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Cool barnacles: Do common biogenic structures enhance or retard rates of deterioration of intertidal rocks and concrete?

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Abstract

Sedentary and mobile organisms grow profusely on hard substrates within the coastal zone and contribute to the deterioration of coastal engineering structures and the geomorphic evolution of rocky shores by both enhancing and retarding weathering and erosion. There is a lack of quantitative evidence for the direction and magnitude of these effects. This study assesses the influence of globally-abundant intertidal organisms, barnacles, by measuring the response of limestone, granite and marine-grade concrete colonised with varying percentage covers of *Chthamalus* spp. under simulated intertidal conditions. Temperature regimes at 5 and 10 mm below the surface of each material demonstrated a consistent and statistically significant negative relationship between barnacle abundance and indicators of thermal breakdown. With a 95% cover of barnacles, subsurface peak temperatures were

reduced by 1.59°C for limestone, 5.54°C for concrete and 5.97°C for granite in comparison to no barnacle cover. The amplitude of short-term (15–30 min) thermal fluctuations was also buffered by 0.70°C in limestone, 1.50°C in concrete and 1.63°C in granite. Furthermore, concentrations of potentially damaging salt ions were consistently lower under barnacles in limestone and concrete. These results indicate that barnacles do not enhance, but likely reduce rates of mechanical breakdown on rock and concrete by buffering near-surface thermal cycling and reducing salt ion ingress. In these ways, we highlight the potential value of barnacles as agents of bioprotection. These findings support growing international efforts to enhance the ecological value of coastal structures by facilitating their colonisation (where appropriate) through design interventions.

Keywords: biogeomorphology; bioprotection; rock coasts; weathering; ecological enhancement; biodeterioration

1. Introduction

The type, extent and complexity of organisms colonising rocky surfaces (including diversity and function) can vary considerably between environments—both natural and artificial—and over time. This is due to the complex interplay of a range of internal factors (e.g., substrate chemical and physical properties) and external factors (e.g., supply of colonists, climate, microclimate, nutrient supply and disturbance regimes) (e.g., Darlington, 1981; Jackson, 2003; Viles et al., 2008). Substrate–coloniser interactions are not simply one-way, however, as epilithic organisms can modify surface properties (including porosity and thermal behaviour) in active and passive ways (e.g., Carter and Viles, 2003; Trudgill, 1987). These influences can alter the efficacy of weathering processes (e.g., Gowell et al., 2015) and the potential suitability of a surface for subsequent colonisers (e.g., Coombes et al., 2015b; Pinn et al., 2008).

Organic involvement in the removal and/or chemical transformation of rock and stone is conceptualised as ‘bioweathering’ and ‘bioerosion’ by geomorphologists (e.g., Naylor et al., 2002; Viles, 2013) and ‘biodeterioration’ by engineers and built heritage scientists (e.g., Dornieden et al., 2000; Sanchez-Silva and Rosowsky, 2008; Warscheid and Braams, 2000). In the natural world these interactions contribute to the formation of distinctive topographical features (landforms) across a range of spatial and temporal scales (see Viles, 1988; Coombes, 2016 and references therein). The colonisation of engineered/built structures is, however, associated with concerns over the progressive loss of functional, and aesthetic and other social values (Harbulakova et al., 2013; Lyytimäki et al., 2008). In contrast, the notion of organisms as protective agents (‘bioprotection’) is broadly recognised within geomorphology (Carter and Viles, 2005; McIlroy de la Rosa et al., 2013). For

example, higher plants have been found to alter weathering regimes by (passively) modifying near-surface microclimates and the delivery and uptake of moisture and other deteriorative agents, including salts, to the surfaces of building stone (e.g., Hanssen and Viles, 2014; Sternberg et al., 2011). Whilst the concept of bioprotection sits well under the broader paradigm of ecosystem service provision (Bolund and Hunhammar, 1999; Costanza et al., 1997), the potential protective roles of organisms growing on hard engineered structures (e.g., Borsje et al., 2011; Coombes et al., 2013a) remains under explored.

1.1 Coastal rocks and engineered structures

In contrast to the active roles of organisms in the bioerosion of coastal rocks (Coombes, 2014; Mottershead, 2013; Naylor et al., 2012; Spencer, 1988), the passive influences of organic covers on rock breakdown in this environment have been little studied (see Moura et al., 2012 for an exception). For example, temperature cycling within rocky substrates is indicative of mechanical stresses that are implicated in both fine-scale and landform-scale geomorphological change (e.g., Aldred et al., 2016; Collins and Stock, 2016; Eppes et al., 2015; Hall and Thorn, 2014; Vasile and Vespremeanu-Stroe, in press). In these respects, organic modulation of thermal regimes (both surface and subsurface) has potential importance for the efficacy of mechanical weathering, topographic change, and material decay (Coombes et al., 2013a).

