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Toward an accelerated biodeterioration test to understand the behavior of Portland and calcium aluminate cementitious materials in sewer networks

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ABSTRACT

Sewer networks contain many aggressive and corrosive agents for pipe materials. One type of damage can be ascribed to concrete corrosion by biogenic sulfuric acid. According to field data, cementitious materials have different behaviors depending in particular on cement type: Those made with calcium aluminate cement (CAC) offer better performance than those made of ordinary Portland cement (OPC). The development of an accelerated and accurate laboratory test is essential to better understand the mechanisms involved for all cementitious materials. However, to define such a test, some additional knowledge is required. The present study deals with *in situ* experiments in order to determine the biochemical parameters influencing the behaviors of OPC and CAC materials. Based on these determinations, supplemented by laboratory studies, it can be concluded that abiotic oxidation of hydrogen sulfide, bioreceptivity of the mineral surface, and growth of bacterial strains depend greatly on cementitious material types. All these results, complemented by literature data, lead to consideration of what the best parameters are to study biodeterioration of cementitious materials, and have been helpful in designing the biodeterioration chamber tested.

1. Introduction

In most industrialized countries, sewer systems are more than 40–50 years old and now require major rehabilitation. From another perspective, in 1991 the Council of the European Union adopted a directive on the need to treat urban wastewater properly. Compliance with these regulations has always led and will probably always lead, to an increase in the construction of sewerage and wastewater treatment plants. More recently, the United Nations General Assembly declared 2008 as an International Year of Sanitation with the objective of halving the number of people without access to safe water and adequate sanitation by 2015.

Thus, the need to rehabilitate parts of the sewer network in large cities and to construct new networks arising from EU directives and United Nations wishes now leads managers and manufacturers to consider the best ways to build sustainable sanitation facilities and to optimize sanitation management protocols.

Among the areas needing improvement, the degradation of materials, and particularly biodeterioration of cementitious materials, appears fundamental. This is an extremely dangerous and damaging phenomenon to sewer network structures, which was studied for the first time by Olmstead and Hamlin (1900), who described the deterioration of bricks in the sewer network of Los Angeles. Jointed mortar between the bricks disintegrated and ironwork was heavily rusted. These authors also stated that the mortar joint had ballooned to two to three times its original volume, leading to the destruction or the loosening of some bricks.

This type of damage can be ascribed to cementitious material corrosion by biogenic sulfuric acid and represents 9% of the damage described in sewer networks (Kaempfer and Berndt, 1999). Phenomena involved are depicted in Fig. 1. Relatively thick layers of sedimentary sludge and sand accumulate at the bottom of the pipes, which leads to the establishment of anoxic areas (typically

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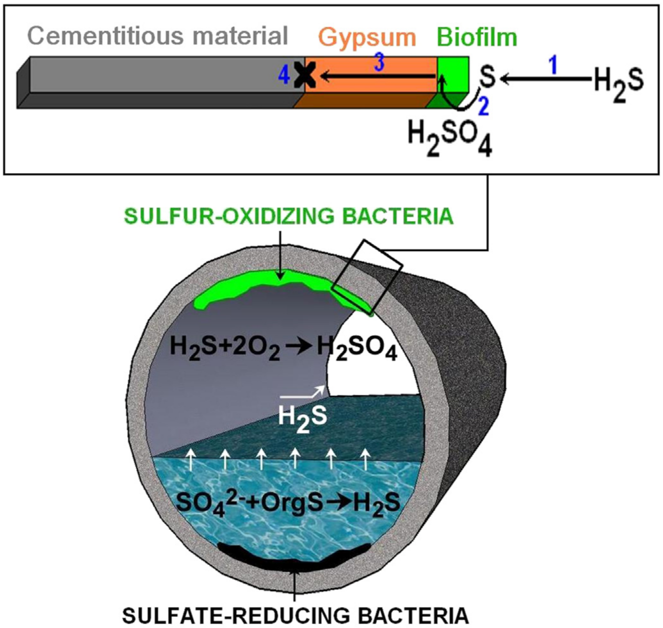

Fig. 1. Schematic representation of sulfur cycle in sewer network with the four steps involved in the biodeterioration of cementitious materials.

1 mm thick). Under these anaerobic conditions, sulfate-reducing bacteria (SRB) can grow using oxidized sulfur compounds present in the effluent as electron acceptor and excrete hydrogen sulfide (H_2S). Hydrogen sulfide degassed in the aerial part of the pipe can impact the cementitious materials in two ways: either directly by reacting with the cementitious materials and leading to a decrease in pH, or indirectly through its use as a nutrient by sulfur-oxidizing bacteria (SOB), which produce sulfuric acid (Islander et al., 1991; Roberts et al., 2002; Okabe et al., 2007). The cement matrix is then dissolved by sulfuric acid and, depending on its composition, formation of expansive secondary mineral products such as gypsum and ettringite is possible.

