

## RESEARCH ARTICLE

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# No evidence that seaweed cover enhances the deterioration of natural cement-based mortar in intertidal environments

Timothy Baxter  | Martin Coombes | Heather Viles

Oxford Resilient Buildings and Landscapes Lab (OxRBL), School of Geography and the Environment, University of Oxford, Oxford, UK

**Correspondence**

Timothy Baxter, Oxford Resilient Buildings and Landscapes Lab (OxRBL), School of Geography and the Environment, University of Oxford, Oxford OX1 3QY, UK.  
Email: [timothy.baxter@ouce.ox.ac.uk](mailto:timothy.baxter@ouce.ox.ac.uk)

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**Abstract**

The breakdown of rocks and engineering materials in marine environments is both enhanced and retarded by surface-colonizing marine organisms (seaweed, barnacles, etc.). However, the impact of marine growth on the deterioration of materials used to construct and repair maritime heritage assets, such as natural cement, is poorly understood.

This study assesses whether seaweed cover (*Fucus vesiculosus* and *Fucus serratus*) influences the breakdown of mortar prepared using natural cement through an exposure trial at Portland Port, Dorset, UK. Using microclimate monitoring and three different indicators of weathering and material breakdown (surface hardness, surface roughness and ultrasonic pulse velocity), samples of mortar with and without a cover of seaweed were compared after 6 months of exposure to intertidal conditions. Our results show that temperature variations were significantly dampened under seaweed canopies compared to uncovered substrate both in summer and winter. As mechanical rock weathering processes are influenced by surface temperature regimes, we infer that these stabilizing effects may translate to a reduction in the efficacy of particular rock breakdown processes. Seaweed cover was not found to have significant effects on the surface hardness of the samples. Conversely, significant differences in surface roughness and pulse velocity were observed, indicating that the seaweed-covered samples experienced less surface and subsurface breakdown.

Overall, we found no evidence that seaweed significantly enhances the deterioration of natural cement-based mortar during the first few months of exposure. Instead, we present the first empirical evidence of the bioprotective potential of seaweed covering materials commonly used in maritime built heritage restoration. Future work is now needed to examine the geomorphic roles of seaweed and other marine organisms on different types of materials used in maritime heritage conservation, and the extent to which their impacts on different deteriorative/protective processes vary in time and space, particularly under future climatic scenarios.

**KEYWORDS**

biogeomorphology, built heritage, microclimate, natural cement, weathering

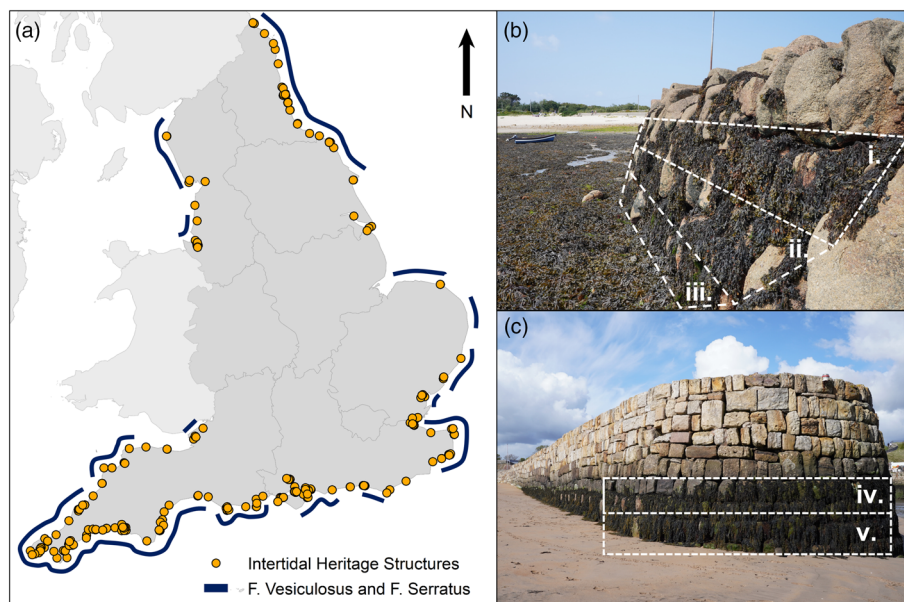
## 1 | INTRODUCTION

Canopy-forming seaweeds grow prolifically on rocky shores and on the surfaces of artificial structures in marine environments (e.g. Lee et al., 2009; Tsiamis et al., 2020; Watanuki & Yamamoto, 1990). This

includes built heritage assets, such as historic harbours and breakwaters that are valued for their historical importance and cultural significance (Fulford et al., 1997; Figure 1). As well as providing functional habitats for understory species (Bertness et al., 1999; Burnaford, 2004; Umanzor et al., 2017; Watt & Scrosati, 2013),

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**FIGURE 1** (a) Distribution of *F. vesiculosus* and *F. serratus* in England (blue line, NBN Atlas occurrence data, download from [nbnatlas.org](https://nbnatlas.org) [accessed 10 May 2022]) along with listed buildings and scheduled monuments built of stone that are located within the intertidal zone (orange circles, Historic England GIS data obtained from [historicengland.org.uk](https://historicengland.org.uk) [accessed 10 May 2022]). © Historic England 2022. Contains Ordnance Survey data. © Crown copyright and database right 2022). Seaweed, including (i) *F. spiralis*, (ii) *F. vesiculosus*, and (iii) *F. serratus* colonizing the walls of (b) Old Town Quay, a scheduled monument on the Isles of Scilly. An 18th-century breakwater colonized by (iv) *F. spiralis* and *F. vesiculosus* and (v) *Ascophyllum nodosum* at (c) St Andrew's Harbour, a Category A listed building in Fife, Scotland. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/esp.5467)]

seaweed acts as an important biogeomorphological agent via a range of processes (see Figure S1 in the online Supporting Information), both enhancing and retarding rock weathering and erosional processes, and mediating the transport of sediment in coastal and marine environments (Carling, 2014; Frey & Dashtgard, 2012; Garden & Smith, 2015; Smith & Bayliss-Smith, 1998). As with other marine organisms that form dense biotic covers and encrustations, such as barnacles and mussels (Baxter et al. 2022a; Coombes et al., 2017; Gonzalez et al., 2021), seaweed canopies are thought to reduce the efficacy of mechanical weathering processes by regulating microclimatic conditions through increased moisture retention and shading at the rock's surface (Coombes, Naylor et al., 2013; Gowell et al., 2015; Scrosati & Ellrich, 2018). At the same time, holdfast growth has been observed to cause the mechanical disintegration of rock and concrete to a depth of up to 10 mm (Hughes et al., 2013; Morrison et al., 2009).

