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Inconsistent bioreceptivity of three mortar mixes in subtidal sites

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ABSTRACT

Concrete is extensively used in coastal engineering and development which, in addition to its high carbon footprint, threatens intertidal habitats and ecosystems. Eco-engineering addresses this by designing habitat features into coastal infrastructure. The chemical bioreceptivity of cement has been shown to vary, but ordinary Portland cement is generally considered to be the least bioreceptive.

In this study, we compare two low carbon mortars (a natural, single source cement (VP), and an ordinary Portland cement/ ground granulated blast furnace slag blend (GGBS)) with an ordinary Portland cement-based control mix (OPC). The three mortars were made into smooth blocks which were secured to crates and deployed subtidally in two estuary sites on the south UK coast for 1 year. At 3-, 6- and 12-months intervals a crate was recovered from each site and species abundance, biomass and assemblage composition were determined.

After 12 months, the VP mortar was significantly more species rich than both the OPC control and GGBS mortar, and organisms were significantly more abundant (numeric counts only), though this varied by mortar and site. However, OPC controls showed significantly higher percentage cover of biota than both low carbon mixes in both harbours. Overall, the GGBS mortar showed the least bioreceptivity of all three mortars. It is evident that the primary chemical bioreceptivity of OPC, GGBS and VP is inconsistent between ecological metrics and study sites and that using lower carbon cements does not necessarily enhance colonisation. The primary chemical bioreceptivity of these mortars may therefore perform inconsistently and other intrinsic factors that impact bioreceptivity and primary succession, such as rugosity, should be prioritised when designing ecological enhancements. Sustainability of materials, such as opting for low carbon cements, should also be a priority.

1. Introduction

Concrete is a durable, cost-effective and versatile material which currently has no functional substitute for the construction of coastal infrastructure in the marine environment (Scrivener, 2014; Alexander and Nganga, 2016). Coastal infrastructure is now ubiquitous on global coastlines (Cencini, 1998; Davis et al., 2002; Chapman and Bulleri, 2003; Airoldi and Beck, 2007; Gittman et al., 2015), and Floerl et al. (2021) determined that coastal development has replaced half of natural coastline associated within 30 global urban centres across North America, the UK, Australia, and New Zealand. Concrete is the predominant material in the majority of coastal development and infrastructure (Bijen, 1996; Lukens and Selberg, 2004; Kosmatka et al., 2008). As coastal infrastructure proliferates (Dugan et al., 2011; Duarte et al., 2013; Duarte, 2014), so too does the presence of concrete in intertidal and subtidal ecosystems, threatening coastal ecosystems through coastal squeeze and habitat loss (Bugnot et al., 2021). The 'hardening' of soft-sediment shorelines can alter natural processes (Dugan et al., 2018) and benthic species diversity and community structure (Martin et al., 2005; Dugan et al., 2008; Hawkins, 2012; Hawkins et al., 2016; Heery et al., 2017; Critchley and Bishop, 2019).

The carbon footprint of concrete construction is also significant with the cement industry contributing ≥5–8% to global CO_2 emissions (Worrell et al., 2001; Meyer, 2009; Lenhe and Preston, 2018). Concrete is also considered an ecologically deficient analogue for natural hard substrate, such as rock (Connell and Glasby, 1999; Chapman, 2003; Moschella et al., 2005; Vaselli et al., 2008; Pister, 2009; Bulleri and Chapman, 2010). Epibiotic communities and population size associated with artificial structures differ to natural rocky shores (Connell, 2001; Chapman and Bulleri, 2003; Bulleri et al., 2005; Drakard et al., 2021; Baxter et al., 2023) and in many incidences have lower biodiversity (Bacchiocchi and Airoldi, 2003; Chapman and Bulleri, 2003; Bulleri and

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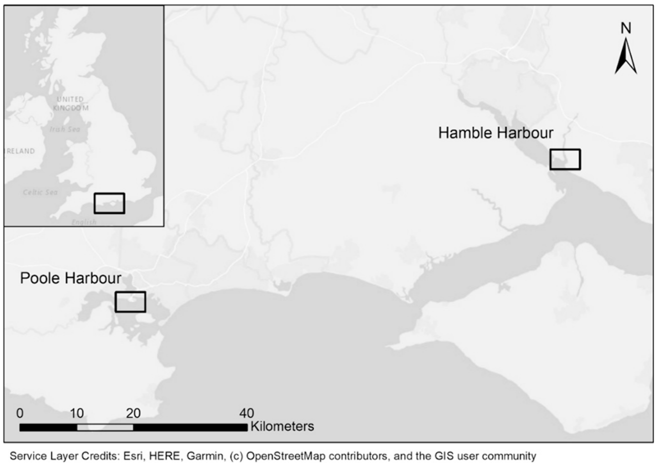

Fig. 1. The deployment site locations of Poole Harbour and Hamble Harbour on the south coast of the UK.

Chapman, 2004; Moschella et al., 2005; Bulleri and Chapman, 2010; Chapman, 2006; Underwood and Chapman, 2006; Vaselli et al., 2008; Firth et al., 2013; Hall, 2017) and a greater prevalence of non-native species (Glasby, 1999; Mineur et al., 2012). To address this ecological deficit in coastal infrastructure, ecological enhancement (also known as eco-engineering) is used to provide habitat for marine biota that was otherwise absent (Naylor et al., 2011; Naylor et al., 2017; Strain et al., 2018; O'Shaughnessy et al., 2020; Evans et al., 2021). By virtue of the associated biological communities (Evans et al., 2021), ecological enhancement may also provide ecosystem services (Chapman and Underwood, 2011; Strain et al., 2018), such as water filtration (Vozzo et al., 2021), improved fisheries (Chowdhury et al., 2021), and substrate bioprotection (Bone et al., 2022a).

Primary bioreceptivity is the propensity a material has for biological colonisation by virtue of its chemical composition and physical properties (Guillitte, 1995). Extensive investigations have been made into the primary bioreceptivity of cementitious materials (Sanmartín et al., 2021; Bone et al., 2022b), particularly in more recent years as coastal engineers and practitioners incorporate ecological designs into their coastal structures and seek to encourage biocolonisation. This often involves modifying the binder used (Perkol-Finkel and Sella, 2014; Huang et al., 2016; McManus et al., 2018; Morin et al., 2018; Hayek et al., 2020, 2021; Ly et al., 2021; Natanzi et al., 2021) to alter the surface chemistry, pH, albedo, hygroscopy and porosity in an attempt to increase bioreceptivity and attract marine organisms more readily than unmodified industry standard binder and are reviewed in Bone et al. (2022b). To address the growing demand for ecological enhancement, several companies now produce commercial off-the-shelf subtidal or intertidal units as standalone, integrated or retrofit options (Perkol-Finkel and Sella, 2015; Hall et al., 2018; Perkol-Finkel et al., 2018; Evans et al., 2019; Bone et al., 2022c; Sella et al., 2022; Bishop et al., 2022; Drakard et al., 2023; Hickling et al., 2023). Examples of these can be found on coastlines worldwide, but focussed predominantly in North America, Europe and Australasia (Strain et al., 2017). Often these units comprise part of a larger coastal defence structure (Tschirky et al., 2018; Salauddin et al., 2021), and so they must be multipurpose, being robust and durable enough to ensure a long service life and be habitable for the marine life they hope to host. Several studies have been conducted on the concrete matrices used in these commercial products, comparing them with ordinary Portland cement (OPC)-based controls, to ensure they meet industry standards and provide a comparatively optimised surface for biocolonisation (Perkol-Finkel and Sella, 2014; Hickling et al., 2022). Similar research has been conducted on concretes for use in artificial reef research pilots (Georges et al., 2021; Ly et al., 2021; Vivier et al., 2021). It is evident from these works that the materials used in

Table 1
Species list with average abundance per block. Standard error (±) given in brackets. Non-native taxa indicated with an asterisk (*). Taxa indicated with a dagger (†) denote those recorded as numeric counts, all other taxa were recorded as percentage cover.