Lichen and even microbial biofilms are implicated in short-term (hourly to diurnal timescales) swelling and shrinking of coastal rocks via albedo effects and moisture retention (Gómez-Pujol et al., 2007; Mayaud et al., 2014). And seaweeds have been shown to buffer surface thermal extremes and limit the amplitude of temperature and

humidity cycles over diurnal and shorter timescales (Coombes et al., 2013a). In doing so, some organic covers are thought to limit wetting-drying cycles, and damaging salt crystallisation and hydration events (e.g., Gowell et al., 2015). In contrast to microorganisms and plants, we are aware of only one published empirical study (Pappalardo et al., 2016) exploring the potential influence of common sedentary marine animals (such as barnacles, mussels and encrusting worms) on rock breakdown in the coastal zone.

1.2 Ecological engineering at the coast

There is a proliferation of hard artificial structures globally including seawalls, groynes, breakwaters, piers, harbours and ports (Airoldi and Beck, 2007; Firth et al. 2016). The contribution of weathering to the progressive deterioration of construction materials is therefore of considerable interest to engineers and asset managers (CIRIA, 2007; Fookes et al., 1988; Özvan et al., 2011). Given that engineered structures offer novel surfaces for colonisation (Connell, 2001; Glasby and Connell, 1999; Moschella et al., 2005), organic influences on deterioration (whether negative or positive) are an important component of performance and durability to consider. At the same time, a recognition that artificial structures are often poor ecological surrogates for the natural rocky shores they may replace (e.g., Bulleri and Chapman, 2004; Gacia et al., 2007; Firth et al. 2013; Firth et al. 2016) is fuelling considerable international effort to develop and test ways of *encouraging* their colonisation. This includes structural design interventions and retrofit solutions aimed at facilitating settlement and recruitment of benthic species, to support biodiversity and maintain ecological function (e.g., Chapman and Blockley, 2009; Evans et al., 2015; Firth et al., 2014, Firth et al. 2016; Sella and Perkol-Finkel, 2015).

A potential conflict of interests therefore exists between efforts to enhance artificial structures for ecological gain (as novel habitats) and the need to maintain engineering function in the face of perceived biodeterioration risks. This is one barrier to wider uptake and testing of ecological enhancement techniques (Naylor et al., 2016; Naylor et al., under review). If common forms of organic growth are found to have negligible or minor impact on the durability of construction materials, or indeed acts as a 'buffer' against weathering-related deterioration, this can do much to allay concerns about actively encouraging colonisation of engineered structures. A robust evidence base on the nature of these effects is currently missing, particularly for organisms that are globally abundant on these kinds of structures.

1.3 Aims and approach

We aimed to examine the extent to which barnacle encrustation affects substrate thermal regimes and salt ion ingress. In doing so we explore the potential influences of barnacles on weathering of coastal rock and the deterioration of materials used in coastal engineering. Field-based microclimate data have proved extremely useful in weathering studies (e.g., Coombes et al., 2013a; Hall and André, 2001; Viles, 2005) but the extent to which surface measurements reflect subsurface regimes is unclear. This is a limitation because any organic influence on internal (i.e., subsurface) thermal cycling has more immediate relevance for deteriorative processes through the establishment of thermal gradients and associated stresses (e.g., Warke et al., 1996). Subsurface thermal monitoring in the field—and especially in the tidal zone—is, however, challenging at best. Laboratory simulations have therefore been used by weathering geomorphologists, allowing sample blocks to be prepared to consistent specification and electrical monitoring equipment to be employed with much greater confidence under strictly-controlled environmental conditions (e.g., Coombes, 2011a;

Smith et al., 2005; Trenhaile, 2006; Warke and Smith, 1998). Given the challenges of introducing living organisms to such set-ups there is a notable scarcity of data on organic influences on *subsurface* thermal regimes and, to our knowledge, no such data exist for rocky shore environments.

To address this gap we used pre-colonised materials to examine the influence of common biogenic structures (barnacle shells, called 'tests') on the subsurface thermal regimes of rock and concrete in the laboratory. We also compared the concentration of potentially deteriorative salt ions (chloride and sulphate) in these materials with and without a cover of barnacle tests. Barnacles were chosen as they are particularly common on intertidal rocks and readily colonise artificial structures. They have a free-swimming larval phase settling to sessile adults with hard tests composed of calcium carbonate (Southward, 2008). Tests remain affixed to the surface after the organism dies (and may persist for several months and years) making them particularly practical targets for a laboratory study. Furthermore, the establishment of barnacles is an important early step in the development of diverse benthic communities (Farrell, 1991; Harley, 2006; Tews et al., 2004; Thompson et al., 1996), and there is considerable opportunity to facilitate their settlement and recruitment to engineered surfaces (for ecological gain) using simple textural manipulation (Coombes et al., 2015a). The influence of barnacles on deterioration processes, such as thermal degradation and salt weathering, is therefore an important question we aimed to address.

2. Materials and Methods

2.1 Experimental blocks

Sample blocks (50 x 50 x 30 mm) of Portland limestone, Cornish granite and marine grade concrete were attached to two rocky shore platforms in Cornwall, UK, at mean tide level (see Coombes et al., 2011). After 32 months of exposure, five blocks of each material type that had been colonised by barnacles (*Chthamalus* spp.) to varying extents (0% to 95% cover, Table 1 and Figure 1) were removed for the temperature experiments. Those blocks with a relatively even distribution of barnacles (in contrast to those with spatially-clumped covers) were selected for these experiments. Control blocks that had been stored in the laboratory (having never been exposed to the sea) were used as a fresh 'unexposed' comparison.

