BACTERIA-BASED SELF-HEALING CONCRETE FOR APPLICATION IN THE MARINE ENVIRONMENT

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ABSTRACT

Marine concrete structures are exposed to one of the most hostile of natural environments. Many physical and chemical phenomena are usually interdependent and mutually reinforcing in the deterioration of marine exposed concrete: expansion and microcracking due to physical effects increases concrete permeability paving the way for harmful chemical interactions between seawater, concrete and embedded steel reinforcement. Early research in self-healing concrete has focused on the autogenous ability of hydrates to heal cracks over time, this form of healing is however restricted to early and small cross sectional crack width reductions, while limited research is available on the autogenous healing of concrete incorporating GBFS (Ground blast furnace slag). A novel approach to self-heal concrete is a bio-inspired technique, where bacteria immobilized in the concrete are activated through crack induced water ingress, forming a mineral healing precipitate [1]. The current study characterises the autogenous healing of blast furnace slag cement (CEM III/B 42.5 N) mortar cubes submerged in both fresh- and synthetic sea- water, as the first step towards developing a bacteria-based self-healing concrete for application in the marine environment.

Compression tests of the mortar cubes showed their strength to be in good agreement with the Norm EN 196-1 [2]. ESEM analysis of the specimens after 54 days submersion revealed two distinctive surface crystal morphologies. Specimens submerged in fresh water displayed rhomboidal surface crystals 10 µm thick, while those specimens submerged in synthetic seawater were covered in a 50 µm carpet of spicules. EDS analysis showed the mineral to be calcium based, suggests the presence of two calcium carbonate polymorphs. FT-IR analysis of the surface precipitates supported observations made by ESEM, as those specimens submerged in fresh- and synthetic sea- water displayed spectra indicative of two calcium carbonate polymorphs, calcite and aragonite respectively. This research provides a valuable reference from where an improved bacteria-based system can later be developed for combating crack-induced deterioration of concrete in the marine environment.

1. INTRODUCTION

Many physical and chemical phenomena are usually interdependent and mutually reinforcing in the deterioration of marine exposed concrete: expansion and microcracking due to physical effects increases concrete permeability paving the way for deleterious chemical interactions between seawater, concrete and embedded steel reinforcement. Hydraulic minerals such as GBFS are used in the construction of marine concrete structures, as they decrease the pore structure of the concrete slowing chemical ingress. Early research in self-healing concrete has focused on the autogenous ability of hydrates to heal cracks over time, this form of healing is however restricted to early and small cross sectional crack width reductions, while limited information is available on the autogenous healing ability of concrete incorporating GBFS. In this study we have characterised the autogenous healing ability of blast furnace slag cement (CEM III/B 42.5 N) mortar cubes submerged in both fresh water and synthetic seawater (from here on called sea water). This work represents a reference on the way to developing a bacteria-based self-healing concrete for application in the marine environment.

2. MATERIALS

Blast furnace slag cement (CEM III/B 42.5 N LH)(ENCI, The Netherlands) mortar cubes (4 x 4 x 4 cm) were cast with aggregates up to 2 mm in accordance with the European standard EN 196-1 [2]. Tap water and technical grade chemicals were used to produce seawater.

3. METHODS

Mortar cubes were cast, carefully demoulded after 24 hours and tightly sealed in plastic bags for a total curing period of 28 days at room temperature. Cured specimens were then submerged in fresh water and seawater, again at room temperature. Submersion water was changed every two weeks. The mortar cubes were air-dried to prevent damage of the surface precipitates and tested for their compressive strength 2, 7, 28, and 84 days after casting. Environmental Scanning Electron Microscope (ESEM) equipped with Energy Dispersive X-ray spectrometer (EDS) were employed to characterise surface precipitates, while Fourier-Transform Infrared (FT-IR) spectroscopy was also used to analyse precipitates scraped from the dry surface of the specimens 54 days after submersion.

