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Microscopic study into biodeterioration of marine concrete

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ABSTRACT

This research presents an exploratory study into the biodeterioration of marine concrete. Monocular and inverted light microscopy, scanning electron microscopy (SEM) with energy dispersive X-ray analyser (EDX) were used to observe colonisation of site specimens at the fine aggregate cement interface, enabling the further understanding of this interaction. Algal filaments have been observed growing between fine aggregate and cement. Colonisation has been observed, entangled around, and adhered to fine aggregate. This degradation mechanism occurs when the material bond is weakened as a direct result of the physical activity of an organism, such as its growth. Loss of surface material, either through biodeterioration or through other mechanical means, such as power washing, is not the primary cause of degradation, but may exacerbate the condition.

1. Introduction

The fouling of concrete surfaces by microorganisms can have detrimental effects, accelerating deterioration of the structure (Gaylarde and Morton, 1999). Once established on concrete revetment armour steps, as observed at the Fylde coast, UK study site, growths form a slippery surface and may constitute a danger to the public. More direct damage can be caused to the concrete itself by the acids and other metabolites produced by the organisms, which together with the ability of some species to tunnel into surfaces, leads to degradation, increased porosity and decreased durability (Allsopp et al., 2004). Durability of marine concrete, the essence of this study, is arguably its principal property; it is important that concrete should be capable of withstanding the harsh conditions throughout the expected life of the structure.

In cement composites with aggregate inclusions the matrix in the vicinity of the inclusion can be quite different in its microstructure to that of the bulk cement matrix. This modified matrix can be as great as 50–100 μm in area (Bentur et al., 1995). The higher porosity at this interface, together with a smooth, well rounded texture of some types fine aggregate (beach sand), favour the appearance and development of biodeterioration. Experimental evidence indicates that porous concrete creates a favourable environment for microbial colonisation, because aquatic organisms including algae adhere to both the inner and outer surfaces (Tamai et al., 1992).

Algae are a diverse group of photosynthetic organisms ranging from microscopic single-cell micro-organisms to very large organisms such as seaweed. Many commonly occurring fouling algae belong to the macroalgal group Chlorophyta (green algae). The Chlorophytes comprise a number of genera and species that actively bore in carbonate substrates. They produce branching networks of tunnels varying greatly in size. Some may be as little as 2 μm in diameter. In some species such fine filaments may collect together in main canals as wide as 25 μm (Golubic et al., 1975). Concrete structures in tropical and sub-tropical seas have been shown to be subject to the same biodeterioration forces as carbonate substrates. Many of the species implicated in calcium carbonate disintegration have been demonstrated to be capable of the biodeterioration of concrete (Scott et al., 1988). Attached macroalgae obtain different elements for their metabolism from the substratum. When algae colonise concrete structures they start to absorb calcium, silica and magnesium (Javaherdashti et al., 2009). Research into the degradation of marine concrete (Jayakumar and

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Saravanane, 2009) showed that marine algae had utilized crystals like Yeelimite, Gismondine and Portlandite (calcium hydroxide) as a source of minerals. This study looks at a site where *Ulva* is the dominant algal genus, a conspicuous bright grass-green seaweed, consisting of inflated irregularly constricted, tubular filaments that grow from a small discoid base, it is a common, green macroalga found throughout the world. Filaments from the site ranged from 10 cm to over 20 cm in length. Their dispersal, colonisation and adhesion have been described elsewhere (Callow and Callow, 2002).

The aim of this study was to observe marine algal colonisation at the fine aggregate-cement matrix interface, and to see how its presence may affect fine aggregate performance within the cement matrix. To achieve this aim fine aggregate (sometimes referred to as sand) within precast concrete elements has been microscopically examined and monitored for seven years at the marine study site.

This research presents an exploratory site study into the biodeterioration of marine concrete. Microscopic examination of the bond between fine aggregate, cement and algae enables the further understanding of this interaction. The mechanism observed and presented in this study occurs when the material bond is weakened as a direct result of the physical activity of an organism, such as its movement or growth (Morton, 2003).

