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Concrete deterioration caused by freshwater mussel *Limnoperna fortunei* fouling

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ABSTRACT

Similar as biofouling of Dreissena species (zebra mussels and quagga mussels) on infrastructure concrete prevalent in the USA and Europe, the freshwater mollusk *Limnoperna fortunei* has also caused biofouling and exhibits chemical and physical deterioration on concrete structures. Given that numerous inter-basin water diversion projects containing enormous concrete structures have been constructed in *L. fortunei* colonized regions, it is critical to study the concrete deterioration caused by the mussel fouling such that effective prevention strategies can be proposed. This study analysed the characteristics of concrete deterioration associated with the fouling. Analysis of the affected concrete structures indicated that the pores of different sizes increased, resulting in increased water absorption and carbonation depth, while the compressive strength of the concrete decreased as a consequence of the mussel colonization. Concentrations of aluminum, manganese and iron increased while calcium decreased in the mussel-colonized concrete. These changes are due to the physiological requirements of mussel growth and adhesion activities. *L. fortunei* adhesion removes the calcium from the surface of the concrete and accelerates the concrete deterioration.

1. Introduction

Limnoperna fortunei is a freshwater bivalve mollusc originating from southern China and invasively spreading to many Asian and South America countries. This species shares very many similar biological and ecological characteristics as the *Dreissena* species (zebra mussel) (Ricciardi, 1998; Karatayev et al., 2007). *L. fortunei* colonizes in widespread habitats with water temperatures ranging from 0 to 35 °C, flow velocities of 0.1–2 m s^{-1}, water depths between 0.1 and 40 m, dissolved oxygen from 0.2 to 11.33 mg l^{-1}, and pH levels of 6.0–7.8 (Darrigran et al., 2011). It easily invades water transfer works and attaches onto concrete walls and structures with extremely high density, resulting in biofouling, structure corrosion, pipe clogging, decrease in water transfer efficiency, water pollution, etc., and has become a prevalent problem which is causing global concern.

In China and South America, severe fouling problems caused by the *L. fortunei* have been reported for a number of industrial facilities, including water and wastewater processing plants, power plants, and water transfer projects (Boltovskoy et al., 2015). Vivid examples of these problems are observed in the water diversion works that draw water from the Dongjiang River (also called East River), a tributary of the Pearl River in southern China, and its tributary, the Xizhijiang River, to Shenzhen and Hong Kong (Xu et al., 2015). All of the reservoirs, lakes, and water transfer systems connected with these water diversion works have been colonized by *L. fortunei*, thereby requiring maintenance and cleaning every year. Additional large tunnels, and in particular the huge "South-to-North Water Transfer Project" aimed at connecting the water-rich areas of the middle and lower Yangtze River with the water-poor areas of Beijing and North China, will lead to additional biofouling problems by *L. fortunei* because the project will provide a suitable habitat and a lack of predators for the molluscs.

In recent years, *L. fortunei* fouling has become increasingly common in hydroelectric power stations in China. Fouling is common on underwater concrete structures, valves, trash racks, gates, etc. Dense mussel beds c. 10 cm in thickness significantly restrict water flow, enhance concrete corrosion, clog pipes, jam mobile components, and pose serious safety risks for the plant's personnel (Yu et al., 2015). Given that numerous inter-basin water diversion projects have been undertaken and that most of these projects contain enormous concrete structures that commonly suffer from

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fouling and corrosion, it is critical to understand how concrete deteriorates as a result of mussel colonization such that effective strategies for protecting the concrete structures can be proposed.

Biochemical and molecular biological studies on the *L. fortunei*'s adhesive proteins indicate that the species oxidizes tyrosine residue to generate both adhesive force (surface coupling) and cohesive force (protein cross-linking in adhesive plaque matrices) of the byssal threads (Ohkawa and Nomura, 2015). Experimental studies involving the detachment, displacement and reattachment of *L. fortunei* indicated that such activities were affected by light, temperature and substratum orientation and that the adhesive force of the byssal threads could reach 20 N and withstand a flushing flow with a velocity as high as 2 m s^{-1} (Xu et al., 2012; Duchini et al., 2015). Pérez et al. (2003) indicated that the adhesion of the *L. fortunei* threads caused physical and chemical deterioration of concrete structures by inserting into the concrete surface, separating concrete constituents and even causing fissures, facilitating water infiltrate into the structures and increasing rebar corrosion.

