



Surface integrity could limit the potential of concrete as a bio-enhanced material in the marine environment

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ABSTRACT

Coastal sprawl is among the main drivers of global degradation of shallow marine ecosystems. Among artificial substrates, quarry rock can have faster recruitment of benthic organisms compared to traditional concrete, which is more versatile for construction. However, the factors driving these differences are poorly understood. In this context, this study was designed to compare the intertidal and subtidal benthic and epibenthic assemblages on concrete and artificial basalt boulders in six locations of Madeira Island (northeastern Atlantic, Portugal). To assess the size of the habitat, the shorelines in the study area were quantified using satellite images, resulting in >34 % of the south coast of Madeira being artificial. Benthic assemblages differed primarily between locations and secondarily substrates. Generally, assemblages differed between substrates in the subtidal, with lower biomass and abundance in concrete than basalt. We conclude that these differences are not related to chemical effects (e.g., heavy metals) but instead to a higher detachment rate of calcareous biocrusts from concrete, as surface abrasion is faster in concrete than basalt. Consequently, surface integrity emerges as a factor of ecological significance in coastal constructions. This study advances knowledge on the impact and ecology of artificial shorelines, providing a baseline for future research towards ecological criteria for coastal protection and management.

1. Introduction

Artificial shorelines are common worldwide and are proliferating at increasing rates (Floerl et al., 2021). They promote a decline in local marine biodiversity, native populations' connectivity and contribute to a higher occurrence and proliferation of opportunistic and non-indigenous species (Bulleri and Airoidi, 2005; Bulleri and Chapman, 2010; Sedano et al., 2019; Castro et al., 2020; Castro et al., 2022; Ferrario et al., 2020). Moreover, the physical footprint of artificial

shorelines is more intense in productive coastal ecosystems, such as bays, lagoons, estuaries, and islands (Bugnot et al., 2018; Floerl et al., 2021; Sempere-Valverde et al., 2023a). However, the shallow marine communities on islands are particularly vulnerable to disturbances (Canning-Clode et al., 2013; Ávila et al., 2018; Freitas et al., 2019). In oceanic islands, the area available for colonization is much smaller than in the continental platform, which increases the risk of stochastic effects. Furthermore, the high levels of endemism, high niche availability and low plasticity of the local communities, which depend on island distance

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to the continent, can increase the risk of impacts by anthropogenic pressures such as coastal sprawl, resource extraction and tourism, and biological processes such as marine invasions (Spalding et al., 2007; Ávila et al., 2018; Freitas et al., 2019; Sempere-Valverde et al., 2023a). To minimize the impacts caused by shoreline construction it is imperative to understand the environmental and ecological factors and processes responsible for the low ecological performance of artificial shorelines (Firth et al., 2016; Sempere-Valverde et al., 2023a).

Artificial substrates are colonized from a zero-coverage status, which might explain why communities on artificial habitats are often less rich than those in natural areas (Dong et al., 2016). However, approximately two years after deployment most species have settled into the habitat and, thereafter, begin to establish themselves, reaching climax communities in 5 to 20 years (Hawkins et al., 1983; Pinn et al., 2005; Gacia et al., 2007; Coombes, 2011). Nevertheless, and despite these being dynamic communities, the differences between natural and artificial coastlines can persist even in centuries-old artificial structures, regardless of the substrate they are made of, indicating that, in general, artificial shorelines are poor surrogates of natural habitats (Firth et al., 2016; Hill et al., 2021; Rallis et al., 2022). Artificial structures such as seawalls have low structural complexity at various spatial scales and a low presence of tide pools, pits, grooves, bumps, ledges, and crevices, which reduce microhabitats' heterogeneity when compared to natural areas (Moreira et al., 2006; Loke and Todd, 2016; Cacabelos et al., 2018; MacArthur et al., 2020; Strain et al., 2020). Eco-engineering interventions may be a solution to increase the resemblance between artificial and natural habitats by promoting surface area (i.e., modifying the slope of artificial shorelines) and structural complexity on artificial structures (Firth et al., 2016; Ostalé-Valriberas et al., 2018; Sempere-Valverde et al., 2023a). It can be a powerful tool for mitigate current and future impacts by coastal constructions. However, more research is needed on the effects of different substrata on benthic assemblages composition to provide recommendations on suitable natural and artificial materials that reduce the footprint of artificial shorelines, as physicochemical characteristics of the substratum (i.e., albedo, hardness, mineralogy, and hydrophobicity) can play a vital role in the ecological succession and composition of benthic assemblages (Sempere-Valverde et al., 2023a for review).

Although concrete is considered a low-cost and versatile material for marine construction, quarry rock generally shows a faster initial recruitment of benthic organisms (bioreceptivity) and often reach richer communities than concrete (Connell and Glasby, 1999; Sempere-Valverde et al., 2018; Sedano et al., 2020a). However, these effects may differ in certain habitats such as marinas (Sempere-Valverde et al., 2023b). Moreover, the interaction of benthic organisms with the substratum is expected to be more relevant during early-settlement, as secondary settlers will increasingly interact with the primary cover of biodiversity rather than the rocky substrata (Liversage et al., 2014; Coombes et al., 2015). The lower ecological performance of marine concrete might result from the leaching of heavy metals such as Al, Cr, V and Zn and its high surface alkalinity (Müllauer et al., 2015; Sella and Perkol-Finkel, 2015), which may hinder early colonization and/or promote the settlement of alkotolerant taxa, such as barnacles and other calcifying organisms (Bronson et al., 2003; Bone et al., 2022a). However, the effects of metal leaching and surface pH in shaping marine assemblages is still poorly understood (Green et al., 2012; Hsiung et al., 2020). Recent eco-engineering and research initiatives are trying to address this knowledge gap by testing the bio-receptivity of novel marine concrete mixtures with lower alkalinity, reduced heavy metals release and smaller overall carbon footprint (see Bone et al., 2022a). These concrete mixtures are being increasingly used for marine construction and are known to have a better bio-receptivity than traditional concrete during early colonization (Firth et al., 2020; Hsiung et al., 2020; Bone et al., 2022a). However, current knowledge over long timeframes and geographical scales remains scarce despite of the construction interventions being made having long-lasting effects on the

marine environment. In this regard, coastal management must prioritize the conservation of natural habitats and the use of nature-based shorelines for coastal defense, applying informed ecological engineering to both design and materials when using artificial hard substrata, as it can influence the ecological succession of the benthic community (Coombes et al., 2015; Firth et al., 2016; Strain et al., 2018; Sedano et al., 2020a, 2020b; Airoidi et al., 2021).