	Poole Harbour			Hamble Harbour		
	OPC	GGBS	VP	OPC	GGBS	VP
Red Seaweeds						
Filamentous	0	0	0	1(0)	0	1(0)
Branching coralline	0	0	0	0	0	1(0)
Green Seaweeds						
Ulva sp.	1(0)	1(0)	1(0)	0	0	1(0)
Porifera						
Grantia compressa†	1.4 (0.2)	1(0)	2(0.3)	1.6 (0.2)	1.4 (0.2)	1.3 (0.1)
Halichondria panacea	1(0)	1(0)	1.3 (0.3)	11(4.7)	3.2 (0.8)	5.8 (2.9)
Sycon ciliatum†	0	0	0	0	1.7 (0.3)	1.5 (0.5)
Ascidians						
Ascidia mentula†	0	0	0	1.1 (0.1)	1(0)	1.5 (0.5)
Ascidiella aspersa†	2.24 (0.4)	2.3 (0.3)	3.2 (0.4)	1.9 (0.2)	2.3 (0.3)	2.4 (0.2)
Botrylloides leachii	1(0)	0	1(0)	1(0)	1.3 (0.3)	2(1)
Botrylloides violaceus	0	0	0	1(0)	0	2.3 (1.3)
Botryllus schlosseri	1(0)	1(0)	1(0)	4.6 (2.7)	1(0)	5.5 (3.0)
Ciona intestinalis†	1.2 (0.2)	1.1 (0.1)	1.3 (0.2)	0	1(0)	1.3 (0.3)
*Corella eumyota**†	1.4 (0.2)	1(0)	1.1 (0.1)	1(0)	1(0)	1.3 (0.2)
*Didemnum vexillum**	4.8 (2.5)	1.5 (0.4)	1.3 (0.3)	3.4 (2.4)	1.3 (0.3)	4.8 (2.4)
Molgula sp.†	0	0	0	1.1 (0.08)	1.6 (0.2)	1.6 (0.2)
*Styela clava**†	0	0	0	1(0)	1(0)	1(0)
Bryozoa						
Bugula sp.	0	0	0	3.1 (1.4)	7.7 (2.6)	5.5 (1.6)
Eucratea loricata	1.3 (0.1)	1(0)	1(0)	22(2.2)	6(1.2)	21.7 (2.5)
Membranipora membranacea	1(0)	2(0)	0	2.3 (1.3)	1(0)	1.5 (0.3)
*Watersipora subatra**	1(0)	1(0)	1(0)	3.1 (1.3)	1.5 (0.5)	1.5 (0.3)
Polychaetes						
*Ficopomatus enigmaticus**	0	0	0	11.2 (2.7)	5.9 (1.3)	4.2 (0.8)
Polychaete, muddy tubes	3.5 (1.3)	2.3 (0.4)	1.3 (0.2)	1.1 (0.08)	1.8 (0.7)	1.8 (0.5)
Spirobis spirobis	1(0)	1(0)	1(0)	0	1(0)	0
Spirobranchus triqueter	1(0)	1(0)	1.8 (0.2)	1(0)	2.3 (1.3)	1(0)
Crustacea						
*Amphibalanus amphitrite**	1(0)	0	0	1(0)	1(0)	1(0)
*Austrominius modestus**	1(0)	1(0)	1(0)	1.2 (0.2)	1.7 (0.3)	6.2 (1.7)
Semibalanus balanoides	1(0)	1(0)	1(0)	1(0)	1(0)	1(0)
Mollusca						
Mya arenaria†	0	0	0	0	1(0)	1(0)
Mytilus edulis†	1(0)	1(0)	1(0)	1(0)	1(0)	1(0)
Ostrea edulis†	1(0)	1(0)	1(0)	1(0)	1(0)	1(0)
Total	**20**	**18**	**18**	**24**	**26**	**29**

ecological enhancements should be justified from an engineering, environmental (low carbon) and ecological perspective, in addition to the structure's architecture. Further, this evidence is crucial to ensure continued incorporation of habitat features in coastal and marine construction and to maximise the economic value of commercially available ecological enhancements.

Table 2
Main test results for species richness, abundance, and biomass in Hamble Harbour. Bold values indicate significant result.

Factor	df	Deviance	Resid. Df	Resid. Dev	*P*	% Explained
Native and Non-Native Combined						
Species Richness						
Mortar Type	2	4.37	105	50.6	**<0.0001**	8.0
Survey Interval	2	22.38	103	28.2	**<0.0001**	40.7
Mortar * Interval	4	3.19	99	25.0	**<0.0001**	5.8
Abundance - Percentage Cover						
Mortar Type	2	301.51	105	685.5	**<0.0001**	30.6
Survey Interval	2	5.82	103	679.7	**<0.0001**	0.6
Mortar * Interval	4	122.17	99	557.6	**<0.0001**	12.4
Abundance - Counts						
Mortar Type	2	36.45	105	388.7	**<0.0001**	8.6
Survey Interval	2	73.11	103	315.6	**<0.0001**	17.2
Mortar * Interval	4	10.40	99	305.2	**<0.0001**	2.5
Biomass - Loss on Ignition						
Mortar Type	2	1.37	103	61.6	**<0.0001**	2.2
Survey Interval	2	44.43	101	17.1	**<0.0001**	70.6
Mortar * Interval	4	0.50	97	16.6	**<0.0001**	0.8
Non-Native Only						
Species Richness						
Mortar Type	2	0.2	103	6.1	**<0.0001**	3.0
Survey Interval	2	1.6	101	4.5	**<0.0001**	25.7
Mortar * Interval	4	0.1	97	4.3	**<0.0001**	2.3
Abundance - Percentage Cover						
Mortar Type	2	1.5	103	50.8	**<0.0001**	2.9
Survey Interval	2	15.8	101	35.0	**<0.0001**	30.1
Mortar * Interval	4	2.9	97	32.1	**<0.0001**	5.5
Abundance - Counts						
Mortar Type	2	2.7	103	76.7	0.2077	3.4
Survey Interval	2	2.3	101	74.3	0.2596	2.9
Mortar * Interval	4	13.5	97	60.9	**0.0036**	17.0

Table 3
Main test results for species richness, abundance, and biomass in Poole Harbour. Bold values indicate significant result.

Factor	df	Deviance	Resid. Df	Resid. Dev	*P*	% Explained
Native and Non-Native Combined						
Species Richness						
Mortar Type	2	0.5	104	34.9	0.3948	1.5
Survey Interval	2	3.6	102	31.3	**0.0019**	10.2
Mortar * Interval	4	3.1	98	28.2	**0.0317**	8.6
Abundance - Percentage Cover						
Mortar Type	2	13.6	104	242.4	**<0.0001**	5.3
Survey Interval	2	45.8	102	196.6	**<0.0001**	17.9
Mortar * Interval	4	18.1	98	178.5	**<0.0001**	7.1
Abundance - Counts						
Mortar Type	2	11.9	104	165.3	**<0.0001**	6.7
Survey Interval	2	47.7	102	117.6	**<0.0001**	26.9
Mortar * Interval	4	5.5	98	112.1	**<0.0001**	3.1
Biomass - Loss on Ignition						
Mortar Type	2	1.3	102	33.3	0.1369	3.7
Survey Interval	2	1.4	100	31.8	0.1104	4.1
Mortar * Interval	4	2.5	96	29.4	0.1087	7.1
Non-Native Only						
Species Richness						
Mortar Type	2	2.6	104	92.1	**<0.0001**	2.7
Survey Interval	2	12.9	102	79.2	**<0.0001**	13.6
Mortar * Interval	4	3.7	98	75.5	**<0.0001**	3.9
Abundance - Percentage Cover						
Mortar Type	2	0.6	104	90.8	0.6611	0.6
Survey Interval	2	5.5	102	85.3	**0.0193**	6.0
Mortar * Interval	4	3.4	98	81.9	0.2973	3.7
Abundance - Counts						
Mortar Type	2	3.4	104	67.0	**<0.0001**	4.8
Survey Interval	2	20.4	102	46.6	**<0.0001**	29.0
Mortar * Interval	4	1.3	98	45.3	**<0.0001**	1.9

Ordinary Portland cement is used in the construction of over half of artificial coastal structures globally (Lukens and Selberg, 2004; Perkol-Finkel and Sella, 2014) but has a high pH of 12–14 (Taylor, 1990; Manso et al., 2015). Consequently, initial biocolonisation of concretes with a high OPC content can be delayed, due to the prohibitively hostile surface conditions (Grant, 1982; Nandakumar et al., 2003). Carbonation reduces the surface pH to 9–10 (Taylor, 1990), permitting biological growth (John, 1988; Manso et al., 2015), but the speed of this process is variable depending on environmental conditions (Hayek et al., 2020). OPC has also performed poorly compared to other binders (Manso et al.,

Table 4
Individual PERMANOVA results for tests between mortar, interval and mortar*interval on species abundance data (number of permutations 9999).

Source	df	SS	MS	Pseudo-F	*P* (perm)
Hamble Harbour					
Mortar	2	8820.2	4410.1	5.4275	**0.0001**
Interval	2	73,020	36,510	44.933	**0.0001**
Mortar * Interval	4	8608.6	2152.2	2.6487	**0.0016**
Poole Harbour					
Mortar	2	5417.2	2708.6	3.2134	**0.0002**
Interval	2	30,898	15,449	18.328	**0.0001**
Mortar * Interval	4	7851.1	1962.8	2.3285	**0.0004**

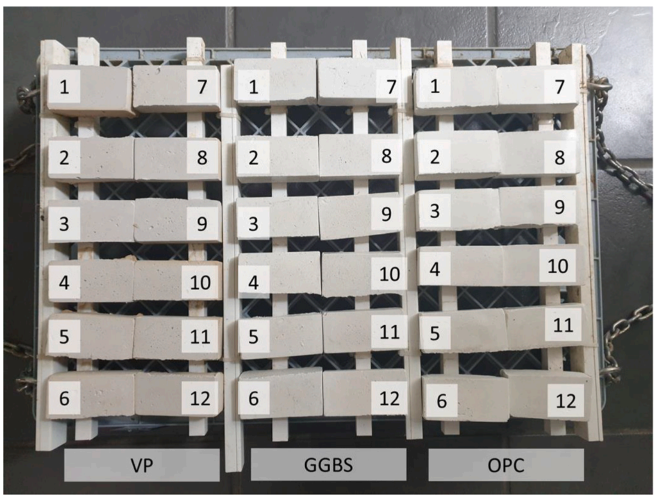

Fig. 2. An example of how each of the six crates were set up. Numbers denote mortar block replicate.