Research examining the biogeomorphological roles of marine organisms has typically focused on understanding the effects of marine growth on the breakdown of rock (e.g. Andrews & Williams, 2000; Baxter et al., 2022a; Gonzalez et al., 2021; Pappalardo et al., 2018; Trudgill, 1987) or engineering materials used to construct modern infrastructure, such as concrete (e.g. Chlayon et al., 2018; Coombes et al., 2011, 2017; Lv et al., 2015). This includes studies that have specifically analysed the role of seaweed as a biogeomorphic agent in marine environments (Table 1). In contrast, relatively little is known of the impacts of marine organisms on the breakdown of materials used in the maintenance, repair, and restoration of built heritage assets. Unlike modern infrastructure, designations aimed at protecting the historic fabric of built heritage assets (e.g. listed buildings and scheduled monuments) often restrict the types of materials that can be used for conservation work (Historic England, 2016a,b).

Generally, only original material or materials with compatible technical and aesthetic properties are considered appropriate for repair works. As such, materials used for built heritage conservation often differ from those used to construct modern infrastructure in marine environments. For example, natural cement (e.g. Vicat Prompt™ and other brands) is regularly used as a binder in mortars used to repair historic masonry structures (Gosselin et al., 2008), including harbours and coastal fortifications (e.g. Historic Environment Scotland, 2016), due to its compatibility with materials used to construct maritime structures before the 20th century. This compares to artificial cements (e.g. 'Modern Portland' cements), which are frequently used to produce concrete for modern coastal defences and maritime infrastructure (Dupray et al., 2010; Thomas, 2016).

An improved understanding of the biogeomorphological effects of seaweed and other canopy-forming marine organisms on materials used to repair historic maritime structures will allow practitioners to make more informed decisions about the conservation of built heritage as well as marine biodiversity. Traditionally, the growth of seaweed on artificial structures has been viewed negatively (e.g. Fletcher, 1988), and a recent survey of harbourmasters and other marine managers from around the UK found that seaweed growth was generally perceived to negatively impact the conservation of maritime built heritage (Baxter et al., 2022b). In particular, seaweed was thought to have a detrimental impact on the condition of mortar. As yet, however, the effects of seaweed on materials used in built heritage conservation, including natural cement, have not been quantitatively assessed.

To address this research gap, an exposure trial was developed to examine the effect of seaweed on the physical properties of natural cement-based mortar exposed to intertidal conditions. Similar to canopy-forming seaweeds (Coombes, Naylor et al., 2013; Gowell

**TABLE 1** Some examples of studies examining the geomorphic roles of seaweed growing on a range of natural and artificial substrates

Location	Biological cover	Substratum type	Landform/structure	Scope of study	Reference
Nova Scotia, Canada	<i>A. nodosum</i>	Unknown	Rocky shore	Influence of seaweed on near-surface microclimates during temperate winter conditions.	Scrosati and Ellrich (2018)
Cornwall and Dorset, UK	<i>F. vesiculosus</i> , <i>F. serratus</i> , <i>F. spiralis</i> , and <i>A. nodosum</i>	Concrete, limestone	Harbour wall, support pylons, rock armour revetment	Influence of seaweed on (1) near-surface microclimates during temperature summer conditions and (2) conditions for mechanical rock decay.	Coombes, Naylor et al. (2013)
Algarve, Portugal	Various marine species	Carbonate siltstone	Rocky shore	Influence of biological covers on shore platform downwearing rates.	Moura et al. (2012)
Galway Bay, Ireland	<i>A. nodosum</i> , <i>F. vesiculosus</i> , and <i>Lithothamnion</i> sp.	Granite, limestone	Rocky shore	Biomechanical and biochemical deterioration of rocky shore substrate.	Morrison et al. (2009)
Lancashire, UK	<i>A. nodosum</i> , <i>F. vesiculosus</i> , <i>F. spiralis</i> , <i>Porphyra umbilicalis</i> , <i>Halidrys siliquosa</i> , <i>Ulva</i> sp.	Concrete	Rock armour revetment	Biomechanical biodeterioration of marine concrete.	Hughes et al. (2013)
Pudcherry, Tamil Nadu, India	<i>Chaetomorpha antennina</i>	Concrete	Exposure trial of concrete cubes	Biochemical deterioration of marine concrete.	Jayakumar et al. (2010)
Laboratory study	Artificial seaweed (chemically inert foam)	Mudstone	Laboratory simulation	Influence of (artificial) seaweed on salt weathering and mechanical rock breakdown.	Gowell et al. (2015)

et al., 2015) and encrusting organisms that grow on natural shores and concrete surfaces (Baxter et al., 2022a; Coombes et al., 2017), we hypothesized that seaweed canopies moderate the breakdown of material by decreasing the efficiency of mechanical weathering processes by dampening temperature variability during air-exposed low-tide periods. Seaweed may also influence salt crystallization (Gowell et al., 2015) and wetting–drying cycles by moderating moisture retention (Coombes, Naylor et al., 2013) and act as a physical barrier against erosional processes (e.g. wave abrasion), although these effects were not examined directly in this study. By using surface roughness, surface hardness, and ultrasonic pulse velocity (UPV) as proxies for weathering state, we reveal differences in the physical properties of samples of mortar with and without a cover of seaweed. Overall, our results show that rates of deterioration of mortar prepared using natural cement were not enhanced by seaweed cover during the first 6 months of exposure. Instead, the net effects of seaweed cover may be broadly bioprotective due to its influence on near-surface microclimatic regimes.

## 2 | METHODOLOGY AND METHODS

### 2.1 | Field block exposure trial

Sample blocks of mortar were prepared using a prompt natural cement (Vicat Prompt™) following the advice of several professionals in maritime built heritage conservation. Prompt natural cement is a quick-setting natural hydraulic binder that rapidly hardens with the addition of water. It is produced by firing standard-composition limestone high in clay content between 500 and 1200°C, followed by very fine grinding. Vicat produce the only prompt natural cement that is manufactured industrially, and this is made using argillaceous limestone excavated from homogeneous rock strata in the Chartreuse mountains near Grenoble, France. Due to its durability and long-term strength gain, resistance to seawater, fast hardening and setting time (2 min at 20°C), and ‘natural’ colour and aesthetic, Vicat Prompt™ natural cement has been used to construct and repair historic maritime structures throughout Europe since the middle of the 19th century. This includes St Andrew’s Harbour (Fife, Scotland), Cove Harbour (Berwickshire, Scotland; Historic Environment Scotland, 2016), Portreath Harbour (Cornwall, England), and the Château d’If fortress (France), which have all been repaired within the last 20 years.