The field-exposed blocks were dried in ambient conditions in the laboratory for several weeks prior to the experiments. This meant that the barnacles were no longer living but their test structures were retained, unaltered, attached to the rock/concrete surface. Mortality from predation, competition and other stochastic disturbance events means that a significant proportion of barnacle tests found on rocky shores do not contain living tissue (Barnes, 2000); at the time of block removal from the field, up to 80% of barnacle tests attached to the experimental shores were found to be empty. Our approach therefore allowed us to make controlled and broadly representative measurements in the laboratory for globally-abundant biogenic structures (barnacle tests) in the intertidal zone.

Prior to the start of the experiments blocks were coated with polyurethane varnish on all but the (colonised) upper face to restrict moisture movement through this one face (Coombes, 2011a; Smith and McGreevy, 1983). Two holes (3 mm diameter) were pre-drilled into the underside of each block (in the centre) to allow insertion of thermal probes to a depth of 5 mm and 10 mm from the upper surface (Figure 2a).

Using two depths allowed observation of thermal gradients developing within the blocks (e.g., Warke et al., 1996).

2.2 Intertidal simulation in the laboratory

The approach adopted involved measuring subsurface temperatures of the materials when placed in an environmental cabinet programmed to simulate temperate coastal (low tide) conditions. The thermal cycle used replicated a 6-hour low-tide event (in real time) as recorded on a hot summer day on a rocky shore in South West England (original data from Coombes, 2011a). The cycle consisted of a relatively constant rise in air temperature from 18°C (at initial tidal exposure) to 29°C (at re-immersion). Relative humidity was set at a constant 80% based on in situ measurements on a variety of coastal structures (Coombes et al., 2013a). In addition to ambient temperature regulated by the cabinet, an infra-red lamp was used to heat the samples. Direct heating in this way better reflects field conditions than indirect (convective) heating alone (Warke and Smith, 1998). The lamp was set to switch on/off at 15 minute intervals to simulate short-term fluctuations in temperature as frequently occur on rocky shores due to interruptions in insolation by passing cloud and wind gusts (Coombes, 2011a; Gowell et al., 2015).

The cabinet simulation was repeated five times per material group. In each case, five field-exposed blocks of either limestone, granite or concrete were used with barnacle covers ranging from 0% to 95%, plus one control block that had never been exposed to the sea (Table 1). Before each repeat, the blocks were placed in a tidal simulator. This was to ensure water and salt content was as comparable as possible to rocks exposed at low tide in the field. For the tidal simulator a similar set-up was used as described by Coombes (2011a) and Coombes and Naylor (2012). Briefly, a cycle of

synthetic seawater was established between two plastic tanks using aquarium pumps and electric timers. This simulated a semi-diurnal cycle (in real time) consisting of two 6-hour periods of immersion ('high-tides') and two 6-hour periods of exposure to the air ('low-tides') every 24 hours. Blocks were left to cycle in the tidal simulator for one week prior to the first cabinet simulation in order to attain a quasi-equilibrium saturation state (Trenhaile and Mercan, 1984).

At the start of each cabinet simulation blocks were removed from the intertidal set-up, all sides except the upper face were carefully dried with paper towel, and they were weighed. Drying the sides in this way ensured that weight change recorded during the cabinet simulations reflected evaporation from the colonised face only (as would be the case for in situ surfaces). Blocks were kept horizontal during this process to retain any water naturally ponded within the barnacle test matrix; our simulations therefore represent horizontal/near-horizontal rocky platforms and engineered surfaces. Thermistor probes (PB-5009-0M6, Gemini Data Loggers) attached to dual channel TinyTag data loggers (TGP-4520, Gemini Data Loggers) were fully inserted into the pre-drilled holes. The loggers recorded temperature continuously at 1-minute intervals. The blocks were placed in a tray of polystyrene beads (in an attempt to limit thermal exchange to the upper surface, e.g., Carter and Viles, 2003) and positioned under the lamp inside the environmental cabinet (SANYO-FE 300H, Figure 2b) for the duration of the cycle (6 hours). Once completed, blocks were removed from the cabinet, the temperature probes removed, and the blocks re-weighed and returned to the tidal simulator prior to subsequent repeat runs. Data were downloaded from the loggers onto a laptop using TinyTag Explorer software (SWCD-0040, Gemini Data Loggers).

2.3 Salt ion penetration

After almost 5 years (56 months) since initial exposure, loss of samples to waves limited the amount of material that was available for salt ion analysis. No granite blocks were available after this time, however two additional blocks of limestone and concrete were harvested. Holes were drilled into these blocks in areas with and without a cover of barnacles using a hand-held rotary drill. Drilling dust was collected using 'dust bubbles' (Dustbubble Ltd.) which was analysed for chloride and sulphate ions using ion chromatography (Dionex IC DX500) (e.g., Schnepfleitner et al., 2016). Holes were drilled in stages to obtain dust from four different depth zones (0–2 mm, 2–7 mm, 7–12 mm and 12–17 mm from the colonised surface).