2. Materials and methods

2.1. Concrete specimens

The study site for this research is part of a coastal protection scheme, which involved the placing of 65,000 m^3 of ready mix concrete and 44,000 m^3 of precast concrete revetment armour. The project has been surveyed and monitored over the full length of the construction period, approximately 7 years. The fine aggregate studied was used in the manufacture of the revetment armour. The precast concrete units, measure 5 m by 3.5 m, weigh 20t and contain 8 m^3 of synthetic fibre reinforced concrete. Original casting of units was monitored and the same units have been regularly examined over the years *in situ*. The 'as struck' concrete surface exposed to the sea was cast in a horizontal, 'upside down' position against a steel mould. The compressive strength class is C35/45, BS8500-1 exposure class XS3, XF4, XC3, XC4 and water/cement ratio of 0.45. The minimum cement content of 340 kg/m^3, CEMIIIA, with 50% ggbs, chloride class 0,2. Concrete prisms (150 mm × 150 mm × 500 mm long) were also supplied by the manufacturer, some were dry diamond cut into 25 mm lengths, (Norton, Clipper brick and tile cutter) washed and examined. Some specimens (cut as above) were placed at the site, in the splash zone strapped to a pipe. At intervals the specimens were retrieved, microscopically examined, and returned to the site. Subsequently, colonised surface fragments breaking from the revetment armour units were obtained.

2.2. Study site fine aggregate details

Marine dredged sand was extracted from the beach, 5 km from site, and blended with crushed limestone for use as fine aggregate by the precast concrete manufacturer. The sand was washed with sea water to reduce silt content and then screened to remove any significant debris such as litter and driftwood. The chloride content of the sand was monitored weekly. The fluvio-glacial deposits on the floor of the eastern Irish Sea adjacent to the study site are the dominant source of sediments. Whole-rock mineralogical analysis of a range of intertidal sediment samples has shown that they are predominantly quartz with associate plagioclase, orthoclase, calcite, dolomite, chlorite/kaolinite and mica (Bryant et al., 1996). Beach sand samples were collected by hand 1 km seaward from the sea defence site, adjacent the dredging area.

2.3. Study site and exposure conditions

The concrete stepped revetment armour allowing open access to the beach is constantly colonised by algae, predominantly *Ulva*, creating a slip hazard to the public. The colonisation of newly placed pre-cast elements on site-was noted; some became covered with algae after only a few weeks of exposure. The local authority have utilised high pressure water (1200 psi), dispensed from motorised units with multi oscillating jets, to remove the algae. The fully exposed units face westwards and are subject to cyclic wetting and drying conditions. The exposure is very harsh due to wave action, which is exacerbated by sand and occasionally shingle and debris. Because of this, surface erosion during service was anticipated in the design stage. This erosion has occurred at many locations, particularly at inter-tidal regions, where an exposed aggregate appearance was noted and patch repairs have been carried out. The primary role of the revetment armour is coastal protection and as such is subject to the wear associated with tidal and wave action, hence the design team and client expected a degree of surface deterioration.

2.4. Sample analysis – microscopy

Approximately 25 Concrete samples (50 mm × 25 mm × 10 mm) retrieved from site over a five year period were initially observed with a Leica Strata Lab, monocular light microscope, and then with a Meiji MT4000 Biological and a Zeiss Axiovert 40 MAT inverted microscope with a large specimen stage, ideal for the examination of heavy and bulky concrete specimens. All samples had filamentous growth. Individual sand grains collected from the beach and algal specimens from the study site were also observed on glass slides with a cover slip. The Axiovert was fitted with a 5 megapixel, high-resolution digital camera. These images were measured with the AxioVison AC software (Zeiss, 2001). This software allowed accurate measurement, image processing and analysis of algal filaments, diatoms and sand grains on a captured image. Visual examination of samples revealed large-scale features such as the nature of the external concrete and sand surfaces, and the presence of fine aggregate within the matrix.