The aggregate used for the mortar mix was a sharp quartz sand (Bramshill) with a well-graded grain size distribution (0.75 µm to 10 mm). The binder:aggregate:water ratio was 5:5:2 by volume following standard procedures (Vicat, 2003). Small amounts of citric acid were added to the mixture (binder: citric acid ratio = 1000:7) to delay the setting time by ~10 min and increase workability. A mortar of this mixture is expected to develop strength rapidly (i.e. within the first few hours) due to the hydration of aluminates within Vicat Prompt™, and then more gradually over several days, months, and years due to the slow hydration of belite (C<sub>2</sub>S). Compared to its compressive strength after 2 years (~60 MPa), this mortar mix is expected to gain ~22.5% of its strength in the first day (~13.5 MPa), 50% over 28 days (~31 MPa), and 80% over 6 months (~48 MPa; inferred from data in Vicat, 2003). After mixing, the mortar was equally distributed into

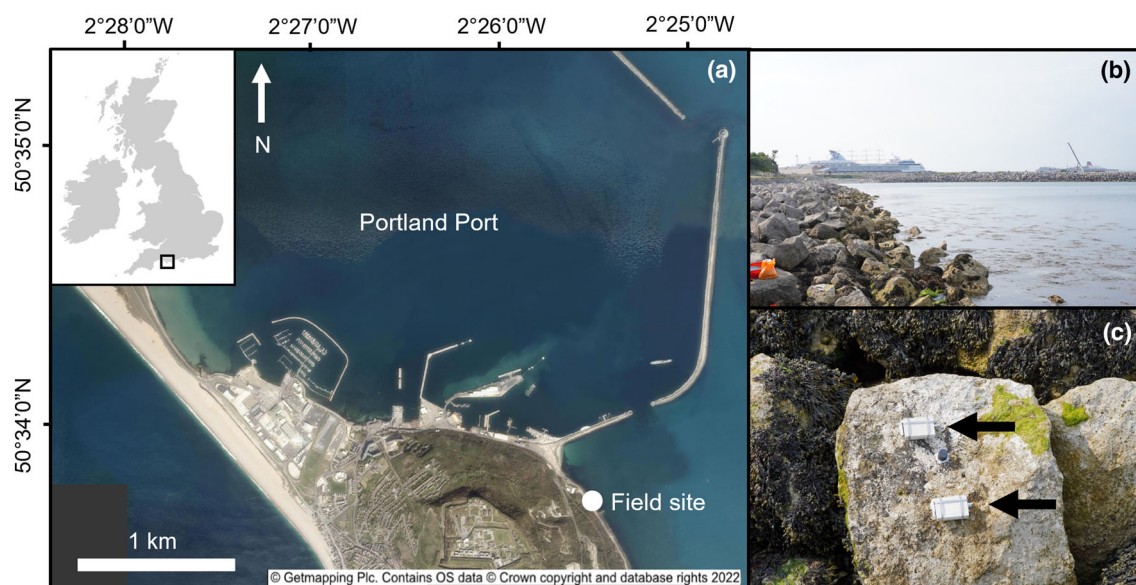
22 identical silicone moulds (55 × 80 × 25 mm). The samples were de-moulded after 5 days of curing under laboratory conditions. Two samples were kept as controls, both of which were stored in a small plastic container in dry conditions within a low-temperature laboratory refrigerator for 6 months.

Twenty sample blocks were attached to semi-horizontal surfaces of limestone rock armour 200 m south of Balaclava Bay, Portland Port (Dorset), UK (50°33'49"N, 02°25'31"W) at mean tide level (Figure 2). The study site was chosen based on the rock armour having an existing cover of algae, and ease of obtaining access and permissions. Portland Port experiences a double-low tide (i.e. ~4 h of low water consisting of two minima separated by a small rise) and is microtidal (<2 m mean spring tidal range). According to the MarLIN wave exposure categories (accessed at [www.marlin.ac.uk/glossarydefinition/waveexposure](http://www.marlin.ac.uk/glossarydefinition/waveexposure)), the study site is on a 'moderately exposed' coastline; the open coast faces away from the prevailing westerlies in a northeastern direction and has a short fetch (<20 km). Although the coastline can experience strong winds, it is partially sheltered to the south by the Isle of Portland and to the north by the Grade II listed Inner Breakwater of Portland Port. At mean tide level, the rock armour is dominated by canopies of *Fucus vesiculosus* and *Fucus serratus* that are 5–10 cm thick.

To investigate the effects of macro-algal cover on the physical properties of mortar, we examined and compared sample blocks attached to areas with 95–100% seaweed cover to those attached to uncolonized areas (0% cover). Hereafter, these areas are referred to as 'covered' plots and 'uncovered' plots, respectively. Individual, purpose-built frames made using PVC-coated stainless steel cable ties and plastic cable mounts were used to house the sample blocks. The frames, which were securely attached to the substrate using marine epoxy (Plastic Padding® Marine Epoxy; Figure 2C), were designed to ensure the sample blocks were not damaged during their attachment or removal. Initially, the 20 sample blocks were evenly distributed between the covered and uncovered plots (i.e. 10 samples were covered with seaweed and 10 samples were left uncovered). In the covered plots, the frames housing the sample blocks were secured directly to substrate

under the algal canopies; in some instances, a small area of colonizing macro-biology was cleared so that the frames could be attached securely. Care was taken to ensure that the sample blocks in the covered plots were directly covered with seaweed (i.e. without air voids between the samples and the seaweed canopy) and that the algal canopies were of similar densities and thicknesses (i.e. ~5 cm). The uncovered plots were already clear of macro-algae and other macro-organisms. All sample blocks were positioned at the same tidal height (i.e. mean tide level), irrespective of whether they were in covered or uncovered plots. The sample blocks were left exposed to intertidal conditions for 6 months, between 30 June 2021 and 7 January 2022. Unfortunately, five of the uncovered samples and three of the seaweed-covered samples became detached during the trial and were lost. This left 12 samples available for post-exposure analysis—five attached to uncovered plots and seven attached to covered plots.

