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ECOENG-4868; No. of Pages 13
ARTICLE IN PRESS
Ecological Engineering xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Ecological Engineering
journal homepage: www.elsevier.com/locate/ecoleng

Partial replacement of cement for waste aggregates in concrete coastal and marine infrastructure: A foundation for ecological enhancement?

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ARTICLE INFO

Article history:
Received 1 December 2016
Received in revised form 27 June 2017
Accepted 27 June 2017
Available online xxx

Keywords:
Marine
Concrete
Ecology
Biodiversity
Water quality
Elements

ABSTRACT

The effects of climate change and an expanding human population are driving the need for the expansion of coastal and marine infrastructure (CMI), the development of which is introducing hard substrate into the marine environment on a previously unseen scale. Whilst the majority of previous research has focussed on how physical features affect intertidal macrobiotic communities, this study considered the effects of differences in the chemical composition of concrete on subtidal biofilm and macrobiotic communities. Two commonly used cement replacements, pulverised fly ash (PFA) and ground granulated blast-furnace slag (GGBS), were used in a combination of proportions to assess how concrete tiles with differing surface chemistries affect development of early successional stages of marine biofouling communities. Controlled leaching experiments showed that although total metal leaching varied considerably between tile type, tiles containing GGBS resulted in statistically lower amounts of metal released compared with tiles containing PFA. Concrete treatment had no effect on the percentage cover or richness of diatoms, but there were significant increases in both over the duration of the experiment. Concrete treatments containing GGBS had a lower richness of native macro-fouling species compared to the control, but there was no significant difference in non-native species richness among treatments. Results suggest that different components can be used to alter the surface chemistry of concrete to further enhance the ecological value of CMI more than physical features can achieve alone.

1. Introduction

1.1. Expansion of coastal and marine infrastructure (CMI)

With the pressures of climate change and many of the world's population living on or near the coast (Small and Nicholls, 2003), there is growing demand for development of the marine and coastal environment (Nicholls and Kebede, 2012). Furthermore, with the introduction of artificial hard substrata into the marine environment on a large scale (*sensu* "ocean sprawl"), there is a pressing need to determine the effects that this is having on the biofouling communities that colonise them, their ecology and impacts on the wider marine environment. The recent surge of interest in the ecology of the built environment has yielded a wealth of research describing the impacts of these structures on the receiving environment (Dafforn et al., 2015; Bishop et al., 2017), the fundamental differences in both the structure and functioning of artificial habitats compared to their natural analogues (see Firth et al., 2016a for review) and changing attitudes of humans to hard artificial structures (Evans et al., 2017; Morris et al., 2016; Scyphers et al., 2015). There is a growing consensus that artificial structures are characterised by lower diversity and abundance of native species (Aguilera et al., 2014; Burt et al., 2009; Chapman, 2006; Firth et al., 2013) and are known to support high diversity and abundance of non-native and opportunistic species (e.g. Bulleri and Airoldi, 2005; Firth et al., 2011, 2015; Mineur et al., 2012).

The nature of the material used in CMI can influence the ecological attributes (e.g. biodiversity, community composition) of organisms that settle on it. This is largely due to variations in habitat heterogeneity at a range of spatial scales (Anderson and Underwood, 1994; Chapman and Underwood, 2011; Connell, 2000; Coombes et al., 2015; Firth et al., 2013; Harlin and Lindbergh, 1977; Moschella et al., 2005), but is also linked to chemical cues (Anderson, 1996; Neo et al., 2009) and even colour (Pomerat and Weiss, 1946; Satheesh and Wesley, 2010). Because artificial envi-

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http://dx.doi.org/10.1016/j.ecoleng.2017.06.062
0925-8574/

Please cite this article in press as: McManus, R.S., et al., Partial replacement of cement for waste aggregates in concrete coastal and marine infrastructure: A foundation for ecological enhancement? Ecol. Eng. (2017), http://dx.doi.org/10.1016/j.ecoleng.2017.06.062

Table 1
Comparison of the mean metal concentrations in (a) the individual concrete components and (b) in the four treatment types. (c) EQS = Environmental Quality Standard each metal. Values in bold represent those that are above EQS. * = Highest value for the comparison among either the individual components or among treatments. SD = Standard deviation.

(a)

		Concentration (mg/kg)										
		Cr	Ni	Cu	Zn	As	Mo	Cd	Ba	Hg	Tl	Pb
Cement	Mean	**41.6***	**17.9**	**65.5***	**45.9**	9.92	1.19	**0.31**	129	0.04	<0.01	**27.8**
	SD	0.6	1.94	1.62	0.62	10.54	0.11	0.05	0.009	1.52	n/a	0.0003
Granite	Mean	0.17	0.12	2.34	1.25	0.62	0.01	0.01	3.3	0.02	0.06	1.2
	SD	0.0007	0.0019	0.0782	0.0573	0.0198	0.0117	0.0017	0.0002	0.099	0.0006	0.0024
Sand	Mean	0.14	0.03	1.13	1.13	0.67	<0.01[e]	0.01	7.1	0.02	0.06	0.76
	SD	0.0064	0.0008	0.0538	0.0633	0.0412	n/a	0.0006	0.0011	0.2219	0.0005	0.0033
PFA	Mean	**32.1**	**47.7***	**39**	**50.6**	23.1*	3.92*	**0.33***	180	**0.08***	0.19*	**50.2***
	SD	0.3	0.3	0.38	1.53	0.65	0.13	0.11	0.008	5.51	0.0012	0.0049
GGBS	Mean	**26.5**	2.04	2.04	**147.5***	10.2	<0.01[5]	0.07	603*	0.01	0.01	**8.2**
	SD	0.27	1.56	0.5	2.99	5.63	n/a	0.009	0.009	9.61	0.003	0.001