2.5. SEM – EDX

Algal morphological characteristics, concrete topography and, fine aggregate distribution were observed using a FEI Quanta 200 scanning electron microscope (SEM) fitted with an energy dispersive X-ray analyser, (EDX) using Genesis software. EDX was used for the elemental analysis of synthetic fibres within the cement matrix and of algal filaments. 10 site specimens were cleaned with a jet of air, to remove unattached algae, before gold sputtering (Emitech K550X) at 25 milliamps for 2 min. Specimens were examined by secondary electron (SE) signal to show morphology, backscattered electrons (BS) to reflect differences in atomic number, with a low accelerating voltage of 10–12 kv to reduce beam damage. The chamber can accommodate samples up to 5 cm × 5cm × 2 cm in size.

2.6. Algal identification

The sea defence site offers hard substrata in areas that are largely sedimentary, thus providing discrete new habitats for opportunistic colonising species. The revetment supports a plant and animal community characteristic of a rocky shore, tending to be dominated by encrusting mussels, barnacles and a variety of algal species. Resident algae include: *Ascophylum nodosum*, *Fucus vesiculosus*, *Fucus spiralis*, *Porphyra umbilicalis and Halidrys siliquosa*. *Ulva* was identified to the genus level on the basis of morphological characteristics observed (Meiji MT4000 Biological) such as thallus and cell arrangement (Blomster et al., 1998). Fresh algal samples were also taken from site, cleaned, (Decon 90), and ground to powder. DNA was successfully extracted from one specimen, using (DNeasy) Blood and tissue kit, (Qiagen), according to manufacturer's protocol. New barcodes (sequences) were aligned with published sequences, (The Consortium for the barcode of life, 2009).

3. Results and discussion

It has been shown that algal filaments at the study site can grow freely between fine aggregate and the cement matrix of the concrete revetment armour. The light-inverted microscope images, Figs. 1–4., demonstrate the existence of complex microbial populations around the surface of the fine aggregate, within the armour concrete. This complexity is increased when one considers that algal assemblages are composed of a large number of species, providing an incredibly complex system for investigation. Fig. 1 indicates the destructive presence of growth which will lead to the eventual release of the fine aggregate. It is not suggested that this mechanical degradation mechanism, by algal growth is solely responsible for the erosion observed at the site, but it is suggested that it should be considered as a factor along with tidal action, power washing and biofouling control, such as treatment with a chlorine-based disinfectant.

Fig. 5 shows the upward and outward epilithic growth of coiled algal filaments, exiting the substratum between fine aggregate particles. Fig. 6 shows a compressed, branched filament with epilithic characteristics of algal growth on fine aggregate within the matrix. EDX was used throughout the investigation, enabling element analysis to distinguish between synthetic micro fibres (22 μm in diameter) and algal filaments, often of similar size. Micro fibres showed 86% (Wt.) carbon and 14% oxygen, where algal filaments showed 24% carbon and 66% oxygen. EDX analysis of the colonised cement matrix compared to new concrete at the test site indicated the loss of calcium over two years and is the subject of further work.

Material from marine deposits around the coast of Great Britain has been used in concrete production for several decades (Newman, 1968). Marine aggregates are an important source of sand for the construction market in the UK and continental Europe; however, no provision is made in the current standards for the control of algae growing within or on the surface of beach sand.

