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The decisive role of acidophilic bacteria in concrete sewer networks: A new model for fast progressing microbial concrete corrosion

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ABSTRACT

This study introduces a novel approach intertwining analytics of spatial microbial distribution with chemical, mineralogical and (micro)structural related aspects in corroded concrete sewer environments. Samples containing up to 4 cm thick corrosion layers were collected from concrete manholes and analysed using hydrogeochemical, microbiological, biochemical and mineralogical methods. Opposed to the current opinion DNA and RNA indicating microbial activity were found throughout the entire deterioration layer down to the corrosion front. Elemental distributions of corresponding areas revealed a dynamic pH- and diffusion-controlled system in which a distinct succession of elemental accumulations was unequivocally correlated with responding pH levels, associated dissolution and precipitation of solids, as well as with the spatially resolved presence of microbes. Microbial activity further coincided with massive iron deposition zones, within the inner anoxic to anaerobic corrosion layers. As a possible microbial catalyst for iron oxidation and in-situ acid production in this zone, we propose *Acidithiobacillus ferrooxidans* which were isolated from the deteriorated concrete. Based on the data we propose a new model in which biogenic induced in-situ acid production is a decisive factor, steering high concrete corrosion rates of > 1 cm yr^{-1}.

1. Introduction

The degradation of sewer systems due to microbial induced concrete corrosion (MICC) has been one of the main problems of modern society's subsurface infrastructure within the last century [1–3]. Besides of huge economic relevance, also health related concerns due to hazardous gas production and associated odor problematic are recognized [4–7]. The general process mechanisms have been subject to numerous studies, and can be summarized as a complex chain of coupled biotic and abiotic redox reactions [8–12]. Initial sulfate reduction proceeds within anaerobic sediment layers, which accumulate along the bottom of preferentially slow flowing sewer pipes and power mains holding long retention times [13–15]. There, various species of sulfate reducing bacteria (SRB) lead to hydrogen sulfide (H_2S) production, which is accompanied by fermentation processes producing carbon dioxide (CO_2) and volatile organic compounds (VOC's) [16–18]. Gaseous compounds produced, are liberated into the atmosphere of the concrete pipes and manholes, where they partly dissolve into the condensates along the concrete walls and subsequently diffuse into the concrete pore structure. After an initial period of abiotic pH reduction due to acid-base reactions involving CO_2 and H_2S in the alkaline concrete environment, secondary H_2S re-oxidation by a succession of sulfur oxidizing bacteria (SOB) results in biogenic sulfuric acid (H_2SO_4) production and subsequent concrete deterioration [15,19]. In order to efficiently control MICC, it is central to understand the succession, distribution and interaction of various species of microorganisms involved combined with the chemical, mineralogical and material related aspects of concrete degradation. A mutualistic relationship between different autotroph SOB and heterotrophs, e.g. *Acidiphilium*, has been reported [8,11,20]. Cho and Mori [21] described the interaction of autotrophic bacteria and acid-resistant fungi which oxidize H_2S to thiosulfate ($S_2O_3^{2-}$). The latter thiosulfate ions again can be utilized by *Acidithiobacilli* spp. Current models suggest the highest cell concentrations at and close to the concrete surface within oxygen (O_2), CO_2 and H_2S rich layers. O_2 concentrations are reported to decrease drastically with depth in the corrosion layer of the concrete, mainly due to chemical oxygen consumption, reaching anoxic conditions at 400 to 600 µm. Cell accumulations are described to decrease accordingly [11,22]. However, these models are based on observations, drawn from bulk samples of various in situ testing sites, with limited information

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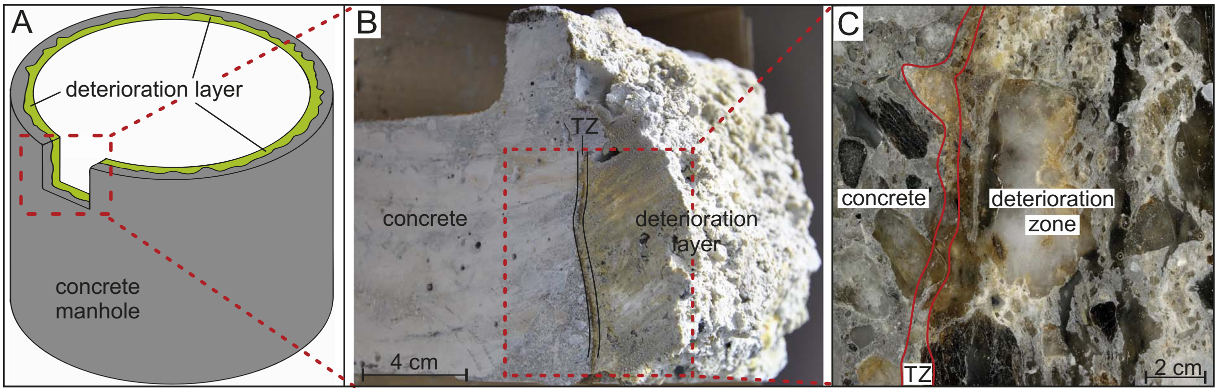

