Getting into the Groove: Opportunities to enhance the ecological value of hard coastal infrastructure using fine-scale surface textures

Martin A. Coombes[a]* (Martin.Coombes@ouce.ox.ac.uk); **Emanuela Claudia La Marca[b]** (Emanuelaclaudia.lamarca@unipa.it); **Larissa A. Naylor[c]** (Larissa.Naylor@glasgow.ac.uk); **Richard C. Thompson[d]** (R.C.Thompson@plymouth.ac.uk)

[a]School of Geography and the Environment, University of Oxford, UK

[b]Department of Earth and Sea Sciences, University of Palermo, Italy

[c]School of Geographical and Earth Sciences, University of Glasgow, UK

[d]School of Marine Sciences and Engineering, Plymouth University, UK

*Corresponding Author: Martin A. Coombes, School of Geography and the Environment, South Parks Road, Oxford, UK OX1 3QY

Abstract

Concrete flood defences, erosion control structures, port and harbour facilities, and renewable energy infrastructure are increasingly being built in the world's coastal regions. There is, however, strong evidence to suggest that these structures are poor surrogates for natural rocky shores, often supporting assemblages with lower species abundance and diversity. Ecological engineering opportunities to enhance structures for biodiversity conservation (and other management goals) are therefore being sought, but the majority of work so far has concentrated on structural design features at the centimetre–meter scale.

We deployed concrete tiles with four easily-reproducible fine-scale (millimetre) textures (control, smoothed, grooved and exposed aggregate) in the intertidal zone to test opportunities for facilitating colonisation by a dominant ecosystem engineer (barnacles) relative to natural rock. Concrete texture had a significant effect on colonisation; smoothed tiles supported significantly fewer numbers of barnacles, and those with intermediate roughness (grooved concrete) significantly greater numbers, after one settlement season.

The successful recruitment of early colonists is a critical stage in the development of more complex and diverse macrobenthic assemblages, especially those that provide physical habitat structure for other species. Our observations show that this can be facilitated relatively simply for barnacles on marine concrete by manipulating surface heterogeneity at a millimetre scale. Alongside other larger-scale manipulation (e.g. creating holes and pools), including fine-scale habitat heterogeneity in engineering designs can support international efforts to maximise the ecological value of marine urban infrastructure.

Keywords

Marine concrete; Ecological engineering; Ecosystem Engineers; Intertidal ecology; Reconciliation ecology; Urbanization

1. Introduction

Rapid population growth in most of the world's coastal regions means that more and more 'hard' structures such as sea walls and breakwaters are being built to manage the risks of sea level rise and increased storminess (Firth et al. 2013a; Pethick 2001) and to support sustained socio-economic growth (Airoldi and Beck 2007). Structures built from rock and, in particular, concrete are also increasingly being deployed in the near-shore and subtidal zones as part of marine renewable energy schemes (Witt et al. 2012). While all of these structures provide novel habitats for marine life (Bulleri 2006) there is strong evidence to suggest that the conditions they provide and the assemblages they support differ to natural rocky shores. Coastal structures, for example, typically support fewer species with lower abundances, and consequently altered competitive interactions among and between species (e.g. Bulleri 2005; Bulleri and Chapman 2010; Bulleri et al. 2005; Jackson et al. 2008). As such, the transformation of coastal habitats via urbanisation is a conservation issue of global concern, particularly in the face of concurrent major drivers of change including pollution and climate change (Hawkins 2012; Hawkins et al. 2008; Thompson et al. 2002).

This creates a substantial management problem, given that the economic and social justification for building hard structures is clear but is in conflict with broader public interest and policy requirements to conserve biodiversity at a national and international level (Naylor et al. 2012). In Europe, for example, the Water Framework Directive (WFD) requires that careful environmental appraisal is undertaken for all heavily modified water bodies (including ports, harbours and defended coastlines, whether existing or new build) to identify measures for maximising ecological potential (Bolton et al. 2009). As an approach to engineering that explicitly considers ecological criteria in design, ‘ecological engineering’ (sometimes called ‘reconciliation ecology’) has significant potential to address this conflict of interests (Bergen et al. 2001; Lundholm and Richardson 2010).