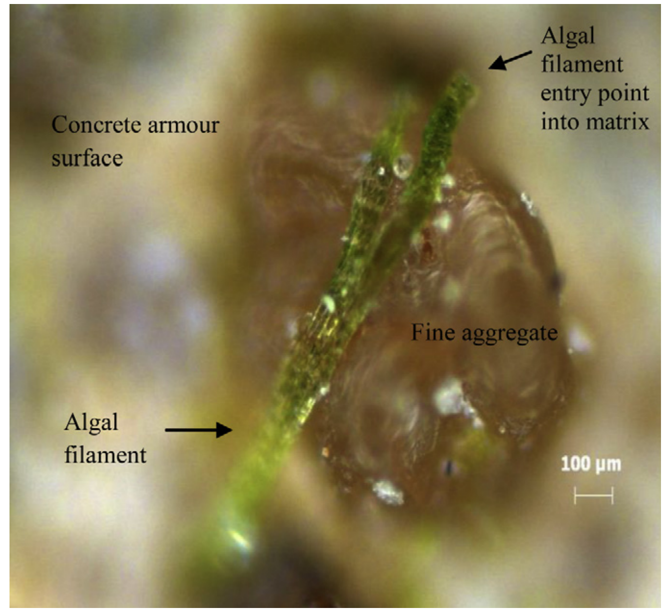

Fig. 2. Light inverted microscope surface view of revetment armour concrete sample, after 2 years exposure. Boring, mature algal filaments can be seen wrapping around the partly exposed fine aggregate, eventually penetrating the cement matrix.

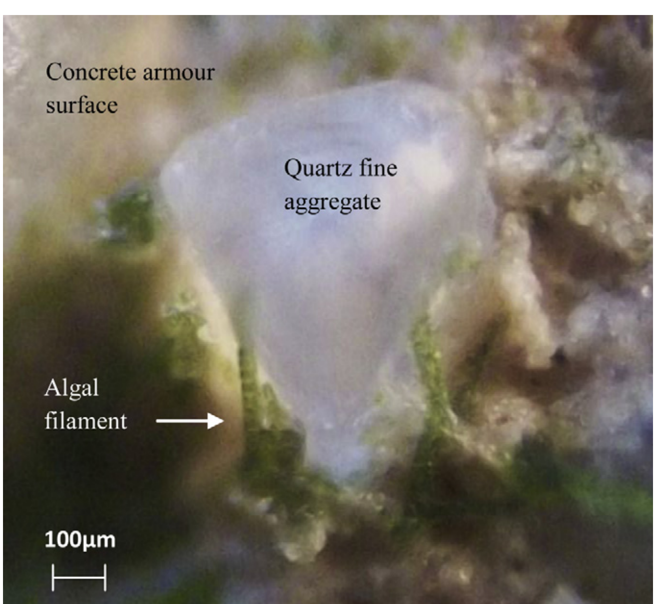

Fig. 1. Light microscope surface view of revetment armour concrete sample, after 2 years exposure. Algal filaments can be seen growing from the surface of the matrix, up and around the contour of the almost fully exposed quartz fine aggregate.

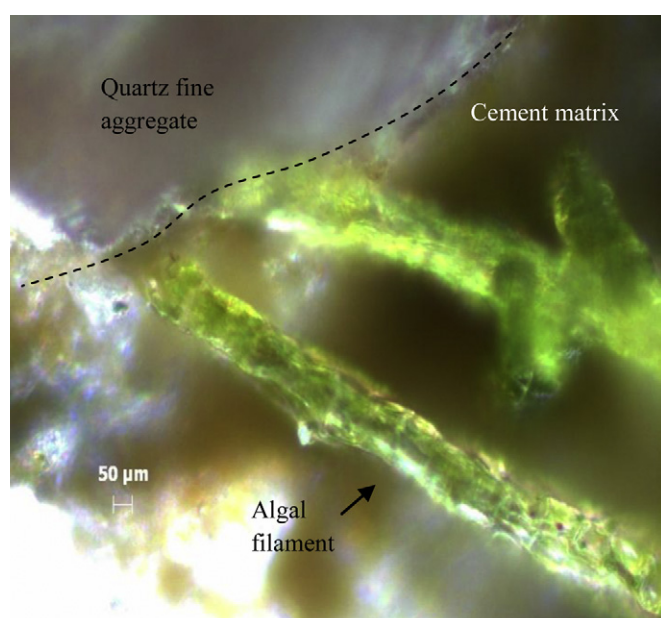

Fig. 3. Light inverted microscope surface view of revetment armour concrete sample, after 3 years exposure. Mature algal filaments are growing out of the aggregate cement interface (indicated by the dotted line).

