Developments in the Built Environment 10 (2022) 100078

Contents lists available at ScienceDirect

Developments in the Built Environment

journal homepage: www.sciencedirect.com/journal/developments-in-the-built-environment

The intrinsic primary bioreceptivity of concrete in the coastal environment – A review

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ARTICLE INFO

Keywords:
Blue-green infrastructure
Eco-engineering
Coastal engineering
Greening the grey
Marine biodeterioration
Biofouling
Fouling

ABSTRACT

The proliferation of artificial concrete structures (ACSs) in the marine environment causes intertidal habitat loss and is a poor surrogate for natural rocky shores in terms of species richness, abundance, and community composition. As hard engineered coastlines increase, there is growing interest in how new concrete structures can facilitate improved habitat and biodiversity compared to existing concrete structures. Experiments that have substituted cement binder and aggregates in varying proportions and combinations have demonstrated that it is possible to enhance the primary bioreceptivity of concrete, either chemically or via microtopographical texture. This review synthesises key literature and identifies which concrete formulas prove most effective at enhancing bioreceptivity and those that have limited value, providing recommendations for coastal practitioners and for formulas that warrant further study. It is evident that the efficacy of chemical bioreceptivity of concrete is likely to be spatio-temporally limited (months) and enhancing surface roughness should be prioritised as a way to enhance colonisation. However, both chemical and physical methods require further investigation in within *in situ* marine settings for longer durations (>12 months).

1. Introduction

The construction of artificial coastal structures (ACSs, Fig. 1) and hardening of coastlines worldwide is proliferating (Dugan et al., 2011), a phenomenon referred to as 'ocean sprawl' (Duarte et al., 2013; Duarte 2014), leading to the loss of intertidal habitat (Bugnot et al., 2021) and modification of sediment-based ecosystems (Bishop et al., 2017; Dugan et al., 2018). Concrete comprises a large proportion of coastal structures (Bijen 1996; Kosmatka et al., 2008) as concrete is considered a versatile, durable and cost-effective material (Alexander and Nganga 2016) for which there is currently no viable alternative in the marine environment (Scrivener 2014). However, when compared to other natural intertidal rock substrata, ecologically, concrete is considered an insufficient surrogate (Connell and Glasby 1999; Chapman 2003; Moschella et al., 2005; Vaselli et al., 2008; Pister 2009; Bulleri and Chapman 2010). As coastal development continues to threaten coastal ecosystems on global scale (Bugnot et al., 2021), it is necessary to find ways to incorporate habitat within ACSs. Significant headway has been made in determining how this can be achieved with eco-engineering interventions, such as the introduction of water or mud retaining features, microhabitats such as cracks and crevices (Fig. 2), and sloping and horizontal surface orientations (Strain et al., 2018; O'Shaughnessy et al., 2020).

There have also been many studies that have focused on improving the intrinsic primary bioreceptivity of concrete as the substrate material (references herein). Primary bioreceptivity is defined as the aptitude a material possesses for colonisation of biological life by virtue of the material composition and physical properties (Guillitte 1995) and, since the inception of this term, most research has focussed on lab-based studies, usually from a cultural heritage perspective with terrestrial conditions and biota (Sanmartín et al., 2021a). However, there are several studies that have looked to enhance the bioreceptivity of concrete in intertidal and subtidal settings, or to specifically attract marine organisms, by varying the binders (Perkol-Finkel and Sella 2014; Huang et al., 2016; McManus et al., 2018; Morin et al., 2018; Hayek et al., 2020; Natanzi et al., 2021; Ly et al., 2021), aggregates (Neo et al., 2009; Bedoya et al., 2014; Dennis et al., 2018; Hanlon et al., 2018; Ly et al., 2021; Potet et al., 2021) and additives used to modify its chemistry, pH (Guilbeau et al., 2003; Mos et al., 2019; Hayek et al., 2020; Hsiung et al., 2020), and surface porosity (Morin et al., 2018) and roughness (Pinheiro and Silva 2004; Neo et al., 2009; Sweat and Johnson 2013; Bedoya et al., 2014; Coombes et al., 2015; Dennis et al., 2018; Strain et al., 2018; MacArthur et al., 2019; Sedano et al., 2020). There may be some coastal

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https://doi.org/10.1016/j.dibe.2022.100078
Received 2 March 2022; Received in revised form 20 April 2022; Accepted 21 April 2022
Available online 29 April 2022

settings or structures that are not appropriate for macroscale eco-engineering interventions, such as highly exposed shores, and so enhancing the bioreceptivity of the concrete material as a substrate for colonisation aims to maximise its ecological value in the absence of other habitat features. As the enhancement of ACSs gains traction in academic literature (Evans et al., 2022) and guidance (Naylor et al., 2017), in the coastal construction and engineering industry (Dale et al., 2011) and in legislation, it is necessary to clarify all options available to coastal practitioners to increase marine colonisation.

The purpose of this review is to synthesise and discuss how the bioreceptivity of concrete can be enhanced within the context of ACSs. It will focus on the superficial chemical and physical bioreceptivity of concrete, by virtue of its composition as per Guillitte's (1995) definition and stimulate conversation as to how coastal practitioners might enhance colonisation and biodiversity of concrete ACSs and underwater cultural heritage conservation by simply modifying the formula of concrete. Concrete formulas that prove to be of limited value or particularly effective will be identified and recommendations for further study will be made.

1.1. Scope of review

This review was conducted using online searches of terms pertaining to this field and databases including Web of Science, Scopus and Google Scholar was predominantly used to find relevant research, as well as suggested reading from these websites based on papers recently downloaded, and further references found therein. There are many terms synonymous with 'bioreceptivity', which were also searched to capture a broad range of published studies from a variety of journals and perspectives (ecological, engineering, materials science etc.). These synonymous terms included the following and, where applicable, were searched in both US and UK English and with hyphenated forms (i.e., 'bioreceptive' and 'bio-receptive'): bioreceptive, bioreceptivity, biological receptivity, biofouling, fouling, biocolonisation, biological colonisation. Studies examining bioreceptivity of concrete in the coastal zone in this review were predominantly conducted in the north-east Atlantic (50%), with the remaining studies being conducted in the north-west Atlantic, the north-west Pacific, the north Indian Ocean, the Mediterranean Sea, the Caribbean Sea and the Red Sea. No studies were conducted in the southern hemisphere, or on the continents of Africa, the Arctic or Antarctica.

It is important to note here the distinction between 'bioreceptive' concretes and 'eco-friendly/environmentally friendly' concretes as the latter does not necessarily predispose the former. 'Eco-friendly' concretes usually involve the incorporation of materials that are either recycled, obtained from sources that minimise harm to the environment,

Fig. 1. Examples of artificial coastal structures (ACSs). Top left, clockwise; a concrete seawall; a stone masonry seawall; a rock groyne; concrete dock. Images by Jessica R. Bone.

obtained from local sources and so reduce the carbon footprint associated with shipping and transport, or are produced in an energy efficient manner (Wang et al., 2021). These benefits do not necessarily relate to or enhance bioreceptivity, but this can co-occur, for example the incorporation of recycled oyster shell to increase concrete surface texture (references herein). Use of 'abundance' in this review refers to the number of individuals of a given species, 'richness' refers to the number of species, and 'diversity' refers to the variation of organisms within a given dataset, though the latter two definitions are often used interchangeably.