2.4 Data analysis

Temperature data recorded at 10 mm depths (the maximum depth recorded here) were used to calculate two different metrics for each repeat run of the cabinet simulation: (1) peak temperature attained by each combination of material/barnacle cover class and (2) mean amplitude of thermal fluctuations induced by the lamp (i.e., the average of twelve 30-minute warming-cooling cycles from each 6-hour simulation). Vertical thermal gradients were also evaluated by calculating the maximum instantaneous difference in temperature between 5 mm and 10 mm depths for each block, during each simulation. These measures were chosen as indicators of internal mechanical stresses, reflecting thermal extremes and the magnitude and rate of thermal cycling within the substrates. Pre- and post-cabinet weights were used as a simple measure of evaporative water loss. For the analysis of salt ion concentrations, raw data (mg/L) were used.

For statistical evaluation, comparisons between experimental factors (material type and barnacle test cover class) were made using ANOVA (F) where possible. Where

significant differences were found, post-hoc comparisons (Holm-Sidak method) were used to determine which levels of the test differed from each other. Where non-normality (Shapiro-Wilk test) and unequal variance (Brown-Forsythe test) could not be corrected for using data transformation, non-parametric Kruskal-Wallis H tests (ANOVA on ranks) were performed with post-hoc Tukey HSD tests, as appropriate. All statistical tests were performed using SigmaStat5 analysis software.

3. Results

3.1 Subsurface thermal regimes

Representative temperature data recorded during the cabinet simulations are shown in Figure 3. The characteristic saw-tooth pattern induced by the lamp switching on and off (e.g., Gowell et al., 2015; Warke and Smith, 1998) is superimposed on a general trend of increasing temperatures that reflect the cabinet programme. Block temperatures frequently rose above ambient air temperature, although there were notable differences between blocks depending on barnacle cover (discussed in Sections 3.1.1 and 3.1.2). Relative humidity was maintained between 70% and 80% for all cabinet simulations.

3.1.1 Peak subsurface temperatures

The influence of barnacle cover on peak subsurface temperature (at 10 mm depth) was significant for all three materials ($H[5] = 18.93$, $p = 0.002$ for limestone; $H[5] = 23.79$, $p < 0.001$ for granite; $F[5] = 12.68$, $p < 0.001$ for concrete). The general pattern was for lower peak temperatures within blocks that had a greater cover of barnacle tests (Figure 3 and Table 2) although there were distinct differences

between material types. For limestone, peak temperatures were significantly lower with a 50% or more cover of barnacles in comparison to the bare unexposed control ($p = 0.01$, Table 2). For granite, blocks with 75% or more cover had significantly lower peak temperatures than the control ($p < 0.01$). For concrete, blocks with an almost complete cover of barnacles (95%) had significantly lower peak temperatures than unexposed controls and field-exposed blocks with a cover of 35% or less ($p < 0.01$). Those with 65% and 90% cover also attained significantly lower peak temperatures than field-exposed concrete without any barnacles ($p < 0.01$).

Regression analysis showed that barnacle test cover explained a high proportion of the variation in peak subsurface temperatures (76% for limestone, 77% for concrete and 87% for granite, Figure 4a and Table 2). This represents a reduction in peak temperatures for every 10% increase in barnacles in the order of 0.2°C, 0.4°C and 0.6°C for limestone, concrete and granite, respectively. For field-exposed blocks with the least (0%) and greatest (95%) covers, this amounted to a buffering of peak subsurface temperatures by 1.59°C in limestone, 5.54°C in concrete and 5.97°C in granite.

3.1.2 The amplitude of thermal fluctuations

Barnacle cover had a significant overall effect on the amplitude of short-term (30 minute) thermal fluctuations recorded at 10 mm depths ($H[5] = 18.66$, $p = 0.002$ for limestone; $F[5] = 35.99$, $p < 0.001$ for granite; $F[5] = 10.59$, $p < 0.001$ for concrete), but the magnitude of this effect varied between material types (Table 2). For granite, thermal fluctuations were significantly reduced with a cover of 75% or more relative to those with 45% or less ($p < 0.001$). Concrete with an almost complete cover of barnacles (95%) had significantly reduced thermal fluctuations relative to the control

($p < 0.05$, Table 2). Blocks with 65% cover or more also had significantly reduced fluctuations relative to the bare field-exposed block ($p < 0.05$). For limestone, there were no significant differences between control and field-exposed blocks, but those with 50% or more barnacles had lower amplitude thermal variations relative to those with 25% cover ($p \leq 0.01$, Table 2).

Barnacle cover explained 63% of measured variation in thermal cycle amplitude for limestone, 85% for concrete and 91% for granite (Figure 4b). Over the full range of barnacle covers tested (0% to 95%) subsurface thermal fluctuations were reduced by 0.70°C, 1.50°C and 1.63°C in limestone, concrete and granite, respectively.