In the coastal zone, a growing amount of experimental work is being undertaken globally to test manipulation of engineering designs for ecological gain (see Chapman and Underwood 2011, Firth et al. 2013b, Firth et al. 2014, and Naylor et al. 2011 for some recent discussions). The potential economic benefits of facilitating the growth of commercially exploitable species (e.g. Martins et al. 2010) and organisms that may afford some level of protection to engineering materials from marine weathering agents (e.g. Coombes et al. 2013) have also been highlighted. Much of this work is founded upon the known importance of physical habitat complexity for rocky shore species, and robust experimental evidence demonstrating the influence of various engineering design features on ecology, such as tidal position (e.g. Moschella et al. 2005) and the presence of water-retaining features (e.g. Browne and Chapman 2014; Firth et al. 2013c).

Following pioneering work on the design and deployment of subtidal artificial reefs (see Baine 2001 for a review), to date most ecological enhancement trials in the intertidal zone have focused on increasing physical habitat complexity at the centimetre–meter scale. This can be achieved either post-construction (e.g. drilling holes in otherwise flat walls) or by retrofitting and (more rarely) designing-in habitat ‘units’ during the build to provide refuge during low tide (e.g.

artificial rock pools) (Browne and Chapman 2011; Chapman and Blockley 2009; Firth et al. 2014; Martins et al. 2010; Moschella et al. 2005). In comparison, very little has been done to test enhancement opportunities at finer scales (millimetres) simply by roughening the materials that structures are built from. This is surprising given substantial experimental evidence of the importance of fine-scale texture for the development of marine biofilms, the settlement of invertebrate larvae and spores, recruitment of juveniles, and the nature of community interactions on rocky substrata (e.g. Chabot and Bourget 1988; Decho 2000; Hutchinson et al. 2006; Menge 2000; Walters and Wethey 1996). On artificial structures, existing fine-scale topographic features have been shown to significantly influence the abundance of dominant organisms (e.g. Moschella et al. 2005), but attempts to manipulate texture at this scale remain noticeably absent.

On natural rocky shores, fine-scale habitat heterogeneity (millimetres and less) is created by weathering, involving the wetting and drying of rocks, salt crystallisation, chemical breakdown, and biological weathering and erosion (Coombes 2014). Whilst the rate that these processes create roughness is largely dependent on rock type, one critical factor that artificial structures generally lack in comparison to natural shores is time. Engineering materials are subject to the same weathering processes as in situ rock (e.g. Coombes et al. 2011) but they are inevitably ‘newer’, less weathered, and less physically complex (at multiple spatial scales) than the rocks comprising rocky shores. Consequently, artificial structures are comparatively lacking in fine-scale complexity unless pre-weathered rock can be used or artificial texturing is applied. The potential ecological significance of weathering processes in altering substratum properties and hygro-thermal behaviour is also recognised (Coombes and Naylor 2012). For example, weathering morphologies on limestone—which develop relatively quickly in the intertidal zone—can support rich species assemblages (Coombes 2014), as demonstrated on older historic structures (see Firth et al. 2013c and Moschella et al. 2005 in reference to Plymouth Breakwater).

Concrete, which can be cast in situ or used as precast units (Allen 1998; CIRIA 2010), typically lacks fine-scale topographic complexity when produced using standard moulding techniques (Fig. 1). Furthermore, a disproportionately small amount of experimental work has been done on the responses of intertidal species using, specifically, marine-grade concrete (e.g. Anderson and Underwood 1994; McGuinness 1989) and even less on concrete manipulation at a sub-centimetre scale (e.g. Borsje et al. 2011; Perkol-Finkel and Sella 2014). This is a significant knowledge gap given that concrete is perhaps of greatest applied relevance in a context of coastal urbanisation, habitat homogenisation, and biodiversity conservation (Hawkins 2012). Certain concrete chemistries may also limit (via exclusion and/or delay) the development of epilithic communities, via pH effects and metal leaching for example (Terlizzi and Faimali 2010; Wilding and Sayer 2002). More broadly, the potential to generate novel ecosystem service flows using ecological engineering techniques in urban environments, including biodiversity maintenance, is underexplored in the marine realm (Gaston et al. 2013).