There is a paucity of literature that focuses on the surface roughness intrinsic on the concrete surface as a consequence of its composition and mixing. Many studies focussing on roughness to enhance bioreceptivity often fail to define what 'roughness' constitutes in terms of scale, and roughness may co-occur with other features at the centimetre (cm) scale. It is often implied that roughness is very fine scale (micrometers to millimetres), but this is not always confirmed. Therefore, it is necessary to attempt to define the parameters of surface roughness (Strain et al., 2018) for the purposes of this review. According to Guillitte's (1995) definition, the intrinsic physical bioreceptivity of concrete occurs on a microscale where it's superficial porosity and micro-texture, or roughness, occur as a result of the material composition (Guillitte and Dreesen 1995). As no quantitative definition is used consistently within the eco-engineering field, though roughness can be measured quantitatively with Roughness Average (Ra), literature has been assessed using qualitative definitions. Enhanced concrete studies that focus on 'crevices', 'pits', 'cracks', 'rockpools', or variations thereof, have not been included, in addition to textures at the >cm scale or described as 'macro-scale'. Following Sanmartín et al.'s (2021a) review of Guillitte (1995), the expansion and clarification of what constitutes primary bioreceptivity in built structures allows for the inclusion of many studies that manipulate the topographic heterogeneity of ACSs with the addition of pits, grooves, holes, cracks and crevices. However, reviewing the literature that reports on macroscale features warrants their own paper and is both beyond the scope of this review, and already well summarised in Strain et al. (2018) and O'Shaughnessy et al. (2020). This review will focus predominantly on superficial porosity and roughness as a consequence of the concrete or mortar composition. However, it has been supplemented by some key studies (e.g., Tran et al., 2013; Coombes et al., 2015; MacArthur et al., 2019) that have manually modified the surface roughness of wet concrete, to provide further context about what textural benefits might be achieved if a concrete mixture was appropriately modified. Research on the surface heterogeneity of concrete to enhance bioreceptivity in the marine environment is scarce, and so studies focussing on terrestrial biota and rock material, such as limestone, sandstone and granite, have also been included (Table 1). Some studies have used 'surface texture' synonymously with roughness, and these studies are included where they meet the criteria stated above.

2. Chemical bioreceptivity

There is some evidence that concrete is already more bioreceptive when compared to other materials and leaches chemo-attractive cues that encourages the settlement of some species (Anderson and Underwood 1994). For example, Anderson (1996) conducted lab and field tests that determined that calcium hydroxide leachate from cement enhanced recruitment of Sydney rock oysters (*Saccostrea glomerata (commercialis)* Gould, 1850). Several explanations as to the mechanism of this chemical cue were offered, including its indication of a potential site of high planktonic productivity and thus food resource, or its molecular role in triggering metamorphosis in larvae. Davis et al. (2017) found that, compared to High Density Polyethylene (HDPE) and granite, concrete was more bioreceptive to algal turf in mesocosm experiments, which may have been due to the dissolution of calcium from the

Fig. 2. Examples of coastal eco-engineering. Top left, clockwise: An artificial rockpool containing water (Marineff Project); a Vertipool containing mud (Bone et al., 2022); a 'letter box' crevice in a concrete seawall; a cubic void containing water in a concrete seawall; a concrete seawall with a 'rockface' textured surface created with a formliner. Images by Jessica R. Bone.

Table 1
Mechanisms affecting bioreceptivity of concrete in the coastal environment and potential application. The main findings of the different bioreceptive mechanisms are reviewed in this paper.

	Bioreceptive Mechanism	Main Conclusions	Advised Outcome	References
Chemical	Marine concrete	Calcium hydroxide leachate enhanced recruitment of Sydney rock oysters *Saccostrea glomerata* (Gould, 1850)	Further research required	Anderson (1996)
	Shell aggregate - Oyster	Increased mollusc abundance Other factors tested (surface complexity/orientation) showed greater impact	Use shell for textural benefits	Hanlon et al., (2018); Potet et al., (2021)
	Shell aggregate - Crushed whelk Hemp aggregate	Hemp unsuitable for aquatic application. Shell and hemp increased surface roughness which was not possible to disentangle from chemical influence and so chemo-attractant benefits unclear	Use shell for textural benefits	Dennis et al. (2018)
	Crushed crustose coralline algae-covered coral rubble (CCACR) aggregate	Settlement of target organism greatest on highest concentration of CCACR aggregate but no effect on recruitment after 42 days. When roughness was included in analysis the concentration of CCACR showed no significance.	Use for textural benefits	Neo et al. (2009)
	Non-biological recycled aggregate	Crushed ceramics were not compared to reference samples so value unclear Recycled glass had limited to no bioreceptive value compared to limestone or shell sand	No clear bioreceptive benefits but beneficial for use in ‘eco-friendly’ concretes	Bedoya et al., (2014); Ly et al., (2021)
	CEM I or ordinary Portland cement	High alkalinity when first cast leading to initial delays in colonisation	Substitute with bioreceptive binder where appropriate	Nandakumar et al. (2003)
	Reducing the percentage content of ordinary Portland cement and replacing with lower pH alternatives	Concretes with lower proportions of ordinary Portland cement had greater live cover	Use for lower pH benefits though likely temporally limited	Perkol-Finkel and Sella (2014)
	Carbonated concrete	Carbonated concrete colonised more rapidly and leads to an initial domination of algae. Also has a lower pH, though benefits are temporally limited, particularly in warming and acidifying oceans	Temporally limited value	Guilbeau et al., (2003); Mos et al., (2019); Hayek et al., (2020), 2021; Hsiung et al., (2020)
	CEM III or partial replacement of binder with ground granulated blast furnace slage	Percentage cover on CEM III was greater than CEM I concrete, though it was tested as a low percentage replacement for CEM I (24%)	Use for enhanced bioreceptivity at ≥50% GGBS content, though likely temporally limited	Huang et al., (2016); McManus et al., (2018); Morin et al., (2018); Hayek et al., (2020); Natanzi et al., (2021); Ly et al., (2021)
	CEM II or partial replacement of binder with pulverised fly ash	CEM II was found not to enhance colonisation, though it was tested as a low percentage replacement for CEM I (24%)	Further research required	McManus et al. (2018)
	Calcium aluminate cement, titanium dioxide additive	When compared to controls, calcium aluminate cement and concrete containing titanium dioxide were not as prone to biofouling due to biocidal properties of the metal content	Avoid use where possible	Dalod et al., (2014); Harilal et al., (2020)
Physical	Increasing porosity	Retains moisture, organic and inorganic particulate matter, and larvae.	Use for enhanced bioreceptivity	Morin et al. (2018)
	Increasing surface roughness	Greater surface roughness may increase surface area available for colonisation and facilitate	Use a variety of surface textures for enhanced bioreceptivity	Pinheiro and Silva (2004); Neo et al., (2009); Sweat and Johnson (2013);