3.3. Subsurface thermal gradients

Temperature differences measured between two depths (5 mm and 10 mm) were generally small (always less than 0.5°C) and were most pronounced during the warmest parts of the cabinet simulations (i.e., the final few hours) and in combination with direct heating from the lamp. For illustration, data for the final hour of simulation, when ambient temperatures were between 26°C and 29°C, are shown in Figure 5. Temperatures for field-exposed blocks with 0% and 95% barnacle cover are shown for comparison. Thermal variations (as induced by the lamp) were often less pronounced at 10 mm depths compared to 5 mm, but this effect was very small and likely reflects probes being relatively close together (Figure 5). In limestone, faster rates of thermal gain (when the lamp was on) and loss (when the lamp was off) by the outermost zone (to 5 mm depth) gave rise to frequent vertical temperature gradient inversions (Figure 5a). In a similar way, retention of thermal energy at depth coupled with more efficient cooling of the upper surface meant that slightly higher temperatures were sometimes recorded at 10 mm depths than nearer the surface,

especially during 'shade' periods (Figure 5b and Figure 5c). As well as overall lower temperatures and dampened thermal variations, the magnitude of thermal differences was buffered to some extent by a cover of barnacles (Figure 5).

Maximum recorded temperature differences between 5 mm and 10 mm depths are summarised in Table 3 and Figure 6. These tended to be slightly higher for limestone and concrete than for granite, but overall differences between material types were short of statistical significance ($H[2] = 5.08$, $p = 0.079$). Peak thermal gradients did vary significantly, however, between different barnacle cover classes for limestone ($F[5] = 3.98$, $p = 0.009$) and granite ($F[5] = 7.65$, $p < 0.001$), but not concrete ($F[5] = 1.11$, $p = 0.382$) (Figure 6). Pairwise comparisons showed that for field-exposed limestone, vertical thermal gradients were significantly reduced in blocks with 50% or more barnacle tests relative to those with none ($p \leq 0.02$, Figure 6). For field-exposed granite, blocks with 25% or more cover of barnacles had significantly lower peak thermal gradients relative to those with none ($p \leq 0.01$, Figure 6). Regression analysis indicated that barnacle cover explained 51% of the measured variation in peak thermal gradients in limestone, compared to 23% in granite and 11% in concrete (Table 3).

3.4 Evaporative water loss

Weight change during the cabinet simulations was used as a measure of evaporative loss (of water retained both by barnacle tests and within rock pores) and implied evaporative cooling (e.g., Gowell et al., 2015). The relationship between barnacle cover and weight loss is shown in Figure 4c. For all materials, a higher cover of barnacle tests resulted in greater evaporative loss during simulated 'low tide' periods (Table 2). This effect was significant for limestone ($F[5] = 3.49$, $p = 0.016$) and highly

significant for concrete ($F[5] = 72.19$, $p < 0.001$) and granite ($F[5] = 122.66$, $p < 0.001$). For granite, barnacle cover explained 91% of the variation in weight loss compared to 59% for concrete and 23% for limestone. Field-exposed limestone always lost more weight (through evaporation) than the unexposed control, and this difference was at or near statistical significance irrespective of barnacle cover ($p \leq 0.07$). Evaporative loss from granite was always significantly higher when colonised with barnacles (25% cover or more) compared to without ($p < 0.001$). A greater water loss from concrete with 65% or more cover of barnacles relative to the uncolonised control was also at or close to statistical significance ($p \leq 0.06$).

The relationship between weight change (evaporative loss) and subsurface thermal metrics is illustrated in Figure 7. Across all three materials, evaporative loss was associated with 58% of variation in the amplitude of thermal fluctuations and 73% of the variation in peak subsurface (10 mm) temperatures. There were, however, marked differences between material types; evaporative loss could explain 81% and 75% of measured variation in concrete and granite, respectively, but this was less than 0.1% for limestone (Figure 7).

3.5 Salt ion ingress

Concentrations of salt ions (chloride and sulphate) within limestone and concrete are shown in Figure 8, for areas with and without a cover of barnacle tests. At all depths, higher concentrations were found within concrete than in limestone, particularly sulphate. Ion concentrations varied significantly with depth in limestone, for both chloride ($F[3] = 16.92$, $p < 0.001$; Figure 8a) and sulphate ($H[3] = 25.30$, $p < 0.001$; Figure 8b), indicating progressively less penetration with depth. A similar pattern was found for sulphate in concrete ($H[3] = 16.04$, $p = 0.001$; Figure 8d) but was absent for

chloride (Figure 8c). Variability between samples was generally high meaning that differences between samples with and without a cover of barnacles were not statistically significant overall. A consistent trend for lower ion concentrations under barnacle tests was found however (Figure 8), and this was significant for chloride in limestone across the different depth zones (paired $t[3] = 3.653$, $p = 0.035$).

