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BIOLOGICAL INFLUENCES ON INTERNAL STONE TEMPERATURES: LABORATORY PROCEDURES AND PRELIMINARY RESULTS FOR INTERTIDAL BARNACLES

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Abstract

The direct roles of microorganisms in the breakdown of rock and stone are well recognised. The ways in which animals, plants and microorganisms modify the efficiency of other weathering processes (both positively and negatively) are less well studied. Recently, macro-organisms (e.g., ivy and seaweed) have been suggested to have a bioprotective function via influences on microclimate, by buffering thermal extremes and dampening the temporal variability of temperature and humidity at the rock-air interface. While these studies are important with respect to rock breakdown, the influence of biota on internal rock temperature regimes and sub-surface thermal gradients may be more critical for the efficiency of deteriorative processes associated with thermal fatigue. However, these biogeomorphological interactions have proved particularly difficult to measure in the field.

We describe a novel laboratory-based approach for assessing the influence of epibiota on the internal temperature of rock when exposed to simulated field conditions. Blocks of materials used in coastal engineering (granite, limestone and marine concrete) colonised to varying degrees by encrusting barnacles (0% and 95% cover) were exposed to simulated intertidal conditions in the laboratory. Blocks were periodically placed in an environmental cabinet and subjected to conditions replicating a summertime low-tide event (6-hour warming period). Temperature probes positioned at varying distances below the surfaces of the blocks were used to record temperature within the materials. We present preliminary results suggesting that sub-surface thermal regimes contributing to the deterioration of coastal engineering materials are moderated by barnacles colonising their surfaces, and that the magnitude of the effect is related to substratum lithology and surface cover.

Keywords: bioprotection, thermal weathering, intertidal, barnacles, biogeomorphology

1. Introduction

The role of organisms in the deterioration and conservation of rock and stone cultural heritage is a strong sub-field of biogeomorphology (Siegesmund *et al.*, 2002; Viles and Cutler, 2012). Much of this work has focused on the direct biochemical and biophysical deteriorative influences (i.e., biodeterioration) of microorganisms on terrestrial buildings and monuments (Scheerer *et al.*, 2009; Viles, 2012). Microorganisms also influence stone thermal regimes by altering surface colour (Warke *et al.*, 1996) and via influences on porosity and evaporative cooling (Coombes and

Naylor, 2012). Microorganisms also have a protective role (i.e., bioprotection) through direct and indirect stabilisation effects (e.g., Hoppert *et al.* 2004; Viles, 2012).

In comparison, much less has been done to examine how macro-organisms (animals and higher plants) affect rock and stone deterioration. Lichens have received some attention, which contribute to breakdown in terrestrial and coastal environments (Moses and Smith 1993; Gómez-Pujol *et al.*, 2007). Lichens also protect rocks by shielding surfaces from rain and pollutants, and moderate conditions for thermal weathering (Mottershead et al., 2000; Carter and Viles 2003, 2005). More recently, the influence of higher plants on stone surface temperatures has been suggested as a bioprotective mechanism; ivy canopies covering historic walls in England were found to reduce fluctuations in temperature and humidity, reducing microclimatic extremes in summer and winter (Sternberg *et al.* 2011). Ivy is also thought to shield surfaces from pollutants and driving rain. Macroalgae (seaweed), which can completely cover surfaces in the intertidal zone, has also been found to have a similar influence on maritime structures (Coombes *et al.* 2013). These influences are significant, given that both extremes and fluctuations in temperature and moisture are thought to be important mechanisms of stone deterioration (e.g., Warke *et al.* 1996; McGreevy *et al*, 2000; Viles *et al.*, 2011). Organic influences on rock moisture and wetting and drying regimes are also important with respect to the crystallisation of salts in coastal environments (Mottershead *et al.*, 2003).