(*continued on next page*)

Table 1 (*continued*)

	Bioreceptive Mechanism	Main Conclusions	Advised Outcome	References
		attachment. Percentage cover is often greater on rougher textures, though this is not always the case.		Bedoya et al., (2014); Coombes et al., (2015); Dennis et al., (2018); Strain et al., (2018); MacArthur et al., (2019); Sedano et al., (2020); Hayek et al., (2021); Vivier et al., (2021).
	Colour	Black acrylic stimulated greater growth compared to white but colour effects are likely to be temporally limited.	Further research required for coloured concrete	Swain et al., 2007; Dobretsov et al., (2013)
	Pre-existing algal spores in marine sourced aggregates	Marine aggregates are predominantly sourced from relict geological or fossil deposits and thus do not contain biological material that would 'kick-start' colonisation. Biological material is unlikely to survive the caustic environment of wet concrete.	Unlikely to impact bioreceptivity	Hughes et al. (2013)

concrete surface promoting growth. Dodds et al. (2022) found that compared to other artificial substrates, such as metal or plastic, concrete generally supports more species and in particular, more calcifying sessile invertebrates.

It is known that the chemical and mineralogical composition of a substrate can influence the preferential colonisation of some marine species (Bavestrello et al., 2000; Guidetti et al., 2004; Herbert and Hawkins 2006; Jones and Bennett 2017). Therefore, there is sufficient rationale for exploring how marine species might react to the chemistry of different concrete materials in the marine environment, by virtue of the choice of aggregate, binder and other additives.

2.1. Aggregate alternatives

An increasingly common experimental aggregate is shell (Richardson and Fuller 2013; Li et al., 2015; Nguyen et al., 2017; Varhen et al., 2017; Dahiru et al., 2018; Eziefula et al., 2018; Ruslan et al., 2021; Uddin et al., 2021; Han et al., 2022). In addition to utilising a waste by-product of the shellfish industry and potentially improving the affordability of concrete production, it is thought the use of crushed shell enhances surface roughness and provide chemical cues to induce settlement of mollusc larvae, and so enhance bioreceptivity of biogenic species such as oysters. Several taxonomic groups rely on conspecific chemical cues to settle in suitable habitat, such as barnacles (Browne and Zimmer 2001), sea urchins (Hay 2009) and oysters (Vasquez et al., 2013). Hanlon et al. (2018) replaced shale aggregate with ground non-native Pacific oyster (*Magallana gigas* Thunberg, 1793) shell and compared the colonisation to a standard concrete mix without oyster shell. Following 6-months subtidal deployment in Falmouth, UK, it was revealed that the replacement of shale with oyster shell did lead to some differences in the initial community structure but did not recruit *M. gigas,* despite deployment coinciding with seasonal recruitment. However, molluscs on the concrete tiles containing oyster shell were >35% more abundant than on concrete tiles with shale. Despite this, the inclusion of oyster shell had a limited impact on species richness and abundance compared to other factors tested (surface complexity, surface orientation). Hanlon et al. (2018) noted that the high alkalinity of the fresh cement in the tiles may have negated the effect of shell chemical cues. Additionally, native molluscs may not have been able to detect chemical cues from a non-native oyster and so the use of non-native shellfish by-products may be redundant for native heterospecifics. Dennis et al. (2018) compared the bioreceptive performance of concretes made with different proportions of crushed whelk shell or hemp fibres to a concrete control with 10 mm coarse aggregate. The experimental tiles were deployed on the coast of Wales, UK, for 12 months and percentage cover, species richness and biomass was determined. Initial biofilm colonisation measured *in situ* after approximately 2 months was greatest on hemp concrete but not significantly so. After 12 months, live cover was significantly greater on both shell and hemp concretes compared to the control concrete. Hemp concrete had higher species richness and significantly higher mobile species richness than both shell and control concrete. Despite hemp concrete demonstrating the greatest bioreceptivity, it was noted that further testing on its mechanical properties were required as its generally deemed unsuitable for aquatic application (Dennis et al., 2018 and references therein). It was also noted that both hemp and shell concretes had noticeably rougher textures and it is therefore not possible to disentangle the influence of fine-scale surface roughness from the concrete chemistry as drivers of colonisation. Additionally, replications of this study should consider collecting time series data to validate that the results obtained in Dennis et al. (2018) and demonstrate when the biodiversity and assemblage structures of the different concrete mixes become divergent.

Crustose coralline algae are known to provide chemical cues for the settlement of coral (Morse and Morse 1984; Morse et al., 1988; Morse et al., 1996), starfish (Johnson and Sutton 1994) and abalone (Roberts et al., 2010). It was unknown if it was chemo-attractive to the fluted giant clam (*Tridacna squamosa* Lamarck, 1819), so Neo et al. (2009) added crushed crustose coralline algae-covered coral rubble (CCACR) to concrete tiles in concentrations of 0%, 30% and 60% to determine settlement rates of fluted giant clam larvae. Settlement was greatest on the concrete samples containing 60% CCACR but the CCACR had no effect on the recruitment of juvenile clams 42 days after exposure to the tiles. It was postulated that concrete was no longer leaching the chemo-attractant properties favoured by larvae during initial settlement or that the cues had become diluted beyond detection in the water. Alternatively, their habitat requirements may have changed post-settlement and CCACR cues were no longer prioritised. When variation in roughness was combined with CCACR concretes, rougher tiles were preferentially colonised by juvenile clams over smoother ones and the concentration of CCACR showed no significant effect.

Non-biological waste products have also been used as concrete aggregates, though the bioreceptive benefits of many examples are unclear. Bedoya et al. (2014) introduced crushed ceramics to concrete, but with no reference samples using typical aggregate to compare to, the value of adding crushed ceramics to concrete to enhance bioreceptivity remains unclear. Ly et al. (2021) used recycled glass from smashed car windows to produce concrete artificial reefs. Bioreceptivity experiments performed on mortar samples showed that the glass-based concretes were slightly more bioreceptive than other aggregates used (limestone sand and shell sand) at some sites. Glass-based concrete was used to produce the 3D-printed artificial reefs as it performed well in strength testing, and utilised recycled products.