To address this gap we tested the hypothesis that the settlement and recruitment of a dominant early colonist (barnacles) on marine-grade concrete would vary between treatments with different fine-scale (millimetre) surface textures. We focus on barnacles as they have been described as ‘ecosystem engineers’ in the intertidal zone, having a facilitative role in the establishment and maintenance of other species’ populations through the provision of physical habitat structure (e.g. Harley 2006; Sueiro et al. 2011). For example, the presence of empty barnacle shells (called ‘tests’) and within-test habitat has significant impacts on community development, including the abundance and diversity of algae, sessile and motile invertebrates, and fishes (e.g. Barnes 2000; Bros 1987; Farrell 1991; Harley and O’Riley 2011; Thompson et al. 1996). We therefore aimed to determine whether fine-scale textural manipulation can be used to enhance concrete for barnacles and, as a consequence, offers opportunities to support greater species richness.

2. Materials and Methods

Small settlement tiles (5 cm x 5 cm x 3 cm) of marine-grade concrete (BS EN 197-1) were cast specifically for purpose using a mix of Portland cement (350 kg/m^3), sand (640 kg/m^3), and crushed granite aggregate (nominal maximum size = 40 mm, 1280 kg/m^3). A free water cement ratio of 0.5 was used without admixtures (Allen 1998; CIRIA 2010). The tiles were cast in a steel mould coated with releasing fluid, vibrated, and cured for 7 days in a lime-water curing tank at 21°C. Compressive strength at 28 days was 48 MPa (BS EN 12390-2).

Before the tiles had fully cured, four different textural finishes were applied: (1) control (plain-cast with no additional treatment), (2) smoothed, (3) grooved and (4) exposed aggregate, as described in Table 1. Representative surface profiles of the treatments are shown in Fig. 2 for comparability.

In early May 2010, experimental plots were established at Mean Tide Level (MTL) on two semi-horizontal rocky shores in South West England, UK, roughly 20 km apart (Fig. 3). Shore 1 (Tregear Point, near Porthleven) is south-west facing and composed of Devonian age dark grey rocks of the Mylor Slate Formation. Shore 2 (Gala Rocks, near Zennor) is north-west facing and is composed of basaltic rocks with intrusions of granite and serpentines. Quadrat sampling showed that Chthamalid barnacles occupied the majority of space at MTL on both shores (85 $\pm$ 10 % at Tregear Point and 80 $\pm$ 20 % at Gala Rocks, two-sample $t(28) = 1.35$, $p = 0.19$). Distinction between the two dominant co-occurring Chthamalid species on these shores (*C. montagui* Southward and *C. stellatus* Poli) was not made for the purposes of this study, having overlapping ranges in this area (Southward 2008). The cold-water, earlier-settling barnacle *Semibalanus balanoides* (Linnaeus) also occurs at Gala Rocks in relatively low numbers, but is largely absent at Tregear Point. Limpet densities indicated that grazing pressure was higher at Gala Rocks, but comparable to Tregear Point (26 $\pm$ 4 m^{-2} and 24 $\pm$ 3 m^{-2}, respectively, two-sample $t(28) = 1.83$, $p = 0.08$).

On each shore, 50 clearings were made by removing the existing cover of barnacles with a paint scraper and wire brush, maintaining a spacing of at least 30 cm. A blowtorch was applied to the rock clearings to control for the possible influence of biochemical cues (from biofilm and remains of conspecifics) on larval settlement (e.g. Thompson et al. 1998). This was done before the *Chthamalus* spp. settlement season, which begins in early-mid July in South West England (Southward 2008). On each shore, ten replicates of the four concrete treatments were randomly assigned to the clearings and fixed in place using marine epoxy. The remaining ten clearings were used to monitor colonisation of the natural rock, which had comparable surface roughness to the 'exposed aggregate' concrete (Fig. 2e–f).