2014; Perkol-Finkel and Sella, 2014; Manso and Aguado, 2016) but not exclusively (McManus et al., 2018; Veeger et al., 2021). The production of OPC requires high temperatures (≥1500 °C), which requires significant energy input to achieve and is estimated to consume 2% of global primary energy consumption (Worrell et al., 2001). CO_2 is also produced during the clinker production, which involves the decomposition of limestone, and accounts for approximately half of the CO_2 emitted in the cement production industry (Worrell et al., 2001).

The carbon footprint of concrete may be reduced through the partial replacement of OPC by an alternative binder (Schneider et al., 2011) such as ground granulated blast furnace slag (GGBS), a recycled by-product of iron ore extraction (Neville, 2011). In concrete containing a blend of OPC and GGBS (CEMIII), the pH is lowered (Guilbeau et al., 2003; Park and Tia, 2004) and initial colonisation may improve (Hayek et al., 2020). GGBS may be used to replace OPC by up to 85% (British Standards Institute, 2011). GGBS may enhance bioreceptivity in the marine environment, but results can be context dependent. After 1 month of intertidal exposure on County Meath coast, Ireland, Natanzi et al. (2021) found that OPC/GGBS 50–50 mix concrete had greater microalgal biomass in a sheltered environment, but there was no difference between 100% OPC-based concrete and 50% OPC 50% GGBS concrete in the exposed environment. Following 7 weeks of subtidal deployment in Plymouth Sound, UK, McManus et al. (2018) found that the 100% OPC-based concrete tiles had the greatest native macrofouling species richness compared to tiles containing 24% GGBS. For GGBS to have a significant impact on bioreceptivity, McManus et al. (2018) recommended that GGBS should replace OPC by a significant amount, which Natanzi et al. (2021) suggested should be at least 50%.

Vicat Prompt cement is a natural (single source) binder that has been used in the construction and repair of historic masonry and maritime structures for >100 years thanks to its durability, strength, seawater resistance and appropriate aesthetic (Gosselin et al., 2012; Baxter et al., 2022). It is more environmentally beneficial with a lower carbon footprint than artificial (blended) Portland binders, as it is fired at a lower temperature (between 800 °C and 1200 °C) and is very similar in composition to lime (Vicat, 2003). It is used in the manufacture of commercially available ecological enhancements throughout Europe (personal communication Artecology 2020), such as Vertipools™ (Bone et al., 2022c; Drakard et al., 2023) and experimental enhancement tiles (MacArthur et al., 2019).

It is therefore prudent to determine how lower carbon cements may impact bioreceptivity of cement-based materials for subtidal sessile biota and compare with OPC, given the increasing use of lower carbon cements in commercial ecological enhancements. Additionally, there is a paucity of field experiments quantifying in situ biocolonisation of concrete mixes, particularly in the subtidal environment and for longer than a few (>3) months. In this context, it was necessary to test and compare cements known to be used in coastal engineering and ecological enhancements in a field setting subject to natural environmental conditions. Further, this allows primary colonisation and succession to occur naturally over the course of a year, incorporating multiple seasons and larval dispersals. We aimed to determine how bioreceptive to marine colonisation lower-carbon cements Vicat Prompt and ground granulated blast furnace slag were compared to a control cement (OPC) and how this changed over time with the following hypothesis:

The lower-carbon mortar blocks will be more bioreceptive than the OPC control mortar blocks after 12 months.

2. Method and materials

2.1. Mortars

Two low carbon mortars (Mortar 1 'GGBS' - CEM III/B cement, 60% ground granulated blast furnace slag by Ecocem Ireland Ltd., 40% ordinary Portlant cement; mortar 2 'VP' - a natural Roman binder, brand name Vicat Prompt) were trialled alongside a control mortar comprised of 100% ordinary Portland cement ('OPC' - CEM I 52.5R cement, brand name Blue Circle Snowcrete).

The mortar mixes comprised of binder at a 1:1 weight ratio with silica sharp sand (0–4 mm, sourced from Travis Perkins PLC.), and 1:2½ cement to water weight ratio. A retarder was added to the VP mortar according to manufacturer guidance to increase the setting time enough to pour the mixture into the moulds. The mortar mixes were hand-mixed and poured into silicone moulds to aid release of the cast blocks and avoid use of releasing agent. The silicone moulds produced mortar blocks with the dimensions 20 × 40 × 80 mm. Sixty replicate blocks were produced for each mix and cured in an indoor environment for a minimum of 14 days as recommended for each cement. Once cured, twelve replicates of each blend were fixed to a plastic crate, elevated and separated by 10 mm width plastic trunking (Fig. 2) to permit adequate water flow around each block and avoid biotic contamination with its neighbour (sensu Ly et al., 2021). Each block had a "textured" side from the unfinished, exposed mortar following pouring, with all other sides smooth from their contact with the silicon moulds. To prevent surface texture from confounding the results, the "textured" side was placed face down on the crate using 3 mm cable ties and this face was not included in data collection.

A total of six crates were set up with three crates deployed at each of the two study sites in June 2021; Poole Harbour, Dorset, UK (50.708745, −1.9863721, What3Words rungs.safely.range) and Hamble Harbour (50.852506, −1.3079996, What3Words bought.haggis.desiring), Hampshire, UK (Fig. 1). Poole Harbour is a microtidal estuary with a double high tide, where for ~16 h a day the water is above mean tide level (Humphreys, 2005). Salinity ranges between 26.3 ppt to 34.5 ppt in this area of the harbour (Humphreys, 2005) with an average water temperature of 16 °C. Hamble Harbour is a highly modified, muddy estuary very popular for sailing with over 3000 moorings. It is sheltered

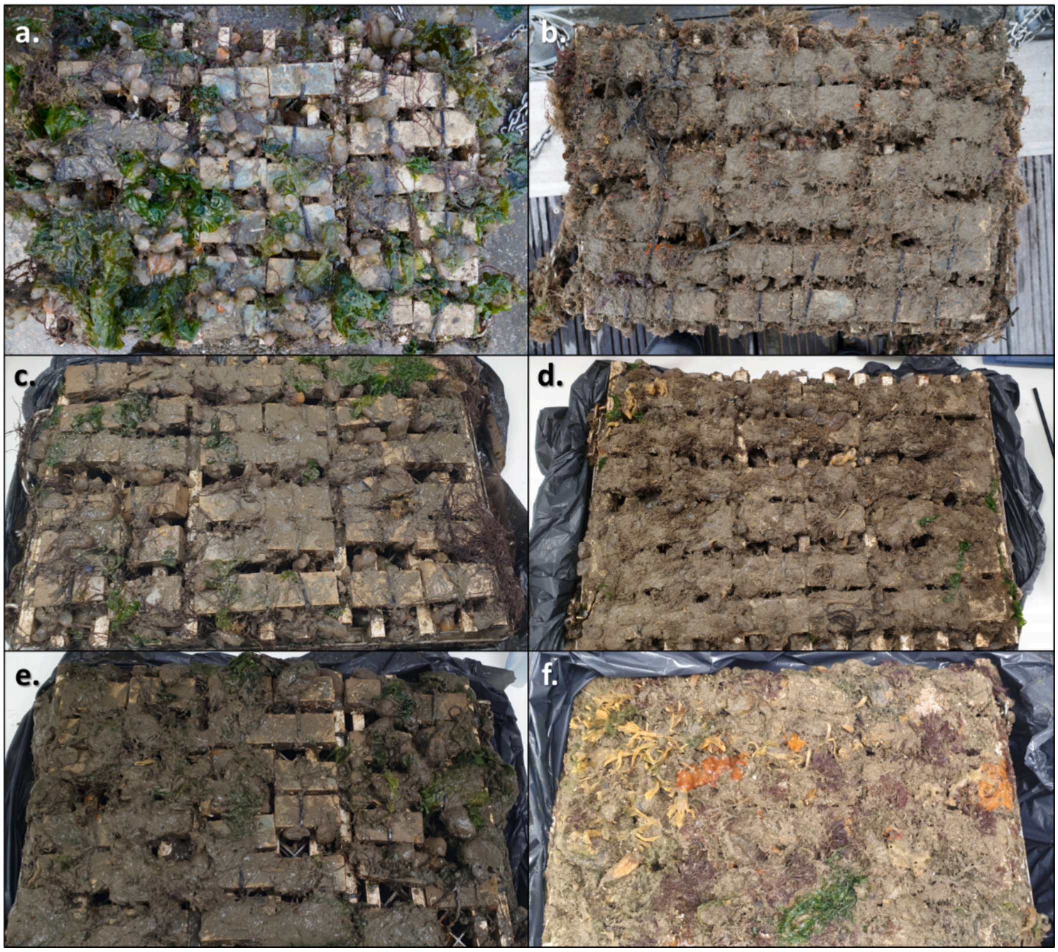

Fig. 3. The colonisation of the crates in Poole Harbour (left column) and Hamble Harbour (right column) at 3 months (a, b), 6 months (c, d) and 12 months (e, f). Note that these photographs were taken prior to rinsing the blocks of sediment and debris.

and protected from prevailing south-westerly winds by the Isle of Wight and its location within Southampton Water. Salinity rarely drops below 30 ppt and average water temperature is around 16 °C. For both study sites, nearby intertidal habitats are primarily soft-sediments and those provided by artificial structures, such as seawalls. Crate deployment was within highly modified areas of both harbours. Any references to seasons hereafter refer to boreal seasons.