Differences in pre- and post-exposure surface roughness, surface hardness, and UPV were compared between the covered and uncovered samples, as well as the control samples stored in the laboratory during the exposure period. As the surfaces of the sample blocks in both the covered and uncovered plots were not directly colonized with seaweed or other macro-biology during the exposure period, any differences in surface roughness, surface hardness, and UPV detected between the samples post-exposure were attributed to differences in seaweed cover (i.e. the overhanging canopy) rather than the effects of colonizing organisms (i.e. the effects of seaweed holdfast attachment). Hardness data has been used as an indicator of the efficiency of weathering processes in a number of terrestrial and coastal studies (e.g. Aoki & Matsukura, 2007; Coombes, Feal Pérez et al., 2013; Feal Pérez & Blanco-Chao, 2012; Gowell et al., 2015; Mol & Viles, 2010; Pappalardo et al., 2016, 2018), including assessments of the effects of biotic covers on the deterioration of historic masonry structures (Coombes et al., 2018; Cutler et al., 2013). Surface roughness has also been used to determine the extent of material breakdown (McCarroll & Nesje, 1996; Moses et al., 2014), both in coastal environments (e.g. Micallef & Williams, 2009) and for stone used in terrestrial



**FIGURE 2** (a) Location of the study site at Balaclava Bay, Portland Port, Dorset and (b) an on-site view of the limestone rock revetment showing the Grade II listed inner breakwater in the background. (c) Examples of 'uncovered' samples of mortar secured to the rock revetment within purpose-built frames. An iButton Thermochron (Maxim® DS1921G) is attached in a waterproof plastic casing between the samples. [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

built heritage assets (e.g. Coombes et al., 2018). UPV has been used as a non-destructive technique to detect the development of subsurface flaws and cracks within engineering materials used in historic masonry structures (e.g. Benavente et al., 2006; Svahn, 2006; Vasconcelos et al., 2007), including natural hydraulic mortars (e.g. Fusade & Viles, 2019). Typically, substrates that have experienced a greater degree of weathering are expected to be rougher, less hard, and have lower UPV values than unweathered substrates (Moses et al., 2014). The application of each technique is outlined in the following sections.

In addition to measuring the physical and surface characteristics of the sample blocks, near-surface temperature data were collected in the covered and uncovered plots. The effects of canopy-forming marine organisms on near-surface temperatures have been used as an indicator of variable weathering regimes in a number of previous studies (e.g. Coombes, Naylor et al., 2013; Gonzalez et al., 2021; Gowell et al., 2015).

## 2.2 | Surface hardness

An Equotip Piccolo 2 (D-type) was used to collect surface hardness data for the sample blocks before and after they were exposed to intertidal conditions. Both pre- and post-exposure hardness measurements were recorded under laboratory conditions; the Equotip was applied perpendicular to the upper (horizontal) surface of the sample blocks which were placed on a solid limestone base atop a purpose-built, reinforced worksurface to prevent interference from vibration (Wilhelm et al., 2016). The Equotip Piccolo expresses hardness as a 'Leeb' value (HL) and has a resolution of 1 HL and an accuracy of  $\pm 4$  HL (Viles et al., 2011). On the upper surface of each sample block, 30 equally spaced measurements were recorded using the single impact (SIM) method (Wilhelm et al., 2016) before and after the field exposure trial (i.e. before attachment and after removal). To avoid measurements collected post-exposure being taken from the same spot as those recorded pre-exposure, the upper surface of each block was divided into two halves; pre-exposure measurements were recorded in one half and post-exposure measurements in the other. Readings were not taken on the outer 0.5 mm of the samples to avoid potential edge effects (Gowell et al., 2015). As moisture can also affect the reliability of Equotip readings (Desarnaud et al., 2019), measurements were made when the blocks were dry and had reached a constant weight. For each sample block, the 30 measurements recorded both before and after the exposure period were averaged and then subtracted from one another as an overall measure of surface hardness change. Surface hardness measurements for the control samples were collected in a similar way, before and after being stored in the laboratory for the duration of the exposure period.

## 2.3 | Surface roughness

As a non-destructive assessment of surface roughness, the topography of five randomly selected  $5 \times 5$  mm ( $25 \text{ mm}^2$ ) areas on the upper surface of each sample block was quantified using an optical profilometer (INNOWEP TRACEIT<sup>®</sup>) both before and after exposure (Sanmartin et al., 2020). A TRACEIT<sup>®</sup> optical profilometer analyses the length and angle of shadows produced on the surface of samples by

three white LEDs to create topography measurements with a horizontal (XY-axis) resolution of  $<3 \mu\text{m}$  and a vertical (Z-axis) resolution of  $<1.5 \mu\text{m}$  (INNOWEP, 2022). For each measurement, the arithmetic average roughness (Ra) was determined from the average of 1563 transects in both the X- and Y-axis directions (Gadellawlaa et al., 2002). A mean Ra value was then determined for each sample by averaging across the five measurement areas. Differences between pre- and post-exposure mean Ra values were then determined for each sample. An overall measure of surface roughness change was also determined for the control blocks using the same method.

Additional surface roughness measurements were made using a Keyence VHX 5000 3D microscope to verify the data obtained from the optical profilometer. As access to the 3D microscope was not possible before the exposure trial, measurements using this device were only recorded after the exposure period, for both the field-exposed samples and the control samples. Under  $100\times$  magnification, the topography of 10 randomly selected areas ( $3548 \times 2660 \mu\text{m}$ ) on the upper surface of each sample block was imaged. Ra values were then determined for each area by averaging 1597 transects in the X-axis direction and 1197 transects in the Y-axis direction. Post-exposure mean Ra values for each sample were then determined by averaging across the 10 measurement areas. When using both the TRACEIT and 3D microscope, care was taken to ensure that surface roughness measurements did not overlap with the impact features created by the Equotip.

## 2.4 | Ultrasonic pulse velocity

UPV measurements were carried out on each sample block before and after field exposure with a Portable Ultrasonic Non-destructive Digital Indicating Tester (Pundit Lab, Proceq, UK) with 150 kHz frequency transducers. Direct transmission was used, with transducers placed at each end of the samples on the longest axis (Fusade & Viles, 2019). The propagation velocity (vp) (m/s) was measured and results reported as the mean of three repeat measurements. Differences in mean UPV collected pre- and post-exposure were then compared between the covered and uncovered samples and the controls, which were measured the same way.