It is evident that the mechanism by which mollusc shell may chemically enhance bioreceptivity is unclear. The evidence to support the exudation of chemoattractant from mollusc shell, particularly to target conspecifics, is limited and often confounded by other variables such as high alkalinity of the concrete or increased roughness due to the shell aggregate (Dennis et al., 2018; Hanlon et al., 2018; Potet et al., 2021). If chemical cues were leached, it is likely to be in insufficient concentrations due the amount of shell aggregate embedded within the concrete/seawater interface. Any benefits appear to be temporally limited (Neo et al., 2009) or unpredictable. For example, only the aggregate in the surface is likely to exude cues but if the concrete surface is intensively weathered, more shell aggregate and thus chemical cue will be exposed. Burt et al. (2009) demonstrated the importance of secondary bioreceptivity (Guillitte 1995; Sanmartín et al., 2021a) following an experiment when coral recruitment on concrete substrate did not occur as expected. They emphasized that chemical cues of new substrates are short-lived, due to the colonisation of biofilms that mask the substrate surface and inhibit leaching, unless new surfaces are abraded (Cerrano et al., 1999). Therefore, the primary bioreceptivity of a substrate is likely temporally limited from when it is first placed in the environment, or freshly abraded, as the primary biological colonisation that occurs will limit contact between the substrate surface and successive organisms. Additionally, it is unknown if mixing shell with cement, which is chemically aggressive when wet, will lead to the decomposition of chemical cues rendering them inert. Thus far, it is the authors' opinion that the literature experimenting with the use of shell in concrete for its chemo-attractive properties is not conclusive enough to warrant their inclusion for this reason alone. However, there is evidence that shell concrete can lead to increases in abundance of certain taxa (Hanlon et al., 2018) and increase species richness (Dennis et al., 2018), either due to increased roughness (Potet et al., 2021) or accelerated carbonation. Georges et al. (2021) found that CEMV based concrete with 20% shell aggregate underwent carbonation more rapidly than CEMV containing standard aggregate due to the additional voids caused by the shell aggregate. Shell aggregate reduces the carbon footprint of the concrete, by reducing the use of quarried aggregates, as well as using a waste product that would otherwise be discarded. Further study should identify how long the chemical cues of shell or coralline algae-based aggregates remain active *in situ* and if they are leached in any detectable quantities by target species in the field. Furthermore, surface roughness should be homogenised to eliminate texture as a confounding variable when determining chemical bioreceptivity.

2.2. Reducing pH and carbonation

Ordinary Portland cement (OPC) is the most common binder in concrete (Crow 2008; Kosmatka et al., 2008) and used in over half of ACSs (Lukens and Selberg, 2004; Perkol-Finkel and Sella 2014) but it is not considered the most bioreceptive. The lime content of OPC makes it alkaline with a pH of 12–14 (Taylor 1990; Manso et al., 2015), compared to a pH of around 8 for seawater, making it initially hostile to marine life, delaying the onset of colonisation (Grant, 1982; Nandakumar et al., 2003). Atmospheric CO_2 reacts with $CaCO_3$ in the cement pore solution of concrete in an aging process known as carbonation with the speed of this process depending on the environment the concrete is exposed to (Hayek et al., 2020). This reduces superficial alkalinity to a pH of approximately 9–10 (Taylor 1990), by which time biological colonisation can begin in earnest (John 1988; Manso et al., 2015).

Manso et al. (2014a) attempted to lower the pH of OPC by adding boric and oxalic acid. The addition of the acid did not significantly impact pH and is therefore not likely to enhance bioreceptivity and, with respect to boric acid, could negatively impact mechanical properties making it unsuitable for use in industry. The exploration of alternatives to OPC includes magnesium-phosphate cement which is manufactured at a lower temperature than OPC and thus requires less energy to produce (Phair 2006). Unlike the high alkalinity of OPC, magnesium-phosphate cement (MPC) is neutral or slightly acidic, which allows concrete to be readily colonised, and demonstrates industry acceptable physico-mechanical properties (Manso et al., 2014a). Manso et al. (2014b) determined that MPC demonstrated a higher bioreceptivity for freshwater micro-algae (*Chlorella vulgaris* Beijerinck, 1890) compared to OPC under laboratory conditions after 10 weeks. Initial colonisation occurred more rapidly for MPC by one week and complete coverage was achieved 4 months sooner than OPC samples. Furthermore, Manso and Aguado (2016) determined that despite carbonated OPC specimens demonstrating up to 20% more voids and greater porosity than MPC specimens, the latter were more bioreceptive after 10 weeks, indicating that chemical composition of the binder played a greater role in colonisation than physical properties (porosity, surface roughness). However, Veeger et al. (2021) found the opposite in an experiment with MPC and OPC cements, with MPC concrete showing slower and less growth than OPC concrete after 8 weeks. Veeger et al. (2021) acknowledged these results may have been affected by the MPC blend used in their study, which contained unknown additives, and the choice of biofilm used in inoculation. It should be noted that these tests (Manso et al., 2014a, 2014b; Manso and Aguado 2016; Veeger et al., 2021) were conducted on concretes for use in the terrestrial environment, or using freshwater algae, and results may differ in marine environments.

The reduction of concrete pH has been explored for concrete in marine environments. Perkol-Finkel and Sella (2014) tested five concrete matrices in temperate and tropical marine settings that included lower proportions of OPC and additives to reduce pH and thus were designed to possess a lower alkalinity. In addition to meeting crucial industry standards for mechanical strength and durability, three of the concrete matrices were found to be more bioreceptive after 12 months, with greater live cover than concrete dominated by OPC. Additionally, surface roughness was also deemed to be of significant importance in enhancing bioreceptivity. In a lab-based study Hayek et al. (2020) compared the initial colonisation of bacterial biofilms on carbonated and non-carbonated concrete samples in seawater. Carbonated concrete had a lower surface pH and colonised immediately, whereas non-carbonated concrete experienced a lag of 7 days before initial colonisation occurred. Carbonated and non-carbonated CEM I and CEM III mortar samples were submerged in seawater and their pH over time was compared. CEM I cement is pure OPC, whereas CEM III is a mixture of OPC and 60% ground granulated blast-furnace slag (GGBS). The CEM I and CEM III carbonated samples had initial pH values of 7.3 which remained constant over the immersion period, whereas the CEM I and CEM III non-carbonated samples had initial pH values of 9.3 and 8.6 respectively and decreased to 7.5 and 7.3 respectively over the immersion period. Carbonated concrete initially performed better in terms of bacterial colonisation but after 60 days the bacterial biofilm on non-carbonated samples exceeded carbonated samples. CEM III consistently outperformed CEM I and was recommended for use as marine concrete to enhance bioreceptivity.

Differences are also apparent in the colonisation of carbonated vs. non-carbonated concretes in algae and sessile invertebrates. Guilbeau et al. (2003) found pH neutral and carbonated concretes colonised more readily with algae after 16 days submerged on the coast of Florida, US, whereas non-carbonated samples were dominated by barnacles. It is worth noting that carbonation reduces the porosity of concrete by the precipitation of calcium carbonate within pore spaces (Dalod et al., 2014; Liu et al., 2018), which may reduce physical bioreceptivity (Tran et al., 2012). Despite this, larger pore spaces may remain unaffected by the carbonation process (Ngala and Page 1997), particularly in concretes containing GGBS (Gruyaert et al., 2013). However, this is likely to be ameliorated over time by abiotic and biotic erosive action exposing and expanding pore spaces (Tran et al., 2014).