2.1. Settlement and recruitment

Once the first Chthamalid larvae (cyprids) were detected (in mid-July) both shores were visited periodically and digital photographs were taken of each treatment. Between mid-July and early November Tregear Point was visited 16 times where settlement was heavy, and Gala Rocks was visited 4 times where settlement was considerably lighter. The number of barnacle cyprids (settlement) and metamorphosed juveniles (recruitment) were subsequently counted on each treatment by superimposing a grid over the photographs using ImageJ computer software. Counts were not made within 5 mm of the treatment edges to avoid possible edge effects, giving a sampling area of 16 cm^2 in each case. For the clearings on the natural rock, small stainless-steel tags glued to the surface during installation were used as reference markers to ensure that counts were made within the same area on each visit. Final counts of established recruits were made in mid-November when settlement had finished.

2.2. Species richness

The primary focus of this paper is the influence of fine-scale textural manipulation of concrete on barnacle colonisation. However, supplementary data were also collected to assess the potential significance of enhancing for barnacles for biodiversity more broadly. For this, subsequent observations of remaining tiles on both shores were made after three settlement seasons (in January 2013), when the number of adult barnacles and associated invertebrate species were recorded by functional group (e.g. Firth et al. 2014).

2.3. Data analysis

Cyprid counts were generally very low at Gala Rocks on the dates visited and as such a meaningful analysis of these data was not possible. However, a significant settlement event captured at Tregear Point on 13th August enabled us to test the hypothesis that cyprid settlement would differ between texture treatments on this shore. For this, a one-way Analysis of Variance (ANOVA) was performed using cyprid counts with ‘treatment’ as a fixed factor (five levels: control concrete, smoothed concrete, grooved concrete, exposed aggregate concrete and cleared rock).

The hypothesis that barnacle recruitment would differ between treatments was tested across both shores by performing a two-way ANOVA on counts of recruits present at the end of the settlement season (November). For this test ‘shore’ was a random factor with two levels (Tregear Point and Gala Rocks) and ‘treatment’ was a fixed factor with five levels, as above. A Cochran’s test was used to check for data heterogeneity, which was corrected for using transformation where appropriate. Post-hoc pairwise comparisons were performed using Student-Newman-Keuls (SNK) tests. All tests were performed using GMAV5 software (Underwood et al. 1997).

3. Results

3.1. Barnacle cyprid settlement

An appreciable settlement of *S. balanoides* had occurred at Gala Rocks during the period between the tiles being deployed in May and the first Chthamalid cyprid counts on 25th July, but this was almost exclusively within the rock clearings. At Tregear Point the first Chthamalid cyprids were recorded on 17th July and, in comparison to Gala Rocks, settlement of *S. balanoides* was negligible across all treatments on this shore.

Chthamalid cyprids were observed on each visit (on both shores) in July and August, on every treatment except four smoothed concrete tiles at Gala Rocks. An ANOVA performed using data for a heavy settlement event at Tregear Point (13th August) showed that textural treatment had a significant influence on cyprid settlement, $F(4, 45) = 17.51$, $p < 0.001$ (Table 2, Fig. 4). Here, significantly fewer cyprids settled on smoothed concrete and significantly more settled on grooved concrete compared to the other treatments, which were not different.

3.2. Barnacle recruitment

Metamorphosed recruits were always observed first in association with the particular textural features of each treatment. This included air holes in the control concrete, the ridges of the grooved concrete, and the pits on the naturally weathered rock. At Tregear Point, recruitment to these three treatments was similar for the first three weeks of monitoring, after which a marked relative increase was observed on the grooved tiles (Fig. 5). Grooved concrete also had the highest numbers of recruits of all the treatments on each visit to Gala Rocks. On both shores, smoothed concrete tiles consistently had the lowest numbers of recruits on successive visits.

By the end of August, differences in recruitment between treatments were pronounced, and these patterns persisted to the end of the settlement season (Fig. 6). An ANOVA performed using final counts made in November showed that the effect of 'treatment' was significant, but interaction between 'treatment' and 'shore' indicated that the magnitude of this effect varied between locations (Table 3). Smoothed concrete had fewer recruits than all other treatments at Tregear Point, followed by control concrete and exposed aggregate concrete. Clearings on the natural rock and the grooved concrete had significantly more recruits than the other treatments on this shore, but were themselves not different (Fig. 6). At Gala Rocks, lowest and highest numbers of barnacle recruits also occurred on smoothed and grooved concrete, respectively. Here, recruitment to the control concrete was comparable to clearings on the natural rock, both of which had fewer barnacles than the other treatments (Fig. 6). Overall, recruitment was significantly lower at Gala Rocks compared to Tregear Point, $F(1,90) = 196.46$, $p < 0.001$ (Table 3).