## 2.5 | Near-surface temperature

Six temperature loggers (Maxim<sup>®</sup> DS1921G iButton Thermochron) housed in protective plastic waterproof capsules (Maxim<sup>®</sup> DS9107+) were attached to the substrate using marine epoxy (Plastic Padding<sup>®</sup> Marine Epoxy). Three temperature loggers were attached in covered plots and three were attached in uncovered plots adjacent to the sample blocks. The temperature loggers in the covered plots were secured directly beneath the existing algae canopy (Coombes, Naylor et al., 2013). During air-exposed low-tide periods, the loggers recorded air temperature near the surface of the substrate, between the rock and seaweed canopy. During high-tide periods when the loggers were submerged, seawater temperature near the surface of the substrate was recorded. All loggers were positioned at mean tide level for comparability (Coombes, Naylor et al., 2013). The loggers have an operating range of  $-30$  to  $70^\circ\text{C}$ , a resolution of  $0.5^\circ\text{C}$ , and an accuracy of  $\pm 0.5^\circ\text{C}$ . The same devices have previously been used to examine the

roles of marine organisms as ecosystem engineers (e.g. Jurgens & Gaylord, 2016; McAfee et al., 2022) and in weathering research to evaluate the influence of organisms on rock-surface thermal regimes in marine environments (e.g. Baxter et al., 2022a; Coombes & Naylor, 2012; Gowell et al., 2015) and on terrestrial built heritage assets (e.g. André et al., 2012, 2014; Coombes et al., 2018; Sternberg et al., 2011; Viles et al., 2011). The loggers were pre-programmed to measure the near-surface rock temperature at 30-min intervals over two 31-day periods—a 'summer' period (30 June to 30 July 2021) and a 'winter' period (6 December 2021 to 7 January 2022).

For both the summer and winter study periods, and in the covered and uncovered plots, the mean daily temperature maxima ( $T_{\max}$ ), mean daily temperature minima ( $T_{\min}$ ), mean daily temperature range ( $T_{\text{range}}$ ), and mean daily highest rate of change in temperature over consecutive 30-min periods ( $T_{\Delta 30}$ ) were calculated for each measurement day (Baxter et al., 2022a; Coombes, Naylor et al., 2013). These metrics were calculated as measures of thermal variability, which we compared between the covered and uncovered plots.

## 2.6 | Statistical analysis

Two sample t-tests were performed to compare differences in Equotip surface hardness (mean HL), UPV (mean propagation velocity), and TRACEiT surface roughness (mean Ra) before and after the exposure period between the covered and uncovered samples. In all instances, assumptions for parametric tests (i.e. normality and equal variance) were checked beforehand. As the surface roughness data collected using the 3D microscope failed to meet the assumption of equal variance (Shapiro Wilks,  $p < 0.01$ ), a non-parametric Mann-Whitney U test was used to compare post-exposure differences between the covered and uncovered samples.

## 3 | RESULTS

### 3.1 | Surface hardness

The mean surface hardness of both the seaweed-covered and uncovered samples was higher after the exposure period (Figure 3a); the

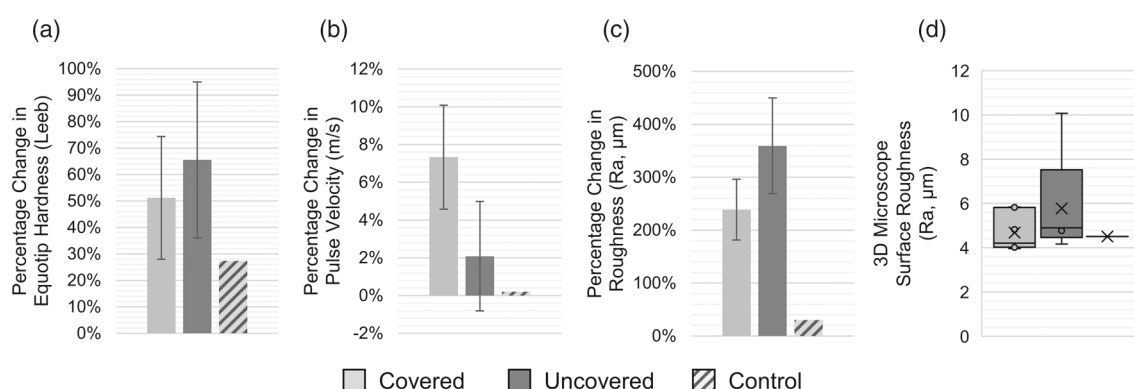
mean surface hardness of the seaweed-covered samples increased from 236 HL pre-exposure to 357 HL post-exposure, while the mean surface hardness of the uncovered samples increased from 239 HL to 395 HL. The surface hardness of the control samples also increased, although to a lesser extent (i.e. from 226 HL to 288 HL). The mean percentage change in surface hardness between the seaweed-covered and uncovered samples was not significantly different ( $t[10] = 0.946$ ,  $p > 0.05$ ).

### 3.2 | Ultrasonic pulse velocity

The mean UPV of both the seaweed-covered and uncovered samples was higher after the exposure period (Figure 3b); the mean UPV of the seaweed-covered samples increased from 2840 m/s to 3002 m/s, while the mean UPV of the uncovered samples increased from 2840 m/s to 2900 m/s. The mean percentage change in UPV was, however, significantly greater for the seaweed-covered samples compared to the uncovered samples ( $t[10] = 3.18$ ,  $p < 0.01$ ). The UPV of the control samples did not change significantly (i.e. 2810 m/s to 2816 m/s after 6 months in storage).

### 3.3 | Surface roughness

Mean surface roughness (Ra) measured using the optical profilometer (TRACEiT) was higher for both the seaweed-covered and uncovered samples after field exposure (Figure 3c); the mean surface roughness of the seaweed-covered samples increased from 0.547  $\mu\text{m}$  pre-exposure to 1.786  $\mu\text{m}$  post-exposure, while the mean surface roughness of the covered samples increased from 0.543  $\mu\text{m}$  to 2.615  $\mu\text{m}$ . The mean surface roughness (TRACEiT) of the control samples also increased, although to a lesser extent. The mean percentage change in surface roughness (TRACEiT) was significantly greater for the uncovered samples compared to the seaweed-covered samples ( $t[10] = 2.70$ ,  $p = 0.024$ ). Average (median) surface roughness measured after exposure using 3D microscopy was also higher for the uncovered samples compared to the seaweed-covered samples (i.e. 4.896  $\mu\text{m}$  compared to 4.210  $\mu\text{m}$ ; Figure 3d), although this difference was not statistically significant ( $U = 24$ ,  $n_1 = 5$ ,  $n_2 = 7$ ,  $p > 0.05$ ).



**FIGURE 3** Differences in the percentage change of (a) surface hardness, (b) ultrasonic pulse velocity, and (c) surface roughness measured using an optical profilometer (TRACEiT) between seaweed-covered samples (light grey), uncovered samples (dark grey), and controls (hashed) (mean  $\pm$  standard deviation [SD]). Differences in (d) surface roughness between covered and uncovered samples measured using the 3D microscope after exposure to intertidal conditions are also shown.

