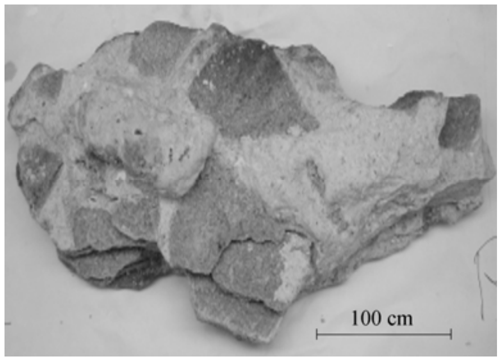

Figure 1 Top-view of the cement lining (sample A). This surface appears to have been the surface attached to the roof arch

3.2 Bioacid and bulk pH analysis of sample B-cement-based coating

An alternative cement based lining material (sample B) with claimed bacterial inhibition properties was also examined in this study. About 15 samples were taken from two sewage pipes in Sydney. Description

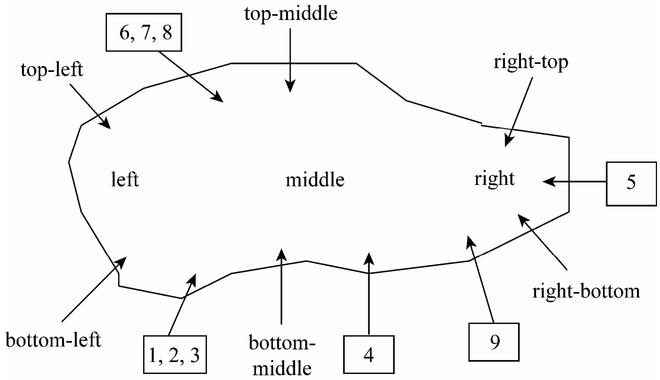

Figure 2 Location of the sampling points in the cement lining (sample A)

Table 2 Location and description of the cement lining sub-samples (in sample shown in Fig. 2)

Sub-Sample	Location
A-1	top layer sampled from bottom-left
A-2	middle layer sampled from bottom-left
A-3	bottom layer sampled from bottom-left
A-4	mixed layers sampled from bottom middle
A-5	mixed layers sampled from right
A-6	top layer sampled from top-left
A-7	middle layer sampled from top-left
A-8	bottom layer sampled from top-left
A-9	bottom layer sampled from bottom-right
A-10	mixed scrapings (fine particulates resulting from sample fracturing).

Table 3 Surface pH and anion analysis of concrete lining (sample A) sub-sections

Sub-sample	Bulk pH	Surface pH	Oxalate /mg·kg^{-1}	Citrate /mg·kg^{-1}	SO_4^{2-} total /mg·kg^{-1}
A-1	2.28	1.68	322.8	0	12700
A-2	2.36	1.76	230.2	0	8100
A-3	2.05	1.45	681.8	0	11900
A-4	2.6	2.00	243.8	0	8700
A-5	2.35	1.75	0	0	24000
A-6	2.59	1.99	495	0	15100
A-7	2.49	1.89	1137.6	0	18600
A-8	2.65	2.05	936.8	93.9	21800
A-9	2.75	2.15	0	0	19600
A-10	2.18	1.58	1117.6	0	19800

of the samples and their locations in the pipes are provided in Table 4. Sampling of the coated pipes involved scraping the surface in 3 layers. First the "snottites" were removed. These are predominantly liquid material hanging from the roof, which were dislodged with a light scraping (see Fig. 3). The underlying surface deposit was then scraped off; also designed to remove the top lining surface. This was followed by a hard scraping which removed about 2 mm of the lining material. Samples were taken from the crown sewer and at the low and high walls of the pipes. A blank sample of the lining was taken by drilling into a non sewage exposed test panel with a masonry drill bit. Samples were also taken from uncoated concrete at the Millpond St (samples B-13 and B-14). The concrete underneath the coating was very rough and mushy and only composite samples of aggregate, cement and surface liquid were removed. The softening of the concrete suggests corrosion of the substrate. It is recognised that sulphuric acid is present in these samples and the specific aim of analysing these substrate was to determine if fungal activity and

Figure 3 Snottites growth on the surface of a cement based lining material (Sample B)

thus the generation of organic acids is supported on these coatings. Organic anion analysis of the various samples is reported in Table 4.

Table 4 shows that the oxalic and citric acids are the main metabolic products of fungi growth in these cement based samples. Although sulphuric acid was detected in the extracts, these were not measured quantitatively. These results demonstrate the coupled actions of fungi and the *thiobacillus* strains in degrading cement based coatings.