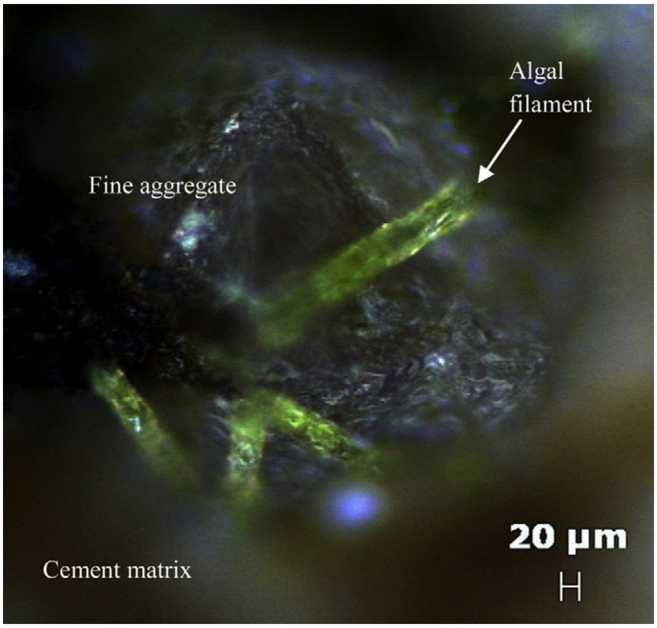

Fig. 4. Light inverted microscope surface view of revetment armour concrete sample, after 2 years exposure. Boring, mature algal filament seen wrapping around partly exposed fine aggregate, eventually penetrating the cement matrix.

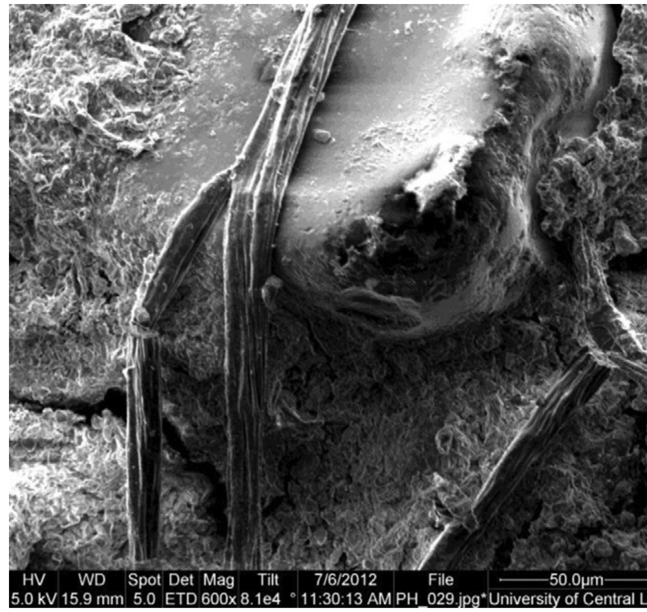

Fig. 6. SEM, secondary electron micrograph, surface view of revetment armour concrete surface, after 3 years exposure. This sample was not sputter coated, showing the filament in its natural condition. A branched mature filament can be seen growing over the exposed fine aggregate.

Research by Round (1965) pointed out how little was known about the algal communities that live on sand, (see Figs. 7 and 8). His report was followed by a number of studies describing problems of algal attachment, production and burial in marine sands (Cadee and Hegeman, 1974). Since then, more has been learnt about species composition (Edlund et al., 1996), life cycles (Jewson and Lowry, 1993) and aspects of colonization, however, we still know relatively little about the ecology of individual species and their specialized adaptations for living on sand. Steele et al. (1970) found viable cells buried to a depth of 0.2 m below the sand surface in a Scottish sea loch. A similar finding occurred 200 km from the source of the marine aggregate used at the study site, in Lough Neagh, where high concentrations of living cells were found attached to sand grains down to 0.5 m below the sand surface (Jewson and Briggs, 1993). Considering the constant mixing of sediment at a beach surface, it may follow that microbial endoliths could occupy some of the beach extraction of fine aggregate used at the study site.

