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Mechanism study of the role of biofilm played in sewage corrosion of mortar

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HIGHLIGHTS

- The biofilm developed on mortar can act as a barrier against sewage corrosion.
- The porosities of biofilms decrease with the increase of sewage concentration.
- In ordinary sewage the thinner biofilm offers less protection on mortar corrosion.
- Dense biofilms play major role in protecting mortar from intensified sewage corrosion.

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ABSTRACT

The artificially intensified sewage was prepared to simulate and accelerate the microbial corrosion of concrete in sewer, and the changes in weight of mortar with and without biofilm in sewage were investigated comparatively, as well as the microbial structure and activities of biofilm developed on mortar surface. Furthermore, the influence mechanism of biofilm on mortar deterioration was analyzed based on grey correlation. The results show that the biofilm developed on mortar can act as a barrier against sewage corrosion to varying degrees. The biofilm growing in sewage with chemical oxygen demand (COD) of 3000 mg/L has the most significant protective effect on mortar, which can be attributed to its high pH and dense structure. For specimens in ordinary sewage, the biofilm thickness plays the major role, especially in the first month, whereas that in sewage with too high concentration, the increasing corrosives reduced the protection of biofilm to mortar in later period.

1. Introduction

Worldwide, cement concrete has long been extensively used in the municipal infrastructure due to its excellent durability. However, the deterioration of concrete sewage pipelines, wastewater collection and treatment facilities has been reported in many places of the world, and millions of dollars are being spent in its repair and maintenance. The restoration of the overall damaged sewer systems in Germany is estimated to cost about €100 billion per year. In Los Angeles County, approximately 10% of the sewer pipes are subject to significant corrosion, and the rehabilitation costs are as high as $400 million. It is estimated that, the United States will still need to invest $390 billion to repair existing sewage facilities in the next 20 years [1,2]. In China, the collapse of road frequently occurred in recent years, which are mainly caused by the aging of underground sewage pipe network. After more than 40 years of service, the 5 cm of concrete pipe had only about 2 cm left [3]. As the diameter of sewage pipes in China is small, so a lot of non-full flow designed pipes in the 1980s are now in full flow operation with the continuous expansion of towns and the rapid increase of population.

The corrosion mechanism of sewage to concrete is very complex, in addition to the physical and chemical effect [4–6], the microbiological attack has been identified as the most important reason induced corrosion of concrete sewers [7,8]. As early as 1945, Parker discovered that bacteria were involved in the deterioration of internal sewer concrete, and proposed the corrosion mechanism is a result of the sulfur cycle, which has also been extensively accepted [9]. This is a complex process that involving the physical adsorption of gaseous H_2S, chemical and biological oxidation of sulfide to various sulfur species, and reaction between the sulfuric acid and the concrete [10]. The heaviest corrosion of concrete sewer pipes often occurred in the area at the crown and near the sewage level [11]. Moreover, the nitric acid or organic acid

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Table 1
Compositions of the nutrient solution (g/20 kg mother liquid).

Sewage samples	COD (mg/L)	Starch	Glucose	Peptone	Urea	$(NH_4)_2HPO_4$	$MgSO_4$	NaCl
AS1	300	12.0	6.0	6.0	4.0	1.8	1.3	0.6
AS2	3000	125.0	62.0	14.0	8.0	4.5	2.4	1.0
AS3	6000	200.0	110.0	28.5	12.0	6.7	3.6	1.2
AS4	9000	307.2	167.7	46.4	20.0	5.6	3.0	1.5

Fig. 1. Simulation chambers with different sewage concentration in test.