3.3 Bioacid and bulk pH analysis of sample C-epoxy-based coatings

Three epoxy mortar based coatings (I, II and III) in 3 separate sewers were sampled by taking a 5.08 cm diameter ×10 cm length cores of the lining and concrete substrate (see Fig. 4). The top surface (2–3 mm) of the coating was sliced and milled and assayed for bulk pH and both organic and sulphuric acids. Locations of the cores in the pipes, bulk pH and anion analyses are shown in Tables 5–7.

The bulk pH observed for the three coatings varied from 3.3 to 9.3. It is apparent from Tables 5–7 that all the coatings at these pH contained only organic

Table 4 Organic anion analysis of cement based lining (Sample B)

Sample	Sampling address	Location	Material	Layer	Oxalate/mg·kg^{-1}	Citrate/mg·kg^{-1}
B-1	A	roof	coating	snottites	5271.67	1626.73
B-2	A	roof	coating	surface scraping	1575.19	877.35
B-3	A	roof	coating	lining scraping	14.08	46.09
B-4	A	wall-low	coating	surface scraping	235.00	1760.32
B-5	A	wall-low	coating	lining scraping	258.92	284.87
B-6	A	wall-high	coating	surface scraping	336.28	74.46
B-7	A	wall-high	coating	lining scraping	2500.29	11.72
B-8	A	QA panel	coating	0–50 mm scraping	0	0
B-9	B	roof	coating	snottites	97.37	0
B-10	B	roof	coating	lining scraping	223.41	0
B-11	B	wall-low	coating	surface scraping	161.02	2293.78
B-12	B	wall-low	coating	lining scraping	67.57	67.57
B-13	B	wall	concrete	surface scraping	751.04	0
B-14	B	roof	concrete	concrete scraping	639.30	147.80
B-15	B	wall-high	coating	surface scraping	2956.75	0
B-16	B	wall-high	coating	lining scraping	919.30	2.40

Note: In all samples sulphate was also detected. Address A: Perry St, Matraville; B: Millpond Rd, Botany.

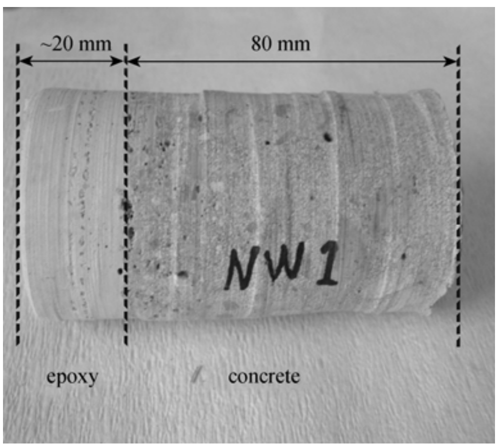

Figure 4 Photographs of an epoxy-based coating and concrete core

acids and no sulphuric acid. This is clear evidence of the sequential growth of the organisms and the potential important role of fungi in degrading the coatings at these high pHs. Organic acids have been implicated in the degradation of a wide range of polymeric materials [3, 15–18].

It is apparent that the metabolites generated by the fungi differ based on the substrates that are colonised. The main metabolic products generated by fungi on the inorganic surfaces, namely in the concrete lining and cement – based coatings are principally oxalic and citric acids (see Tables 3 and 4). Whereas epoxy based coatings promoted the generation of gluconic, lactic, malic, pyruvic and succinic acids (see Tables 5 and 6). The selectivity of the acid production was not investigated in this study, but it appears to be linked to the substrates that have been colonised.

The role of pH on organism growth on the various pipe substrates is shown in the relationship between substrate bulk pH and the organic and sulphuric acids generation in Figs. 5 and 6, respectively. Fig. 5 shows that very little organic acid is generated above pH 8.0, the typical "natural" pH of the epoxy based coating. As the surface is colonised by fungi, the pH is reduced to 3.0. However as the bulk pH approaches 2.0, the organic acid generation declined. This is associated with the low tolerance of fungi to acidity [19]. Fig. 6 shows that at pH below 3.0, no sulphuric acid was detected. The sulphuric acid generation escalated only as the pH approached 2.0. The growth and metabolism of fungi between pH 8.0 and 2.0 and the subsequent growth of *thiobacilli* strain above 3.0 is consistent with the proposed sequential microbial activity in the sewer [12, 13, 19]. The occurrence of such activities on the coating surfaces suggests that the growth of the organism is independent of the substrates.