Replacing the OPC content of concrete with an alternative binder that has a lower alkalinity has been found to enhance bioreceptivity (Manso et al. 2014a, 2014b; Perkol-Finkel and Sella 2014; Manso and Aguado 2016; Hayek et al., 2020) and carbonated concretes colonised more rapidly than non-carbonated concretes (Guilbeau et al., 2003; Hayek et al., 2020). Carbonation will naturally occur to concrete surfaces in contact with atmospheric carbon dioxide (Dooley et al., 1999; Hsiung et al., 2020) and so concrete-based ACSs will eventually increase in bioreceptivity as their pH decreases, and for the majority of their service life will be at an acceptable pH value for colonisation. It may be that a lag in bioreceptivity has temporal repercussions, depending on the time of deployment (Underwood and Anderson 1994; Nandakumar 1996) and the larval supply available when their pH has reduced, particularly if alkotolerant species, such as barnacles (Dooley et al., 1999; Guilbeau et al., 2003), dominate while surface alkalinity is still high. Hsiung et al. (2020) demonstrated that after 12 months there is little difference between the species richness, abundance and assemblage composition of carbonated and non-carbonated concrete tiles deployed in the UK and Singapore. Differences between the carbonated and non-carbonated surface porosity may have accounted for slight differences in species richness in Singapore, but this did not persist. Furthermore, Veeger et al. (2021) found that concrete samples, with their pH ranging between 11.6 and 12.2, showed significant biological growth with some samples becoming colonised within a week. Veeger et al. (2021) opined that the pH correlates with another determining factor, such as weathering enhancing surface roughness, but is not, itself, the factor responsible for colonisation. Mos et al. (2019) determined that initial colonisation of sea urchins (*Tripneustes gratilla* Linnaeus, 1758) on non-carbonated concretes showed greater survival and growth compared to greywacke (sandstone) and granite in warmed and acidified treatments. Thus, in a warming and acidifying ocean, the calcium carbonate leachate from fresh concrete may enhance species survival, though field testing is required to confirm these findings. Additionally, the value of this benefit may again be temporally limited.

2.3. Binder alternatives

GGBS and pulverised fly ash (PFA) are industry waste products that can be incorporated into concrete. GGBS is a by-product from iron ore extraction in a blast furnace. The molten iron is tapped off and all remaining materials form the slag, which is cooled and ground for use in construction materials. PFA is extracted from coal burning flues and can enhance durability of concrete and resistance to the deleterious effects of sulphate attack and chloride ion migration, which are common deteriorative issues in marine settings (Neville 2004; Santhanam and Otieno 2016). The use of pozzolans, broadly defined as finely ground siliceous and or aluminous materials, in concrete can reduce the surface pH (Guilbeau et al., 2003; Park and Tia 2004). GGBS and PFA can be used as a direct replacement for OPC up to 85% and 35% respectively (British Standards Institute 2011). However, pozzolan replacements can contain high concentrations of trace metals (Mullauer et al., 2015) which can leach out over long periods of time, although this is dependent on the microstructural characteristics of the cement paste (Jang et al., 2015). McManus et al. (2018) compared the bioreceptivity and leachate capacity of concrete mixes that substituted CEM I cement with direct replacement of 24% GGBS and PFA. Concrete tiles testing bioreceptivity were hung in Plymouth Sound, UK, for 7 weeks. Diatom coverage showed significant differences between the concrete mixes but post hoc tests failed to reveal which concrete mix incurred greater coverage. The greatest native macro-fouling species richness was on the control treatment, which consisted of 100% OPC, and lowest on tiles containing GGBS. Assemblages on mixed tiles (24% PFA and 24% GGBS) were least similar whereas the control tiles showed the greatest similarity between assemblages. McManus et al. (2018) opined that higher zinc content in GGBS limited colonisation due to its biocidal properties, but it was noted that OPC cement contained the highest concentration of copper, another biocidal metal, and yet performed best in the trial. Although there were significant results, it was unclear if heavy metal leachate significantly affects colonisation, particularly as the mixes with the lowest leachate concentration contained GGBS. There is no evidence that trace heavy metals transfer from hard substrate to epifaunal colonisation (Woodhead et al., 1985, 1986; Price et al., 1988). Additionally, many open systems are unlikely to retain sufficiently harmful concentrations of heavy metals (Foekema et al., 2016). It was also noted that far greater percentages of GGBS and PFA are used in industry as cement replacement, and that increasing the replacement from the 24% used in the study may enhance results.

Natanzi et al. (2021) compared the bioreceptivity of concrete mixes on the coast of County Meath, Ireland, with variation in the cement (100% CEM I vs. 50% CEM I and 50% GGBS), aggregate (limestone vs. granite) and presence of plasticizer (with or without). CEM I/GGBS blends with granite aggregate demonstrated the lowest resistance to pH reduction compared to CEM I only with limestone aggregate samples. Samples were deployed on both sheltered and exposed sides of an intertidal breakwater for 1 month. CEM I/GGBS blend tiles on the sheltered side had greater biomass of cyanobacteria, green algae and diatoms compared to CEM I only tiles. Conversely, on the exposed side, trends in microalgal biomass showed no significant difference. Morin et al. (2018) found that CEM III concrete tiles outperformed CEM I concrete tiles in bioreceptivity of diatoms (*Entomoneis* sp.) after 28 days under laboratory conditions. Ly et al. (2021) compared the bioreceptivity of geopolymer binders with CEM III cement. Geopolymer binder is made from alumina-silicates and alkaline reagents such as sodium or potassium hydroxide. CEM III concrete blocks deployed subtidally in the UK, France, and Portugal had greater percentage cover than geopolymer concrete, though blocks deployed in Spain showed little difference. Biomass on geopolymer concrete was greater at 1- and 3-month intervals but overtaken at 6 months by CEM III concrete. Additionally, CEM III concrete outperformed geopolymer concretes in flexural and compressive strength. Hayek et al. (2021) found that CEM III outperformed CEM I based concretes after 113 days immersion on the north French coast. Hayek et al.'s (2020, 2021), Natanzi et al.'s (2021), and Ly et al.'s (2021) studies demonstrate that higher proportions of GGBS in concrete can positively impact initial bioreceptivity, as well as better resisting chloride ion migration, thus mitigating deteriorative effects of seawater on concrete. Huang et al. (2016) found that a custom concrete mix ('green' artificial reef concrete) containing almost 70% GGBS in its cement formula performed to industry standard in mechanical testing and was readily colonised by *Ulva* spp. once deployed in the intertidal zone. The absence of alkotolerant barnacles and low levels of the hydration product portlandite suggested that the surface pH of the 'green' artificial reef concrete was lower than standard OPC. However, there was no comprehensive biotic data to support this conclusion, nor was the 'green' artificial reef concrete compared to an OPC or equivalent control. Subsequently, this study would benefit from replication involving OPC-based controls with time-series biotic data to confirm its findings. Hickling et al. (2022) compared the epibenthic colonisation of three concrete mixes (CEM II vs. CEM II and 10% addition of micro silica pozzolan vs. GGBS and alkali activation material) immersed subtidally on the Devon coast, UK, for one year. The 'CP' mixture (CEM II and 10% addition of micro silica) was rougher than the other mixes following washing of the surfaces following demoulding to expose the aggregate. Although no significant differences were found between species richness and diversity indices, percentage cover of sessile growth varied significantly (31–45%) and was greatest on the 'C' mixture (CEM II). Assemblage structure between the different mixes was also significantly different, likely due to the differing proportions of the bryozoan *Bugula* spp., which was greatest on the 'CP' mix. Although the exposed aggregate for the 'CP' was to represent the 'best practice' design, it makes it challenging to disentangle if differences between the mixtures were as a result of material composition or surface roughness.