(b)

		Concentration (mg/kg)										
		Cr	Ni	Cu	Zn	As	Mo	Cd	Ba	Hg	Ti	Pb
Control	Mean	**7.2***	3.1	**12.5***	**8.7**	2.2	0.21	0.06*	25.4	0.022	0.053	**5.5**
PFA	Mean	**6.8**	4.3*	**11.5**	**8.9**	2.7*	0.32*	0.06*	27.4	0.023*	0.059*	**6.4***
GGBS	Mean	**6.6**	2.5	**10**	**12.8**	2.2	0.16	0.05	44.4	0.02	0.051	**4.7**
Mixed	Mean	**6.2**	3.7	**8.9**	**12.9***	2.7	0.27	0.05	46.4*	0.022	0.057	**5.6**

(c)

		Cr	Ni	Cu	Zn	As	Mo	Cd	Ba	Hg	Ti	Pb
EQS[a]		0.6[b] (32)	8.6[d] (34)	3.76[b,c]	7.92	252	n/a	0.24	n/a	(0.07)[d]	n/a	1.3[d] (14)

[a] Environmental Quality Standard.
[b] WFD (2015).
[c] Assumes DOC < 1 mg/l.
[d] EU (2013).
[e] For the purpose of calculations < values converted to half the LOD. All EQS as annual averages unless in brackets denoting maximum admissible concentrations.

ronments generally have lower native species richness and are more likely to be dominated by opportunistic or non-native species, there are opportunities to enhance CMI for conservation purposes and ecosystem services (Chapman and Underwood, 2011; Dafforn et al., 2015; Firth et al., 2016a; Seaman, 2007). To date, the majority of research has focussed on the physical properties of artificial structures, but knowledge gaps exist of other factors that could be driving the differences between the ecology of natural and artificial marine environments; for instance, substrate surface chemistry (but see Nandakumar et al., 2003; Perkol-Finkel and Sella, 2015; Sella and Perkol-Finkel, 2015).

1.2. Replacing cement with waste aggregates in coastal and marine infrastructure

When hard substrata, artificial or otherwise, are introduced into the marine environment, biofilms (formed of benthic microalgae, bacteria and other micro-organisms embedded in a matrix of extracellular polymeric substances (EPS)) are the first colonisers. Previous research has shown that biofilm succession and species composition can be affected by fine-scale substratum roughness (Sweat and Johnson, 2013), environmental pollution (Sanz-Lazaro et al., 2015) and surface chemistry (Nandakumar et al., 2003). Marine biofilms are known to interact directly with macro-fouling organisms (Salta et al., 2013) and differences in biofilm community structure may influence their attachment (Ank et al., 2009).

Portland cement is the major construction material used globally in artificial structures, often making up over half of coastal and marine developments (Kampa and Laaser, 2009). Although biotic communities can and do colonise concrete substrates (e.g. Firth et al., 2016b; Griffin et al., 2010), concrete is considered a poor substrate material for biotic recruitment due to its high surface alkalinity (pH ~13) and the fact that it can contain toxic metals, which can interfere with larval settlement (Nandakumar et al., 2003), and affect the emergent community structure and its functioning (Perkol-Finkel and Sella, 2015; Sella and Perkol-Finkel, 2015). Typically, concrete has four main ingredients: coarse aggregate (e.g. gravel), fine aggregate (usually sand), cement and water; although its properties can be amended to improve strength or resistance to sulphate and chloride attack (Snelson and Kinuthia, 2010). This can be achieved by changing the types and proportions of ingredients, as well as by using additional ingredients such as silica fume, pulverised fly ash (PFA), ground granulated blast-furnace slag (GGBS), carbon fibres (Graham et al., 2013) and hemp fibres (Dennis et al. 2017). Not only do these materials change the physical properties of concrete, but they can also inherently change its chemical composition. Cement production is extremely energetically expensive, accounting for 8% of global CO_2 emissions (Achternbosch et al., 2011). There is therefore an incentive to use cement replacements, not only as it reduces the carbon footprint of the end product (concrete), but also uses waste products that may otherwise go to landfill (Bignozzi, 2011).

PFA is a waste product from burning coal, removed from flue gases by electrostatic precipitators. It is well reported that the addition of fly ash into cement mixes can greatly improve durability, resistance to sulphate attack and chloride penetration, and reduce the likelihood of leaching effects (e.g. Chalee et al., 2010; Thomas and Matthews, 2004). GGBS is a by-product of the steel industry made by grounding iron slag into a fine powder, which when used as a (partial) replacement for cement, can provide resistance to sulphate attack without any loss of durability or compressive strength (Pavia and Condren, 2008). The use of PFA and GGBS as replacements for cement in concrete is well established. GGBS can be used as a direct replacement for Portland cement, on a one-to-one basis by weight, with replacement levels of between 30% and 85% reported. Typically, 40–50% replacement is most common in order to maintain structural integrity. PFA replaces a certain percentage of Portland cement, usually between 6–35% according to