4 CONCLUSIONS

This study has shown that successive growth of micro-organisms and their corresponding metabolic products have roles in the corrosion of concrete and protective coating materials. The activity of fungi is prominent between pH of 2.0–8.0, reaching a maximum around 2.0. As pH become more acidic (pH<3.0), the

Table 5 Anion and bulk pH analysis of coating I cores

Sample	Location	Coating	pH	Sulphate /mg·kg^{-1}	Gluconate + lactate /mg·kg^{-1}	Malate + pyruvate + succinate /mg·kg^{-1}	Total organic acid /mg·kg^{-1}
CI-1	wall	I	8.6	0	0	0	0
CI-2	roof	I	8.55	0	0.7	34.7	35.4
CI-2	wall	I	8.36	0	0	37.1	37.1
CI-2	roof	I	8.23	0	0	8.6	8.6
CI-2	wall	I	7.2	0	6.4	97.5	103.8
CI-2	roof	I	8.32	0	3.5	184.1	187.5
CI-2	wall	I	8.29	0	3.6	51.2	54.8
CI-2	roof	I	8.18	0	0	64.9	64.9

Note: Address: Herbert St.

Table 6 Anion and bulk pH analysis of coating II cores

Sample	Location	Coating	pH	Sulphate /mg·kg^{-1}	Gluconate + lactate /mg·kg^{-1}	Malate + pyruvate + succinate /mg·kg^{-1}	Total organic acid /mg·kg^{-1}
CII-1	wall	II	8.06	0	0	0	0
CII-2	wall	II	8.11	0	5.3	40.3	45.6
CII-3	roof	II	8.02	0	0	43.1	43.1
CII-4	wall	II	7.81	0	0	100.3	100.3
CII-5	wall	II	7.38	0	0	70.6	70.6
CII-6	roof	II	9.34	0	7.2	268.9	276.1
CII-7	wall	II	5.73	0	4	170	174.1
CII-8	roof	II	7.53	0	0	393.8	393.8

Note: Address: Kissing Point Rd.

Table 7 Anion and bulk pH analysis of coating III cores

Sample	Location	Coating	pH	Sulphate /mg·kg^{-1}	Gluconate + lactate /mg·kg^{-1}	Malate + pyruvate + succinate /mg·kg^{-1}	Total organic acid /mg·kg^{-1}
CIII-1	wall	III	4.59	0	34.7	802.6	837.3
CIII-2	wall	III	3.31	0	61.9	1163	1224.9
CIII-3	wall	III	5.83	0	23.2	602.4	625.7
CIII-4	roof	III	8.03	0	3.2	0	3.2
CIII-5	roof	III	8.68	0	4.4	0	4.4
CIII-6	roof	III	8.36	0	3.5	76	79.5
CIII-7	roof	III	7.53	0	4	59.8	63.8
CIII-8	wall	III	4.03	0	31.2	648.1	679.3
CIII-9	wall	III	4.61	0	30	786.8	816.8

Note: Address: SWSOOS 2 south cell section 7 Sydney airport.

activity of the alkalophilic fungi is reduced, whilst that of the acidophilic *thiobacillus* strain is escalated. These results show that the initial corrosion of concrete and the protective coatings are likely to be incurred by the fungi. The importance of fungi in sewer corrosion is in preparing the pipe surface for the colonisation and thus the greater corrosive actions of *thiobacilli* strains.

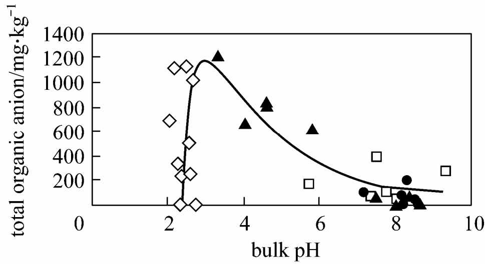

Figure 5 Organic acid production as function of surface bulk pH
● coating I; □ coating II; ▲ coating III; ◇ concrete lining

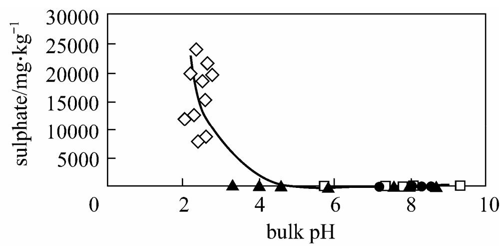

Figure 6 Sulphuric acid production as function of surface bulk pH
● coating I; □ coating II; ▲ coating III; ◇ concrete lining

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