The replacement of CEM I binder with CEM II or III, or the inclusion of GGBS with CEM I has been used to enhance bioreceptivity to diatoms, bacteria, cyanobacteria, green algae (Huang et al., 2016; Morin et al., 2018; Hayek et al., 2021; Natanzi et al., 2021) and overall percentage cover (Ly et al., 2021; Hickling et al., 2022). In order for GGBS to provide a clear positive impact for bioreceptivity however, it should replace OPC by a significant amount as recommended by McManus et al. (2018). Until further work can determine the threshold at which GGBS content becomes bioreceptively significant, it is recommended that GGBS replaces at least 50% of OPC as per Natanzi et al. (2021). Although lower alkalinity binders currently outperform OPC binders in the field, this may change as the ocean becomes more acidic. Davis et al. (2017) found that photosynthetic yield of algal turf on concrete in acidified treatments was 6% greater than other substrata (HDPE and granite). As many concrete ACSs being constructed now will aim to still be *in situ* in 50–100 years' time, further research should investigate the role different concrete matrices will play in bioreceptivity under warming and acidifying climate scenarios.

Veeger et al. (2021) found that adding bone ash (charred cattle bones) significantly increased bioreceptivity after 8 weeks of growth on OPC based concrete. Differences in algal growth between treatments containing no bone ash and bone ash were not apparent in earlier stages, which was thought to be because the phosphorus that the bone ash contained was not a limiting factor at that point in the experiment. Alternatively, the concrete may not have undergone sufficient weathering to expose sufficient concentrations of phosphorus-rich bone ash to the colonizing algae until several weeks had passed. The addition of phosphorus to a mineral substrate is known to promote biological growth (Jones and Bennett 2017) but can affect the durability of concrete, and so the inclusion of phosphorus-rich bone ash in concrete could be used to overcome this hurdle provided it does not exceed 20% binder replacement (Falade et al., 2012).

There are some examples of concrete that are ill-advised for use to enhance bioreceptivity, due to toxic or biocidal properties. For example, Dalod et al. (2014) compared the bioreceptivity of CEM I and calcium aluminate cement with green algae *Klebsormidium flaccidum* under lab conditions. It was found that calcium aluminate cement was not as prone to biofouling as CEM I, which is likely as a result of the high content of aluminate which has biocidal properties (Alexander and Fourie 2011; Herisson et al., 2015). Harilal et al. (2020) added nano-TiO_2 and nano-$CaCO_3$ to a conventional fly-ash based concrete and compared it with control concrete. Following six months immersion subtidally at Kalpakkam, India, the modified concrete was significantly less fouled than the control comparison due to the biocidal properties of the nano additives and their reaction products filling pores and reducing surface roughness. There are few examples where anti-fouling additives are added to a concrete mix, as it is more common practice for anti-fouling coatings to be applied superficially, which affects the quaternary bioreceptivity of concrete and is therefore beyond the scope of this review.

3. Physical bioreceptivity

The physical primary bioreceptivity of a material, and its influence on biofilm and meiofaunal colonisation, will affect secondary bioreceptivity by impacting the evolution of successive communities (Guillitte 1995). There is extensive literature documenting the biofouling capacity of building materials and it is generally agreed that surface roughness and porosity are key factors mediating biological colonisation (Deruelle 1991; Ortego-Calvo et al. 1995; Miller et al., 2006; Miller et al., 2009; D'Orazio et al., 2014), particularly small-bodied organisms (Strain et al., 2018). Additionally, roughness can mitigate against chemically toxic properties of a substrate. A biocidal coating applied to granite was found to increase bioreceptivity for algae and cyanobacteria under lab conditions, as the coating added micro-cracks to the surface, providing anchor points for colonisation and nullifying the impact of biocide (Sanmartín et al., 2021b).

3.1. Porosity

Increasing the porosity of concrete can enhance the deposition and accumulation of organic and inorganic particles, in addition to retaining moisture, which is known as extrinsic bioreceptivity. The deposition of spores and the use of pore spaces as habitat for biofilm taxa is referred to as intrinsic bioreceptivity (Guillitte 1995).

Guillitte and Dreesen's (1995) pioneering study determining the bioreceptivity of common construction materials (calcareous limestone, siliciclastic limestone, brick, mortar) examined the impact of porosity, roughness and mineral composition on the colonisation of terrestrial algae, cyanobacteria and moss. Aerated concrete was colonised rapidly, two weeks prior to the other materials. Vegetation coverage on the aerated concrete and siliciclastic limestone was 100% after six months, and both materials had a higher diversity of taxa than the mortar, brick and calcareous limestone. Initial colonisation patterns were correlated with material porosity, as a result of enhanced water retention and deposition of spores, with the most porous materials (aerated concrete and siliciclastic limestone) colonised rapidly with complete coverage and greatest taxonomic diversity after 6 months. Dubosc et al. (2001) demonstrated that more porous variations of OPC based concrete samples remained damp during the periods where the samples were not wetted, leading to a dominance of algal species less tolerant of desiccation on those concretes after 2 months. Although lab conditions were designed to emulate a terrestrial environment, these results could apply to the intertidal zone where concrete undergoes daily wetting and drying cycles. Giannantonio et al. (2009) found biofouling of terrestrial fungi was enhanced in concrete mixes that had higher water: cement ratios, which increased concrete porosity by reducing density after one week in lab conditions. This subsequently reduced the strength of the structure and so is not suitable for marine application. Giannantonio et al.'s (2009) findings were supported by Tran et al.'s (2014) field-based study that modified mortar porosity by using varying ratios of water: cement. The more porous samples demonstrated greater microbial fouling after a year and a half of exposure to natural fouling in a park in France. Snoeck et al. (2022) found that adding superabsorbent polymers to CEM I-based mortar samples to enhance the material's water retentive capability and macroporosity increased algae coverage after 10 weeks compared to controls.

Porosity may be less important than roughness in subtidal environments, where concrete is permanently immersed, and the retention of moisture is not a limiting factor for growth or survival of marine life. Tran et al. (2012) found porosity was not an important factor in determining bioreceptivity of mortars that were exposed to >80% humidity under lab conditions for 96 days. Instead, roughness was deemed to be the primary factor as it promoted adhesion of algal spores. In order to obtain a porous surface, Morin et al. (2018) used a vibrating table to create a dense layer at the concrete base and a porous layer at the top surface creating a bi-layered concrete. The porous layer comprised 20% of the total concrete thickness. Compared to a dense reference concrete, the porous bi-layered concrete had greater diatom growth after 28 days.

3.2. Roughness

The intrinsic bioreceptivity of different limestones were assessed by Miller et al. (2009) and both roughness and capillarity were important factors determining the amount of chlorophyll *a* measured on the sample surfaces. The rougher limestones were subject to greater microbial colonisation after 90 days and it was opined that the increased roughness reduced shear force stress and increased surface area available for colonising. By contrast, open porosity did not have as much influence on colonisation. With limestone, greater porosity may lead to greater evaporation of retained moisture, increasing environmental hostility and reduced colonisation.