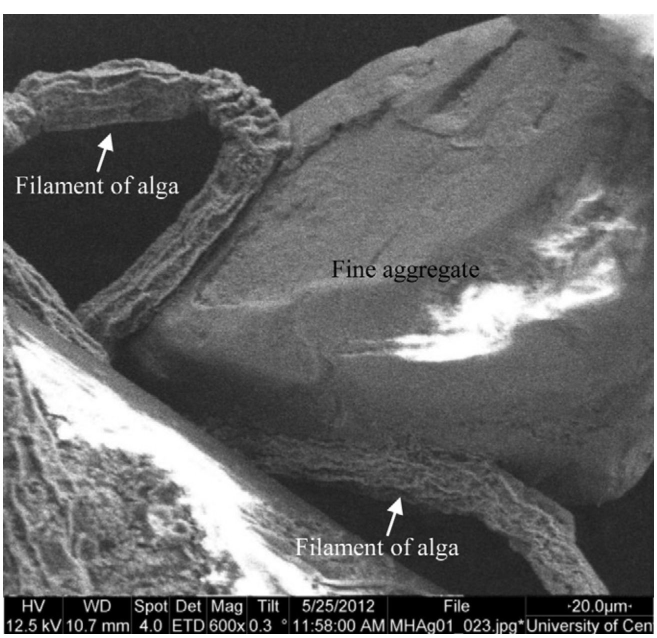

Fig. 5. SEM, secondary electron micrograph, side view of revetment armour concrete surface, after 3 years exposure. This sample was not sputter coated, showing the algae filament in its natural condition. The filament can be clearly observed growing freely around the almost fully exposed fine aggregate.

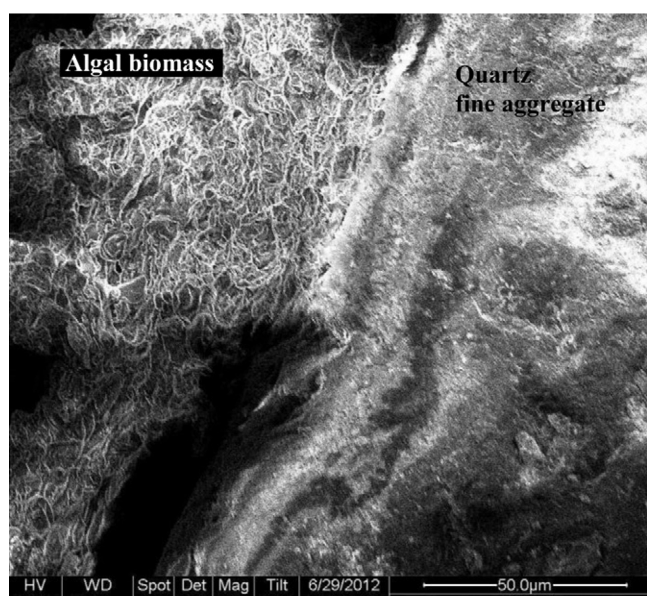

Fig. 7. SEM, secondary electron, low voltage micrograph, surface view of revetment armour concrete surface, after 3 years exposure. The algal biomass can be clearly seen attached and growing on the partly exposed quartz fine aggregate particle.

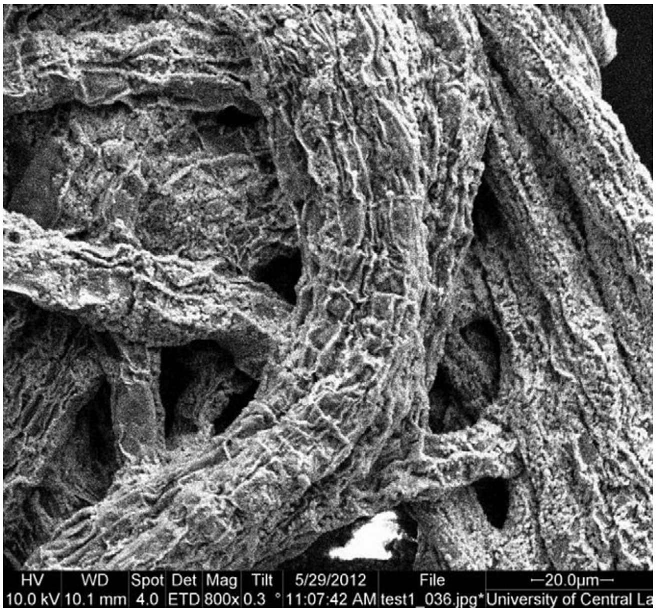

Fig. 8. SEM, secondary electron micrograph, side view of void within revetment armour concrete matrix, after 2 years exposure. The dehydrated, branched algal filaments can be clearly seen.