Studies examining the role of microclimate in rock breakdown have been largely restricted to the rock surface. This is surprising given that thermal cycles and vertical thermal gradients below the surface are critical controls on the efficiency of mechanical stress processes (Yatsu 1988; Smith *et al.* 2011; Mottershead 2013). Observations of the influence of organisms on internal stone thermal regimes are particularly uncommon. We are aware of only one set of studies measuring the influence of lichen on sub-surface stone temperatures (Carter and Viles 2003, 2004, 2005), and the influence of sedentary animals (i.e., macro-organisms) has never been examined. This is due, in-part, to the practical challenges of measuring sub-surface rock temperature in the field. Laboratory simulations are particularly useful in this respect. Coombes (2011) describes an approach for simulating temperate intertidal conditions in the laboratory that was successfully used to monitor rock surface temperatures during simulated low-tide periods (Coombes and Naylor 2012). Here we describe an adapted methodology for the first attempts to measure the influence of sedentary barnacles on thermal regimes below the rock surface.

2. Materials and Methods

2.1 Tidal simulation

The approach adopted to simulate intertidal conditions in the laboratory is described in detail by Coombes (2011) and Coombes and Naylor (2012). Briefly, an automated cycle of synthetic seawater was establishing between two plastic tanks using aquarium pumps and electric timers (Figure 1). Timers were programmed to replicate a semi-diurnal tide cycle at mid-tide level, consisting of two 6-hour periods of immersion (‘high-tides’) and two 6-hour periods of emersion (‘low-tides’) every 24-hours.

Figure 1. Experimental set-up used to simulate intertidal conditions in the laboratory.

2.2. Sample preparation

Samples (50 mm x 50 mm x 30 mm blocks) of Portland limestone, Cornish granite and marine concrete previously colonised by barnacles (*Chthamalus* spp.) on a rocky shore in Cornwall were used in the experiment (Coombes *et al.*, 2011). These blocks were removed from the field three months prior to the start of the experiment (in January 2012) and left to dry at room temperature. The barnacles were therefore no longer living, removing the necessity for complicated laboratory procedures to keep the organisms alive, but ensuring that the hard calcareous shells of the barnacles (called 'tests') were retained intact on the rock surface (Figure 2). In the field, empty (i.e., non-living) barnacle tests commonly form a significant proportion of the cover matrix due to mortality by predation and other disturbance processes. When dry, each block was coated with varnish on all but the (colonised) upper surface to restrict moisture movement through this one face (Coombes, 2011). Two holes (3 mm in diameter) were then drilled into the centre of each block from the underside, spaced 10 mm apart. One of the holes was drilled to a distance of 5 mm from the block surface, and the other to a distance of 10 mm from the surface (Figure 3). This was intended to allow some observation of thermal gradients within the blocks (e.g., Warke and Smith, 1998).

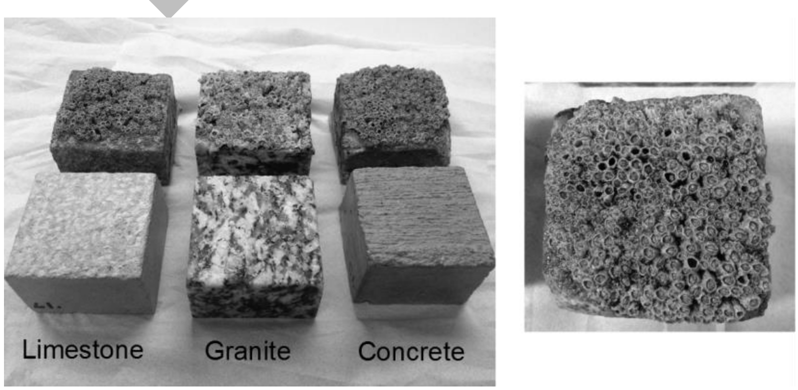

Figure 2. Experimental blocks (50 mm x 50 mm x 30 mm) shown in colonised and control pairs (upper and lower row, respectively). Enlargement of colonised limestone block also shown.

During the preliminary experiment described here, and prior to on-going experiments with larger levels of replication, two blocks each of limestone, granite and concrete were used. One of each sample pair had been removed from the field and prepared as described above, having a high density of barnacles (covering 95% of the surface) and the other was a control that had not been exposed in the field, having no barnacle cover (Figure 2). Before the start of the experiment, all blocks were placed in the tidal simulator (Section 2.1) for one week to attain a water and salt content that was considered comparable. This was essential to ensure that the thermal data collected during the experiment (Section 2.3) reflected the influence of barnacles as much as possible, more so than any effect of differing moisture and/or salt content for example.