The present study focuses only on the second stage of the global process (i.e., the biodeterioration of cementitious materials in the presence of H_2S), which can be broken down into four steps, as shown in Fig. 1: abiotic oxidation of H_2S into elemental sulfur onto the surface of cementitious material; oxidation of sulfur-containing molecules to sulfuric acid by bacteria; diffusion of sulfuric acid into the degradation product layer; and acid attack on healthy cementitious materials.

According to previous on-site experiments (Goyns, 2001, 2003; LCA 1, 2) cementitious materials made with calcium aluminate cement (CAC) perform better than those made with ordinary Portland cement (OPC).

Most of the data published are based only on OPC studies. By contrast, the good behavior of CAC in sewer networks is poorly documented. Therefore, it appears necessary to better understand the deterioration mechanisms associated with CAC and OPC materials by defining an accelerated test relevant to these materials, as well as to any other materials that can be used in sewer networks.

Many studies have already been performed with different accelerated tests aimed at mimicking the bio-physicochemical conditions encountered in sewer networks. Some of them (Monteny et al., 2000; Roy et al., 2001; De Belie et al., 2004) simply proposed chemical tests as the phenomenon can be considered at its last step as an acid attack. The basis of these tests is the immersion of concrete samples into a sulfuric acid solution for about one month, after which the sample's weight loss is measured. Some of the proposed tests are complemented by a step of sample surface brushing in order to mimic the tidal area effect in the pipe and therefore to create the worst possible conditions. In general, the results obtained by these chemical tests are not in agreement with *in situ* experimental results.

Some other studies deal with biochemical accelerated tests by introducing microorganisms, in order to more closely simulate reality. A Heidelberg University (Germany) group (Hormann et al., 1997; Schmidt et al., 1997) worked on the design of a simulation chamber using only one bacterial strain (*Acidithiobacillus thiooxidans*). Mortar samples were placed in a reactor and for 5 min h^{-1} they were immersed in the culture media. This test has two major disadvantages: Being immersed in a culture medium at pH 3.5 leads to a chemical test rather than a biological one, and the washing of the sample each hour modifies the sample surface conditions.

A University of Ghent (Belgium) team (Vincke et al., 1999; De Belie et al., 2004) has developed a test that recreates the worst conditions encountered in sewer networks. Samples of mortars were exposed to cycles of deterioration: 3 days of exposure to 250 ppm of H_2S, 10 days of immersion in the culture medium of *A. thiooxidans*, 2 days of washing by water, and finally 2 days of drying. This test is far from realistic conditions and some of the steps are not justified considering *in situ* conditions. Moreover, with this test, biodeterioration of samples is also disturbed by chemical reactions at the sample surface.

The University of Hamburg (Germany) has developed a biodeterioration chamber that allows recreating the conditions met in sewer systems (Milde et al., 1983; Sand et al., 1992, 1994; Ehrich et al., 1999). For this purpose, a wide chamber (1 m^3) with air circulation (250 m^3 h^{-1}) and controlled relative humidity (close to 98%) and temperature (approximately 30 °C) is used. The mortar samples are sprayed with a solution of mineral salts essential for the growth of 12 bacterial strains isolated from the sewer network of Hamburg. The atmosphere in this chamber contains between 15 and 20 ppm of H_2S. This accelerated test appears to represent *in situ* mechanisms and displays an acceleration factor of 24 compared to on-site conditions (Sand et al., 1992; Ehrich et al., 1999).

This present paper focuses on both *in situ* and laboratory studies carried out on mortar samples, with the objective of providing useful knowledge concerning the effect of biodeterioration on Portland and calcium aluminate cements. Moreover, these new data are analyzed in order to improve the accelerated biodeterioration tests currently examined.

2. Materials and methods

2.1. Samples

Mortars were cast with OPC or CAC. Their chemical oxide compositions are given in Table 1. For all samples, the water-to-cement and siliceous-sand-to-cement ratios are, respectively, 0.37 and 1.44.

Table 1
Composition of the two cements.

	Al_2O_3	CaO	SiO_2	Fe_2O_3	MgO	TiO_2	SO_3	K_2O	Na_2O	P_2O_5	LOI	IR
OPC	5.07	63.93	20.87	3.31	0.83	0.24	3.39	1.01	0.20	0.94	0.94	0.26
CAC	51.87	37.06	5.31	2.25	0.54	2.19	0.15	0.31	0.05	0.19	–	–

LOI: Loss On Ignition; IR: Insoluble Residue.