The crates were deployed subtidally, suspended at least 1 m from the surface and seabed (sensu Ly et al., 2021). Both harbours are sheltered, muddy estuaries with crates suspended from either a jetty (Poole Harbour) or a pontoon (Hamble Harbour) with permission from harbour authorities and asset owners. A short video briefly showing block production and crate deployment may be viewed here (https://www.youtube.com/shorts/UnsPqyXc-Ko).

2.2. Surveying

Colonising biota was assessed following the collection of one crate from each site at 3-, 6- and 12-month intervals and transported to the lab the same day (24 replicates of each mortar mix). Blocks were gently rinsed by potable water to remove sediment and debris. High resolution photographs were taken of each block side (Sony A7R3 CDC camera, Sony FE 24-70 mm zoom lens), except the ends and "textured" surface face. The percentage cover and numeric counts of organisms was visually estimated on these same block sides to identified to species level wherever possible using appropriate taxonomic keys, while biota from the block ends and textured face was discounted. Table 3 denotes which taxa were recorded as percentage cover and numeric counts. Sessile organisms were gently scraped off the block surfaces using a spatula (sensu Pappalardo et al., 2018). To determine biomass, organisms removed from each block were weighed when wet, dried in an oven at 100 °C for 24 h, or until a constant weight was achieved, and then dried in a chamber furnace at 500 °C for 12 h to obtain ash free dry weight (g) (Luczak et al., 1997; Heiri et al., 2001).

2.3. Data analysis

Data from the study sites were analysed separately. To test for statistically significant differences in abundance, species richness, and biomass between the mortar formulas over time within each site, generalised linear models (GLM) were run in R Studio (Version 1.2.1335) with mortar (OPC, GGBS and VP) and interval (3-, 6-, and 12-months) as fixed factors. Assumptions of statistical tests were verified by examination of residuals against fitted model plots, as per Zuur et al. (2009). Data were tested for normality with Shapiro Wilkes test and were transformed (log+1) if significant or where heteroskedasticity was identified. A Levene's test was used identify unequal variances. For abundance (count and percentage cover), species richness, and biomass, Poisson distribution was used on data with equal variances and Quasi-Poisson distribution was used when the data were over dispersed (Crawley, 2012). Pairwise tests were run using the "emmeans" package (Lenth, 2021). This was repeated for non-native species richness, percentage cover and numeric counts.

As the mortar samples were not randomised on the crates and kept in their mortar mix groups, a three-way ANOVA using a GLM with Quasi-Poisson distribution was run to determine if there were edge effects,

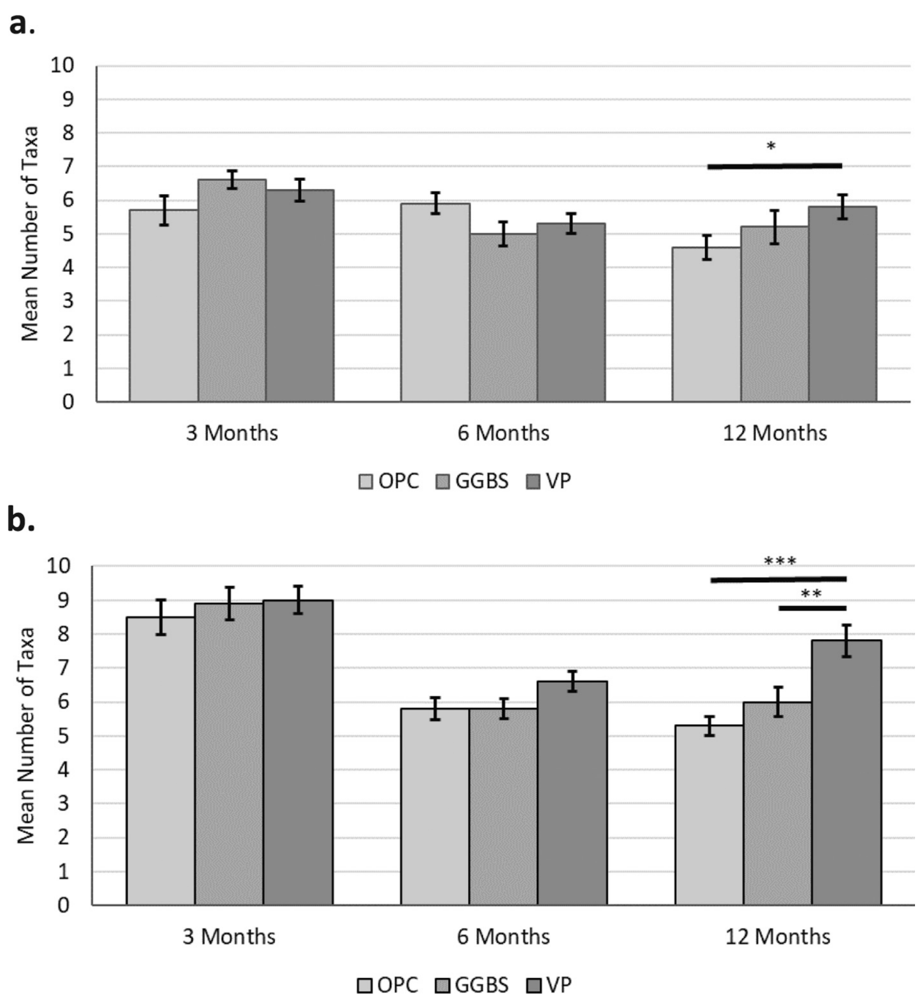

Fig. 4. The mean number of taxa identified on the mortar blocks (OPC – ordinary Portland cement, GGBS – ground granulated blast furnace slag, VP – Vicat Prompt) at 3, 6 and 12 months in Poole Harbour (a) and Hamble Harbour (b). Statistically significant differences indicated by * (<0.05), ** (<0.01) and *** (<0.001). Error bars show standard error.

with the factors 'location' ('interior' for mortar blocks in the middle of the crate and 'exterior' for mortar blocks on the edge of the crate), 'mortar' and 'interval' tested against all dependent variables.

Plymouth Routines in Multivariate Ecological Research (Primer-e v.7) was used to perform individual PERMANOVAs to test for differences in sessile assemblage structure between mortar, interval and interactions between mortar and interval using species abundance data (Anderson, 2005). The data were square root transformed prior to use, to avoid the weighting of common species over rare. A Bray–Curtis resemblance matrix was used with 9999 permutations and PERMANOVA run with unrestricted permutation of raw data. Significant results were followed by post hoc tests to determine which mortars at which interval were significantly different. Multidimensional scaling (MDS) plots were used to visually demonstrate assemblage similarity between mortars at each interval. To test for similarity between mortar assemblages, SIMPER analyses were run.

3. Results

It was determined that there were no discernible edge effects arising from the experimental design. Mortar block location on the crate was responsible for 0.2% to 1.1% of explained variance for Hamble Harbour dependent variables. For Poole Harbour, mortar block location was responsible for 0.004% to 0.9% of explained variance, except for count abundance, where mortar block location explained 7.4%, mortar 9%, and interval 18%.

The biota colonising the mortar blocks were typical of shallow subtidal communities (Fig. 3), including colonial and solitary sea squirts, barnacles and bryozoans (Table 1). It should be noted that the plastic crates, metal chains and plastic cable ties used in the experimental set up were also significantly fouled at the end of the study period. The undersides of the crates were entirely covered in solitary sea squirts, with the crate sides dominated by similar communities as the blocks though this was not formally quantified. Crabs and small benthic fish were often found in the interstices of the plastic crate. Seven non-native species were recorded in low abundances, with all 7 recorded in Hamble Harbour and 5 recorded in Poole Harbour.

3.1. Species richness

An overall total of twenty and thirty species were recorded over the 12 months on all mortars in Poole Harbour and Hamble Harbour respectively. The highest overall total on a single mortar mix over 12 months in Poole Harbour was 20 species on OPC, and 18 species on both GGBS and VP. In Hamble Harbour, each mortar mix yielded 29, 24, and 26 species on VP, OPC and GGBS respectively over the course of 12 months.