### 3.4 | Near-surface temperature

Time-series data of near-surface temperature collected in the seaweed-covered and uncovered plots during both the summer and winter study periods are shown in Figure 4. This includes near-surface air temperature data recorded during air-exposed low-tide periods and seawater temperature data recorded during high-tide periods (i.e. when the loggers were submerged).

### 3.5 | Summer study period

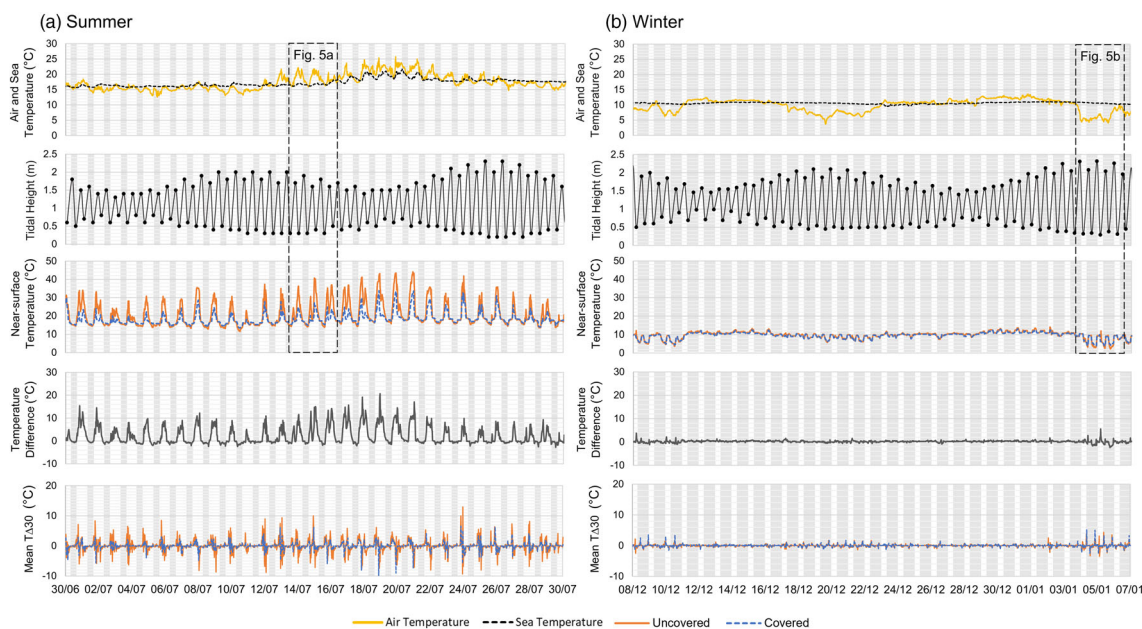
During the summer study period, the mean daily maximum temperature ( $T_{\max}$ ) was consistently higher in the uncovered plots compared to the seaweed-covered plots. On average,  $T_{\max}$  was  $7.97^{\circ}\text{C}$  (31.1%) higher in the uncovered plots compared to the covered plots. The mean daily minimum temperature ( $T_{\min}$ ) was also consistently lower in the uncovered plots compared to the covered plots;  $T_{\min}$  was on average  $0.81^{\circ}\text{C}$  (5.6%) lower in the uncovered plots compared to the covered plots. Consequently, the mean daily temperature range ( $T_{\text{range}}$ ) was consistently higher in the uncovered plots, with values averaging  $8.78^{\circ}\text{C}$ , which was 92.3% higher than in the seaweed-covered plots.

On four occasions, the mean near-surface temperature of the uncovered plots was  $>15^{\circ}\text{C}$  higher than the covered plots, with a maximum difference of  $20.70^{\circ}\text{C}$  recorded on 19 July 2021. This coincided with peak ambient air temperatures of  $\sim 25^{\circ}\text{C}$  and a neap tide with the low occurring during the hottest part of the day. The mean greatest daily change in temperature over a 30-min period ( $T_{\Delta 30}$ ) was nearly always higher in the uncovered plots than the covered plots,

with the opposite trend occurring on only six occasions during the 31-day study period. On average,  $T_{\Delta 30}$  values were  $2.51^{\circ}\text{C}$  (i.e.  $5.02^{\circ}\text{C/h}$ ) higher in the uncovered plots compared to the seaweed-covered plots, with maximum  $T_{\Delta 30}$  values of  $13.0^{\circ}\text{C}$  (i.e.  $26^{\circ}\text{C/h}$ , 24 July) and  $9.8^{\circ}\text{C}$  (i.e.  $19.6^{\circ}\text{C/h}$ , 19 July), respectively.

### 3.6 | Winter study period

The near-surface temperature regimes in the covered and uncovered plots were less variable during the winter study period compared to the summer study period. Air temperature recorded every 10 min by a directional wave measurement buoy in Weymouth Bay ( $50^{\circ}37'22''\text{N}$ ,  $02^{\circ}24'51''\text{W}$ )  $\sim 5$  km from the field site also fluctuated to a lesser degree, remaining relatively stable between the day and night, and never dropping below freezing (Figure 4b). The differences in near-surface temperatures between the covered and uncovered plots were also small during the winter. For instance, when ambient air temperature was above  $10^{\circ}\text{C}$ , the mean near-surface temperature in the uncovered plots was typically in the order of  $1^{\circ}\text{C}$  higher than in the covered plots. The greatest differences between the covered and uncovered plots occurred during low-tide periods when air temperatures were low (i.e.  $7^{\circ}\text{C}$  or below) at the beginning and end of the study period (10 December 2021 and 4–7 January 2022). During these periods, the mean near-surface temperature in the uncovered plots was typically  $1$ – $2^{\circ}\text{C}$  lower than in the covered plots (e.g. Figure 5b). However, it is worth noting that a similar trend was not observed during a cold spell between 19 and 22 December 2021, when temperature differences between the plots remained small.