When modifying the surface roughness of concrete materials to determine how roughness impacts bioreceptivity, the surface of the wet mortar or concrete is often poured against materials or formliners that will provide differing degrees of roughness when the cured concrete is struck (Pinheiro and Silva 2004). Alternatively, the test surface will be roughened with abrasive action either when wet or cured (Tran et al., 2012). Tran et al. (2013) found roughness created by abrading OPC mortar samples during setting with sponges enhanced colonisation of the algae *K. flaccidum* under lab conditions after 25 days. The surface textures were created with a ruler (smooth) and two sponges of differing texture (rough) and the mortars showed a linear relationship with bioreceptivity. The experiment was replicated in natural terrestrial conditions for up to 18 months where the effects of roughness were not as linear as when conducted under lab-based conditions (Tran et al., 2014). There was little difference between the bioreceptivity of the two rough treatments, but rough treatments outperformed smooth mortar. Coombes et al. (2015) compared the bioreceptivity of control, smooth, grooved and exposed aggregate OPC concrete treatments, which were achieved with standard casting and curing, wiping with a cloth, wiped with a coarse wire brush, and jet washed respectively. They were deployed intertidally on the southwest coast of the UK and monitored for cyprid settlement between May and November 2010 for six months. Intertidal barnacles preferentially settled on the grooved concrete, which corresponded to the size of the settling cyprids. The non-linear relationship of barnacle settlement with roughness was also observed in MacArthur et al. (2019), as barnacles preferentially settled on millimetre (mm) scale complexity. Recruitment of barnacles (*Chthamalus montagui* Southward, 1976) on natural limestones on the south coast of England, was determined by the number of potential settlement sites within pits and grooves on the rock surface, which was calculated from the length of cyprid larvae (Herbert and Hawkins 2006).

Bedoya et al. (2014) incorporated crushed waste ceramic as a replacement for typical aggregate in a Portland cement type 1 mix, and the sample plates with a higher percentage of large grain sizes had greater biodiversity after 8 months, although this was not significant. Dennis et al. (2018) found the intrinsic primary bioreceptivity of alternative aggregates (hemp and shell) may have also been due to the increased roughness of the unfinished tile surface after 12 months deployment intertidally. Neo et al. (2009) found that following six weeks of exposure to different concrete mixes, the clam *T. squamosa* preferred rough to smooth concrete tiles post-settlement, which they opined was due to the microscale topography providing some degree of shelter. Strain et al. (2018) found that rougher texture benefited subtidal sessile species and intertidal barnacles, branching coralline algae and, to a lesser extent, bivalves the most. Potet et al. (2021) found that after testing the bioreceptivity of nine different concrete formulas deployed subtidally on the French coast for 15 days, varying size class and substitution rate of oyster shell and siliceous sand aggregates, that micro-texture was more influential in the settlement of flat oysters (*Ostrea edulis* Linnaeus, 1758) than the formula chemistry. In the formula that substituted up to 50% of the aggregate with oyster shell, it was suggested that a microtopography approaching the same dimensions as settling larvae was the optimum rugosity for targeting flat oyster settlement.

Vivier et al. (2021) compared the photosynthetic health of marine biofilms growing on rough and smooth concretes versus plastic controls. After inoculation with natural marine biofilm under lab conditions for six days, microphytobenthic cells preferentially colonised negative reliefs in the rough concrete surface and had better photosynthetic performance and photoacclimation than biofilm on positive reliefs or smooth concrete. It was opined that negative reliefs shielded the biofilm from damaging levels of light and reduced hydrodynamic stress. Increasing open porosity and microscale roughness clearly also have a positive effect on algal percentage cover (Miller et al., 2009; Tran et al. 2012, 2013, 2014; Morin et al., 2018) though roughness may not have a linear relationship with the settlement of larvae, such as barnacles (Coombes et al., 2015; MacArthur et al., 2019). Therefore, enhanced roughness will not be suitable for the recruitment of all primary colonising taxa. Although conducted on acrylic panels, Sweat and Johnson (2013) determined that smoother surface textures favoured the adhesion of diatoms as a result of the increased contact between the material surface and the diatom cells. The cyprids of the barnacle *Amphibalanus* (*Balanus) improvisus* (Darwin, 1854) had greater preference for smoother surfaces than rougher surfaces (Berntsson et al., 1999, 2000). Cacabelos et al. (2016) found that rougher blocks of basalt seawall enhanced intertidal biodiversity over smoother blocks, but that barnacles preferentially settled on the smoother substrate. Sedano et al. (2020) found that microscale structural complexity was only significantly correlated with meiofauna, and larger scale complexity was more associated with sessile and vagile macrofauna. As noted by Sweat and Johnson (2013), recruitment to surface roughness may be dependent on the size of the settling organism, which is supported by Herbert and Hawkins (2006) and Potet et al.'s (2021) observations with barnacle larvae and flat oyster larvae respectively. Subsequently it would be prudent to consider providing a variety of surface textures varying from smooth to coarse as increasing the number of habitats will enhance the biodiversity of the overall structure. Sedano et al. (2020) recommended pairing microscale roughness with macroscale habitats to boost sessile taxa. As with chemical bioreceptivity, most studies focussing on physical bioreceptivity are short term ($<$12 months) and do not demonstrate the effects of roughness and porosity on bioreceptivity long term.

3.3. *Other factors influencing bioreceptivity*

Hughes et al. (2013) postulated that the use of marine aggregates in marine concrete may enhance colonisation of algae due to the pre-existing algal spores and matter present in the aggregate and should be avoided to reduce fouling. However, most marine aggregates are sourced from relict geological or fossil deposits not associated with biological growth and are routinely washed for sorting (Highley et al., 2007). Additionally, wet cement is caustic (Peters 1984) and any remnants of biological content are unlikely to survive the aggressive chemical environment of setting and curing (Sanchez-Silva and Rosowsky 2008). Therefore, the reality of marine aggregates presenting a predisposition for biological colonisation, or ‘fouling’, is extremely unlikely, particularly when the practice of using beach sourced aggregate, as used in the concrete revetment Hughes et al. (2013) sampled, is relatively uncommon due to the issues associated with coastal erosion.

Colour can also affect bioreceptivity, although there is no literature to date for concrete substrates. Black and white acrylic tiles submerged in the Sea of Oman for 20 days, with black tiles showing higher densities of fouling species compared to white tiles (Dobretsov et al., 2013). These findings of black versus white acrylic substrata were supported by Swain et al. (2007), who found higher settlement of green algae *Ulva* sp. and tubeworms on black surfaces after 14 days immersion on the Florida coast, and by Guenther et al. (2009) who found that the hydroid *Ectopleura larynx* (Ellis and Solander, 1786) preferentially settled on black tiles compared to other colours. Sanmartín et al. (2020) compared two granites that differed in colour due to the feldspar content (grey vs. red), but were otherwise similar in roughness, porosity and chemical composition. Significantly greater algal growth occurred on the red granite exposed to natural conditions in a UK woodland after 70 days, likely due to the reflection of red wavelengths that are known to stimulate algal growth more than green or blue wavelengths. It was noted that the effect of substrate colour would likely only impact primary succession as the substrate surface would soon be obscured with initial colonisation.