4. Discussion

4.1. Barnacle influences on material hygro-thermal behaviour

Using previously colonised samples, we found that barnacle tests significantly modify the subsurface thermal behaviour of rock and concrete to depths of at least 10 mm. Temperature extremes and fluctuations were reduced proportionally to barnacle abundance (Figure 4). This can, in part, be explained by the retention of moisture within barnacle test matrixes and enhanced evaporative cooling of the surface when exposed to external heating at low tide (Figure 4c). A similar 'passive' cooling mechanism has been suggested for other epilithic growths including microbial biofilms and seaweed canopies (Coombes and Naylor, 2012; Gowell et al., 2015), but our experiments provide the first evidence of this for sessile animals, and that this has a measurable effect below the surface.

Thermal buffering effects were complicated by differences in substrate physical properties. For the non-porous granite (porosity < 1%), very little water is absorbed and retained within the rock when submerged meaning that all available surface moisture was quickly evaporated upon exposure. The addition of barnacles, even at relatively low densities, therefore had a proportionally greater effect on evaporation

(explaining 91% of variation in granite, Figure 4c) and this explained 75% of the variability in subsurface thermal fluctuations (Figure 7). In marked contrast, limestone is relatively porous—16% in the case Portland Whitbed limestone used here. As such, this material absorbs and retains more water within its pore structure, meaning that the efficiency of evaporative cooling is, by comparison, sustained upon heating irrespective of barnacle cover. For example, barnacle cover explained only 23% of variation in evaporation from limestone (Figure 4c), and this was associated with less than 1% of the variation in subsurface thermal fluctuations (Figure 7). Furthermore, differences in thermal behaviour for limestone blocks with different barnacle covers were much less distinct, and were more variable between repeat experiment runs, than for the other materials (Figure 3, Table 2).

The marine grade concrete used in our experiments had a porosity similar to limestone (14%), yet its near-surface hygro-thermal behaviour was more similar to granite. This can be partly explained by the development of bio-chemical crusts after relatively short periods of intertidal exposure (Coombes et al., 2013b; Coombes et al., 2011). These crusts (which were absent from limestone and granite) limit water uptake and release relative to unexposed (i.e., fresh) concrete, and thereby moderate thermal gain and loss (Coombes and Naylor, 2012). For example, unexposed control concrete attained peak temperatures that were, on average, 2.3°C lower than field-exposed concrete despite both having no barnacles (Figure 3c). Short-term thermal fluctuations were also higher (by 0.5°C) for field-exposed concrete compared to the unexposed control (Table 2). These differences correspond to the reduced evaporative efficiency of field-exposed (i.e., crusted) concrete (Table 2, Figure 4c). Only when concrete was covered with a high

proportion of barnacle tests (65% or more) were subsurface thermal fluctuations equivalent to (or less than) those recorded for unexposed control samples.

These observations indicate that encrusting species such as barnacle will have, proportionally, a much greater influence on evaporation and near-surface thermal variability when growing on non-porous materials (granite and crusted marine concrete in this instance) compared to more porous rocks like limestone. These interactions are further moderated by bioerosive microorganisms, which act to increase near-surface pore space (particularly in calcareous rocks) once exposed in the intertidal zone (Coombes et al., 2011). With respect to moisture retention, the influence of surface orientation warrants further investigation given that retention (both on the surface and within biological structures) may vary considerably between horizontal (as simulated here) and vertical or sloping surfaces.

Substrate albedo, specific heat capacity and thermal conductivity also influence the responsiveness of rocky substrata to external heating (McGreevy, 1982; McGreevy, 1985), mediating the thermal influence of barnacles and other epilithic organisms. In our experiments granite (having a high thermal conductivity) showed the greatest response to radiative heating in the absence of barnacles (Figure 3). Some variability in vertical thermal gradients can also be explained by differences in substrate thermal conductivity (Warke et al., 1996). This may explain, for example, why peak gradients in the porous limestone correlated with barnacle cover more so than in the granite (Figure 6). Experiments using a wider range of depth measurements are needed to evaluate this further. Slight discolouration of field-exposed materials may also explain some of the differences in thermal behaviour relative to the unexposed controls (Warke et al., 1996). This included steeper vertical gradients in the bare field-exposed limestone and granite (0% cover) relative to bare control blocks

(Figure 6). Given that test structures are comparably light in colour, thermal-dampening by barnacles is expected to be greatest for darker-coloured rocks such as mudstones, shales, slates and basalts, which may be especially prone to thermal breakdown (Grab, 2007; Hall et al., 2005; Robinson, 1977). Alongside their influence on evaporative cooling, the influence of barnacle tests on surface albedo probably contributed to the observed thermal dampening, especially for the darker granite and crusted concrete (e.g., Warke et al., 1996).

4.2 Implications for rock breakdown and coastal engineering materials

4.2.1 Thermal shock

Relative to bare surfaces, lower thermal extremes meant that rates of warming were reduced under a near-complete (95%) cover of barnacles in the order of 39% for limestone, 58% for granite, and 59% for concrete. In real terms, measured rates of warming (always less than 0.2°C/min) are an order of magnitude below typically-quoted thresholds for thermal shock ($\Delta 2^\circ\text{C}/\text{min}$, Hall and Thorn, 2014; Richter and Simmons, 1974). This reflects the temperate summertime conditions simulated here (18°C to 29°C over a 6-hour period). The extent to which barnacles (and other forms of biological cover) buffer very rapid changes in temperature nevertheless warrants further investigation. This might include instantaneous cooling of solar-heated surfaces by incoming tidal waters (e.g., Robinson, 1977) and possible rapid heating/cooling in hotter and colder climates (Moukwa, 1990), for which very little data are currently available.