The majority of the previous studies have been focused on the methods for investigation of concrete deterioration caused by microorganism (bacteria, fungi, algae and/or lichens). McCormack et al. (1996) assessed the extent of concrete deterioration caused by microorganisms using physical and chemical parameters including: weight loss and analytical methods such as ion exchange chromatography and atomic absorption spectroscopy. Weight loss and release of calcium were observed to investigate fungal degradation (Gu et al., 1998). Vincke et al. (2002) examined bacterial growth on the concrete surface by Scanning Electron Microscope analysis and calculated the corrosion rate by measuring the thickness of the concrete blocks. Leemann et al. (2010) applied an environmental scanning electron microscope (ESEM-FEG XL30) for analyses of the surface layers and the porosity. Monocular and inverted light microscopy, scanning electron microscopy (SEM) with energy dispersive X-ray analyser (EDX) were used to observe colonization at the aggregate/cement interface and fibre/cement interface (Hughes et al., 2013, 2014). However, methods for assessing the extent of concrete deterioration caused by *L. fortunei* are not yet available. Nevertheless, the macroscopic and microscopic characteristics of concrete deterioration caused by *L. fortunei* adhesion have not yet been studied comprehensively.

The aim of this study is to examine how *L. fortunei* adhesion affects concrete structures by using quantitative methods to detect possible changes in concrete composition and structural characteristics that occur as a consequence of the mussel adhesion. The characteristics of concrete structures with and without *L. fortunei* colonization were compared by applying modern analytical techniques used for measuring micro-performances, including water absorption, pore characteristics and distribution, surface morphology, element composition, and calcium minerals, as well as the macro-performances, including compressive strength and carbonation depth. The analytical approaches employed in this study could potentially be widely used for the assessment of concrete deterioration caused by mussel fouling.

2. Materials and methods

2.1. Experimental preparation

The colonization experiments and measurements were conducted in the Dongshen Water-supply Project, one of the water diversion works that draws water from the Dongjiang River and the Xizhijiang River. This project has been the major water supply system for Hong Kong since 1990 and has suffered from severe fouling by *L. fortunei* for decades, due to water intake from the *L. fortunei*-infected rivers.

Controlled comparison experiments for the assessment of concrete deterioration by *L. fortunei* were conducted by comparing the micro- and macro-performances of the concrete samples that were colonized to those that were not colonized by *L. fortunei*. To prepare for the experiments, twenty-four concrete coupons ($150 \times 150 \times 150$ mm, made of cement, sand, aggregate, and water) were cast and cured in water at a temperature of 20 °C for 28 days to accelerate the hydration process and to form a stable microstructure before assigning samples to the experimental group and the comparative group. Twelve coupons, labelled as the experimental group, were placed in stainless steel boxes and immersed into the Xizhijiang River for *L. fortunei* colonization, while the remaining were labelled as the comparative group and were immersed into tap water at room temperature. After the samples were submerged in water for one year (the colonization period of *L. fortunei* was approximately one year), both the experimental group and the comparative group were removed and tested for the macro-performance characteristics of the concrete, including compressive strength and carbonation depth.

Next, two sets of concrete samples were drilled out from the experimental group of coupons. One set of the samples were from the zones colonized by *L. fortunei*, labelled as "the colonized", while the other set were from the zones without *L. fortunei* adhesion, labelled as "the control". Both sets were tested for the micro-performance characteristics of the concrete, including water absorption, pore characteristics and distribution, surface morphology, element composition, and calcium mineral content.

Furthermore, to study the influence of the colonization period of *L. fortunei* on concrete deterioration, concrete cores (75 mm in diameter and 100 mm in length) were drilled out from the in situ walls of the Dongshen Water-Supply Project, which has been colonized by *L. fortunei* for more than 20 years (the colonization period of *L. fortunei* was estimated to be 20 years). Similarly, the cores from the zones colonized by *L. fortunei* were labelled as "the colonized", while the ones from the zones without *L. fortunei* were labelled as "the control". All of these cores were used for the comparative micro-performance testing. Therefore, the analysis of the micro-performance characteristics of the concrete suffering from one year versus 20 years of *L. fortunei* colonization were compared to determine the influence of the colonization period on concrete deterioration.

2.2. Water absorption experiment

The water absorption ability of the concrete samples from the coupons and the in situ cores were analysed comparatively. Small samples (<1 cm^3) of concrete were drilled down from the surface layers (thickness <10 mm) of the concrete coupons and the in situ cores using a handheld coring drilling machine with a sleeve diameter of 10 mm. The water absorption in 24 h of all the concrete samples was measured according to the procedure given in the Standard Specification for Absorption of Coarse Aggregate (SL 352, 2006).

2.3. Mercury intrusion porosimetry (MIP)

Pores in a cement matrix are usually classified into different types depending on their diameter. Gel pores have pore diameters smaller than 0.003 μm, inter-gel particle pores are between 0.003 and 0.2 μm, capillary pores are between 0.003 and 10 μm, and entrained air pores, include any pores with diameters larger than 10 μm (Moon et al., 2006), as shown in Fig. 1. The capillary pores play the most decisive role in determining the durability of concrete (Rostásy et al., 1980; Garboczi, 1990). A variety of methods are