3.3. Species richness

The vast majority of tiles were lost to waves between the last barnacle monitoring visit (November 2010) and when the sites were revisited in January 2013 (after 32 months). However, counts of invertebrate species richness were made on all remaining tiles (n = 10). After this time adult barnacle abundance was strongly associated with invertebrate species richness, $R^2 = 0.90$, $p < 0.05$ (Fig. 7). The limitations of these data are recognised but nevertheless are discussed in support of the likely positive influences of barnacles on community diversity as previously reported in the literature (see Section 4).

The highest number of species (seven in addition to barnacles) was recorded on a grooved tile that also had the highest barnacle abundance (95% cover). Comparatively, three tiles with the lowest number of barnacles (two smoothed and one plain-cast treatment) had ephemeral green algae (Chlorophyta) but no additional invertebrate species. Gastropoda (*Patella* sp.) were common to most of the remaining tiles and other organisms present included Insecta (*Anurida maritima* Guérin), Malacostraca (*Bathyporeia elegans* Watkin), and juvenile Bivalva (*Mytilus edulis* L.). Although macroalgae (*Fucus vesiculosus* L. and *Ascophyllum nodosum* L.) were present within all of the rock clearings after 32 months—some being completely recolonised at Tregear Point—no macroalgae were present on any of the remaining concrete tiles after this time.

4. Discussion

The settlement and recruitment of Chthamalid barnacles varied significantly between concrete with different fine-scale surface textures, and between concrete and naturally weathered rock. On two different shores, a significantly greater number of barnacles colonised concrete with a grooved texture and significantly fewer colonised smoothed concrete. At the end of the settlement season tiles with a plain-cast finish (the control treatment) had fewer recruits than all but the smoothed tiles, indicating that this standard surface finish is a poor surrogate for natural rocky substrata, at least with respect to barnacle recruitment.

Observed differences were likely the result of a combination of settlement and post-settlement processes, which are mediated to varying degrees by substratum physical properties (Connell 1985). Biochemical cues from biofilm and the presence of conspecifics are particularly important for larval settlement (Le Tourneux and Bourget 1988; Pendergast et al. 2009), but this was controlled for here. Given that concrete tiles were made using the same mix, the influences of physical substratum properties on settlement and post-settlement survival, such as chemical composition, colour, hardness, and weatherability (e.g. Herbert and Hawkins 2006), are also likely to be minimal. Rather, substratum physical complexity is thought to have an overriding influence on the settlement and subsequent recruitment and survival of barnacles, as well as many other epibenthic organisms (e.g. Chabot and Bourget 1988; Savoya and Schwindt 2010; Wethey 1986).

Substratum roughness influences settlement, often involving active larval searching behaviour (e.g. Thompson et al. 1998), as well as post-settlement processes via influences on attachment strength and refuge provision (e.g. Aldred et al. 2010; Walters and Wethey 1996). At Tregear Point, recruitment patterns can be explained at least partly by the influence of substratum texture on cyprid settlement. Here, significantly more cyprids settled on grooved concrete compared to the other treatments, which had the highest number of recruits at the end of the settlement season. Similarly, smoothed concrete had both fewest settlers and significantly fewer recruits at the end of the season. However, no difference in cyprid settlement was found between the control and exposed concrete tiles and the rock clearings, which indicates that settlement patterns alone cannot explain relative differences in adult recruitment. Rather, post-settlement and post-recruitment mortality may have also differed as a function of substratum texture. For example, higher post-recruitment mortality has been observed on the plain-cast (control) concrete compared with the other treatments used in this study (Coombes 2011). This was attributed to competition for space within the millimetre-scale air holes in which Chthamalid cypris larvae preferentially settled. This means that whilst plain-cast concrete may initially support comparable numbers of barnacle recruits as natural rock (Fig. 5), numbers of established adults may ultimately be lower on concrete due to higher post-recruitment mortality (Fig. 6).