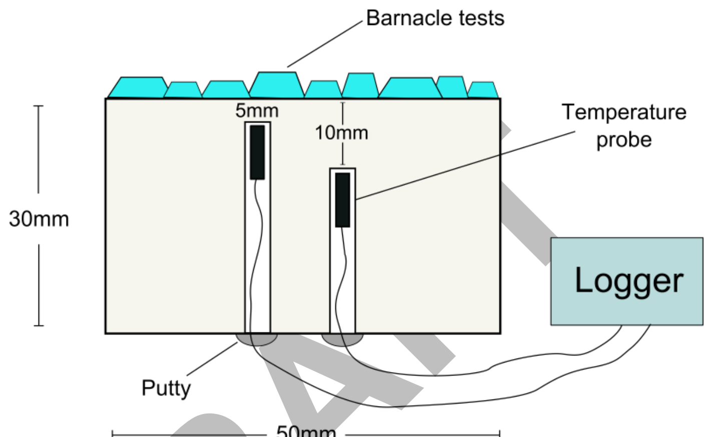

Figure 3. Schematic of a colonised block prepared for temperature monitoring (not to scale).

2.3. Internal temperature measurement

On the day of measurement, sample blocks were removed from the tidal simulator at the start of a 'low-tide' period, dried on all but the upper face and weighed. A flexible thermistor probe (PB-5009-0M6, Gemini Data Loggers) was then fully inserted into each of the pre-drilled holes (two in each block), secured in place with putty, and attached to a dual channel TinyTag logger (TGP-4520, Gemini Data Loggers) (Figure 3). Loggers were pre-programmed to record continuously at 1-minute intervals, to provide simultaneous records of temperature at a depth of 5 mm and 10 mm within each block.

Once prepared, all six samples were placed in a tray of polystyrene beads in an attempt to limit thermal exchange to the upper surface as much as possible, and positioned inside an environmental cabinet (SANYO–FE 300H, Figure 4). The cabinet was pre-programmed to simulate a thermal cycle recorded during a 6-hour, summertime low-tide event (at mean tide level) on a rocky shore in Cornwall (Figure 5, Coombes 2011). Relative humidity was set at a constant 80% based on records obtained on rocky shores in South West England during the summer of 2011 (Coombes *et al.*, 2013).

During the simulation, a lamp was positioned over the blocks to heat them directly; direct heating in this way has been shown to induce thermal changes in stone that are more representative of field conditions than indirect (i.e., convective) heating alone (Warke and Smith 1998). The lamp was set to switch on and off at 15 minute intervals to simulate periods of passing cloud; frequent short-term (minutes) fluctuations in temperature have been recorded on rocky shore platforms, attributed to variations in insolation caused by cloud and cooling by wind (Coombes, 2011). Air temperature and relative humidity in the cabinet were recorded continuously using additional loggers (iButton®) that were shaded from the lamp using aluminium foil (e.g., Carter and Viles, 2004). After the cycle had finished (after 6-hours real time) the blocks were removed from the cabinet, the temperature probes removed, and blocks re-weighed. Data were then downloaded from the loggers onto a laptop using TinyTag Explorer software (SWCD-0040, Gemini Data Loggers).

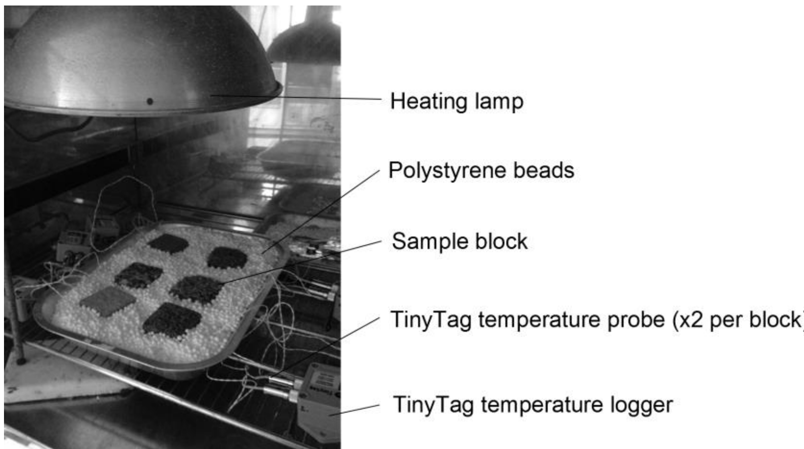

Figure 4. Limestone, granite and concrete samples positioned inside an environmental cabinet simulating temperate summertime conditions on a rocky shore platform.