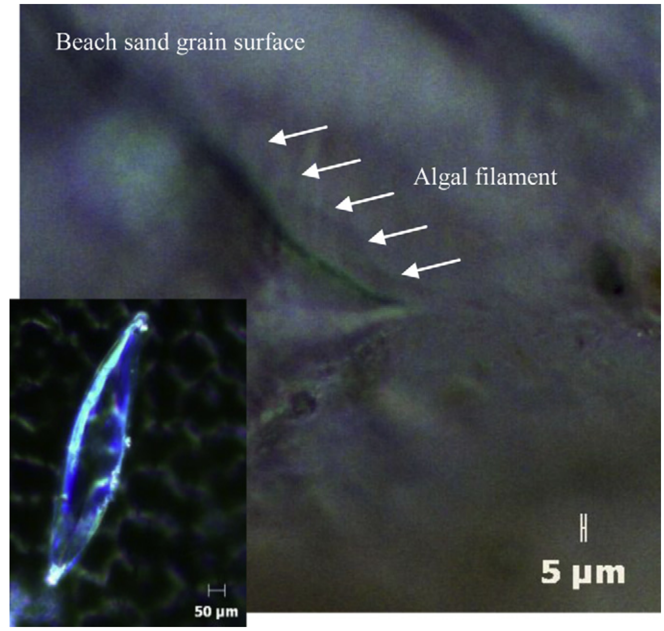

Fig. 10. Light inverted microscope, surface view of beach sand specimen from site. An algal filament can be seen attached to the surface (indicated by arrows). Insert: Diatom from beach sand sample.

Beach sand samples from the vicinity of the study site (the source of fine aggregate used in the concrete production) were examined under the microscope and found to be colonised by algal filaments and diatoms, see Figs. 9 and 10. The existence of microbial populations that live on or within sand is well documented (Miller et al., 1987) investigated the role of micro-topography of sand grains and its influence on distribution of diatoms demonstrating habitat partitioning. The work of Krejci and Lowe (1986) documented the role of sand grain mineralogy on colonisation using SEM for sand grain elemental analysis. Further examples were presented by Greenwood et al. (1999) who also used SEM to examine the distribution and behaviour of diatoms moving through sediments. The work of Huang and Boney (1984) showed that interactions take place between juvenile macroalgae and littoral diatoms. Young plants of *Ulva* grown in the presence of diatoms showed growth enhancement. It is hypothesized that such interactions may take place at the fine aggregate cement interface, between pioneering algal spores and original resident sand dwellers. If the growth of young *Ulva* plants is enhanced in the presence of a diatom population then a more rapid onset of reproductive phases of the green alga will occur, with production of more young plants, in turn interacting with the diatom populations. Certain diatom-green algae synergistic combinations may thus favour a more rapid colonization process by green algae, as seen at the study site, as early colonisation of new precast concrete elements and are in themselves highly resistant to strong alkaline conditions found in concrete.