By the end of the settlement season most recruits were counted not on the roughest treatment (exposed aggregate concrete) but on tiles with intermediate roughness (grooved concrete), on both shores. This may reflect the fact that direct geometric measures of roughness (such as *Ra* in Fig. 2) do not necessarily reflect favourable scales of roughness for colonists, which probably relate more to the size of the settling body and its attachment structures (Herbert and Hawkins 2006; Hills and Thomason 1996; Walters and Wethey

1996). For *Chthamalid* spp. cyprids, which have a length of around 0.5 mm, topographic elements in the order of 1 mm and less are likely to represent the most suitable settlement sites. In their study of *C. montagui*, Herbert and Hawkins (2006) found that natural substratum microtopography was an important factor in recruitment to different calcareous rocks in southern England, and for *S. balanoides* Hills and Thomason (1998) found a preference for fine scale (<0.5 mm) and medium scale (0.5–2.0 mm) roughness elements compared to smoother and rougher alternatives. In this study, the millimetre and sub-millimetre scale ridges of the grooved concrete (Fig. 2c) proved more favourable for Chthamalid cyprids than the coarser roughness of the exposed aggregate treatment. This was reflected by the typically uniform alignment of cyprids and juveniles along the ridges of this treatment observed in the field. Settlement on the control tiles also occurred first in the small (typically < mm) air holes present on their surfaces, and on the exposed aggregate concrete and rock clearings in association with pits, ridges and other weathering forms. In comparison, settlement and recruitment on the smoothed concrete (on which air holes were removed during the curing process) were correspondingly low. These results are not unexpected (e.g. Crisp and Barnes 1954), but our data demonstrate how increasing the availability of such fine-scale features artificially—by manipulating surface roughness—can have significant impact on early-stage colonisation of common engineering materials.

Our finding that the strength of the effect of texture on barnacle colonisation varied between shores (Table 3) is of particular interest, and may be explained by overall differences in barnacle supply. For example, Raimondi (1990) suggests that spatial differences in the settlement of a different chthamalid barnacle (*C. anisopoma*) on rocky shores in the Gulf of California occurred only when settlement was relatively high, and thus when the availability of surface pits and depressions became a limiting factor (a 'saturation' effect). In a similar way, the comparatively low numbers of barnacles at Gala Rocks overall probably meant that texture had less of an influence here compared to Tregear Point, where settlement and recruitment were much higher. Furthermore, barnacle settlement is gregarious (Bracewell et al. 2013; Southward 2008), so that attracting initial colonists will probably favour subsequent settlement and recruitment, reinforcing any initial textural influences to some degree. Competition with the earlier-settling *S. balanoides* at Gala Rocks may also have influenced Chthamalid recruitment here, through exclusion effects (Connell 1961). Indeed, some *S. balanoides* recruits were observed here within rock clearings before *Chthamalus* spp. settlement had begun, and end-of-season recruitment to this treatment was unexpectedly low relative to the concrete tiles when compared to patterns at Tregear Point (Fig. 6).

4.1. Implications for ecological enhancement of coastal structures

The rate and success of larval settlement and recruitment of early colonists are limiting factors in the development of more complex and diverse intertidal assemblages (Anderson and Underwood 1994; Connell et al. 1987; Farrell 1991; Gaines and Roughgarden 1985). The exclusion of barnacles through a lack of fine-scale settlement sites (as is likely on typically smooth engineered structures) has important implications for the ecological potential of concrete structures in the coastal zone. Barnacles are known to facilitate later arriving invertebrates through the provision of biogenic habitat structure (e.g. Farrell 1991; Harley 2006; Thompson et al. 1996), and our supplementary observations after 32 months support this (Fig. 7). As such, targeting early colonists like barnacles by manipulating fine-scale surface texture offers opportunities for enhancing the local biodiversity value of concrete structures where they have to be built, and for supporting marine biodiversity conservation more widely. This includes higher organisms such as some species of fish, which are known to feed on invertebrate communities growing on marine infrastructure (e.g. Wilhelmsson et al. 2006).