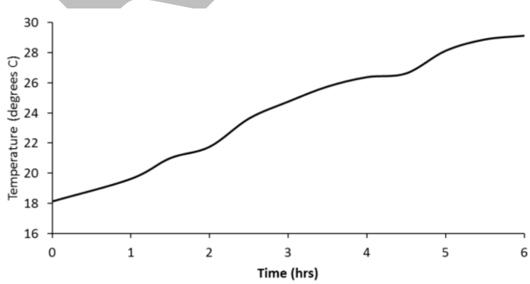

Figure 5. Thermal regime used to simulate low-tide conditions on a temperate rocky shore in summer (data collected in the field on 17th August 2009 at Porthleven, Cornwall, Coombes, 2011).

3. Preliminary Results

Figure 6 shows the temperatures recorded 5 mm below the surface of each pair of blocks (colonised and control) alongside air temperature and relative humidity. Sample blocks quickly attained temperatures higher than the air (within 30 minutes) and, after a period of stabilisation (around 80 minutes), the peaks and troughs in ambient conditions caused by the lamp coming on and off are clearly reflected in all of the records. These short-term fluctuations are superimposed on the general warming regime programmed to simulate summertime field conditions (i.e., Figure 5).

For all three material types, internal temperatures were always cooler for blocks that had a cover of barnacles (95% cover in this experiment) compared to control blocks (no barnacles). This was the case at both measurement depths (5 mm and 10 mm). For the period after conditions in the cabinet had stabilised, the mean difference in temperature between colonised and control blocks was 0.24 °C for concrete, 0.66 °C for limestone and 2.17 °C for granite at 5 mm depth, and 0.30 °C, 0.61 °C and 2.18 °C, respectively, at 10 mm depth. These differences remained fairly constant for the duration of the cycle (Figure 6). Differences measured between the two depths within each block were not consistent (i.e., whether positive or negative) and were very small regardless of whether the blocks were colonised or not, not typically exceeding ± 0.1 °C (Figure 7).

4. Discussion

The environmental cabinet took some time to establish the programmed conditions (Figure 6). Ensuring the correct starting temperature is attained before blocks are placed inside should therefore be adopted for future experiments. Nonetheless, once conditions had become established, the cabinet maintained the programmed thermal regime very well. The ability to adequately control conditions in this manner means that comparable runs of the experiment can be undertaken in the future, with more sample replication, which is needed before absolute conclusions can be made.

In general, barnacles had a consistent cooling influence on internal rock temperatures both at 5 mm and 10 mm below the surface. This can be attributed to the ponding and retention of water within the barnacle test matrixes. This surface water would have evaporated from the colonised blocks upon heating, and thus acted to cool the underlying materials relative to the uncolonised control blocks. The weight of blocks before and after the experiment confirm that colonised samples lost around 50% more water during the simulation than the controls, indicating that cooling via evaporation of water held at the surface by barnacle tests is probably a critical factor for near-surface rock thermal regimes. The amplitude of thermal fluctuations was also noticeably reduced within colonised blocks (Figure 6).