Substratum material influence marine assemblages, although it generally plays a secondary role in the successional patterns, composition, and diversity of benthic assemblages compared to other environmental variables, such as food and larvae abundance, hydrodynamic exposure, and substrate orientation and microtopography (Liversage et al., 2014; Coombes et al., 2015; Canessa et al., 2019, 2020). Therefore, the compounding and interplay of multiple factors and environmental conditions hinder our ability to assess the role of material on marine assemblages, particularly in heterogeneous and patchy ecosystems such as rocky shores (Raffaelli and Hawkins, 2012). Experimental approaches can exclude confounding factors (e.g., Green et al., 2012). However, these often are conducted under controlled settings, missing the interplay of factors found in real world conditions. Field experiments on the other hand, are often limited to a geographic location and to a short timeframe, leading to temporal and spatial constraints in their findings (Underwood, 2000; Green et al., 2012). As a result, most experimental studies on fouling communities in different substrates are based on early community development (e.g., Green et al., 2012; Sempere-Valverde et al., 2018, 2023b). In contrast, long-term (years to decades) studies are mostly survey-based and observational, often hampering the de-entanglement of compounding factors and co-variables shaping biological assemblages (e.g., Bavestrello et al., 2000; Canessa et al., 2019, 2020). Therefore, the high spatial variability in the compounding effects of substratum type and other environmental and ecological factors on benthic assemblages composition, combined with a lack of consolidated information across geographic scales (although see Aguilera et al., 2022), has limited our ability to identify common patterns and processes, leading to general recommendations and policies (Riera et al., 2018; Firth et al., 2020).

In the present context of global change, understanding the factors shaping coastal habitats and the processes generating impacts is essential for marine spatial planning, developing future regulations, and designing better conservation policies and mitigation measures (Airoidi et al., 2016; Firth et al., 2016). This requires understanding the footprint of artificial shorelines (e.g., shoreline modification rates) and their ecological impacts, but also the performance of different designs and materials used for marine construction to raise recommendations. Regarding materials, it becomes important to understand the capacity of different substrates for hosting richer and more diverse mature benthic communities and their potential applicability on ecological engineering. To contribute to addressing these challenges, this study examines the abundance of artificial shorelines on the southern coast of Madeira Island (NE Atlantic) and the effect of artificial substratum type on the mature assemblages that inhabit them. The first objective is to determine the significance of artificial habitats in the studied area by quantifying the fraction of the shoreline represented by artificial substrates. The second objective is to study the effects of substratum-related characteristics on mature benthic assemblages (sessile and epibenthic) on six artificial shorelines older than 6 years. This was done by comparing the assemblages found on the two most common substrata used for coastal defense: concrete and quarry rock (in this case: artificial basalt boulders), to provide knowledge into the long-term ecological performance of these materials. The benthic assemblages were studied at the intertidal and subtidal levels while excluding the confounding effects inherent to spatially heterogeneous assemblages by adopting a randomized-block design. The study hypothesized that, under similar microenvironmental conditions, the distinct physicochemical properties of basalt and concrete influence variables relevant to assess the ecological status and productivity of the mature assemblages inhabiting

them, namely: assemblages' composition, taxonomic richness and diversity, abundance, organic and calcareous biomass, and concentration of heavy metals in assemblages' tissue. Overall, this objective aims to enhance our understanding of the long-term ecological implications of different materials used in the construction of artificial shorelines.

2. Methods

2.1. Study site and characterization of the shoreline

This study was conducted in Madeira Island, NE Atlantic Portugal. Madeira is influenced by trade winds and oligotrophic waters with salinity of typically 36.6 PSU and mean sea surface temperatures ranging from 18 °C in late winter to 23–24 °C in late summer (Canning-Clode et al., 2008; Hoppenrath et al., 2019; Rosa et al., 2022). These conditions produce extreme hydrodynamic regimes on the north coasts of the island, while the south coasts are relatively sheltered and calm, experiencing prevailing westerly waves of <2m significant height, although exposed to southwest sea storm events (García-Romero et al., 2023). As a result, the human population and its associated pressures are higher on the south coasts of the island. Due to the low abundance of artificial shorelines and the often-unsafe fieldwork conditions occurring in the north coast, this study was conducted on the south coast of

Madeira, where the coastline is dominated by rocky shores, boulder fields and reefs (Canning-Clode et al., 2008; Monteiro et al., 2021).

Samplings in this study were conducted in six accessible locations of the south coast of Madeira Island (see Fig. 1). In all locations, samplings were carried out on the exposed sides of breakwaters where both artificial basalt and concrete substrates were present. All breakwaters were located on sandy bottoms that ranged from 5-to-15 m depth from the water surface, although they differed in their use. Breakwaters in Paul do Mar and Santa Cruz were part of fishing ports infrastructure, while breakwaters in Calheta were part of an artificial beach. The ones in Club Naval and Carlton acted as coastal protection for leisure infrastructure in the city of Funchal, and the breakwaters in Aeroporto were part of the coastal defenses of Madeira's Airport.

The relative importance of artificial habitats in the study area was assessed using Google Earth Pro© in June 2022 to identify artificial structures along the shoreline (inspection of visible artificial shorelines using 2020 satellite images). During these samplings, the artificial and natural extensions of the shoreline were digitized, and length measurements were carried out using a resolution of 10 m. Artificial extensions of the shoreline were only annotated when unequivocally identifiable. Only fixed structures were digitized, excluding visible floating pontoons and aquaculture farms. Finally, the year of construction of the artificial shorelines sampled in this study was assessed by