produced by microbial metabolism can also lead to the corrosion of concrete in sewage [12,13]. It is noted that the microbial biofilms are involved in the deterioration process of concrete under sewage environment. For example, the location near the sewage level can provide a constant supply of nutrients, moisture and oxygen by splashing and periodic immersion, which is good for the formation and growth of biofilm [14], thus the concrete corrosion is maximized when the sulfate reduction and sulfur oxidation activities increased in microbial community structures. However, Soleimani et al. demonstrated that E. coli DH5α biofilm was able to provide a protective and sustainable barrier on mortar surfaces against medium to strong sulfuric acid attack [15]. Kong used artificial sewage to study the effect of biofilm on concrete corrosion and also verified that the biofilm can be acted as a physical barrier and reduce the permeability of sewage [16]. Thus it can be seen that, the biofilm has both positive and negative effects on the corrosion of concrete. On the one hand, a layer of biofilm that is grown on concrete surface will provide a protective barrier reducing the transmission of corrosive substances. On the other hand, the production of sulfuric acid by sulfur oxidizing bacteria (SOB), which is the main cause of concrete corrosion, has been demonstrated occurring primarily in the biofilm [17–19]. Therefore, it is necessary to have a deeper understanding of the influence of biofilm on the corrosion of concrete in sewer system.

Several methods have been developed to study the deterioration of concrete in sewage. In situ exposure test can study the real process of corrosion directly, but it often takes a long test period [20]. In order to simulate the sewage corrosion quickly, some aggressive chemical medium [21–24] (e.g., sulfuric acid, sulfate solution, etc.) and cultured bacteria [25–28] (e.g., Thiobacillus culture medium) could be used as the corrosive medium. In China, the artificially intensified sewage with high concentration was prepared by adding some nutrients and controlling optimum temperature to promote bacterial growth, this is a good way to accelerate the test and simulate the microbial corrosion as real as possible [29,30]. However, the effect of artificially intensified sewage on growth and structure of biofilm on concrete or mortar surface has not yet been investigated. Now, most of the studies on biofilm are focused on the biofilm formation and kinetics models in the process of wastewater treatment. The growth of biofilms involves a great deal of influence factors, such as the hydraulic retention time, organic volume load, carrier properties and concentration, hydraulic conditions, etc. [31,32]. It should be noted that concrete is a kind of porous inhomogeneous composite material, which has a rough and alkaline surface. The pH of a fresh concrete is about 12 and most microbes cannot grow when directly exposed to such surface [33]. So the growth law of biofilm on concrete surface should be different from that on the other carriers.

In addition, the structure of biofilm also has significant influence on the corrosion of concrete in sewage. The biofilm with a high porosity has better mass transfer characteristics, and the microbes also have higher activity [34]. The organics and oxygen in sewage will enter into this biofilm layer and react with microorganisms, and the acid ion produced by microorganisms can react with alkaline compounds released from the concrete. Bungay et al. found that the concentration of dissolved oxygen at the bottom of the biofilm is very low in the continuous flowing substrate with high concentration, indicating the consumption of microbial respiration [35]. The main mass transfer form in biofilm is diffusion, and the diffusion coefficient decreases with the increase of both biofilm thickness and density [36,37]. Moreover, the structure of biofilm is composed of a loose upper layer which is dominated by eddy diffusion and a tight lower layer with molecular diffusion [38]. Obviously, both the thickness and pore structure of biofilm can influence the transmission of oxygen and acid ion, which is very important to the deterioration of concrete.

In this study, the artificially intensified sewage with different chemical oxygen demand (COD) values was prepared, and the changes in weight of mortar specimens with and without biofilm in sewage were investigated comparatively. The deterioration of specimen was also evaluated by the techniques including scanning electron microscopy (SEM) and X-ray diffraction (XRD). Moreover, the microbial structure and activities within biofilm developed on mortar surface were investigated by using confocal scanning laser microscopy (CSLM) and microelectrode, and the influence mechanism of biofilm on mortar deterioration was analyzed based on grey correlation. The results obtained are expected to enrich our understanding of the influence mechanism of biofilm on the corrosion of concrete in sewer system.

2. Experimental program

2.1. Mortar specimens

The materials used were Grade 42.5 Ordinary Portland Cement, and river sand with a fineness modulus of 2.8 and an apparent density of 2.61 g/cm^3. The mortar mixture with a w/c of 0.5 was composed of 384 kg cement and 594 kg sand per cubic meter. The dimension of mortar specimens was 70.7 mm × 70.7 mm × 70.7