Fig. 1. Schematic description of the sampling campaign. Samples were cut from several concrete manholes (A). Notice the sharp transition zone (TZ) and up to 4 cm thick deterioration layer (B). Samples were dried and subsequently embedded into a two component epoxy resin in order to guarantee stability for further analyses and imaging (C).

regarding spatially resolved microbial distribution throughout the interior of corrosion layers. Limited information is found in the literature describing MICC processes drawn from field studies and field observations. Analysis of data obtained from samples originating from real sewer environments is central in order to enhance in-depth knowledge of MICC and enables development of possible counteracting measures. This field study aims to investigate the presence and spatial distribution of microorganisms throughout up to 4 cm thick deterioration layers of a strongly corroded concrete sewer system, which has been recently described in [9]. For that purpose, concrete samples, cut from several, strongly deteriorated concrete manholes (see Fig. 1), were analysed by in situ nucleic acid (DNA and RNA) staining in combination with fluorescence microscopy. In order to obtain extensive information, microbial accumulations were linked to element distributions of the same areas, which were measured using an electron microprobe. High resolution spot analyses of mineralogical composition throughout the corrosion fronts were analysed, using Micro-XRD, in order to determine the spatial distribution of newly formed mineral phases. This dataset was integrated into a new model for fast progressing MICC. Intriguingly, DNA and RNA indicating microbial activity were found not only at the surface but also deeply inside the deteriorated concrete at the transition zone to intact concrete. Since we were able to isolate *Acidithiobacillus ferrooxidans* from the material, a bacterial species capable of chemoautotrophic anaerobic growth, iron oxidation and acid production, we propose that this bacterial species plays a decisive role in the progression of MICC.

2. Study site, materials and methods

2.1. Study site description and concrete properties

Concrete samples investigated in this study where extracted from strongly deteriorated concrete manholes of an Austrian sewer system. A detailed description of the system, including concrete properties, corrosion rates, wastewater chemistry, microbial aspects and interstitial fluid chemistry has been recently described in Ref. [9]. In brief, the system investigated is handling the wastewater of around 13,000 people, with a daily average wastewater discharge of around 300 m^3. In 2004, two new power mains were integrated into the system in the course of the fusion of two separated gravity sewers lines. Ever since, community complains about odor rose, which were accompanied by heavy degradation of several concrete manholes within the gravity sewer sections. Measured corrosion rates of up to > 1 cm yr^{-1} led to a required replacement of affected manholes after a service life of only 10 years. Material analytics of non-corroded implemented precast elements revealed a mean comprehensive strength of 88 ± 11 N/mm^2 and a w/c ratio of ~ 0.35. CEM I 42.5 N (C_3A-free) plus fly ash and 0.25 wt% of a PCE based superplasticizer, referred to the cement content, was used for concrete production. This classification corresponds to exposition class XA2 for chemical attack according to ÖNORM B 4710-1 (Concrete - Part 1: Specification, production, use and verification of conformity. Rules for the implementation of EN 206-1 for normal and heavy concrete), thus exceeding the requirements postulated in European concrete standard regulations (EN 206-1).

From heavily corroded manholes expressed interstitial concrete

Table 1
Representative mineralogical characterization of the implemented concrete and expressed interstitial fluids within this system. Showing the mineralogical composition of non-deteriorated (CM 1 and CM 2) and strongly corroded (CM_c 1 and CM_c 2) concrete samples in wt%, containing quartz (Qz), plagioclase (Pl), alkali feldspar (Kfs), calcite (Cal), muscovite (Ms), portlandite (Port), hornblende (Hbl), clinochlore (Clc), gypsum (Gp), bassanite (Bs), anhydrite (Anh) and X-ray amorphous phases (Amph), together with the analytical error (R_{wp}). Additionally, chemical compositions of expressed interstitial solutions (IS1, IS2 and IS3) from strongly deteriorated concrete manholes are shown together with pH and electrical conductivity (EC). For a complete dataset see Grengg et al. [9].

Concrete composition	Sample ID	Qz	Pl	Kfs	Cal	Ms	Port	Hbl	Clc	Gp	Bs	Anh	Amph	R_{wp}
Intact	CM 1	41.3	20.2	6.7	5.4	5.2	1.8	0.0	0.7	0.9	0.0	0.0	17.9	5.79
	CM 2	42.2	19.4	4.9	6.8	4.8	2.4	1.4	1.0	0.0	0.0	0.0	17.1	5.54
Corroded	CM_c 1	27.2	6.6	2.8	0.0	0.0	0.0	0.0	0.0	25.5	1.5	15.2	11.6	7.02
	CM_c 2	31.4	14.5	0.0	0.0	0.0	0.0	0.0	0.0	43.0	0.0	0.0	10.8	7.14

Interstitial fluid chemistry	pH	EC	Na^+	NH^{4+}	K^+	Mg^{2+}	Ca^{2+}	Fe	Zn	Al	Cl^-	NO_3^-	SO_4^{2-}
		mS cm^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
IS 1	0.9	64.2	91	152	266	243	584	2080	3.47	540	168	15.0	18,139
IS 2	1.0	102.0	2978	2994	1383	4322	551	15,693	152	5720	1648	6.58	104,210
IS 3	0.7	101.0	573	210	330	990	567	2818	23	998	376	5.35	40,818