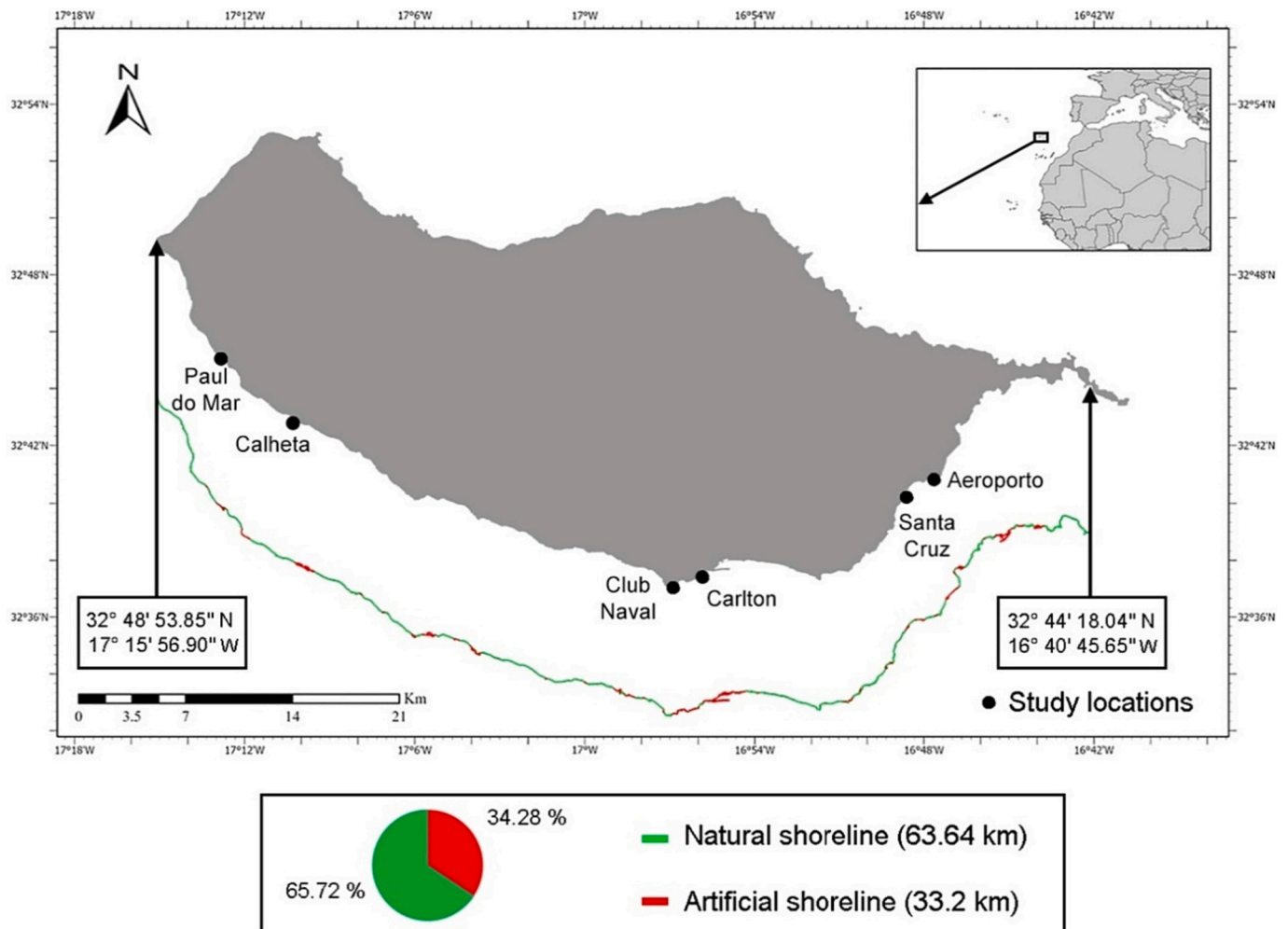


Fig. 1. Study area in Madeira Island (NE Atlantic, Portugal), with the sampled locations represented by dots. The vector routes created for the characterization of the south shoreline of Madeira, from Ponta do Pargo (west) to Ponta do Furado (east), are represented as profiles parallel to the shoreline. Note that the percentages correspond to the current percentage of artificial shoreline from the total shoreline lineal profile, not the percentage of the natural shoreline that has been replaced by infrastructure. Sampled locations: Paul do Mar = 32° 45' 06.2" N, 17° 13' 30.8" W; Calheta = 32° 42' 55.7" N, 17° 10' 07.1" W; Club Naval = 32° 38' 06.1" N, 16° 56' 20.4" W; Carlton = 32° 38' 28.0" N, 16° 55' 18.7" W; Santa Cruz = 32° 40' 59.4" N, 16° 47' 37.8" W; Aeroporto = 32° 42' 21.3" N, 16° 45' 45.8" W.

reviewing satellite images of the studied area from period 1990 to 2020.

2.2. Biotic study

The influence of substratum-type on the structure of mature fouling assemblages, in terms of sessile taxa coverage, epibenthic families abundance and assemblages biomass, was studied in the intertidal and shallow subtidal (through scuba diving) in each of the surveyed locations in Madeira, from September to October 2020. The structure and composition of sessile communities depends on substrate orientation, inclination, and spatial complexity, such as surface heterogeneity and roughness (Sangil et al., 2014; Cacabelos et al., 2016b). Therefore, all the sampled quadrats were taken on vertical surfaces facing southwest to southeast, and the quadrats were located on surfaces as flat as possible. During samplings, samples were collected from basalt and concrete surfaces following a randomized complete block design (Anderson et al., 2008; Chaves & Chaves, 2010). These were collected in pairs (blocks) of two replicates: basalt and concrete, ensuring high proximity, and the same depth, orientation, exposition, distance to the sea bottom and surface complexity within pairs of replicates, to minimize the interplay of environmental variables as confounding factors in the comparison between type of substrata (see Video Abstract).

To allow the randomized complete block design, samplings were carried out on breakwaters with mixed basalt boulders and concrete units. The concrete units were cubes in Paul do Mar, Calheta, Club Naval and Aeroporto, and tetrapods in Carlton and Santa Cruz. At each location, a 25 × 25 cm quadrat was used to collect five pairs of replicates (photo quadrats and scrapes) over concrete and basalt substrates in the shallow subtidal level, from 5 to 10 m depth, and the mid-littoral intertidal level (a total of 20 replicates per location), which was identified as the intertidal belt with higher coverage of *Chthamalus* sp. (Cacabelos et al., 2016b). The shallow subtidal and midlittoral levels were selected due to their status as heavily impacted marine coastal habitats with high abundances of artificial substrata, and because the effects of substratum type can vary in these distinct environments. For example, the intertidal, being in the splash zone and subjected to wave impact stress, may exhibit different substratum erosion rates compared to the subtidal area. Each quadrat was photographed using a Sony RX100 II camera and two Brett C15 torches with XLamp® XM-L2 LED units in the subtidal, and with an Olympus though TG-6 camera in natural light in the intertidal.

After photographing, assemblages within the sampled quadrats were removed with a scraper and collected using ziplock bags (see Video Abstract). These were transported to the lab, sieved with a 0.5 mm mesh, and stored in 96 % ethanol. This material was used to identify and confirm the taxonomic groups in the sessile community under stereomicroscopes (Leica EZ4 and S8APO) using local guides, annotated checklists, and identification keys (see references list in Appendix A.2). The epibenthic biota in the sieved scrapped assemblages was identified at the family level and quantified by individuals per quadrat in a separate datasheet (Sánchez-Moyano et al., 2006). Finally, the scrapped material was dried at 85 °C for 24 h and weighed to quantify dry organic biomass. Samples were then submerged for 24 h in a solution of 5 % chloride, washed with abundant water, dried at 85 °C, and weighed for the mineral biomass (Alvarado-Rodríguez et al., 2019).

Photo-quadrat images were used to obtain taxa relative coverage, estimated by deploying 100 points in a random stratified arrangement (5 × 5 cm grid) using the CPCe software (Kohler and Gill, 2006). Before the CPCe count, the sessile assemblages were identified from the scrapped material at the lowest taxonomic level (to species in most cases), using local guides and identification keys (see Appendix B.2). However, some of these species could not be detected in the photographs (e.g., taxa too small to be identifiable or overgrown by epibionts). This was particularly the case for macroalgae specimens that could be identified to the species, genus, or family level from samples but whose characters were not observable in pictures. Therefore, these species were

added to the sessile coverage data with a score of 1 (presence), but their coverage was pooled under broader groups that could be identified from pictures, such as Crustose Coralline Algae and Filamentous algae.

2.3. Physicochemical characterization of the substrata

After scrapping the samples in the Biotic Study, the substratum below the biotic assemblages was measured for surface heterogeneity using the 'chain-and-tape' method on two 25 cm transects per sampled quadrat (Risk, 1972; McCormick, 1994). For each transect, the contoured length of the rock surface was measured following the rock contour using a 2 mm thread. The averaged length of these two contours was divided by the length of the quadrat (25 cm linear distance) to assess differences in substratum complexity between materials (Risk, 1972).