**FIGURE 4** First row: Air temperature recorded at 10-min intervals (yellow solid) and sea temperature recorded at 30-min intervals (black dotted) by a directional wave measurement buoy in Weymouth Bay ( $50^{\circ}37'22''\text{N}$ ,  $02^{\circ}24'51''\text{W}$ ) as part of the Southeast Regional Coastal Monitoring Programme (obtained from [coastalmonitoring.org](https://coastalmonitoring.org)). Second row: Tidal regime at Portland Port during the summer (a) and winter (b) study periods. Third row: Mean near-surface temperature ( $^{\circ}\text{C}$ ) of seaweed-covered plots (blue dashed,  $n = 3$ ) and uncovered plots (orange solid,  $n = 3$ ) recorded at 30-min intervals over two 31-day study periods between 30 June and 30 July 2021, and between 8 December 2021 and 7 January 2022. Fourth row: Difference in mean near-surface temperature ( $^{\circ}\text{C}$ ) between the covered and uncovered plots. Fifth row: Mean  $T_{\Delta 30}$  ( $^{\circ}\text{C}$ ) in the covered and uncovered plots across the time series. Periods of daylight (05:00 to 21:00 BST in summer; 08:00 to 16:00 GMT in winter) and darkness (21:00 to 05:00 BST in summer; 16:00 to 08:00 GMT in winter) are shown as white and grey bands, respectively. Portions of data shown in greater detail in Figure 5 are indicated. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/terms-and-conditions)]

## 4 | DISCUSSION

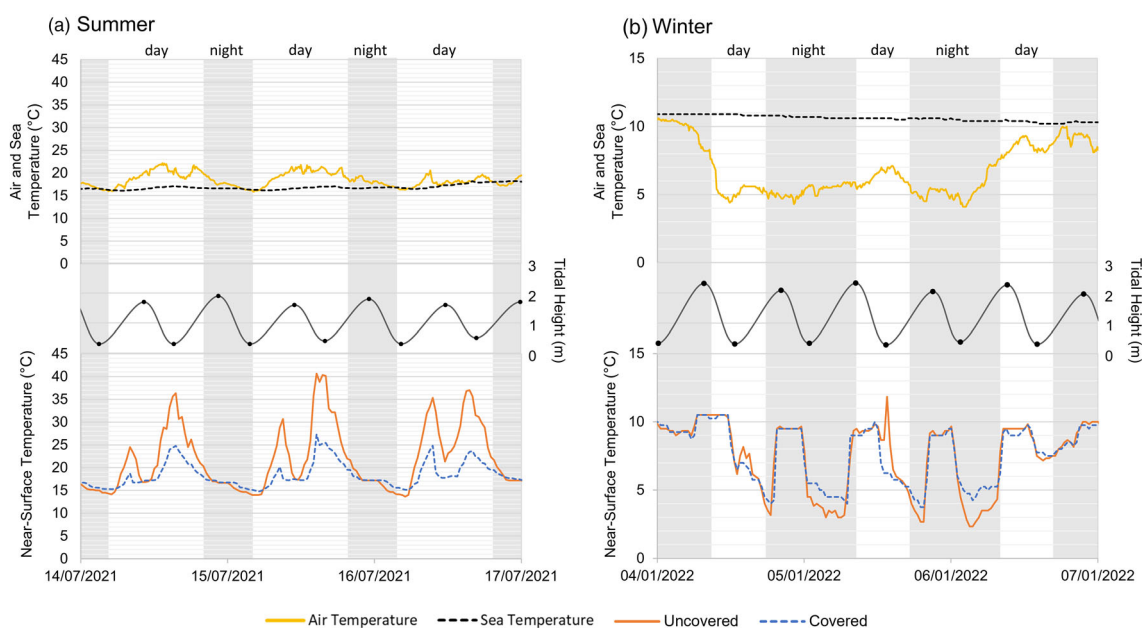
### 4.1 | Seaweed cover influences on indicators of substrate deterioration

After 6 months' exposure to intertidal conditions, seaweed cover was not found to significantly affect the surface hardness of mortar prepared using natural cement. The hardness of both seaweed-covered and uncovered samples increased over time, indicating that during the early phases of exposure, when curing may be continuing and cement mortars are at their most vulnerable, seaweed did not detrimentally impact the condition of the mortar. Instead, differences in surface roughness and UPV between seaweed-covered and uncovered samples suggest that seaweed may provide some protective benefit. Specifically, the increase in UPV was significantly greater for the seaweed-covered samples, indicating a greater degree of internal cohesion than the uncovered samples at the end of the study period (Fusade & Viles, 2019; Svahn, 2006). The seaweed-covered samples also had significantly lower surface roughnesses than the uncovered samples at the end of the study, indicating that they had experienced less surface change and material loss (Fornós et al., 2011; Gómez-Pujol et al., 2006; McCarroll & Nesje, 1996). When considered together, these results suggest that the impact of seaweed on the breakdown of natural cement-based mortar was, at worst, negligible. Rather, seaweed cover appeared to enhance the curing process and/or protect the mortar samples from deterioration during the first few months after initial mixing and exposure to intertidal conditions.

Differences in near-surface temperatures between areas with and without seaweed cover have been used as an indicator of differences in the intensity of thermal weathering regimes on natural rock and engineered structures (e.g. Coombes, Naylor et al., 2013). In our study, near-surface temperature extremes and fluctuations over both diurnal and minute-hour timescales were damped under seaweed canopies,

with the greatest dampening effects observed during the summer study period (Figures 4 and 5). This dampening effect implies a bioprotective mechanism, whereby the frequency and magnitude of thermal variations associated with both 'shock' and 'fatigue' modes of thermal decay (e.g. Hall & Thorn, 2014) are reduced under a cover of seaweed. In comparison to other studies on the bioprotective properties of seaweed (e.g. Coombes, Naylor et al., 2013; Gowell et al., 2015) and other intertidal organisms, such as barnacles and mussels (e.g. Baxter et al., 2022a; Coombes et al., 2017; Gonzalez et al., 2021; Jurgens & Gaylord, 2016), the magnitude of thermal dampening by *F. vesiculosus* and *F. serratus* canopies was relatively high at our study site, which may be related to differences in aspect and, in particular, canopy thickness (Coombes, Naylor et al., 2013).

As has been previously suggested, lower temperatures under seaweed canopies during warm weather and periods of intense insolation (i.e. during low-tide periods) are likely associated with shading effects and enhanced moisture retention and evaporative cooling (Baxter et al., 2022a; Coombes, 2014; Coombes, Naylor et al., 2013). Such thermal-moderating effects, also demonstrated in our data, have implications for the deterioration of natural cement mortars as fluctuations, extremes, and rates of change in temperature are closely linked to the efficiency of mechanical weathering processes acting on historic masonry (e.g. André et al., 2012, 2014; Jang & Viles, 2021; McIlroy de la Rosa et al., 2013; Sternberg et al., 2011; Viles et al., 2011) and natural rock in marine environments (e.g. Baxter et al., 2022a; Coombes, Naylor et al., 2013; Gonzalez et al., 2021; Gowell et al., 2015; Mottershead et al., 2003; Moura et al., 2012). Although we did not directly collect data on substrate moisture, seaweed is known to retain moisture during low-tide periods (Coombes, Naylor et al., 2013; Umanzor et al., 2019), which has further implications for the wetting-drying and salt crystallization processes that influence rock and engineering materials when exposed in the intertidal zone (Kanyaya & Trenhaile, 2005; Santhanam & Otieno, 2016;



