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Optimising the bioreceptivity of porous glass tiles based on colonization by the alga *Chlorella vulgaris*

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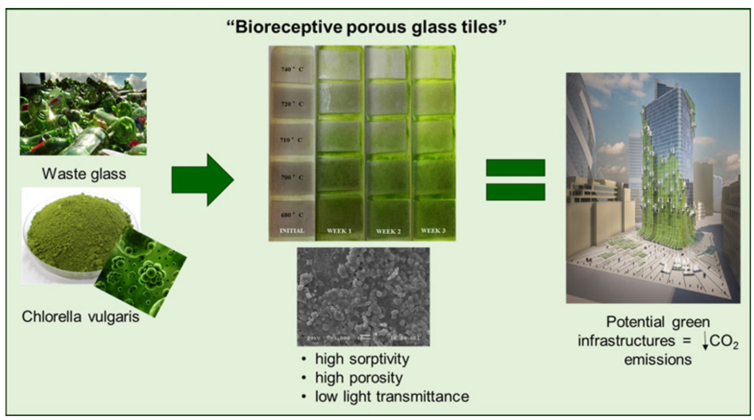
HIGHLIGHTS

- Porous tiles made by sintering waste glass at variable temperatures
- Bioreceptivity assessed by measuring colonisation by the algae *C. vulgaris*
- Tiles sintered at 700 °C gave maximum algal growth and bioreceptivity.
- Bioreceptivity was positively correlated with sorptivity and porosity.
- Bioreceptive tiles can be used in green infrastructure to reduce CO_2 emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Green façades on buildings can mitigate greenhouse gas emissions. An option to obtain green facades is through the natural colonisation of construction materials. This can be achieved by engineering bioreceptive materials. Bioreceptivity is the susceptibility of a material to be colonised by living organisms. The aim of this research was to develop tiles made by sintering granular waste glass that were optimised for bioreceptivity of organisms capable of photosynthesis. Tiles were produced by pressing recycled soda-lime glass with a controlled particle size distribution and sintering compacted samples at temperatures between 680 and 740 °C. The primary bioreceptivity of the tiles was evaluated by quantifying colonisation by the algae *Chlorella vulgaris* (*C. vulgaris*), which was selected as a model photosynthetic micro-organism. Concentrations of *C. vulgaris* were measured using chlorophyll-*a* extraction. Relationships between bioreceptivity and the properties of the porous glass tile, including porosity, sorptivity, translucency and pH are reported. Capillary porosity and water sorptivity were the key factors influencing the bioreceptivity of porous glass. Maximum *C. vulgaris* growth and colonisation was obtained for tiles sintered at 700 °C, with chlorophyll-*a* concentrations reaching up to 11.1 ± 0.4 μg/cm^2 of tile. Bioreceptivity was positively correlated with sorptivity and porosity and negatively correlated with light transmittance. The research demonstrates that the microstructure of porous glass, determined by the

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processing conditions, significantly influences bioreceptivity. Porous glass tiles with high bioreceptivity that are colonised by photosynthetic algae have the potential to form carbon-negative façades for buildings and green infrastructure.

1. Introduction

The critical problems associated with global greenhouse gas emissions to the atmosphere and associated impacts on climate change have been extensively reported (Breyer et al., 2015; Dedinec et al., 2015; Farrelly et al., 2013). A mitigation option for buildings and infrastructure is through the use of green roofs and green building façades (Luo et al., 2015; Whittinghill et al., 2014). However, at present these systems generally have high capital and operating costs (Bianchini and Hewage, 2012; Claus and Rousseau, 2012). An alternative strategy is to engineer bioreceptive surfaces into the built environment which can be colonised by photosynthetic organisms that sequester carbon dioxide and generate oxygen. In this context bioreceptivity is defined as the ability of a substrate material to be colonised by living photosynthesizing organisms (Guillitte, 1995).

Bioreceptivity is determined by both the intrinsic characteristics of a material and also the macro and micro-environment to which the organisms are exposed (Guillitte, 1995). More specifically, primary bioreceptivity depends on the initial intrinsic potential of a material to be colonised by biological communities, whereas secondary bioreceptivity refers to subsequent changes to the bioreceptivity of the colonised material. The bioreceptivity of concrete and natural stone have been extensively investigated as colonisation is generally regarded as a problem and something to be actively discouraged. For example, it was stated that algae are responsible for aesthetic defects in roofing tiles (Giovannacci et al., 2013). More recently there have been a limited number of studies which have aimed to enhance the bioreceptivity of cementitious construction materials (Manso et al., 2015; Manso et al., 2014a; Manso et al., 2014b). This change in emphasis reflects a growing acknowledgment that this represents a sustainable route to incorporate green façades into the built environment.