To compare major and trace elements in substrates and assemblages, an additional pair of samples was obtained in August 2021 at each of the six studied locations (see Fig. 1) in the intertidal and subtidal, collecting benthic assemblages (scrapings) and substratum samples (basalt and concrete rock chips from the substrate below assemblages after scraping). These were dried at 85 °C for 24 h and used to obtain the chemical composition of samples as quantitative major element measurements using X-ray fluorescence (XRF) and trace (minor) elements, which were measured using XRF Pro-Trace calibration. Chemical composition analyses were carried out using a ZETIUM spectrometer.

2.4. Statistical analyses

The relative coverage of sessile taxa (excluding sediment and bare substrate), obtained from photo quadrats, and the individuals' abundance of epibenthic families, obtained from scrapings, were analyzed separately for the intertidal and subtidal. These datasets were square root transformed before calculating Bray-Curtis similarity matrices. In this step, a dummy variable of value 0.01 was added to the epibenthic intertidal datasheet due to the absence of individuals in some replicates (Clarke et al., 2006). The resemblance matrixes were analyzed using a randomized complete block design on permutational multivariate analysis of variance (PERMANOVA) with 1999 permutations (Anderson et al., 2008; Chaves & Chaves, 2010). The design included the assemblages' dry weight as a covariate to exclude the variation in assemblages' structure attributable to assemblages' biomass from the analyses, as well as the fixed factor Substratum (2 levels: basalt and concrete) and the random factors Location (6 levels) and Block (Location) or pairs of replicates (5 levels, nested in Location). Principal coordinates ordinations (PCO) were used to visualize variations in assemblages' structure, including datasheet variables as vectors. Finally, the relation between the sessile and epibenthic communities were explored in the subtidal and intertidal using the RELATE routine in PRIMER v6 and were visualized with distance-based redundancy analyses (dbRDA) on (Clarke and Gorley, 2006; Anderson et al., 2008).

Univariate analyses were conducted on Euclidean distance matrices of the mineral and dry organic biomass of benthic assemblages, and the abundance, taxonomic richness, and log_e Shannon diversity of the sessile taxa and epibenthic families in the intertidal and subtidal. These analyses were carried out using PERMANOVA (1999 permutations) and with the same randomized complete block design than multivariate assemblages analyses (Location, Block (Location) and Substratum).

Differences in surface complexity between substrates were evaluated separately for the intertidal and subtidal, using univariate PERMANOVA, following an orthogonal design with the factors Location (random) and Substratum (fixed). Major elements percentages (%) and normalized minor elements concentrations in parts per million (ppm) for rocky substrates (rock chips) and benthic assemblages (scrapings) were square root transformed and used to construct four Euclidean distance matrices. These were used to test a randomized complete block design using PERMANOVA with 1999 permutations (Anderson et al., 2008; Chaves & Chaves, 2010). The design included the random factors

Location and Block (Location) and the fixed factors Level and Substratum. Differences in mineralogical content between factor levels were graphically represented using non-metric multidimensional scaling (nMDS). All statistical analyses were conducted using PRIMER v6 with PERMANOVA+ add-on (Clarke and Gorley, 2006; Anderson et al., 2008). Raw data is available in this published article as supplementary material (supplementary data.xlsx).

3. Results

3.1. Shoreline characterization

The south shoreline of Madeira is heavily constructed, with >34 % of its total shoreline profile being artificial by the year 2020 (see Fig. 1). Coastal sprawl is more intense in Funchal, the port of Caniçal, and the marina and artificial beach of Calheta. The breakwaters sampled in Calheta were 6 years old, in Paul do Mar and Calheta >10 years old, and in Club Naval, Carlton and Santa Cruz >20 years old.

3.2. Physicochemical characterization of the substrata

The sampled quadrats did not differ in surface heterogeneity between substrates in the intertidal (pseudo- $F_{1,59} = 0.968$; P (perm) =

0.346) and subtidal (pseudo- $F_{1,59} = 0.630$; P (perm) = 0.693) but differed in their elemental composition. Basalt and concrete differed in calcination loss due to the carbonated fraction in cement (Appendix A.1; Table 1.A; Fig. 2.A). According to SIMPER, this variable contributed 75.4 % to the dissimilarity between substrates, while SO_3 and CaO contributed 5.2 % each. Moreover, concrete had higher concentrations of lead (Pb contribution = 25.6 %) and Iodine (I: 13,8 %), while basalt had more tungsten (W: 14.4 %) (Appendix A.2; Table 2.B; Fig. 2.B).

The differences between basalt and concrete in major and minor elements did not influence the composition of benthic assemblages, which rather varied between the subtidal and intertidal levels (Table 2.C and D; Fig. 2.C and D). Overall, scrapings had a lower concentration of major and minor elements in the intertidal than the subtidal, with the following contributions to the dissimilarities between levels. Major elements: SiO_2 (44.4 %), Fe_2O_3 (21.5 %), Al_2O_3 (17.8 %) and MgO (11.0 %). Minor elements: V (27.3 %), I (12.1 %), Mn (9.4 %), Cr (9.2 %), Ni (7.6 %) and Nb (5.8 %).

3.3. Benthic assemblages

Overall, 45 taxonomic entities were identified in the sessile and 46 in the epibenthic assemblages (see Appendix B.1). Location was the main source of variation for the structure of benthic assemblages (see MS in

