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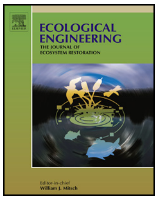

Reefcrete: Reducing the environmental footprint of concretes for eco-engineering marine structures

Harry D. Dennis[a,1], Ally J. Evans[a,*,1], Alexander J. Banner[a], Pippa J. Moore[a,b]

[a] Institute of Biological, Environmental and Rural Sciences, Aberystwyth University, Aberystwyth SY23 3FG, UK
[b] Centre for Marine Ecosystems Research, Edith Cowan University, Joondalup, WA 6019, Australia

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ABSTRACT

The ecological value of engineered marine structures can be enhanced by building-in additional habitat complexity. Pre-fabricated habitat units can be cheaply and easily cast from concrete into heterogeneous three-dimensional shapes and surface topographies, with proven ability to enhance biodiversity on artificial structures. The net ecological benefits of enhancement using concrete, however, may be compromised on account of its large environmental footprint and poor performance as substrate for many marine organisms. We carried out a pilot study to trial alternative cast-able "*Reefcrete*" concrete mixes, with reduced environmental footprints, for use in the marine environment. We used partial replacement of Portland cement with recycled ground granulated blast-furnace slag (GGBS), and partial replacement of coarse aggregate with hemp fibres and recycled shell material. We calculated the estimated carbon footprint of each concrete blend and deployed replicate tiles in the intertidal environment for 12 months to assess their performance as substrate for marine biodiversity. The hemp and shell concrete blends had reduced carbon footprints compared to both ordinary Portland cement based concrete and the GGBS based control concrete used in this study. At the end of the experiment, the hemp and shell blends supported significantly more live cover than the standard GGBS control blend. Taxon richness, particularly of mobile fauna, was also higher on the hemp concrete than either the shell or GGBS control. Furthermore, the overall species pool recorded on the hemp concrete was much larger. Community compositions differed significantly on the hemp tiles, compared to GGBS controls. This was largely explained by higher abundances of several taxa, including canopy-forming algae, which may have facilitated other taxa. Our findings indicate that the alternative materials trialled in this study provided substrate of equal or better habitat suitability compared to ordinary GGBS based concrete. Given the growing interest in ecological engineering of marine infrastructure, we propose there would be great benefit in further development of these alternative "*Reefcrete*" materials for wider application.

1. Introduction

"Ocean sprawl" is causing considerable damage to the ecological condition and functioning of marine and coastal habitats globally (see recent review by Firth et al., 2016b). In addition to causing habitat loss and fragmentation, engineered structures in the marine environment are known to support low biodiversity and 'non-natural' communities of marine life compared to natural rocky habitats (Aguilera et al., 2014; Chapman, 2003; Chapman and Bulleri, 2003; Firth et al., 2013; Moschella et al., 2005), often harbouring non-native and invasive species (Airoldi et al., 2015; Bulleri and Airoldi, 2005; Glasby et al., 2007; Mineur et al., 2012; Tyrrell and Byers, 2007). The field of ecological engineering has emerged to investigate ways of enhancing the ecological value of artificial structures, in an effort to maximise their potential to support biodiversity and natural capital. Researchers have approached this by trialling a variety of engineering manipulations to increase topographical complexity at varying scales, to build-in refuge and habitat niches that are often absent from engineered structures (reviewed by Firth et al., 2016b).

The addition of topographic complexity such as surface texture, cracks, holes and pools has been shown to be an effective means of promoting biodiversity on artificial marine structures (Chapman and Blockley, 2009; Evans et al., 2016; Firth et al., 2014,

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* Corresponding author.
E-mail addresses: harry.dennis@hotmail.co.uk (H.D. Dennis), allyevans01@gmail.com (A.J. Evans), alexbanner95@hotmail.com (A.J. Banner), pim2@aber.ac.uk (P.J. Moore).
[1] Joint first authorship.

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Table 1
Cement binder ratios, aggregate replacement levels and carbon footprint estimates for one control and six alternative concrete blends. Carbon footprint estimates calculated by summing the estimated CO_2 emissions of their component parts, multiplied by their respective ratios within the blends (SOM Tables 1–3). Estimate is also given for ordinary Portland cement based concrete (CEM I Concrete) for comparison. Negative values indicate potential net carbon storage.

Blend	Cement binder ratio (GGBS : CEM I)	Alternative aggregate	Percentage aggregate replacement	Replicates (n)	Carbon footprint (kg CO_2/t)
CEM I concrete	0:100	n/a	n/a	n/a	189.84
GGBS control	70:30	None	None	5	65.52
Low shell	70:30	Shell	25%	3	53.44
Medium shell	70:30	Shell	50%	3	41.35
High shell	70:30	Shell	100%	3	17.18
Low hemp	70:30	Hemp	5%	3	25.41
Medium hemp	70:30	Hemp	10%	3	−14.70
High hemp	70:30	Hemp	25%	3	−135.02

2016a; Martins et al., 2010; Paalvast, 2015; Perkol-Finkel and Sella, 2016; Sella and Perkol-Finkel, 2015). Large-scale pre-fabricated habitat units designed specifically for ecological engineering have also been trialled. These aim to incorporate a number of different biodiversity enhancement features and may also perform a semi-structural function in developments. Notable examples include built-in (Perkol-Finkel and Sella, 2016) or retro-fitted (Browne and Chapman, 2014) rock pool units, BIOBLOCKS and similar breakwater units (Firth et al., 2014; Sella and Perkol-Finkel, 2015) and Reef Balls^{TM} (Harris, 2003; Reef Ball Foundation, 2016; Scyphers et al., 2015). Pre-fabricated ecological engineering units such as these may be the most effective and feasible means of building habitat complexity into marine developments at an ecologically-meaningful scale (i.e. to deliver tangible biodiversity enhancement). They could conceivably be mass-produced at a reasonable cost and incorporated into developments either during construction or retrospectively (see Seattle Seawall Project; Goff, 2010).