'Kick-starting' succession in this way could prove particularly important for structures on which species may otherwise be excluded. This not only includes those lacking suitable settlement sites (i.e. those that are smooth) but also where colonists may be easily out-competed by dominant or invasive species, and where the provision of physical refuge will be most important, such as at the edges of species' vertical ranges. For relatively 'young' engineering materials on which weathering morphologies are largely absent, applying fine-scale roughness offers a way of compensating for the lack of natural physical habitat structure.

These principles have broader implications for biodiversity conservation, ecological enhancement, and restoration more generally, by demonstrating how conservation/enhancement activities targeted towards key species, such as other 'ecosystem engineers' and 'niche constructors' (Boogert et al. 2006; Jones et al. 1994; Wright and Jones 2006), may be one effective strategy. This may be especially true where resources and/or ecological potential are generally limited, such as may be the case in some urban areas (McKinney 2006). Our data demonstrate that in the case of hard coastal infrastructure, a fine, grooved texture can support comparable numbers of barnacles to naturally weathered rock, and this is expected to lead to the faster establishment of a greater range invertebrate species relative to smooth materials.

Where required, the potential for fine-scale textural manipulation to exclude rather than promote ‘fouling’ organisms (Terlizzi and Faimali 2010) is also worth highlighting, by using smooth concrete over rough for example. This is especially the case where exclusion of invasives or species that are not common to an area is a management objective. This may be the case in some ports and harbours, or where little or no ‘natural’ hard-bottomed communities exist (Hulme 2009).

As with any approach to ecological enhancement it is important to note that the potential for design interventions to yield appreciable increases (or decreases) in species abundance and diversity will be site dependent, as factors such as tidal height and local larval supply will often have overriding control on community development (Burcharth et al. 2007). This was demonstrated here by a clear difference in the magnitude of the effect of texture on barnacle colonisation between the two experimental shores. Ecological enhancement via the manipulation of habitat structure is widely seen as having strong potential for supporting conservation efforts in urbanised coastal environments (Chapman and Underwood 2011; Firth et al. 2014; Moschella et al. 2005), but requires careful consideration on a case-by-case basis.

5. Conclusions

Simple and inexpensive manipulation of concrete surface texture, at finer scales than previously tested, can promote colonisation by intertidal barnacles. As a key ecosystem engineer, this provides opportunities for enhancing the conservation value of urban marine infrastructure, by facilitating the provision of biogenic habitat. Several areas now need further research attention. First, the influence of textural manipulation on the development of epibenthic assemblages over longer periods of time needs to be assessed. Specifically, whilst we found some evidence that enhancing concrete for barnacles was associated with more invertebrate species after few years, it remains to be tested whether this translates to appreciable increases in local biodiversity over engineering timescales (decades–centuries). The ability of ‘enhanced’ structures to support biodiversity at the regional scale also needs more attention. Greatest potential here exists in regions where urban structures are particularly common, such as areas of the Adriatic Sea (Airoldi et al. 2005), and where built structures represent possible refuge or stepping-stones for species responding to climate change (Firth et al. 2013a; Hawkins et al. 2008). The extent to which enhancing coastal structures may aid the dispersal of invasive species is also an issue of on-going research priority (Bulleri and Airoldi 2005; Glasby et al. 2007).

More broadly, further testing is needed of the potential for textural manipulation (and other forms of ecological engineering) to contribute to management goals at the coast, in addition to biodiversity conservation. This might include targeting commercially valuable species (e.g. Martins et al. 2010) or those that may provide protection from deteriorative marine agents in a context of engineering durability (e.g. Coombes et al. 2013; Lv et al. 2015; Perkol-Finkel and Sella 2014). There is much potential here for incorporating concepts of 'multifunctionality' and ecosystem services more fully into coastal planning and engineering design, to support broader biodiversity conservation goals (Mander et al. 2007). This said, many engineering questions remain as to the implications of encouraging marine species on concrete, as well as other construction materials, and these need to be addressed using experimental and applied examples before widespread application can be expected (e.g. Coombes et al. 2012). This includes issues of chloride ingress and salt attack, drag coefficients and hydrokinetic loading, thermal decay, aesthetics, and whole-life performance (CIRIA 2010). Epilithic organisms likely have both positive and negative impacts in these respects, all of which warrant further attention.