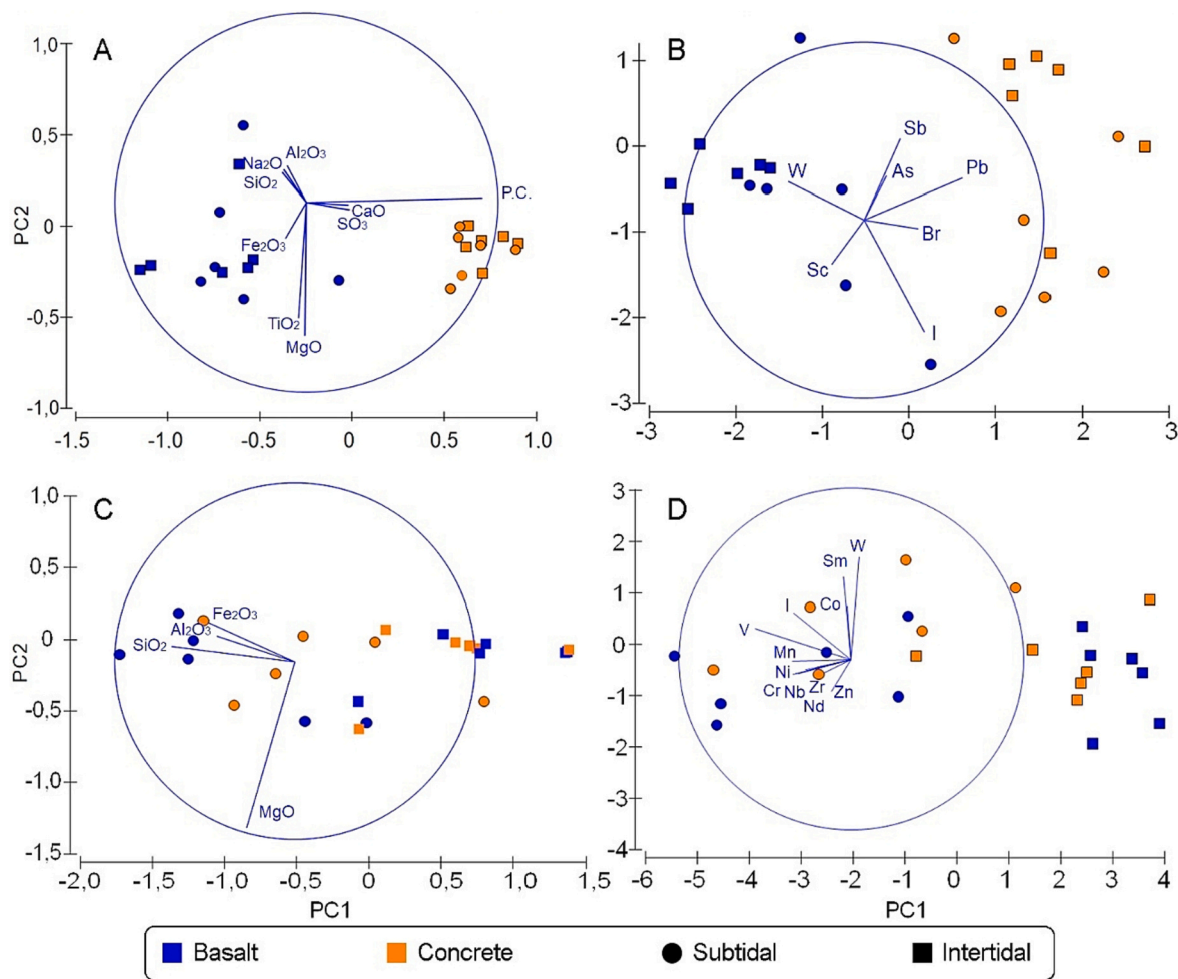


Fig. 2. Principal components analyses (PCAs) for substratum samples (basalt and concrete rock chips, A and B) and benthic assemblages' samples (scrapings, C and D) using major elements concentration (A and C) and minor elements concentrations (B and D). The groups A, B, C and D are equivalent to those in Table 1. Blue vectors indicate those elements with a Pearson correlation higher than 0.2 with any of the PCA axes. Vector length indicates the correlation index and the blue circumference the maximum correlation coefficient (Aguilera et al., 2022). A: major elements percentages on substrates; B: minor elements concentration (ppm) on substrates; C: major elements percentages on scrapings; D: minor elements concentration (ppm) on scrapings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Permutational multivariate analysis of variance (PERMANOVA) results on the Euclidean distances within substratum samples (rock chips) and benthic community samples (scrapings) using major elements percent concentration (%) and minor elements parts per million concentrations (ppm). The groups A, B, C and D are equivalent to those in Fig. 2. Average concentrations and standard errors across relevant levels of variation are included in Appendix A. SIMPER results for those variables with higher contribution to dissimilarities are detailed in text. Df: degrees of freedom; MS: mean sum of squares; bold: significant results (P (perm) <0.05).

Rock chips		A			B		
Source	Df	Major elements			Minor elements		
		MS	Pseudo-F	P (perm)	MS	Pseudo-F	P (perm)
Level	1	0.09	0.54	0.706	10.14	2.94	0.069
Location	5	1.01	1.53	0.163	4.63	1.68	0.096
Substrate	1	11.28	106.14	0.003	61.75	15.23	0.003
Level × Location	5	0.87	1.33	0.267	3.45	1.25	0.284
Level × Substrate	1	0.16	1.24	0.319	5.61	2.03	0.150
Location × Substrate	5	0.53	0.81	0.697	4.05	1.47	0.140
Residual	5	0.66			2.76		

Scrapings		C			D		
Source	Df	Major elements			Minor elements		
		MS	Pseudo-F	P (perm)	MS	Pseudo-F	P (perm)
Level	1	11.50	27.6	0.002	152.09	27.38	0.003
Location	5	0.91	3.17	0.79	10.04	2.82	0.023
Substrate	1	0.30	1.52	0.252	5.93	1.44	0.241
Level × Location	5	0.42	1.45	0.300	5.56	1.56	0.181
Level × Substrate	1	1.02	3.55	0.103	12.91	3.63	0.052
Location × Substrate	5	0.20	0.70	0.682	4.14	1.16	0.350
Residual	5	0.29			3.56		

Table 2

Permutational multivariate analysis of variance (PERMANOVA) results for the Bray Curtis distances within sessile and epibenthic assemblages in the subtidal and intertidal adding benthic assemblages' biomass as covariate (Cov). Df: degrees of freedom; MS: mean sum of squares; bold: significant results (P (perm) <0.05).

Subtidal		Sessile assemblages			Epibenthic assemblages		
Source	Df	MS	Pseudo-F	P (perm)	MS	Pseudo-F	P (perm)
Biomass (Cov)	2	7044	2.092	0.012	6739	2.274	0.004
Location	5	6311	6.438	0.001	4950	3.256	0.001
Substratum	1	1354	2.433	0.038	1589	1.454	0.179
Block (Location)	24	1146	1.410	0.010	1503	1.323	0.013
Location × Substratum	5	505	0.622	0.946	1040	0.915	0.886
Residual	22	813			1329		

Intertidal		Sessile assemblages			Epibenthic assemblages		
Source	Df	MS	Pseudo-F	P (perm)	MS	Pseudo-F	P (perm)
Biomass (Cov)	2	1403	1.618	0.177	9769	3.605	0.001
Location	5	2202	3.039	0.002	7260	4.649	0.001
Substratum	1	421	0.807	0.634	1375	0.921	0.552
Block (Location)	24	491	1.645	0.019	1116	0.998	0.497
Location × Substratum	5	388	1.298	0.271	1584	1.416	0.197
Residual	22	299			1118		

Table 2). In the subtidal, filamentous algae and the macroalgae *Halopteris scoparia* and *Dictyota* sp. were more abundant at the westernmost location Paul do Mar, while calcareous algae (including *Peyssonnelia* sp.), *Codium adhaerens* and the barnacle *Balanus trigonus* were more abundant in the east and south locations (Appendix C.1). In the intertidal, the barnacle *Chthamalus stellatus* was the dominant species, although filamentous algae were also abundant in Calheta. Epibenthic assemblages structure was related to the structure of sessile assemblages in the subtidal (RELATE: Rho = 0.391; P(perm) = 0.01) and intertidal (Rho = 0.235; P(perm) = 0.01). Overall, *Halopteris scoparia*, *Dictyota* sp. and *Peyssonnelia* sp. were the taxa with higher contribution to the structure of epibenthic assemblages in the subtidal, while filamentous algae and *Rivularia* sp. were the ones with higher contribution in the intertidal (see Fig. 3).

