



HAL
open science

How to Improve the Bioreceptivity of Concrete Infrastructure Used in Marine Ecosystems? Literature Review for Mechanisms, Key Factors, and Colonization Effects

Mahmoud Hayek, Marie Salgues, Jean-Claude Souche, Klaartje de Weerd, Sylvain Pioch

► To cite this version:

Mahmoud Hayek, Marie Salgues, Jean-Claude Souche, Klaartje de Weerd, Sylvain Pioch. How to Improve the Bioreceptivity of Concrete Infrastructure Used in Marine Ecosystems? Literature Review for Mechanisms, Key Factors, and Colonization Effects. *Journal of Coastal Research*, 2023, 39 (3), pp.553-568. 10.2112/JCOASTRES-D-21-00158.1 . hal-04051748

HAL Id: hal-04051748

<https://imt-mines-ales.hal.science/hal-04051748>

Submitted on 3 Apr 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **How To Improve The Bioreceptivity of Concrete Infrastructure Used in**
2 **Marine Ecosystems? Literature Review for Mechanisms, Key Factors and**
3 **Colonization Effects**

4 **Mahmoud Hayek[†], Marie Salgues[†], Jean-Claude Souche[†], Klaartje De Weerd[‡], Sylvain**
5 **Pioch[§]**

6 [†] LMGC, IMT Mines Alès
7 Univ Montpellier, CNRS
8 Alès, France

9 [‡] Department of Structural Engineering
10 Norwegian University of Science and Technology NTNU
11 Trondheim, Norway

12 [§]LAGAM
13 University Paul Valéry Montpellier 3
14 Montpellier, France
15 sylvain.pioch@univ-montp3.fr

16 **LRH: Hayek, Salgues, Souche, De Weerd, Pioch**

17 **RRH: Bioreceptivity of marine concrete**

18 **ABSTRACT**

19 With 39,400 km² of coastal and marine areas artificialized and an increasing demand due to the
20 growing global population – 9 billion by 2050 – we need to find ways to mitigate futures construc-
21 tions impacts on biodiversity. In this study, we explore how civil engineering can take further tech-
22 nical measures to enhance marine biodiversity, in a real and valuable “win-win” strategy. The
23 global aim is to integrate eco-engineering practices within coastal projects and include ecological
24 targets (*e.g.* the diversity and speed of biological colonization) early, at the project design stage,
25 with the same level efforts for technical, social and economic studies. Concrete is the most useful
26 material for coastal infrastructures constructions, therefore enhance its positive impact on coloni-
27 zation is by far one of the key-point for developers and coastal managers. To this end, we’ve first
28 reviewed the latest research regarding the bioreceptivity of concrete, focusing on the characteristics
29 of the marine environment that affect the colonization of concrete and the organisms involved.
30 From this base of publications, we’ve updated the intrinsic and environmental parameters that can
31 influence the intrinsic and the extrinsic bioreceptivity of concrete and operate the link with the
32 mechanisms leading to the colonization of concrete and biofilm formation, which wasn’t done be-
33 fore. Based on the persistence of their significant effect (after 78 days of immersion in seawater),
34 the intrinsic parameters that support greater biocolonization are classified from more to less effec-
35 tive in the following order; surface roughness (190 %) > chemical composition (slag cement instead
36 Portland cement) (136 %) > chemical composition (presence of formwork oil) (106 %). We’ve

37 finally analyzed both the ecological effect and the positive and negative effects of biofilm for-
38 mation on the durability of concrete, in the scope to provide clear and operational results for future
39 concrete coastal construction implementation for decision maker.