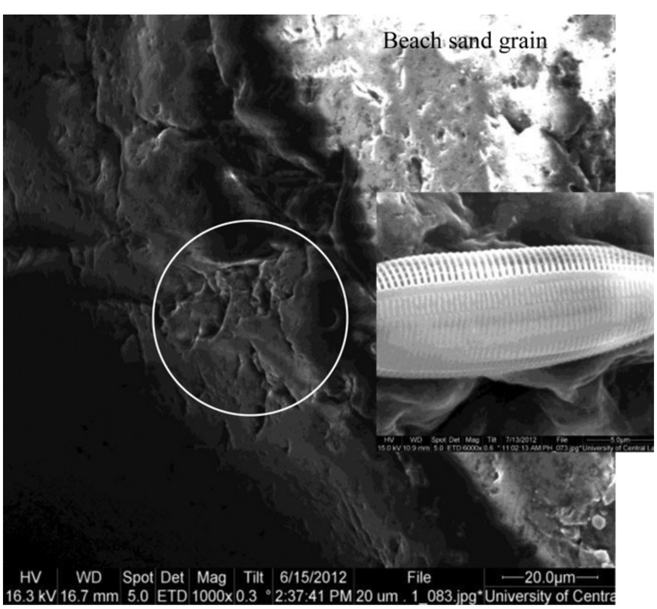

Fig. 9. SEM, secondary electron micrograph, side view of beach sand specimen. This sample was not sputter coated, showing the sand grain in its natural condition. Juvenile algal filaments can be observed growing on the surface of the sand grain (circled). Insert: Diatom from site.

Large quantities of aggregates are obtained from marine deposits, and are widely and satisfactorily used for making concrete including prestigious structures within hostile environments, such as the second Severn Crossing, Canary Wharf development and the Channel Tunnel Rail Link (BRE, 2008). The aggregate has to be used with care: The British Cement Association warns that washed beach sand is generally unsuitable by itself for good quality concrete, due to the single-sized grading, but this can be overcome by blending aggregates. While aggregates for unreinforced concrete can be washed with sea water, as was the case for the study site, for reinforced concrete the aggregates must be carefully washed with potable water to remove excess chloride from sea salt, but they will still retain shell and organic matter that can affect the water demand of the mix; the organic matter refers only to water-soluble organic compounds derived from decaying vegetation, tests for which no longer appear within standards. The results of this study suggest that blanket use of marine sourced aggregates should be reconsidered for concrete that is to remain in contact with sea water, particularly mass (unreinforced) concrete. Washing in water may only partly remove some of the epilithic biomass present on the surface of the aggregate, possibly leaving endolithic algae to continue and thrive. Concrete needs to age in the ocean for at least 6 months before the pH in the surface region approaches the pH of sea water (Guilbeau et al., 2003) hence making a substratum bioreceptive. It has been reported by Cardon et al. (2008) that green algae have resting stages (spores and zygotes) that allow cells to lay dormant in unfavourable environments, even freezing conditions or to survive in ephemeral pools. (Trainor and Gladych, 1995) found that even after soils had air-dried for 35 years, green algae could be cultured.

Therefore the algal content may need to be controlled in structures subject to permanent wetting by sea water to control growth on and inside the surface. BS EN 12620 is the predominant specification concerning the use of aggregates for concrete supported by UK national guidance document PD 6682-1. This guidance should consider undesirable elements such as colonising algae more closely and place precise limits on their presence. For marine concrete structures there is a tangible risk that algae will remain on or within the beach fine aggregate, leading to increased colonisation and the biodeterioration of concrete.

4. Conclusions

The aim of this work was to study marine algal colonisation at the fine aggregate-cement matrix interface, and to discuss how its presence may affect fine aggregate performance within the cement matrix. Fine aggregate samples from within precast elements have been examined microscopically and the results presented. The environmental performance of the fine aggregate has been observed before and after tidal impact, colonization and power washing. Biodeterioration of the concrete, by way of coiled algal filaments tunnelling into the fine aggregate cement interface, has been observed. As a result of this research it is proposed that algal presence and growth within the matrix under immersed and tidal conditions must weaken the bond between fine aggregate and cement, accelerating material loss and concrete surface degradation.

Standards and guidance on the use of beach sand ought to define undesirable elements such as colonising algae more closely and place precise limits on their presence. This multidisciplinary study graphically illustrates the potential for biodeterioration of marine concrete, providing a new insight into the destructive habitat of concrete biofouling. A limitation to this case study however, is that it involves only a single site and therefore may not be representative of marine environments in general.

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