Pragmatically, the feasibility of reproducing ecologically favourable textures during the manufacturing process needs to be examined. This will necessarily involve developing novel moulding techniques, for example, alongside the incorporation of larger-scale habitat features in pre-cast units and during on-site construction. These options are already receiving promising attention as viable possibilities (see Perkol-Finkel and Sella 2014). In practice, the incorporation of physical heterogeneity at a range of spatial scales offers the greatest potential for ecological enhancement in coastal engineering. Fine-scale (millimetre–

centimetre) textures like those tested here can facilitate (or conversely exclude, if required) settlement and recruitment by sedentary organisms such as barnacles, while larger-scale (centimetre–meter) water-retaining features such as holes and pools provide refuge for motile species that may otherwise be absent. 'Multi-scale ecological engineering' is therefore likely to prove the most successful approach to maximising the ecological potential of hard marine infrastructure, and for supporting biodiversity conservation in urbanised coastal regions.

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Table 1. Texture treatments applied to marine concrete

	Production method	Surface roughness	Indicative roughness (R)*
Control (plain-cast)	Standard casting and curing procedures (see Section 2) – no further manipulation was applied.	Smooth surface with the exception of small holes (a few millimetres in diameter Fig. 2a) formed from air bubbles settling out of the mixture whilst curing. Comparable to the surfaces of precast armour units (e.g. tetrapod units) and precast/site-cast structures.	R = 1.09 (R = 1.31 including air holes)
Smoothed	Tiles wiped with a fabric cloth during the curing process, whilst semi-dry.	Slightly more undulating than the control treatment, but without the presence of air holes.	R = 1.12
Grooved	Tiles wiped with a course wire brush during the curing process, whilst semi-dry.	A millimetre-scale texture, with a regular grooved finish.	R = 1.52
Exposed aggregate	Upper layer of cement washed away during the curing process using a water jet.	A millimetre–centimetre scale, spatially-variable texture. Most comparable in texture to the naturally weathered rock on both experimental shores.	R = 1.92

*R = Tr/Tt, where Tr = length of profile trace and Tt = measurement distance (*n* = 10); representative surface profiles of each treatment are shown in Fig. 2.

Table 2. ANOVA result for numbers of cyprids counted on textured concrete and rock clearings for a heavy settlement event at Tregear Point, 13th August 2010 (n = 10)

Source of variation	**d.f.**	**MS**	***F***	***p***
Treatment	4	6.40	17.51	0.001
RES	45	0.37	–	–
Total	49	–	–	–

Table 3. ANOVA result for numbers of *Chthamalus* spp. recruits counted at the end of the settlement season (November 2010) on textured concrete and natural rock on two shores in Cornwall, UK (n = 10)

Source of variation	**d.f.**	**MS**	***F***	***p***
Shore = Sh	1	595.95	196.46	0.001
Treatment = Tr	4	389.82	13.49	0.014
Sh x Tr	4	28.89	13.49	0.001
RES	90	3.03	–	–
Total	99	–	–	–

Figure Captions

Fig. 1. Concrete coastal structures with typically vertical, relatively smooth surfaces often have limited ecological value

Fig. 2. Representative surface profiles for all experimental treatments

Fig. 3. Location of experimental shores in South West England, UK

Fig. 4. Mean (+SE, n = 10) number of barnacle cyprids counted on each treatment for a heavy settlement event at Tregear Point on 13th August (for post-hoc comparisons ‘<’ denotes p = 0.05, ‘<<’ denotes p = 0.01, and ‘=’ denotes no significant difference)

Fig. 5. Mean (+SE, n = 10) number of metamorphosed *Chthamalus* spp. recruits counted on all treatments in July and August 2010 at Tregear Point, Porthleven (points have been shifted slightly for clarity)

Fig. 6. Mean (+SE, n = 10) number of *Chthamalus* spp. recruits counted on all treatments at the end of the settlement season (November 2010) at Porthleven (black bars) and Gala Rocks (white bars). For post-hoc comparisons ‘<’ denotes p = 0.05, ‘<<’ denotes p = 0.01, and ‘=’ denotes no significant difference)

Fig. 7. Invertebrate species richness and barnacle abundance on remaining concrete tiles after 3 seasons (32 months)