4.2.2 Thermal fatigue

Of more immediate relevance, the buffering influences of barnacles as measured here have significance for thermal 'fatigue'. This involves the progressive damage of a material via repeated thermal loading and the formation of tensile stresses that can eventually exceed elastic limits (see Hall and Thorn, 2014 for a comprehensive review). Crucially, this mode of breakdown can operate via low magnitude (but repeated) thermal cycling and can induce crack propagation along existing planes of weakness in rock masses (Eppes et al., in press). The frequency, magnitude and rate of temperature fluctuations are all important for the efficacy of thermal fatigue, as are inherent rock properties (Hall and André, 2001; Hall and Thorn, 2014). In these respects, our finding that barnacle tests have a significant influence on subsurface thermal extremes and short-term fluctuations (as well as vertical gradients, at least for limestone and granite) supports an argument for encrusting species having a bioprotective role with respect to temperature-related deterioration. This can operate via dampening of inter-mineral stresses in crystalline rocks such as granite (Gómez-Heras et al., 2006; Gómez-Heras et al., 2008) and tensile stresses associated with vertical temperature gradients and repeated thermal cycling in other materials like limestone and sandstone (Warke and Smith, 1998; Warke et al., 1996). In engineering, thermal fatigue is recognised as a deteriorative process affecting the durability of rock and natural stone (CIRIA, 2007; Halsey et al., 1998). Recently, Pappalardo et al. (2016) attempted to quantify the influence of barnacles (*C. montagui* and *C. stellatus*) on rock hardness directly (using a Schmidt Hammer) at a range of field sites in Italy. Their observations show that patterns were inconsistent between sites, and differences were generally inconclusive, or at most very small. Based on our observations, where the hardness of barnacle-colonised rock is lower

than bare surfaces, this is unlikely to be explained by enhanced mechanical breakdown associated with thermal cycling.

4.2.3 Concrete infrastructure

A possible protective role of surface-colonising organisms, even to relatively shallow depths of a few millimetres, has particular bearing on the durability of marine concrete. Apparently superficial deterioration can lead to more serious structural hazards by facilitating deeper migration of aggressive salt ions (Moukwa et al., 1989). This poses particular problems for reinforced structures via rebar corrosion (Alexander, 2016; CIRIA, 2010; Hobbs, 2001). As well as a potential role in limiting near-surface cracking and disintegration associated with thermal fatigue (Section 4.2.2), we found consistently reduced concentrations of salt ions under barnacle tests in concrete as well as limestone after almost 5 years of field exposure (Figure 8). This may reflect a reduced frequency of drying-out associated with thermal dampening and moisture retention, and thus a lower occurrence of damaging salt crystallisation events (e.g., Gowell et al., 2015). Thermal cycling has, for example, been shown to enhance chloride ion penetration into marine concrete (Taheri, 1998).

Salt ion patterns were variable for concrete, however, and the influence of barnacle cover may have been obscured by the heterogeneous mineralogy of the aggregate/cement matrix. Further experiments are required to examine salt penetration under different biological covers, and at greater depths. Our observations nevertheless support other studies finding that encrusting species may enhance the long-term resistance of marine concrete to salt ion penetration (Kawabata et al., 2012; Maruya et al., 2003).

4.3. Implications for ecology and ecological engineering at the coast

Biological structures have facilitative ecological roles by alleviating thermal and desiccation stresses for other species (e.g., Harley, 2006). The thermal biology of rocky shore species has received growing research interest (Carwright and Williams, 2014; Harley, 2013), yet the two-way feedbacks between epibiota, substrate thermal properties and near-surface microclimates have gained only limited attention (see Denny and Harley, 2006; Gedan et al., 2011; Miller et al., 2009). Our results indicate that in addition to the provision of physical habitat complexity and refuge, the physical ecosystem engineering roles of barnacles may also include microclimate moderation via influences on substrate thermal behaviour. There is much scope here to couple substrate thermal–hygric behaviours and organismal heat budgets (using field, laboratory and modelling studies) in a context of climate change (Helmuth, 2009). The mediating role of epibiota on substrate thermal behaviours has, for example, particular bearing on the structuring of intertidal communities under altered climates given that many species have very specific physiological tolerances (Bertness et al., 1999; Denny and Harley, 2006; Miller et al., 2009). On developed coastlines, could the use certain materials in engineering offer more favourable thermal conditions for temperature-sensitive species under a warmer climate (sensu Lima et al., 2016)?