**FIGURE 5** Top: Air temperature recorded at 10-min intervals (yellow solid) and sea temperature recorded at 30-min intervals (black dotted) by a directional wave measurement buoy in Weymouth Bay (data obtained from [coastalmonitoring.org](https://coastalmonitoring.org)). Bottom: Tidal regime at Portland Port during a warm spell (a) between 14 and 17 July 2021 and a cold spell (b) between 4 and 7 January 2022. The mean near-surface temperatures (°C) of the seaweed-covered plots (blue dashed,  $n = 3$ ) and the uncovered plots (orange solid,  $n = 3$ ) recorded at 30-min intervals are also shown. Note the different scales in parts (a) and (b). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

Trenhaile, 2006). For example, increased moisture retention caused by seaweed canopies has been linked to reductions in the frequency and intensity of wetting–drying cycles, as well as the likelihood of salt crystallization during drying phases on rocky shore platforms (e.g. Stephenson & Kirk, 2000). The retention of substrate moisture may also be important for chemical weathering processes (Coombes, 2014), although compared to mechanical processes, the influence of seaweed and other intertidal species on chemical modes of breakdown remains relatively understudied.

Although sub-zero temperatures did not occur during our study, we did find evidence of thermal insulation by seaweed during the colder winter period (e.g. Figure 5b), with near-surface temperatures typically being higher under the seaweed canopies when the air temperature was 7°C or below. This complements observations made under more extreme cold conditions, showing that seaweed canopies likely reduce the frequency, severity, rate, and duration of damaging freezing events in temperate environments (e.g. Scrosati & Ellrich, 2018). While such bioprotective mechanisms against extreme cold have been demonstrated in terrestrial heritage settings (e.g. Coombes et al., 2018), this has not yet been identified for heritage materials and structures exposed in the intertidal zone. This is despite the fact that freezing events can cause significant physical damage to coastal rocks when coinciding with low tide (e.g. Robinson & Jerwood, 1987). As such, the potential protective roles of algal canopies growing on maritime heritage in winter as well as summer warrant further attention.

## 4.2 | Wider implications and future research opportunities

Our finding that seaweed cover did not significantly impact the deterioration of natural cement-based mortar during the first 6 months of intertidal exposure has potential implications for the conservation of maritime built heritage and marine biodiversity. Specifically, these results help address some of the concerns raised by maritime practitioners in a recent survey regarding the effects of seaweed growth on built heritage assets (e.g. Baxter et al., 2022b). Furthermore, our findings imply that opportunities exist for the application of nature-based solutions for the management and protection of historic structures in marine environments, alongside habitat provision and biodiversity conservation. For instance, our study supports arguments for not removing seaweed from historic masonry as part of maintenance regimes unless this is necessary for health and safety reasons, or to allow structural inspections. As with soil and turf used in the soft capping of some terrestrial heritage sites (Hanssen & Viles, 2014; Lee et al., 2009; Morton et al., 2011; Wood et al., 2018) and ivy canopies growing on historic walls (Coombes et al., 2017; English Heritage, 2010; Viles et al., 2011), managers of coastal infrastructure may look to retain or even actively encourage biological growth, including seaweed, that has the potential to provide protective engineering functions alongside other associated benefits. This includes maintaining and/or increasing the biodiversity value of coastal engineering structures given that seaweed canopies provide cooler and wetter conditions for diverse understory communities (Scrosati & Ellrich, 2018; Watt & Scrosati, 2013). Management strategies aimed at discouraging the removal of existing seaweed or encouraging its growth may, therefore, present win–win opportunities

for the conservation of built cultural heritage and biodiversity in marine environments.

Focusing on thermal effects, we examined the impact of two species of seaweed (*F. vesiculosus* and *F. serratus*) on the deterioration of natural cement mortar over a 6-month period using multiple weathering indicators (surface hardness, roughness, and ultrasonic pulse velocity). In doing so, we found no evidence of accelerated deterioration associated with seaweed cover, along with some evidence of potential protective effects. Future research is now needed to determine the full suite of biodeteriorative and/or bioprotective effects of different biological covers on built heritage assets (i.e. covers varying in constituent species, morphology, thickness, organism density, etc.), and whether processes of deterioration moderated by surface-colonizing organisms vary with location, environmental conditions, and the type of material being colonized (stonework, plastic, wood, metal, etc.). The effects of marine growth on conservation materials, including natural cement, also need to be examined over longer periods of time and under changing climatic conditions. Indeed, whilst mortar is generally most vulnerable to deterioration in the initial days and weeks after it has been mixed (i.e. during the curing phase), any biodeteriorative or bioprotective effects will likely become more pronounced once exposed over longer periods of time. Understanding how marine growth influences the long-term decay of materials used to build and repair heritage assets is particularly important for future conservation, especially in the case of older structures that have experienced longer periods of environmental exposure and, consequently, may be more vulnerable to decay. In the context of global climate change, any changes in the biogeomorphological functions of seaweed (and other types of marine growth) also warrant further attention. This includes the likely modulation of thermal buffering effects due to increases in extreme weather events, such as heatwaves, and changes in the structure of the biological communities that develop on maritime built heritage in response to changing environmental conditions (e.g. rising sea levels, ocean acidification, and changing temperatures).

## 5 | CONCLUSIONS

After 6 months of exposure to intertidal conditions, we found no evidence of enhanced deterioration of mortar prepared using natural cement when covered with seaweed. Instead, our results suggest that seaweed cover may enhance the curing process and structural integrity of mortar, and limit surface breakdown associated with thermal variability under both warm (summer) and cold (winter) conditions. The thermal dampening and water-retaining effects of seaweed may also limit the decay of natural cement-based mortars caused by other physical decay mechanisms (e.g. wetting–drying and salt crystallization), but this requires further study. Importantly, the biogeomorphological functions of seaweed should be considered in management decisions alongside the other costs, benefits, and values associated with its growth to ensure the continued conservation of maritime built heritage and marine biodiversity. Finally, future work should focus on determining the net effects of seaweed and other intertidal species on materials used in the construction and repair of built heritage exposed to intertidal conditions over varying timescales and under changing environmental conditions.

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## CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## AUTHOR CONTRIBUTIONS

TB, MC, and HV contributed to the conception and design of the study. TB collected the data, conducted the analysis, and drafted the initial manuscript. MC and HV provided supervision. All authors discussed the results and reviewed and edited drafts of the manuscript.

## DATA AVAILABILITY STATEMENT

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

## ORCID

Timothy Baxter  <https://orcid.org/0000-0001-7051-2835>

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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