Main tests showed significant interactions for interval and between mortar * interval at Poole Harbour (Table 3), and for all factors at Hamble Harbour (Table 2). Survey interval accounted for the largest proportion (40.72% and 10.5% respectively) of the variance in species richness between factors at Hamble Harbour and Poole Harbour. At both

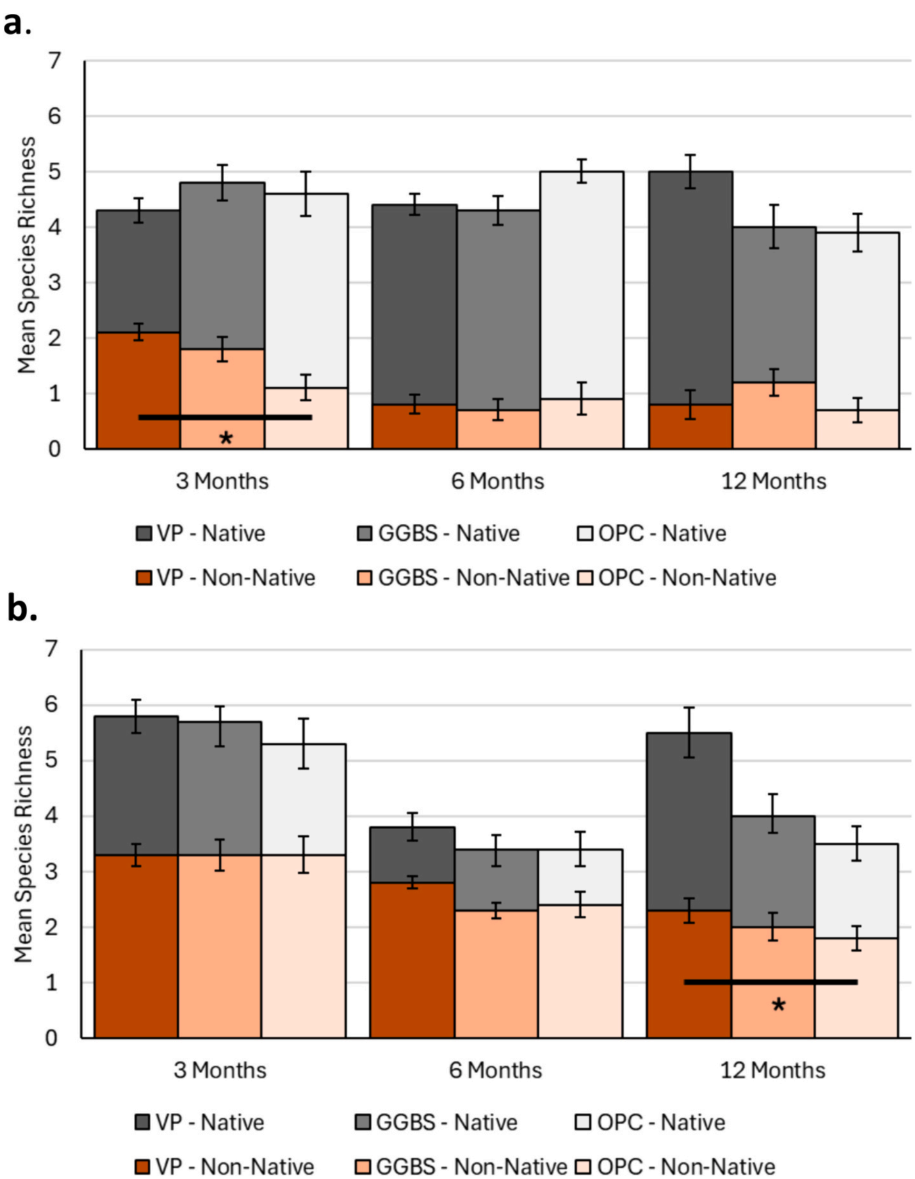

Fig. 5. The mean species richness of native and non-native taxa identified on the mortar blocks (OPC – ordinary Portland cement, GGBS – ground granulated blast furnace slag, VP – Vicat Prompt) at 3, 6 and 12 months in Poole Harbour (a) and Hamble Harbour (b). Statistically significant differences indicated by * (<0.05), ** (<0.01) and *** (<0.001) refer to non-native data only. Error bars show standard error. Non-native and native data are not stacked or cumulative.

sites, there were no significant differences between the mortar species richness at the 3- or 6-month intervals (Fig. 4). Hamble Harbour was slightly more species rich at 3 months than Poole Harbour, but otherwise species richness between the harbours was relatively similar. In both harbours, VP mortar was significantly more species rich than OPC after 12 months, and significantly more species rich than GGBS in Hamble Harbour only.

Of the species recorded in Poole Harbour, the mean number of non-native taxa made up a relatively small proportion of overall species richness. Hamble Harbour non-native species made up a larger proportion of overall species richness but was still outnumbered by native taxa. Survey interval accounted for the largest variance of non-native species richness (Tables 2 and 3) between factors at Poole Harbour (13.6%) and Hamble Harbour (25.7%). Non-native species richness was relatively similar between mortar mixes and broadly followed similar trends to native species richness over time. Apart from a weakly significant difference between VP and OPC at 3 months in Poole Harbour and again at 12 months in Hamble Harbour, there are no significant differences for non-native species richness between mortars at any other interval (Fig. 5).

3.2. Abundance

Unlike species richness, percentage cover trends of biota differ between harbours. In Poole Harbour, percentage cover on a single block does not exceed 32% at any one time and, on average, remains relatively low. Main tests show significant interactions for all factors, with survey interval accounting for the largest proportion (17.9%) of the variance in percentage cover (Table 3). There are no significant differences between the percentage cover of mortars at 3- and 6-months, but at 12-months percentage cover on OPC is significantly higher than both GGBS and VP (Fig. 6).

In Hamble Harbour, percentage cover is generally much higher, and varies between mortars at each survey interval. Main tests showed significant results for all factors, with mortar type accounting for the largest proportion (30.55%) of the variance in percentage cover (Table 2). At both 3- and 6-month intervals, percentage cover on OPC and VP was significantly higher than GGBS. At 12-months, percentage cover on OPC

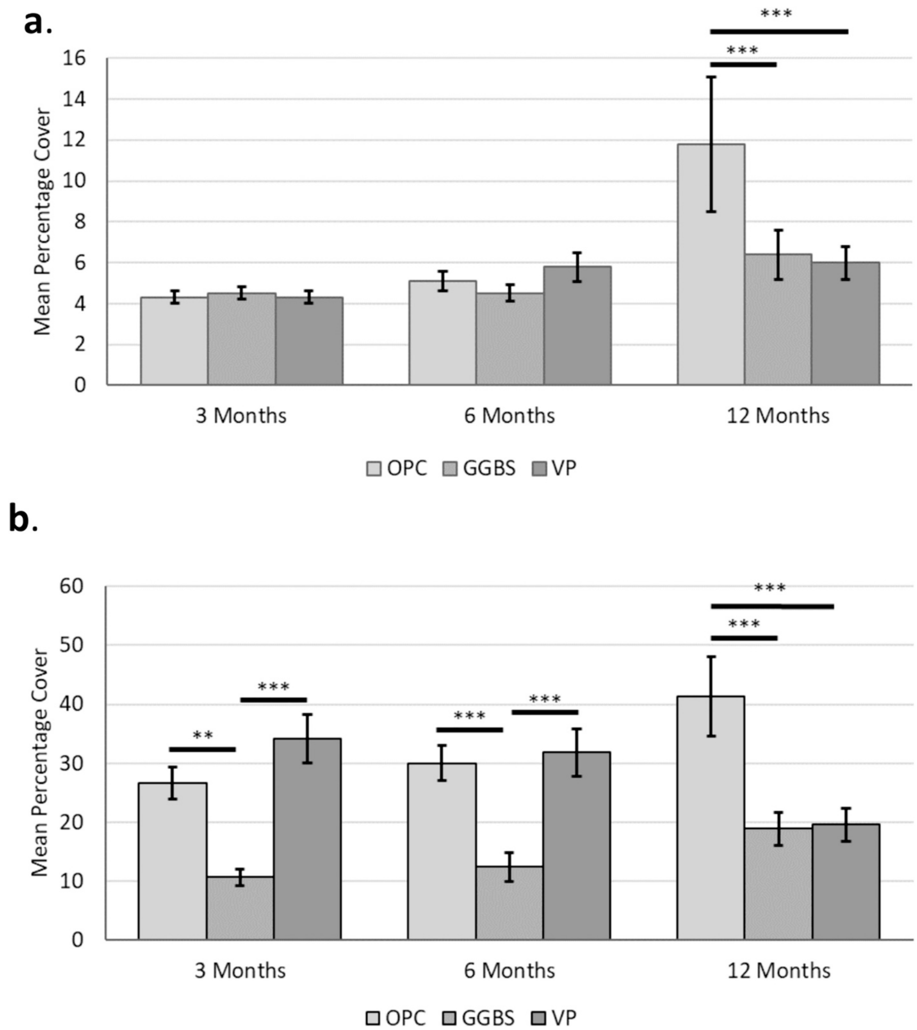

Fig. 6. The mean percentage cover on the mortar blocks (OPC – ordinary Portland cement, GGBS – ground granulated blast furnace slag, VP – Vicat Prompt) at 3, 6 and 12 months in Poole Harbour (a) and Hamble Harbour (b). Statistically significant differences indicated by * (<0.05), ** (<0.01) and *** (<0.001). Error bars show standard error.

significantly higher than both GGBS and VP. Despite the magnitude of percentage cover difference between both harbours, at 12-months the distribution of percentage cover between the mortars is very similar.

In Poole Harbour, numeric counts of abundance decrease over time for all mortar formulas and Poole Harbour was generally less abundant again than Hamble Harbour. Main tests showed significant results for all factors, with survey interval accounting for the largest proportion (26.9%) of the variance in numeric counts (Table 3). Numeric counts for OPC were significantly lower than both GGBS and VP at the 3-month interval. At the 6-month interval, there was no significant differences between the numeric counts of mortar formulas, but at the 12-month interval numeric counts on VP were significantly higher than GGBS (Fig. 7).