Uncertainty concerning possible biodeterioration exists surrounding ecological enhancement that aims to encourage colonisation of engineered structures (Naylor et al., 2016). We have found that the tests of barnacles, which can be encouraged to colonise relatively simply (Coombes et al., 2015a), buffer thermal extremes and cycling within common construction materials. We also found evidence that altered hygro-thermal behaviour is coupled with differences the occurrence of deteriorative salt ions, which occurred in lower concentrations under a cover of barnacles. By

implication, the efficacy of deteriorative weathering processes (notably thermal fatigue and salt weathering) may be reduced. The relative bioprotective potential of encrusting species such as barnacles is heavily contingent on material and construction type and, perhaps to a greater extent, exposure conditions, but our observations provide some of the first evidence that these organic layers are probably more beneficial than deteriorative in a context of mechanical weathering. Efforts to facilitate colonisation of hard coastal structures primarily for ecological gains can therefore yield additional engineering benefits or, at worst, seem to have negligible impact on thermally-related deterioration of the near-surface zone.

Further evidence is now needed to determine the extent to which these influences translate to improved durability and service-life, requiring longer-term studies and integrated field and laboratory experiments focussing on direct measures of deterioration. Consideration is also needed of potential biological roles in other breakdown processes, as it is ultimately the balance and interaction of a suite of processes that contributes to the progressive deterioration of coastal rocks and structures. This includes possible enhancement of chemical weathering by moisture retention for example (e.g., Jayakumar et al., 2010).

5. Conclusions

Using three different materials, we found experimentally that substratum thermal extremes and fluctuations are buffered under barnacles to depths of at least 10 mm. Vertical thermal gradients were also reduced. These effects were broadly proportional to biomass (percentage cover) and were associated with enhanced evaporative cooling via water retention within test matrixes. Importantly, the

magnitude of these buffering effects was contingent on material properties such as porosity and thermal conductivity. These findings highlight the importance of 'rock control' in coastal weathering and erosion (Goudie, 2016; Naylor and Stephenson, 2010; Sunamura, 1994) and suggest that the occurrence, efficacy and rate of intertidal biogeomorphological processes (including bioprotection) are often contingent on rock type (e.g., Phillips, 2016).

More broadly, on rocky platforms the thermal and hygric influences of encrusting species may mediate episodic and rapid (block-scale) erosion (e.g., Naylor et al., 2012) and alter rates of topographic evolution via subaerial weathering (e.g., Moura et al., 2012; Stephenson and Kirk, 2000). As well as further work on barnacles, more evidence for the roles of other common encrusting species (such as mussels and encrusting worms) is needed. For coastal engineering and ecological enhancement, our experiments show that encrusting species do not exacerbate near-surface thermal cycling (and associated physical stresses) and may well provide durability benefits by limiting thermal fatigue and the penetration of deteriorative salt ions. By addressing some of the engineering concerns surrounding possible biodeterioration, our findings support the growing science of ecological enhancement in the coastal zone. Facilitating colonisation through design interventions for ecological gains could also improve engineering asset resilience by reducing mechanical weathering risks.

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Figure captions

Figure 1. Experimental blocks (50 mm x 50 mm x 30 mm) shown in colonised (95% cover) and control pairs (upper and lower row, respectively). Enlargement of colonised limestone block also shown.

Figure 2. (a) Schematic of a colonised block prepared for temperature monitoring (not to scale); **(b)** experimental samples positioned inside an environmental cabinet (see text).

Figure 3. Representative subsurface (10 mm depth) temperatures measured under simulated intertidal conditions for blocks of **(a)** Portland limestone, **(b)** Cornish granite and **(c)** marine concrete with different covers of barnacle tests.

Figure 4. Relationship between cover of barnacle tests (%) and key experimental metrics: **(a)** peak temperature attained (10 mm depth) during 6-hour low-tide simulations; **(b)** amplitude of short-term (30 minute) thermal fluctuations (10 mm depth) induced during the simulations, and; **(c)** water loss (g) during the simulations as an indicator of evaporative cooling. In all cases data points indicate mean values ($n = 5$). Linear regression lines and coefficient of determination (R^2) as indicated.

Figure 5. Illustrative subsurface temperatures recorded at two depths (5 mm and 10 mm) during the warmest part (the final hour) of simulated low-tide periods. Air temperature during this period rose at a constant rate between 26°C and 29°C. Two barnacle cover classes of field-exposed blocks are shown for comparison (0% and 95% cover).

Figure 6. Maximum instantaneous temperature differences between 5 mm and 10 mm depths (mean + SD, $n = 5$) during 6-hour low-side simulations with different covers of barnacle tests (cover classes are grouped for comparison, see Table 1).

Figure 7. Relationship between evaporative water loss and the amplitude of short-term (30 minute) subsurface thermal fluctuations (10 mm depth) during simulated low-tide periods. Data points indicate mean values ($n = 5$). Linear regression lines (dotted = concrete, dashed = granite) and coefficient of determination (R^2) as indicated; best fit line not shown for limestone as this relationship was not significant.

Figure 8. Concentrations of salt ions (chloride and sulphate) present within limestone and concrete at different depth zones under areas with and without a cover of barnacle tests. Mean + SD ($n = 5$). Samples exposed at mean tide level for 5 years. Note that different axis ranges have been used in each case to aid visualisation.

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