4. Overview

Our review has shown that there are several methods by which the intrinsic primary bioreceptivity of concrete may be enhanced by virtue of its composition, and the pouring, curing and setting processes. The inclusion of crushed shell can enhance surface roughness and thus make concrete more bioreceptive, in addition to reducing its carbon footprint. However, its chemo-attractant value is likely to be spatially and temporally limited. Carbonating concrete also has limited long-term value but non-carbonated binders with a lower pH, such as CEM II or III, generally demonstrate greater bioreceptivity over OPC-based concrete provided the ratio of pozzolans is high enough. The use of GGBS and PVA is considered standard in marine concrete (British Standards Institute 2011) as OPC alone is insufficient at resisting chloride penetration (Smith 2016). Surface roughness and porosity generally enhance bioreceptivity, and are likely more important than chemical bioreceptivity (Hayek et al., 2021), but it is important to include a variety of textures and porosity where possible, as marine organisms do not show a uniform response to increased roughness (MacArthur et al., 2019). Additionally, longer term studies are required to determine how physical bioreceptivity impacts successive communities, and how durable a rough and porous concrete surface is. Easily abraded concretes or concretes in highly exposed settings may become less rough and therefore less bioreceptive over time. The initial success of deploying bioreceptive concretes will also be reliant on extrinsic factors, such as larval supply, orientation, aspect, exposure, latitude (Strain et al., 2021), and disturbance and biotic interactions (Ferrario et al., 2016) will all play a role in longer-term success. The pH, and by extension bioreceptivity, of concrete may evolve in a warming/acidifying ocean and this should be addressed with mesocosm experiments testing the pH and leachate of binders under climate change scenarios.

Enhancing bioreceptivity via the methods reviewed here is not a catch-all solution, as habitat preferences will vary among species and within life history stages. However, the magnitude of difference between the community structure and biodiversity of these patches will be site and context dependent (Becker et al., 2021) due to differences in local abiotic (salinity, pollution, climatic etc.) and biotic (larval supply, competition etc.) conditions. The majority, if not all, studies investigating bioreceptivity do not continue until a climax community has been reached, as noted by Dodds et al. (2022), which is likely due to the time constraints associated with this. Climax communities on ACSs could take between 5 and 20 years to form (Hawkins et al., 1983; Pinn et al., 2005; Coombes 2011), and some authors have opined that complete succession may never occur in some contexts (Ferrario et al., 2016). As many ACSs are coastal defence structures, and therefore often situated on highly urbanised and exposed shores, there is an inherent local dynamism of a range of background abiotic and biotic disturbances that may render biotic communities in a constant state of flux. Enhancing the bioreceptivity of concrete may attenuate some of these stressors by increasing the likelihood of attachment and survival. However, there is a need for longer term studies investigating concrete bioreceptivity in the marine environment, particularly with appropriate references/controls. Additionally, Sanmartín et al. (2021a) acknowledge there is also a succession to bioreceptivity, with primary bioreceptivity being superseded by the colonisation of biofilms and subsequent taxa. The deteriorative impacts of seawater, wetting drying cycles and biotic colonisation will produce secondary bioreceptivity over time, creating further micro and macroscale topographic complexity which will in turn modify biotic succession further still (Moschella et al., 2005; Firth et al., 2013b; Coombes 2014; Sanmartín et al., 2021a).

Such small-scale experiments are important for proof of concept to determine which concrete formulas and finishes provide optimal bioreceptivity, but it is crucial they are scaled up to structure scale to assess their performance as a larger contiguous habitat (Strain et al., 2018). Additionally, structure-scale pilots will provide crucial evidence that bioreceptive concretes can be successfully incorporated from design to delivery with negligible impacts on material sourcing, cost, construction and the structural integrity and service life of the structure. Prior to scaling up however, tile experiments may be a useful way to ascertain site-specific variation in available species and environmental parameters that will affect which physical interventions are best suited to the structure location. Post-construction monitoring would also be vital to determine success with appropriate control comparisons (Pioch et al., 2018). Small-scale trials achieve surface roughness either by leaving the surface ‘unfinished’ (Dennis et al., 2018) or by hand-finishing with sponges, brushes or rulers (Tran et al., 2013, 2014; Coombes et al., 2015), which are unlikely to be feasible or acceptable methods for structure-scale interventions. However, formliners for this purpose are now commercially available with a wide range of textures available, and concrete surfaces can be jet-washed to expose aggregates before fully set to enhance roughness. The recommendations for enhancing intrinsic primary bioreceptivity of concrete should be considered in tandem with macroscale interventions, such as water retaining and shading features in the intertidal, and holes and tunnels in the subtidal. Collaboration and communication between asset owners, coastal engineers and marine ecologists is essential (Naylor et al., 2012; Perkins et al., 2015) for the continued research into optimising concrete, that is a suitable compromise between maximising bioreceptive returns and material durability (Lubelli et al., 2021). This would also prevent the implementation of inappropriate features, such as unnecessary interventions in the upper shore zone, and gratuitous ‘green-washing’ (Firth et al., 2020). Regarding ‘green-washing’, caution should be exercised when referring to a concrete mix as ‘bioreceptive’, which implies an enhanced capacity for colonisation, when this has not been proven or simply has no observable detrimental impact to colonisation compared to more standard mixes (sensu Hickling et al., 2022). Further research should focus on replicating existing studies in different settings to identify which aspect of bioreceptivity is most beneficial in different contexts, which would allow for coastal managers to tailor bespoke bioreceptive concrete for their chosen site.

5. Conclusion

This review has demonstrated that there are several methods to enhance the chemical and physical bioreceptivity of concrete (Table 1). However, the evidence presented does not sufficiently justify the use of aggregates and binders to enhance chemical bioreceptivity, as exudation of chemical cues are likely to be spatio-temporally limited in open systems. Often the mechanisms of chemical bioreceptivity are unclear or conflicting, and sometimes rendered null and void following primary succession.

Most studies for both physical and chemical bioreceptivity report short term results ($<$12 months). The evidence for porosity and surface roughness suggests physical properties are more important in enhancing intrinsic primary bioreceptivity in concrete than chemical means, though the durability of rough surfaces in marine settings require further study. However, many of the aggregates and binders included in this review offer other benefits, such as the use of recycled materials and increased durability in the marine environment. Interdisciplinary coastal practitioners, including engineers and ecologists, should work together to create responsible, tailored bioreceptive solutions in ACSs that are suitable for the target site, target species and environment.

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.

Acknowledgements

We thank Violeta Monteiro Ramos for her constructive comments in the earlier drafts. Funded by the European Regional Development Fund, as part of the Marineff Project, selected for by Interreg France Channel England. We are also grateful for the improvements suggested by both reviewers of this paper.

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