In the design of these units, material choice is an important factor. Concrete has been widely favoured because of its ease of casting into heterogeneous three-dimensional shapes and surface topographies. The net ecological benefits of enhancement using concrete, however, may be compromised for a number of reasons. Firstly, concrete has an enormous carbon footprint. Cement production alone has been estimated to account for around 6–7% of global anthropogenic CO_2 emissions (Meyer, 2009). Secondly, concrete production often requires an aggregate component, which again carries an environmental footprint (Flower and Sanjayan, 2007; Marinković et al., 2010), especially when sourced from the marine environment (Newell et al., 1998). Thirdly, high surface alkalinity (pH 12–13) and leaching of metals (McManus et al., this issue; Müllauer et al., 2015) can impair settlement of marine organisms, resulting in communities dominated by a few alkotolerant taxa such as barnacles (Dooley et al., 1999; Guilbeau et al., 2003). As such, communities that establish on concrete marine structures tend to differ from those found in natural habitats (Andersson et al., 2009; Glasby et al., 2007; Glasby and Connell, 1999; but see also Connell, 2000; Knott et al., 2004). Yet if these issues can be addressed, concrete holds huge potential for use in ecological engineering products.

So-called 'green' or 'eco' concretes have been developed and utilised in construction and civil engineering projects previously (Meyer, 2009; Perkol-Finkel and Sella, 2014, 2016; Sella and Perkol-Finkel, 2015). There is an extensive body of literature illustrating how the environmental footprint of concrete can be reduced through partial replacement of Portland cement (the primary source of CO_2 emissions in concrete production) and aggregates with: pozzolanic industry by-products such as fly-ash, silica fume and ground granulated blast-furnace slag (GGBS) (Malhotra and Mehta, 1996; Meyer, 2009); waste materials such as shells, ceramic and end-of-life concrete (Cuadrado et al., 2015; Huang et al., 2004; Kuo et al., 2013; Marinković et al., 2010; Sekar et al., 2011; Yang et al., 2010, 2005); and natural fibres such as hemp and vegetable fibres (Awwad et al., 2012; Kidalova et al., 2012; Li et al., 2006; Pacheco-Torgal and Jalali, 2010; Pandey et al., 2010; Sedan et al., 2008). Pozzolanic industry by-products and other waste materials are often available at zero cost, but their rate of production exceeds their re-use. Hence, they are often disposed of in landfill or by incineration, at an economic and environmental cost (Cheerarot and Jaturapitakkul, 2004; Fry, 2012; Sekar et al., 2011). Pozzolans are capable of producing more chemically-resistant end-product concretes with reduced permeability and greater compressive strengths (Malhotra and Mehta, 1996; Meyer, 2009; Oner and Akyuz, 2007). They are, therefore, regarded as particularly suitable for applications in marine environments (Seleem et al., 2010). Natural fibres are a cheap and renewable resource with the capacity to sequester, rather than emit, carbon (Meyer, 2009). Furthermore, reinforcement with natural fibres – in particular hemp fibres – has been shown to increase the flexural strength of concrete materials (Awwad et al., 2012; Li et al., 2006; Merta and Tschegg, 2013; Sedan et al., 2008).

In some cases, such 'green' concretes have been employed in marine ecological engineering projects, with the aim of enhancing material properties for biodiversity (i.e. beyond considerations of the environmental footprint of production). The addition of pozzolans can reduce the surface pH of concretes (Fernández Bertos et al., 2004; Guilbeau et al., 2003; Park and Tia, 2004), potentially creating more favourable surfaces for colonisation by marine life (e.g. Nandakumar et al., 2003). Thus, Reef Balls^{TM} cast from concrete with microsilica additives (Reef Ball Foundation, 2016) have been deployed in artificial reef projects (Harris, 2003; Scyphers et al., 2015). Similarly, Econcrete^{TM} admixtures with different mixes of pozzolans have been used to make "ecologically active" concrete for both intertidal and subtidal coastal infrastructure developments (Perkol-Finkel and Sella, 2016, 2014; Sella and Perkol-Finkel, 2015). Waste mollusc shell material has also been incorporated into concrete marine structures to create textured surfaces and encourage gregarious settlement (Collins et al., 2015; Cuadrado et al., 2015; Ortego, 2006). Natural fibres, however, whilst suitable for incorporation in both structural (i.e. fibre-reinforced concrete: Awwad et al., 2012; Li et al., 2006; Sedan et al., 2008) and non-structural (i.e. 'hempcrete': Elfordy et al., 2008; Stanwix and Sparrow, 2014) building materials terrestrially, are not generally considered suitable for use in concrete in aquatic environments. This is due to durability concerns relating to increased permeability, reduced chemical attack resistance, dimensional instability and degradation of natural fibres (e.g. see Pacheco-Torgal and Jalali, 2010; Sivaraja et al., 2010). Yet there is evidence to suggest that the inclusion of pozzolans such as GGBS in the concrete matrix can counter these durability issues and prevent or delay internal fibre degradation (Pacheco-Torgal and Jalali, 2010; Pandey et al., 2010; Seleem et al., 2010). Natural fibre reinforced concretes may, after all, hold

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