Main tests showed significant interactions for all factors Hamble Harbour (Table 2), with survey interval again accounting for the largest proportion (17.19%) of the variance. At 3- and 6-month intervals, numeric counts were relatively similar between mortars and intervals, but were significantly less on OPC than both GGBS and VP at the 12-month interval (Fig. 7).

Significant results for survey interval accounted for the largest variance of non-native percent cover (Tables 2 and 3) between factors at Poole Harbour (6.0%) and Hamble Harbour (30.1%) and for non-native numeric counts for Poole Harbour only (29.0%). For non-native numeric counts in Hamble Harbour, a significant relationship between mortar * interval accounted for largest variance (17.0%). There were no significant differences of non-native percentage cover between mortar mixes (Fig. 8) and a weakly significant difference between VP and GGBS at 3 months for non-native numeric counts in Poole Harbour. Conversely, non-native percentage cover was significantly different between VP and GGBS at 3 months, and between VP and OPC and GGBS and OPC at 12 months in Hamble Harbour. For non-native numeric counts, significant differences occurred between VP and both other types of mortar at 6 months only (Fig. 9). In both study sites, non-native counts remained very low and by 12 months in Poole Harbour were absent. However, at 12 months non-native percentage cover peaked in both sites, particularly on OPC. In Hamble Harbour, non-native percentage cover dwarfed native coverage on both GGBS and OPC. This increase was attributed to high coverage of the non-native calcareous tubeworm *Ficopomatus enigmaticus* in Hamble Harbour and *Didemnum vexillum* in Poole Harbour.

3.3. Biomass

For both harbours and all mortars, mean loss on ignition (LOI) does not exceed 0.8 g for 3- and 6-month intervals. Main tests for Poole Harbour showed no significant interactions for mortar, interval or mortar*interval (Table 3). In Poole Harbour, biomass on OPC blocks is significantly greater than GGBS at 12 months (Fig. 10). Biomass for

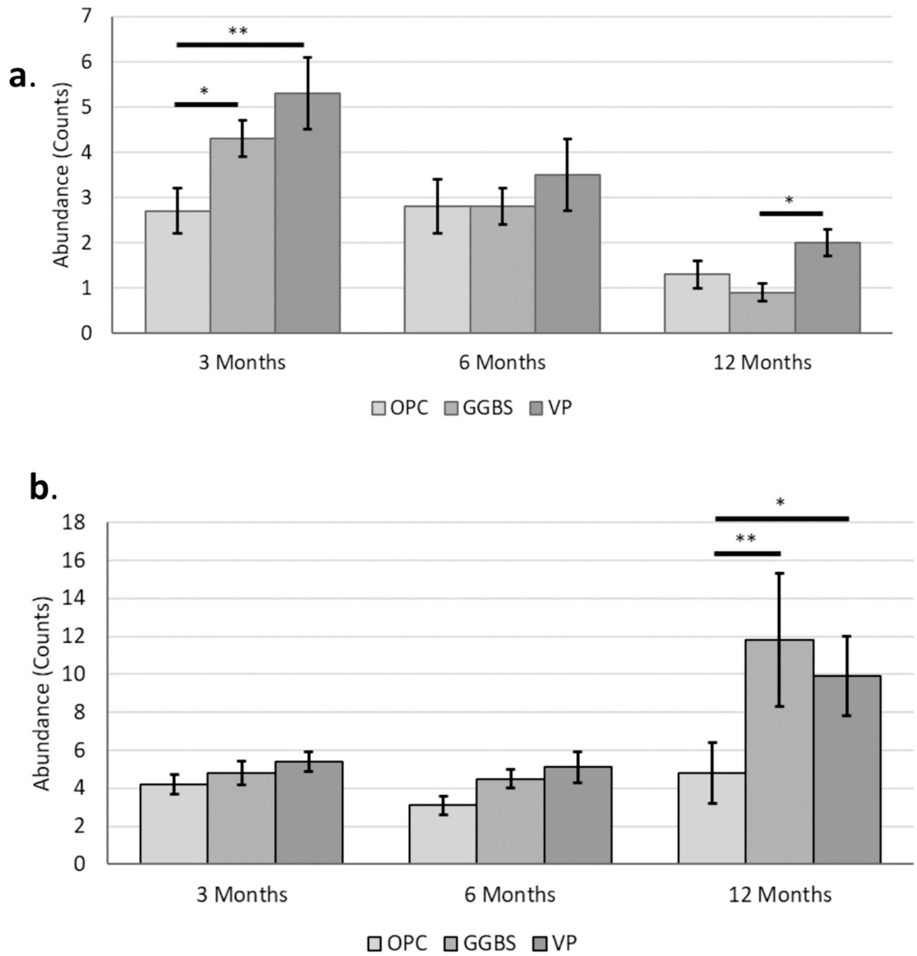

Fig. 7. The mean abundance (counts) on the mortar blocks (OPC – ordinary Portland cement, GGBS – ground granulated blast furnace slag, VP – Vicat Prompt) at 3, 6 and 12 months in Poole Harbour (a) and Hamble Harbour (b). Statistically significant differences indicated by * (<0.05), ** (<0.01) and *** (<0.001). Error bars show standard error.

GGBS and VP at 12 months remains similar to biomass recorded in previous intervals. In Hamble Harbour, main tests showed significant interactions for all factors (Table 2) with survey interval accounting for the largest proportion (70.59%) of the variance, though there were no significant differences between mortars at any survey interval (Fig. 10). Biomass for all mortars in Hamble Harbour at the 12-month interval is greater than previous survey intervals.

3.4. Assemblages

SIMPER analysis showed the average dissimilarity between the two harbours was 77%, with the average similarity within Poole Harbour 45% and the average similarity with Hamble Harbour 42%. The Poole Harbour assemblages were dominated by solitary ascidians and low abundances of other sessile taxa, but Hamble Harbour, although dominated by bryozoans, had comparatively greater abundances of other taxa, particularly calcareous tubeworms and barnacles.

At Hamble Harbour, average similarity within mortar blocks ranged from 41% to 45%, with the same three species (*F. enigmaticus, Eucratea loricata, Ascidiella aspersa*) contributing at least 60% of the assemblage similarity for each mortar. The average dissimilarity between mortar blocks ranged from 57% to 60%, with OPC & VP showing the least dissimilarity and OPC & GGBS showing the greatest dissimilarity. A PERMANOVA test indicated significant differences in assemblage structure between mortars, survey interval and mortar*interval (Table 4). Post hoc tests showed that at 3 months GGBS was significantly different to OPC and VP, at 6 months all the mortars were significantly different from each other, and at 12 months only OPC and VP were significantly different to each other (Table 5, Supplementary Material). This is reflected in multidimensional scaling plots for three-, six- and twelve-month intervals (Fig. 11).

At Poole Harbour, average similarity within mortar blocks ranged from 43% to 48%, with the same three species (*Spirobranchus triqueter, Ascidiella aspersa,* polychaete) contributing at least 70% of the assemblage similarity for each mortar. The average dissimilarity between mortar blocks ranged from 54% to 56%, with GGBS & VP showing the least dissimilarity and OPC & VP showing the greatest dissimilarity. A PERMANOVA test indicated significant differences in assemblage structure between mortars, survey interval and mortar*interval (Table 4). Post hoc tests (Table 6, Supplementary Material) showed that at 3 months all the mortars were significantly different from each other, at 6 months GGBS was significantly different to both OPC and VP, and at 12 months only OPC and VP were significantly different to each other (Fig. 11).

In both harbours, the mortar blocks follow broadly similar patterns in changes in assemblage structure; initially (3 to 6 months), the mortar blocks are significantly different from each other with this appearing more consistent with GGBS. However, at 12 months in both sites, GGBS is not significantly different to the other mortars, but OPC * VP are significantly different to each other.

4. Discussion

In this study, the bioreceptivity of two low carbon cements VP (Vicat

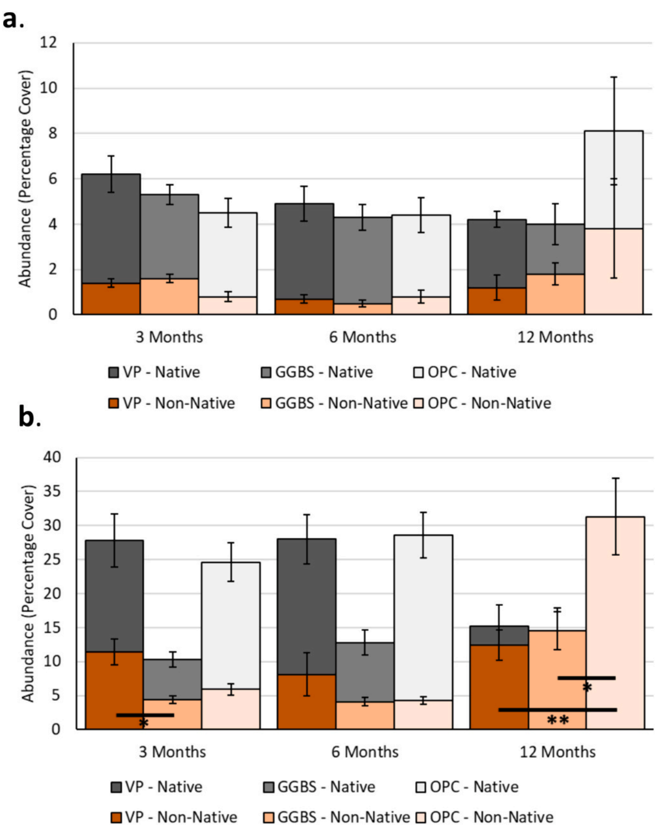

Fig. 8. The mean percentage cover of native and non-native taxa identified on the mortar blocks (OPC – ordinary Portland cement, GGBS – ground granulated blast furnace slag, VP – Vicat Prompt) at 3, 6 and 12 months in Poole Harbour (a) and Hamble Harbour (b). Statistically significant differences indicated by * (<0.05), ** (<0.01) and *** (<0.001) refer to non-native data only. Error bars show standard error. Non-native and native data are not stacked or cumulative.