The type of substratum contributed to the structure of sessile

assemblages in the subtidal (Table 2), where basalt had a higher abundance of crustose coralline algae, including *Peyssonnelia* sp. and *Jania* spp., while concrete had a higher abundance of filamentous algae (Table 3). Basalt had also a higher richness and diversity of epibenthic families than concrete in the subtidal (Fig. 4). Moreover, the coverage of sessile assemblages was higher on basalt than concrete in the subtidal and intertidal, and the abundance of epibenthic assemblage in the subtidal (see Table 4). Finally, the overall calcareous and organic biomass of assemblages were higher on basalt in the subtidal.

4. Discussion

Coastal sprawl in the south of Madeira Island is remarkably high, as it is significantly populated, although to a lesser degree than dense urban areas (Floerl et al., 2021). In Macaronesia, coastal sprawl has been

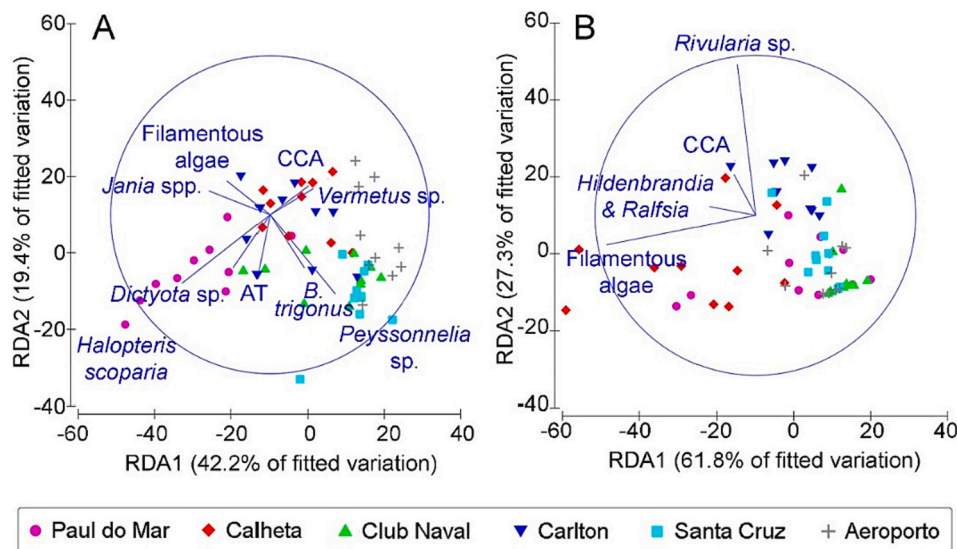


Fig. 3. Distance-based redundancy analysis (dbRDA) on the epibenthic assemblages including sessile variables as vectors, for the subtidal (A) and intertidal (B). Only those variables (blue text) with an average relative coverage higher than 1 % (for the sessile assemblages) and a Pearson correlation higher than 0.3 with any of the ordination axes were included as vectors in the ordinations. Vectors length indicates the correlation coefficient for each variable and the blue circumference the maximum correlation coefficient (Aguilera et al., 2022). CCA: crustose coralline algae; AT: *Asparagopsis taxiformis*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3

Taxa identified by a similarity percentage (SIMPER) routine as having a high contribution to the average similarity within and dissimilarity between substrates using the sessile assemblages in the subtidal data (see Table 2). CCA: crustose coralline algae; Av. Abund: average abundance; S. Contr: contribution to average similarity; S. Cum: cumulated contribution to similarity; Dis. Contr: contribution to average dissimilarity; Dis. Cum: cumulated contribution to dissimilarity.

	Basalt			Concrete		
	Av. Abund	S. Contr (%)	S. Cum (%)	Av. Abund	S. Contr (%)	S. Cum (%)
CCA	21.80	47.09	47.09	17.80	44.33	44.33
<i>Peyssonnelia</i> sp.	16.23	23.97	71.06	15.87	17.95	62.28
Filamentous algae	8.73	9.63	80.70	12.93	19.87	82.15

	Basalt	Concrete	Basalt vs. Concrete	
	Av. Abund	Av. Abund	Dis. Contr (%)	Dis. Cum (%)
<i>Peyssonnelia</i> sp.	16.23	15.87	21.86	21.86
Crustose coralline algae (CCA)	21.80	17.80	17.84	39.70
Filamentous algae	8.73	12.93	16.49	56.19
<i>Jania</i> spp.	5.03	4.60	7.86	64.05
<i>Lobophora</i> sp.	4.93	3.17	6.40	70.45
<i>Asparagopsis taxiformis</i>	2.73	1.17	3.88	74.33

related to the decline of local ecosystems, such as native seaweed canopies (Cacabelos et al., 2016a; Bernal-Ibáñez et al., 2021), seagrass meadows (Tuya et al., 2014), and barnacle beds (Cacabelos et al., 2016b; Martins et al., 2016). Therefore, the impacts of coastal construction are highly relevant, regardless of the construction material used (Cacabelos et al., 2018; Sempere-Valverde et al., 2023b).

The shallow hard bottoms of Madeira are dominated by barren grounds of crustose coralline algae (CCA) resulting from urchins grazing activity (Bernal-Ibáñez et al., 2021; Monteiro et al., 2021). Calcifying epilithic organisms such as CCA can act as ecosystem engineers, as the

superposition of calcareous biogenic layers cumulatively increases structural complexity (Steneck, 1986; this study). These organisms attach to the substratum by depositing a calcareous layer that fits microscopically to the substratum irregularities (Walker and Moss, 1984). When alive, they can re-calcify the spaces created by the deterioration of the original substratum. Nevertheless, as the community develops, the organisms primarily attached to the substratum surfaces die, and the bond between their skeleton and the substratum starts deteriorating. Deterioration rates could depend on the resistance of the primary rock to dissolution and weathering (Walker and Moss, 1984). Surface integrity depends on the intrinsic features of each type of material, and concrete surfaces experience a relatively high physical and chemical erosion than basalt (see Fookes and Poole, 1981). Moreover, cracking is a common phenomenon in concrete due to its relatively low tensile strength, impairing its durability to the point that is a line of research dealing with solutions to this issue (e.g., Tittelboom et al., 2010). In contrast, silica-rich basalt has a higher tensile strength and hardness than concrete, cannot be dissolved by seawater, does not suffer from chlorination attack, and is not affected by bioeroders or acid attack from biological byproducts. Therefore, deterioration of concrete surfaces over time might promote a higher detachment rate of benthic assemblages, particularly calcareous bio-concretions (Fig. 5 A). This detachment could be promoted by environmental and biological phenomena, such as storms and grazers activity (e.g., Alves et al., 2001; García-Romero et al., 2023; Chebaane et al., 2023), and would explain the higher abundance of CCA on basalt, including *Peyssonnelia* sp., and the higher abundance of filamentous algae on concrete. Moreover, calcareous bio-concretions can also provide positive bio-protection effects, which may additionally protect the underlying substrate from deterioration (Coombes et al., 2017; Bone et al., 2022b; Lv et al., 2022). The effects of this increased weathering were observed during sampling events in some locations, where the cementitious surface of the concrete blocks had been washed away, leaving the basalt aggregates exposed (e.g., Fig. 5 B). A similar effect was registered in a recent study comparing sessile assemblages in natural limestone and granite boulders conducted in Sardinia, Mediterranean Sea (Canessa et al., 2020). In this case, limestone had a lower benthic coverage and different assemblage structure than granite, which could be explained by the lower surface stability of the former. Although the structural integrity of the