Material bioreceptivity can be assessed by artificially inoculating the target material with test organisms under selected environmental conditions and using appropriate analytical methods to quantify the growth of resultant biomass (Guillitte and Dreesen, 1995). Microalgae and cyanobacteria have been used as model organisms in bioreceptivity studies (D'Orazio et al., 2014; Guillitte and Dreesen, 1995). Algae are particularly suitable for evaluating primary bioreceptivity as they are pioneer colonisers of construction materials (D'Orazio et al., 2014). In this research the single cellular photoautotrophic algae *Chlorella vulgaris* (*C. vulgaris*) was selected as a model photosynthetic microorganism because it is resistant to extreme environmental conditions and has a high growth rate (Blair et al., 2014). Moreover, *C. vulgaris* is one of the few microalgae strains capable of developing suitable molecular mechanisms to efficiently utilise high concentrations of CO_2, which make it promising for use in CO_2 mitigation technologies (Keffer and Kleinheinz, 2002; Lee et al., 2005). *Chlorella* sp. are known to grow on ceramic roofing tiles and other construction materials under a diverse range of conditions and were considered to be the most widespread genus of microalgae in a review of ceramic architectural materials (Coutinho et al., 2015). *C. vulgaris* has also been reported to grow on bricks and roof tiles (Coutinho et al., 2015; Giovannacci et al., 2013) as well as on cement mortars (Manso et al., 2014a; Manso et al., 2014b).

Numerous laboratory-based studies and field-scale experiments have investigated how bioreceptivity is influenced by intrinsic material properties and environmental factors (Coutinho et al., 2015; D'Orazio et al., 2014; Graziani et al., 2014; Manso et al., 2015; Manso et al., 2014a; Manso et al., 2014b; Miller et al., 2010; Prieto and Silva, 2005; Tanaca et al., 2011). These have demonstrated that properties including the porosity, surface roughness and pH influence the bioreceptivity of a material. Magnesium phosphate cement was found to be more suitable than standard Portland cement as a medium for growth of *C. vulgaris*, which was associated with the former having a lower pH (Manso et al., 2014a; Manso et al., 2014b). Macro-environmental factors such as temperature, humidity and exposure to sunlight also influence the colonisation of material by photosynthetic microorganisms. It has previously been reported that colonisation of limestone, concrete and clay roofing and façade tiles by two species of algae, including *C. vulgaris*, was enhanced by humidity, porosity and surface roughness (Giovannacci et al., 2013).

In this research, recycled waste soda-lime glass was used to develop a highly bioreceptive material, as it was hypothesised glass would be intrinsically more suitable than cementitious materials, which typically have a pH ~ 12. In addition, waste soda-lime glass is widely available, with a low cost and consistent chemical composition. Moreover, controlling the glass particle size distribution and processing conditions allows porous glass tiles to be formed with controllable porosity and water sorptivity (Pantz, 2013), which are important properties influencing bioreceptivity. The aim of this study was to identify the processing and resulting microstructural characteristics of sintered porous glass that give optimum primary bioreceptivity. The influence of sintering temperature, pH, porosity, sorptivity and translucency were investigated. The vision to which this study contributes is the development of new bioreceptive materials that are carbon-negative through colonisation by photosynthetic microorganisms.

2. Materials and methods

2.1. Materials and tile manufacturing process

Crushed clear recycled soda lime silica glass (BOUND Minerals, UK) with a particle size between 2 and 6 mm was used to prepare tiles. The as-received glass was crushed and ground in a disc mill (Gy-Ro, Glen Creston Ltd, UK) for 3 s and the resulting glass particles size separated by sieving to form a glass powder with 5% weight < 212 μm, 50% weight between 212 and 355 μm, 35% weight between 355 and 500 μm and 10% weight between 500 and 850 μm.

An organic binder (1% w/w of Alcotac CB6, BASF) was added to increase the green strength of pressed tiles. The binder and glass powder were mixed with water to give a water to solids ratio of 2. The slurry was mechanically mixed for 2 h, dried overnight at 105 °C and the resulting dried cake lightly broken down using a pestle mortar to pass through a 1.5 mm sieve. Approximately 7% w/w of water was then re-added to the powder-binder mix which formed weak agglomerated particles suitable for pressing. Samples were formed by uniaxial pressing at 7 MPa with a hydraulic press (MIGNON SS DGT) using a mould of dimensions 110 × 55 × 20 mm. The 'green' tiles were dried overnight at 105 °C and then fired in an electric furnace (Lenton Thermal Design Ltd, ECF 12/45) at temperatures between 680 and 740 °C using a heating and cooling rates of 30 °C/min and a 20 min dwell at the maximum temperature. This temperature range was selected as this recycled glass was previously found to soften and sinter at temperatures above ~600 °C (Spathi et al., 2015) and screening experiments during the current study found that tiles sintered between 680 and 740 °C had an