Buffering of internal rock temperatures by barnacles may be indicative of reduced thermal stresses within colonised materials in the intertidal zone, and may be significant with respect to rock breakdown via thermal fatigue and – if barnacles keep rocks wet and cool – by salt weathering. It is, however, notable that the magnitude of this influence varied between the materials. The cooling influence of barnacles on granite was marked (around 2 °C), but was much less on limestone and concrete (less than 1 °C). This likely reflects the inherent variability of materials' thermal responses when heated due to factors such as mineralogy, thermal capacity and porosity (McGreevy, 1985; McGreevy *et al.*, 2000; Coombes and Naylor, 2012). This being said, the internal temperatures of colonised blocks were remarkably similar, regardless of material type; the mean internal temperature of the different colonised blocks varied in the order of 0.2 °C, while this difference was greater than 2 °C for control (uncolonised) blocks. This suggests that a dense cover of barnacles (as was used here) may act to 'standardise' thermal differences between lithologies that may otherwise occur when exposed to insolation. As well as the influence of inherent material properties, the extent of barnacle cover (both per cent cover and matrix thickness) likely controls the magnitude of any effect on internal rock temperatures; this is currently being investigated.

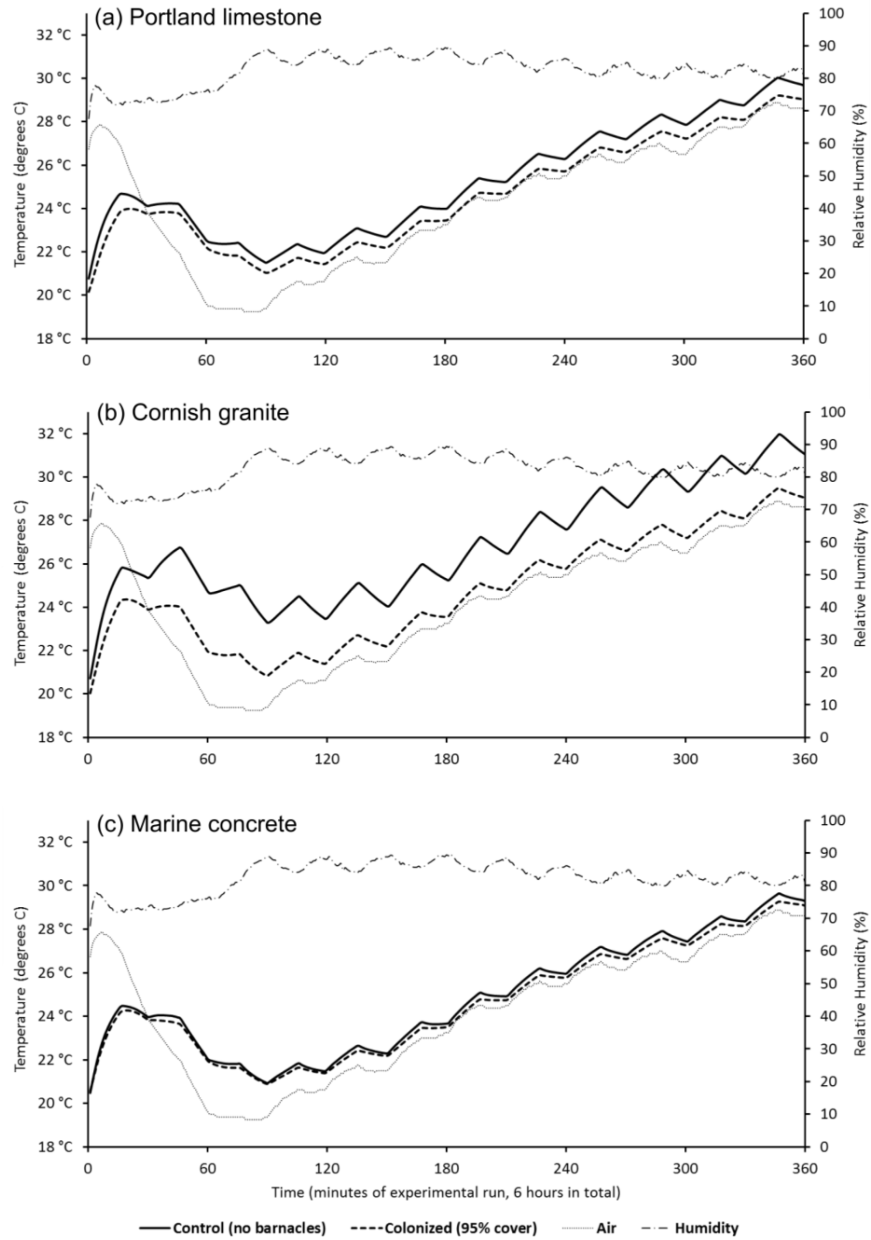

Figure 6. Temperatures of control (no barnacles) and colonised (95% cover of barnacles) blocks (5 mm below the surface) during a simulated temperate summertime low-tide event. Air temperature and relative humidity during the experiment also shown.