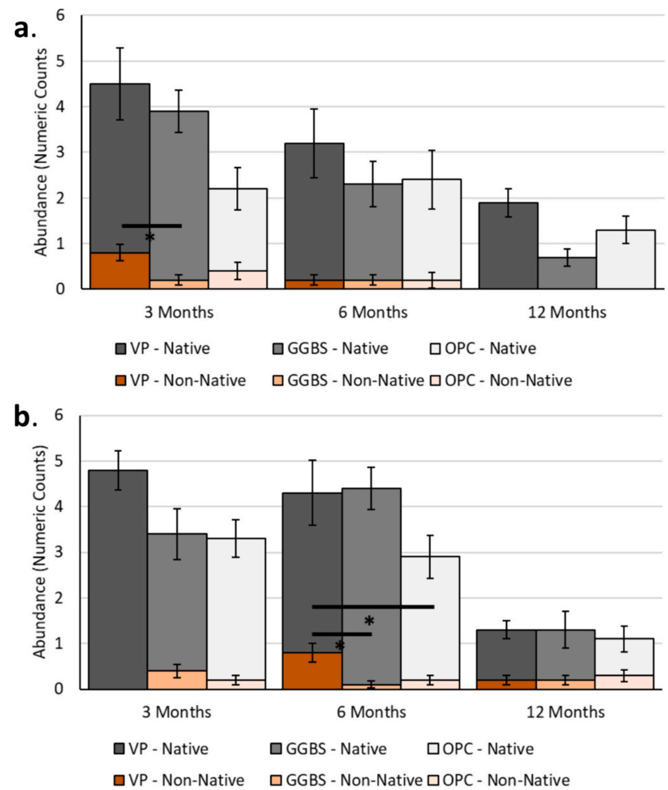

Fig. 9. The mean percentage cover of native and non-native taxa identified on the mortar blocks (OPC – ordinary Portland cement, GGBS – ground granulated blast furnace slag, VP – Vicat Prompt) at 3, 6 and 12 months in Poole Harbour (a) and Hamble Harbour (b). Statistically significant differences indicated by * (<0.05), ** (<0.01) and *** (<0.001) refer to non-native data only. Error bars show standard error. Bars are not stacked or cumulative.

Prompt) and GGBS (ground granulated blast furnace slag) were compared to OPC (ordinary Portland cement). With the exception of percentage cover at 3 and 6 month intervals in Hamble Harbour, and counts after 3 months in Poole Harbour, there are no significant differences between mortars at 3 and 6 months for species richness, abundance or biomass. After 12 months, VP is significantly more species rich than both OPC and GGBS in Hamble Harbour and OPC in Poole Harbour, and significantly more abundant (numeric counts only) than GGBS in Poole Harbour and OPC in Hamble Harbour. However, the control (OPC) mortar shows significantly higher percentage cover than GGBS and VP in both harbours, and higher biomass in both harbours than VP though this was not significant. After 12 months, the assemblage structure of VP blocks is significantly different to OPC.

These results suggest that after 12 months VP may offer some enhanced bioreceptivity compared to OPC and GGBS mortars, which supports this study's hypothesis, but this is not consistent between harbours or metrics. Equally, in circumstances where VP does not show enhanced bioreceptivity (biomass, percentage cover), the control mortar using OPC demonstrates greater bioreceptivity, which does not support this study's hypothesis. The bioreceptivity of VP after 12 months in this study is variable and therefore its use in concrete structures to enhance the primary chemical bioreceptivity may not perform as desired. It is recommended that its use is accompanied by other factors that are known to enhance bioreceptivity, such as varying the surface texture (MacArthur et al., 2019; Hayek et al., 2021; Bone et al., 2022a, 2022b, 2022c).

The differences in the data between 6 and 12 months suggests that succession may be ongoing. The colonisation and succession of the mortar blocks in this study may have been hindered by the timing of deployment (June 2021, summer), having missed peak settlement season for many sessile species, though this may not impact colonisation outcomes longer term (Naylor et al., 2023). Exogenous factors, such as larval supply (Anderson and Underwood, 1994; Strain et al., 2021), can impact the bioreceptivity of concrete (Bone et al., 2022a, 2022b, 2022c). This could explain some of the differences seen between 6 (December 2021, winter) and 12 months (June 2022, summer) that were not seen between 3 (September 2021, autumn) and 6 months, following springtime larval recruitment and growth. The different assemblage structures observed in the two harbours further supports this.

Although the substrate was smooth when deployed, initial colonisation occurred rapidly (≤1 month), which will influence subsequent succession (Sokolowski et al., 2017) through the provision of topographic complexity (Guillitte, 1995; Anderson and Underwood, 1994; Sanmartín et al., 2021) which may hinder or promote further settlement depending on the species (Sutherland, 1978; Osman and Whitlatch, 1995; Svensson et al., 2007; Andersson et al., 2009). It remains challenging to disentangle intrinsic (the substrate material) and extrinsic bioreceptive factors as once a substrate is covered by biofilms and sessile taxa (Sanmartín et al., 2021), the material properties are less likely to influence further settlement unless biofilm is abraded (Bone et al., 2022a, 2022b, 2022c). Further, it is important to note that fine sediment and debris settled on the mortar blocks, particularly in Poole Harbour, necessitating their washing following recovery. This may have inhibited contact with the experimental mortar substrates and influenced primary succession through smothering or scour of settling propagules (Schiel et al., 2006). The colour of the mortars, although reasonably similar (Fig. 2), may have influenced the primary colonisation (Sanmartín et al., 2020). It was observed when checking the experimental set up after 1 month that a green/ blue patina had appeared on the GGBS blocks as a

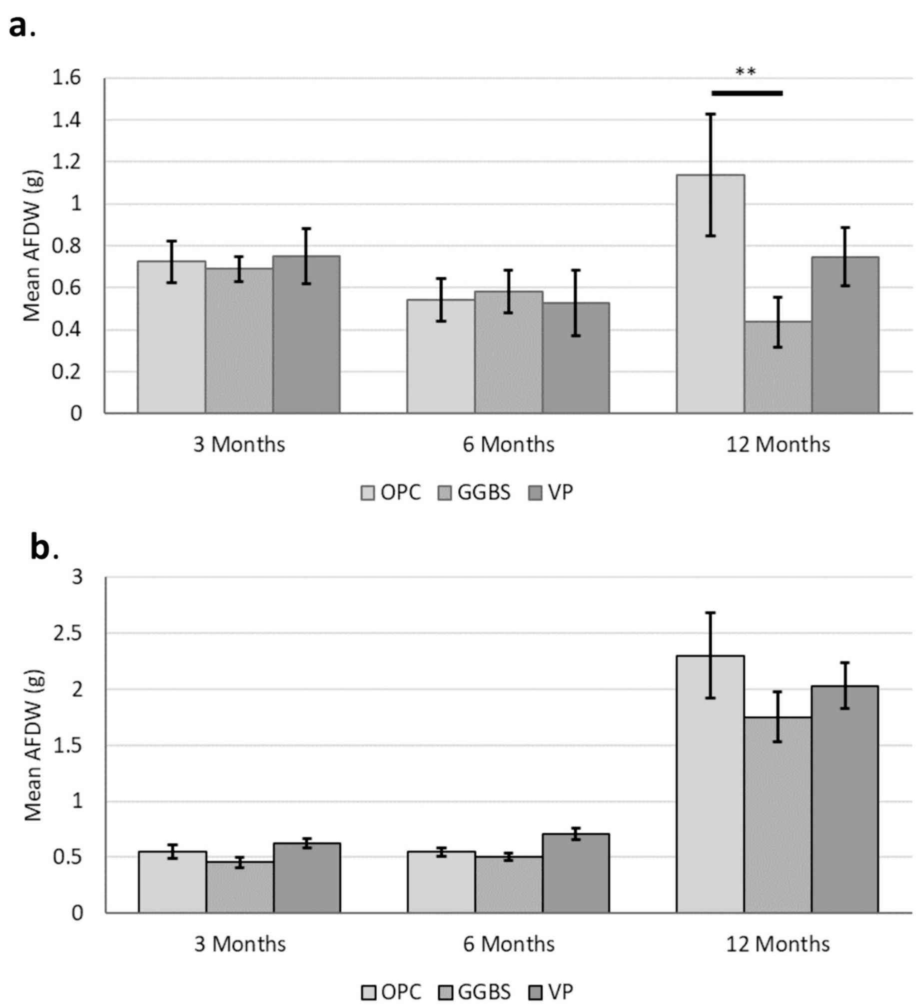

Fig. 10. The mean loss on ignition on the mortar blocks (OPC – ordinary Portland cement, GGBS – ground granulated blast furnace slag, VP – Vicat Prompt) at 3, 6 and 12 months in Poole Harbour (a) and Hamble Harbour (b). Statistically significant differences indicated by * (<0.05), ** (<0.01) and *** (<0.001). Error bars show standard error. Note difference in Y-axis scales between a) and b).

result of their iron content (Sioulas and Sanjayan, 2001).