4. RESULTS

Compression tests showed the strength of the specimens to be in good agreement with those from the European Standard EN 196-1 [2]. ESEM analysis of the surface mineral precipitates revealed two distinctive crystal morphologies. Specimens submerged in fresh water displayed rhomboidal crystals 10 µm thick (Figure 1A), while those specimens submerged in seawater were covered in a 50 µm billowing layer of spicules (Figure 1B). EDS analysis showed the minerals to be calcium based, which suggests the presence of two calcium carbonate polymorphs. The FT-IR spectra for specimens submerged in fresh water exhibited characteristic bands of calcite (Figure 2A,C and D): C-O asymmetric stretching vibration (ν_3), C-O out of plane bending (ν_2), and C-O planar bending vibration (ν_4) centred at 1400, 872 and 712 cm^{-1} respectively; while for those in seawater the stretching vibration (ν_1) became apparent at 1083 cm^{-1} (Figure 2B) and the vibration (ν_4) has split at 700 and 712 cm^{-1} (Figure 2D), which are indicative of aragonite.

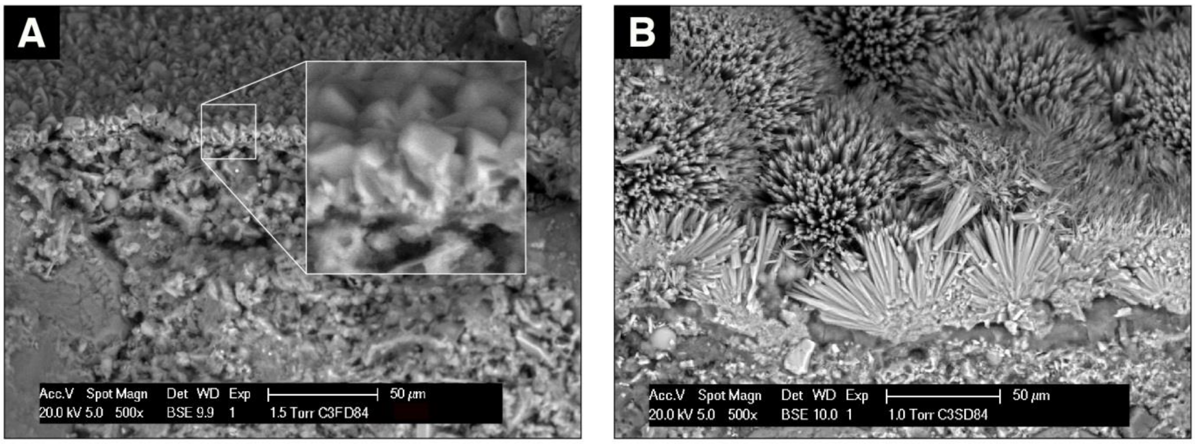

Figure 1: ESEM images showing the respective rhomboidal (A) and spicule (B) surface precipitates of CEM III/B specimens submerged in fresh and sea water.