No marked thermal gradients were measured within the blocks between 5 mm and 10 mm depth, and there was no apparent – or at least consistent – influence of barnacles on temperature differentials at these depths (Figure 7). This might suggest that barnacles have little influence on thermal gradients within rock and concrete, but this is perhaps inconsistent with the general cooling influence found at these depths. This discrepancy may be explained if the distance of 5 mm between the two measurement depths was too small to detect such an influence (Smith *et al.*, 2011), and/or that the temperatures of the blocks changed at a relatively uniform rate at these depths owing to the small size of the samples. Barnacles may influence the development (and the magnitude) of potentially deteriorative thermal gradients between surface and sub-surface layers in larger rock masses, and at greater depths, but this cannot be assessed from the current experimental data.

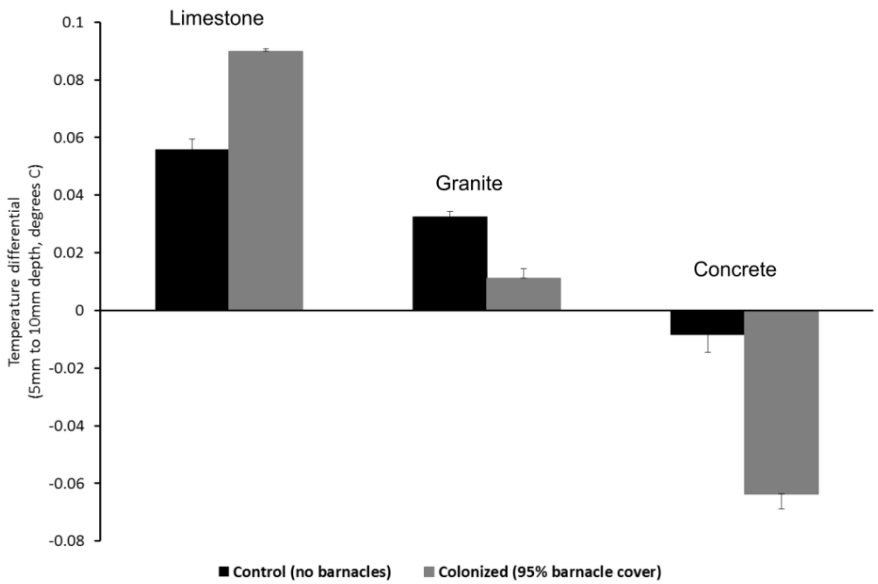

Figure 7. Mean (± SE) difference in block temperature between 5 mm and 10 mm depths during a 6h simulated temperate summertime low-tide event.

5. Conclusions

The first attempts to measure the influence of sedentary macro-organisms on internal rock thermal regimes has been described. Under simulated intertidal conditions, sub-surface temperatures in limestone, granite and marine concrete were reduced when covered by barnacles. This probably occurs via direct shielding of the surface and through indirect cooling by the evaporation of water held within barnacle test matrixes. Importantly, the magnitude of this effect was not consistent between material types, but appears to be most marked in materials that are naturally more thermally responsive such as granite. This is important because if barnacles (and other epibiota) do have a bioprotective role via internal temperature moderation, this may be more or less significant for decay processes depending on lithology and the environmental conditions in which they are exposed.

More experiments are now required using multiple replicate samples to determine if, and to what extent, barnacles have a consistent influence on internal rock thermal regimes, and how this is related to other factors such as surface cover. The implications of biologically-mediated thermal cycling in rock and stone for actual weathering rates requires much more investigation, as epibiota may reduce the efficiency of thermal fatigue and thermal shock, and reduce the frequency that materials dry out sufficiency for deteriorative salts to crystallise in the surface and near-surface zone.

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