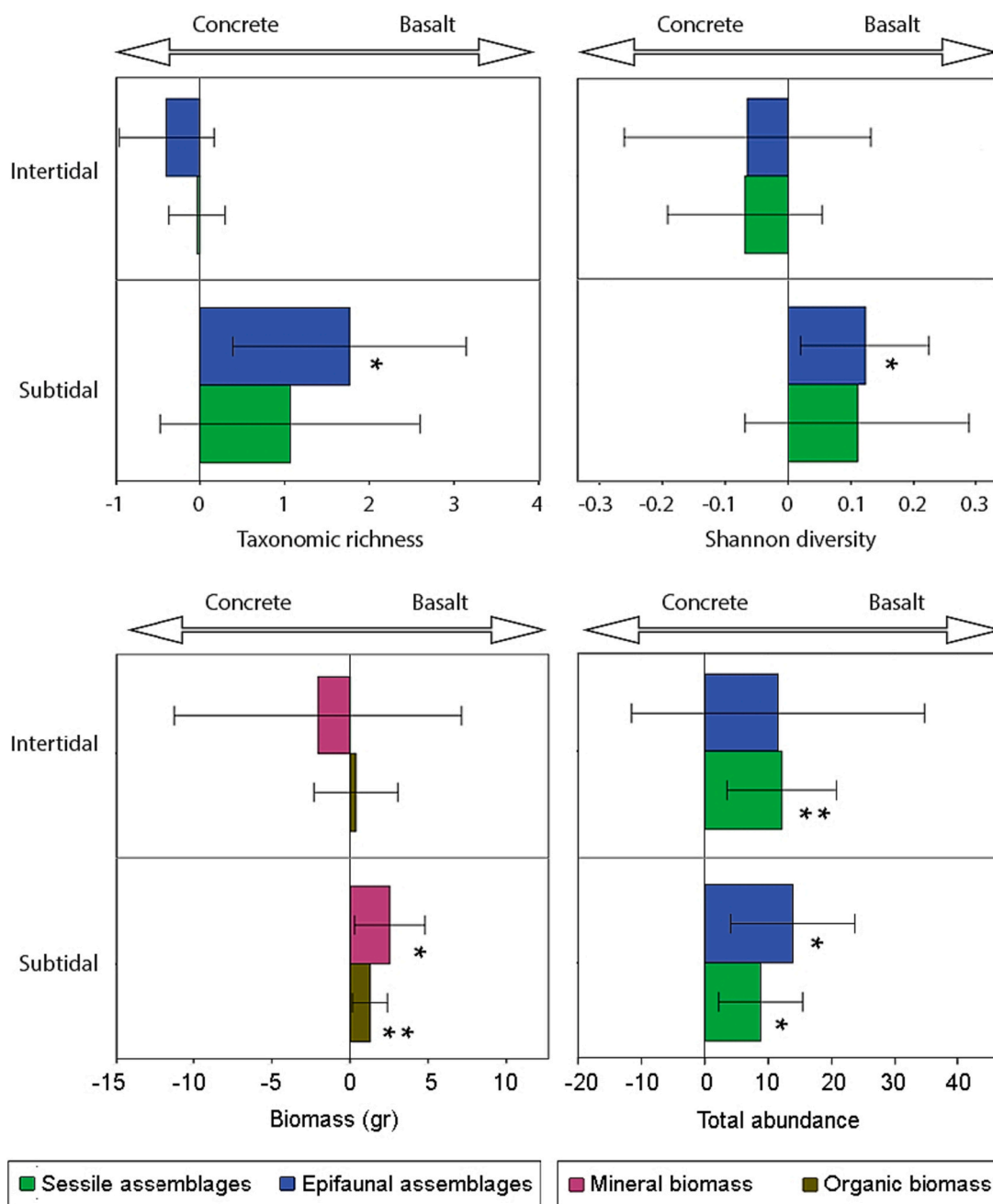


Fig. 4. Mean differences and 95 % confidence interval bars for the taxonomic richness, Log_e Shannon diversity, and assemblages' abundance of sessile taxa and epibenthic families, and the mineral and organic biomass of the benthic assemblages. Values indicate differences between basalt and concrete between pairs of replicates and were obtained by subtracting the values in concrete from those in basalt in each block. Asterisks indicate consistent differences between substrates according to PERMANOVA results in Table 4 and Appendix C.2.

substratum surfaces appears to be the leading cause of the differences found between the studied materials, more research is needed to better understand this process.

Rock elements composition reflected the profiles of mafic basalt and marine concrete, which develops a Sulphur layer close to its surface after long-term exposition to the marine environment. Despite the differences in trace elements between substrates, these were similar between the benthic assemblages on basalt and concrete. Mature assemblages are generally multi-layered, and the bottom layer is formed by the calcareous material left by the organisms that primarily attached to the surface during colonization (Steneck, 1986). Therefore, differences in leaching of trace elements, pH, and surface free energy between substrata are unlikely to have affected the composition of mature sessile assemblages,

since these are generally not in direct contact with the primary substrate, and it is most likely that the differences in the benthic assemblages between substrates are related to physical (i.e., weathering) rather than chemical processes.

The absence of significant differences between substrates in the intertidal (except for sessile assemblages' abundance) could be due to extreme environmental stressors, such as hydrodynamic exposure, temperature desiccation, which reduce the global abundance and diversity in this habitat (Raffaelli and Hawkins, 2012). This would prevent the detection of significant differences in contrast to the more diverse subtidal habitat. Furthermore, the high physical stress created by wave action prevents the formation of multi-layered crusts, which would reduce the importance of substratum weathering rates in structuring the

Table 4

Univariate PERMANOVA results for total abundance of assemblages, both sessile (percent coverage) and epibenthic (number of individuals), in the subtidal and intertidal. Df: degrees of freedom; MS: mean sum of squares; bold: significant results; bold: significant results ($P(\text{perm}) < 0.05$). Differences between substrata (shaded in grey) are indicated as asterisks in Fig. 4.