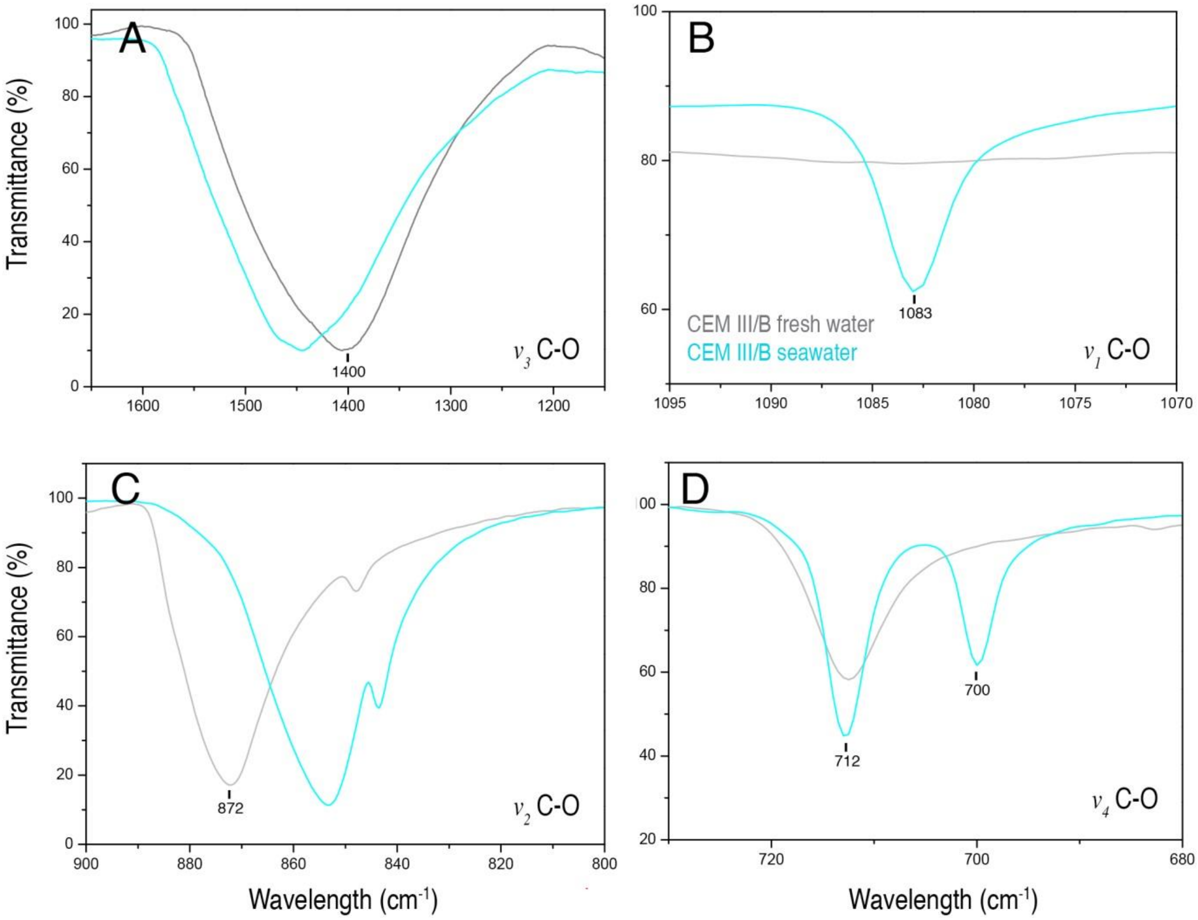

Figure 2: Details of the FT-IR spectra obtained from precipitate produced on the surface of CEM III/B mortar specimens submerged in fresh water are the: C-O asymmetric stretching vibration (ν_3), C-O out of plane bending (ν_2) and C-O planar bending vibration (ν_4) centred at 1400 (A), 872 (C) and 712 (D) cm^{-1} respectively; while the stretching vibration (ν_1) became apparent at 1083 cm^{-1} (B) and the vibration (ν_4) split at 700 and 712 cm^{-1} (D) for those in seawater.

The water-insoluble $CaCO_3$ observed on the surface of the specimens evolves from a reaction between the calcium ions Ca^{2+}, derived from the concrete and the in-water available carbonates CO_3^{2-}. Whether calcite or aragonite formation develops depends largely on the Mg^{2+} concentration of the solution. Mg^{2+} dissolved in the synthetic seawater is readily adsorbed on to the surface of calcite, inhibiting calcite crystal growth. Dissolved Mg^{2+} is not taken up to any great extent into the aragonite crystal lattice, as a result aragonite crystal growth in seawater is relatively unaffected by the presence of dissolved Mg^{2+} [3]. Variations in precipitate thickness can be explained by the precipitation rate of aragonite to calcite relative to temperature. The experiments presented here were conducted at room temperature and aragonite precipitation rates at >25ºC are much more rapid than those of calcite (up to a factor of 4) [4]. The autogenous healing ability of CEM III/B mortar specimens submerged in fresh- and sea- water has been characterised in terms of the mineral type and amount produced, providing a valuable reference from where an improved bacteria-based system can later be gauged for combating crack induced deterioration of marine concrete.

5. CONCLUSIONS

Specimens submerged in fresh water produced a surface layer of calcite in the order of 10 μm, while those submerged in synthetic seawater produced an aragonite layer of 50 μm thick. The difference in polymorph can be attributed to the presence of dissolved Mg^{2+} in the synthetic seawater, which inhibits the more thermodynamically stable calcite, allowing the precipitation of aragonite. The current study has characterised the autogenous healing of blast furnace slag cement mortar cubes submerged in both fresh- and sea- water. This work represents a reference on the way to developing bacteria-based self-healing concrete for application in the marine environment. The next phase will see the design and impregnation of a bacteria-based agent into mortar specimens, with the aim of exerting bacterial control over mineral precipitates for improved healing of concrete in the marine environment.

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