Guillitte and Dreesen (1995) found the polystyrene rests that housed their test materials were also colonised by the photosynthetic microorganisms used in their experiment. They suggested that the colonising organisms were less dependent on the substrate bioreceptivity, but more ambient exogenous factors such as nutrient availability. In our study, the crates were heavily fouled by assemblages that appeared to be very similar to those on the mortar blocks. The set-up materials (plastic, stainless steel) had smooth surfaces akin to the mortar blocks, and the cm-scale holes, ledges and gaps were well utilised by solitary ascidians and small mobile fauna. This observation suggests that substrate material may be less important than overall structural complexity. This was apparent after 1 month when the crates were briefly pulled up for photographing before re-submerging. The majority of macro-invertebrate and algal colonisation at that time appeared to be where the mortar blocks and cable ties securing them touched. GGBS-based concrete, in the initial stages of colonisation, is reported to be superior to 100% OPC due to the lower alkalinity (Morin et al., 2018; Hayek et al., 2020; 2021) though these lab-based studies focussed on microorganisms and lasted no longer than 28 days. The results of this current study do not reflect these findings, with GGBS only showing significantly greater abundance (numeric counts) at 3 months in Poole Harbour and 12 months in Hamble Harbour. Otherwise, biomass, percentage cover and species richness are either similar or significantly less and vary between sites. As no data were collected prior to 3 months, it is not possible to say whether early bioreceptivity was greater on GGBS mortar blocks. Other studies have shown that concrete containing GGBS is not always bioreceptively superior to OPC (McManus et al., 2018). When in different environments in the field, GGBS and OPC have been shown to vary in their bioreceptive performance. Natanzi et al. (2021) found that OPC/GGBS concrete blend had greater biomass than OPC only concrete tiles on the sheltered side of a breakwater in Ireland, but there was no difference on the exposed side. Additionally, when surface texture is factored in it can dominate any effect of cement chemistry on bioreceptivity (Hayek et al. 2021).

Natural (single source) cements are not as readily available as artificial (blended) OPC, and Vicat produce the only prompt natural cement at an industrial scale (Baxter et al., 2022). In addition to its rapid setting, the limited source and relatively high market cost make it unsuitable for large scale application, particularly given the cost-driven barriers to ecological enhancements in coastal construction and engineering (Kleijn et al., 2019; Sella et al., 2022). However, VP's rapid setting makes it suitable in the application of smaller retrofit ecological enhancements. GGBS-based concrete is already often used in coastal and marine infrastructure (British Standards Institute, 2011) as it reduces the ingress of aggressive substances including water and chlorides (Smith, 2016) and increases resistance to sulphate attack and the alkali-silica reaction (Neville, 2011). Therefore, budget allocation should be prioritised toward producing micro- and macro-scale surface complexity, which may be achieved in a variety of ways (sensu Naylor et al., 2017; Strain et al.,

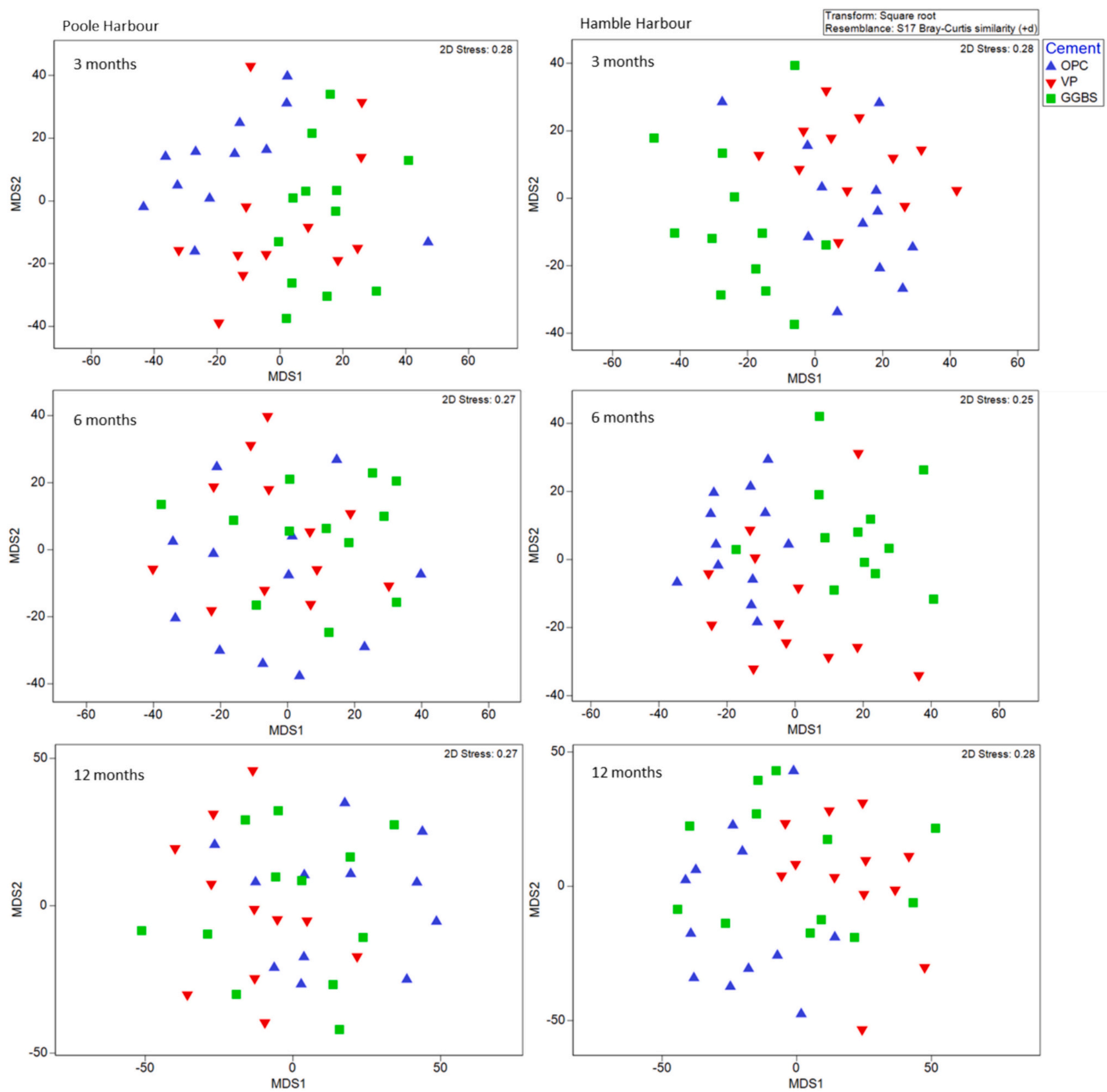

Fig. 11. Multidimensional scaling plots indicating Poole Harbour (left) and Hamble Harbour (right), with 3 months (top), 6 months (middle) and 12 months (bottom), using species abundance data. Blue triangles indicate ordinary Portland cement, red triangles indicate Vicat Prompt, and green squares indicate ground granulated blast furnace slag. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2018; O'Shaughnessy et al., 2019; Evans et al., 2021).

Further study would benefit from additional in situ experimental designs that take advantage of a greater number of study sites and environmental conditions. Additionally, the deployment set up could be improved by creating larger mortar samples that are randomly arranged and spaced further apart to improve independence and create a larger surface area for settlement. Future work would benefit from longer term monitoring on an annual basis for at least five years, particularly as climax communities on coastal structures can take between 5 and 20 years to form (Hawkins et al., 1983; Pinn et al., 2005; Coombes, 2011).

5. Conclusion

It is evident from our work that the primary chemical bioreceptivity of OPC, GGBS and VP is inconsistent between metrics and sites. Other intrinsic factors, such as surface roughness and macroscale structural complexity, and exogenous factors, such as local environmental conditions and larval supply, should be prioritised and considered carefully when designing bioreceptivity into ecological enhancements. The concrete used for ecological enhancements should meet minimum industry standards and prioritise sustainability through low carbon binders and recycled aggregates, and longevity and durability.

CRediT authorship contribution statement

Jessica R. Bone: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Alice E. Hall:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis. **Rick Stafford:**

Writing – review & editing, Supervision, Formal analysis. **Roger J.H. Herbert:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2024.107265.

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