Subtidal		Sessile assemblages			Epibenthic assemblages		
Source	Df	MS	Pseudo-F	P (perm)	MS	Pseudo-F	P (perm)
Location	5	1281	5.049	0.001	1495	1.450	0.222
Block (Lo)	24	242	1.345	0.242	1109	2.942	0.008
Substratum	1	1162	6.456	0.019	2884	7.651	0.012
Lo x Su	5	47.4	0.263	0.925	182	0.483	0.783
Residual	24	178			378		

Intertidal		Sessile assemblages			Epibenthic assemblages		
Source	Df	MS	Pseudo-F	P (perm)	MS	Pseudo-F	P (perm)
Location	5	541	1.250	0.322	8022	1.672	0.125
Block (Lo)	24	233	0.968	0.517	2574	1.568	0.060
Substratum	1	2208	9.160	0.008	1995	1.215	0.290
Lo x Su	5	392	1.627	0.178	3207	1.953	0.098
Residual	24	241			1642		

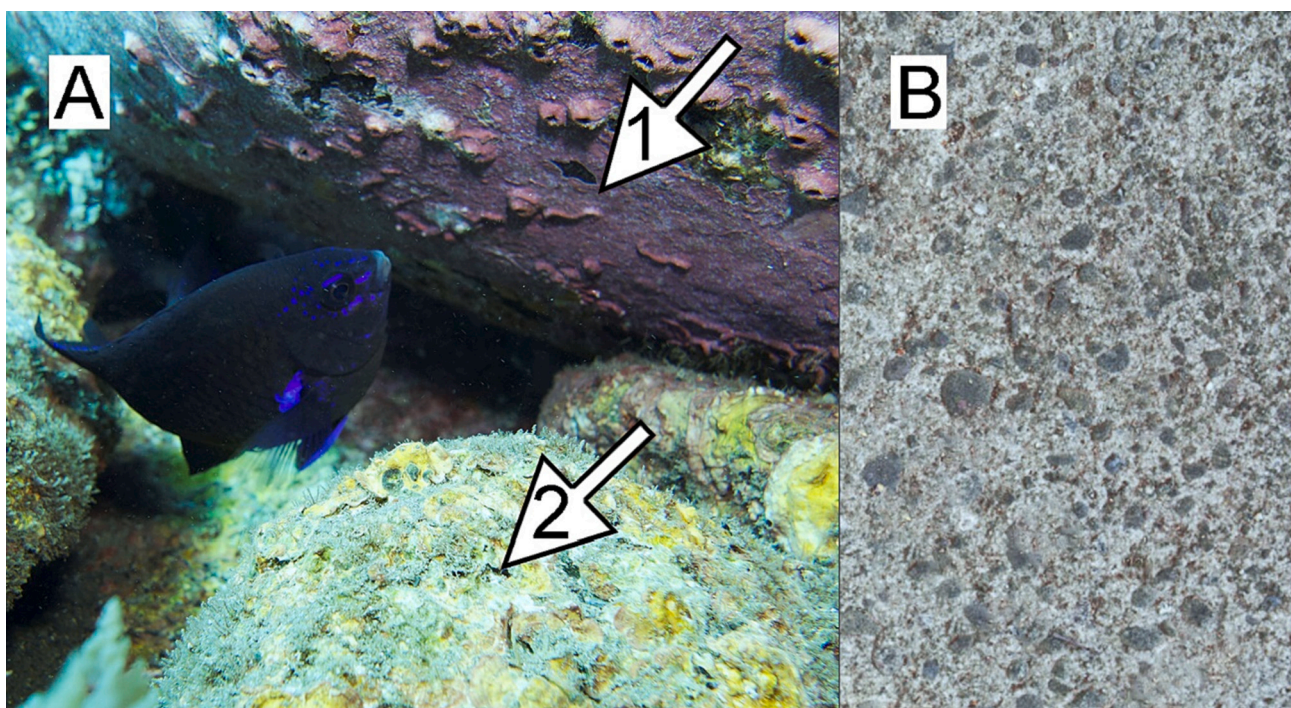


Fig. 5. The most representative assemblages in Madeira were calcareous bio-concretions of crustose coralline algae (Corallinales: A1) and *Peyssonnelia* sp. (A2). These were the main responsible of the differences between basalt and concrete, presumably because of the faster surface erosion rates of the latter. B: concrete surface with aggregates exposed after the erosion of the cementitious material.

benthic assemblages. Nevertheless, the higher sessile abundances on basalt than concrete suggests that substratum type remains a significant factor in assemblages' growth and/or detachment in the intertidal.

The effect size of substratum type in shaping the benthic structure and its richness, diversity, and biomass is expected to differ at the regional scale, highlighting the need to consider local particularities in management and conservation strategies (Firth et al., 2020; Sedano et al., 2020a). This is because the effects of substratum type on benthic assemblages in the marine environment are smaller than the usual spatiotemporal variation of these assemblages at diverse scales (Vaz-Pinto et al., 2014; Cacabelos et al., 2016b; Martins et al., 2016). Following this, the structure of the benthic assemblages in this study differed at 2-to-50 km scale (Location), while differences between substrates were secondary. Nonetheless, the differences between basalt and

concrete and the coastal sprawl rates registered in the island indicate that the effect of substratum type is ecologically relevant in the area. Moreover, the effects of substratum type on the subtidal sessile assemblages determine epibenthic assemblages' abundance, biomass, richness, and diversity (Sedano et al., 2020a; this study).

This study constitutes a pioneering effort in Madeira and will serve as a baseline for future studies and management plans. The effect of the substratum was generally homogeneous in this study, which indicates that basalt should be considered as a more sustainable material than concrete in Madeira and possibly in the entire Macaronesia. In addition, basalt is a local rock that could be obtained as a waste product from the construction industry, allowing the integration of a circular economy in coastal constructions (Ogunmakinde et al., 2022). All of which without ignoring the primordial objective of sustainable development, which is

to minimize the construction of new structures and increase the efficiency of existing ones. On a global scale, the findings of this study contribute to raise knowledge on the field of Greening of Grey Infrastructure, which is being adopted in an increasing number of coastal interventions (Bugnot et al., 2018; Strain et al., 2018; Sempere-Valverde et al., 2023b). Many of these interventions involve concrete mixtures with recycled aggregates as supplementary cementitious material or as substitute for Portland cement, potentially resulting in a lower carbon footprint than traditional concrete throughout their life cycle (Vieira et al., 2016; Samad and Shah, 2017; Qureshi et al., 2020). These include mixes with higher density and impermeability than traditional concrete, which increase surface integrity against chlorination and acid attack, and may reduce surface pH and increase bioreceptivity during early colonization by marine assemblages (Qureshi et al., 2020; Hosseinzadeh et al., 2022; Yang et al., 2022). However, the ecological performance of these concrete mixes in the medium and long term still requires further investigation (Bone et al., 2022a). Finally, our findings indicate that the surface integrity of concrete might compromise the ecological status of mature communities, therefore, local quarry rock might be a more suitable and sustainable material for blue marine infrastructure than concrete (Firth et al., 2020; Doods et al., 2022; Baxter et al., 2023).

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CRediT authorship contribution statement

Juan Sempere-Valverde: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. **Sahar Chebaane:** Data curation, Investigation, Methodology, Writing – review & editing. **Alejandro Bernal-Ibáñez:** Investigation. **Rodrigo Silva:** Investigation. **Eva Cacabelos:** Conceptualization, Investigation, Supervision, Validation, Writing – review & editing. **Patrício Ramalhosa:** Methodology, Resources, Writing – review & editing. **Jesús Jiménez:** Investigation. **João Gama Monteiro:** Conceptualization, Investigation, Methodology, Resources. **Free Espinosa:** Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing – review & editing. **Carlos Navarro-Barranco:** Investigation, Validation. **José Manuel Guerra-García:** Conceptualization, Resources, Supervision, Validation, Writing – review & editing. **João Canning-Clode:** Conceptualization, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare no competing interests.

Data availability

All data generated during this study are included in this published

article in the supplementary data file ‘Supplementary-Data.xlsx’.

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Appendix A. Supplementary data

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