40

ADDITIONAL INDEX WORDS

41 *Eco-engineering practices, marine biodiversity, concrete, colonization, eco-design, bioreceptivity,*
42 *biofilm, durability.*

43

44

INTRODUCTION

46 The global ecological crisis is the concomitant with the Anthropocene, a new geological era in
47 which humans have become the central actors on the planet (Crutzen, 2006; Shukla *et al.*, 2021;
48 Valipour, Bateni, and Jun, 2021). The recent report (2019) of the Intergovernmental Science-Policy
49 Platform on Biodiversity and Ecosystem Services (IPBES) presents a devastating assessment of
50 the impact on biodiversity since the start of the industrial era two centuries ago: in terms of coastal
51 and marine ecosystems, more than 85% of wetlands have been destroyed, and human activities
52 threaten 66% of the oceans. The causes leading to this situation are today well known and include
53 (in order of impact): (1) artificialization and land use, (2) overexploitation of resources (fishing,
54 forestry, etc.), (3) climate change, (4) pollution (plastics, chemical residues, etc.) and (5) invasive
55 species (*Ibid*).

56 Therefore, reducing artificialization and land use is critical to reduce biodiversity loss and preserve
57 the future of humanity. Yet predictions indicate a clear acceleration of urbanization around the
58 world, on land and at sea. Between 2019 and 2040, more than US\$60,000 billion is forecast to be
59 invested in infrastructure in the 56 countries representing 88% of global GDP (Global
60 Infrastructure Hub 2017–2018). More than 1.2 million km² will be urbanized by 2030 – just 8 years
61 from now – representing an increase of more than 185% compared to the period from 1970 to 2000
62 (Seto *et al.*, 2012). By 2050, 3 to 4.7 million km² of roads will be constructed, which represents an
63 increase of more than 25% compared to the current annual rate (Meijer *et al.*, 2018). This process
64 will be particularly significant along coasts, where eight of the ten largest megalopolises in the
65 world are located (such as Lagos, Tokyo, Jakarta and New York). Around the world, the population
66 living within 100 km of a coast is estimated to approach 7.5 billion people by 2050 (de Fraiture *et al.*,
67 2007), leading to a need for increased coastal development and potentially disturbing essential
68 coastal habitats (Weilgart, 2007). Global marine infrastructure extended over approximately
69 32,000 km² in 2018 (Bugnot *et al.*, 2020) and is expected to reach 39,400 km² by 2028: a surface
70 area equivalent to the country of Bhutan. The area of seascapes impacted by these structures was
71 estimated to be between 1 and 3.4 million km² in 2018, which is expected to increase 50–70% by
72 2028 (*Ibid*). The phenomenon of ‘coastal squeeze’, a term introduced by Doody (2004) to refer to
73 the threat to the existence of coastal habitats caused by the compound impacts of sea-level rise and
74 human activities, will not abate under current development conditions. Most of these structures are
75 made from concrete, the most durable materials for the aggressive marine environment. Table 1
76 summarize the types of concrete structures found in coastal areas.

77 From the 1970s through the 1990s, coastal ecology literature dealing with biodiversity focused
78 mainly on artificial substrates use to promote restoration, studied from colonization or settlement
79 phenomena problematics (Relini *et al.*, 1998; Zobel, 1974). However, since the 2000s, hard
80 artificial infrastructure made with concrete, has been implicated as a major risk factor for local and
81 native biodiversity, by introducing invasive species with ubiquitous and rapid growing
82 characteristics, in comparison with surrounding natural rocky area (Bulleri and Airoidi, 2005;
83 Bulleri and Chapman, 2010, 2004; Jackson *et al.*, 2001). In contrast, several studies about
84 ecological design of coastal infrastructure published since 2010 has clearly demonstrated that it is
85 feasible to enhance biodiversity through changes in concrete chemical composition, roughness,

86 surface treatment, or inclusion of variously sized pits or holes (Chapman and Underwood, 2011;
 87 Evans, Bax and Bernal, 2016; Evans, Bax and Smith, 2018; Martins *et al.*, 2010; Phan, van Thiel
 88 de Vries and Stive, 2015; Souche *et al.*, 2016). In addition, other studies also has indicated that
 89 physical alteration and damage to artificial structures due to natural processes (*e.g.* weathering,
 90 wave action, chemical erosion) could be reduced by the positive protective role of marine
 91 organisms (Coombes *et al.*, 2017, 2013; Gowell, Coombes and Viles, 2015; La Marca *et al.*, 2014;
 92 Naylor and Coombes, 2015; Perkol-Finkel and Sella, 2014).

93 Table 1. Types of structures in coastal areas, their functions and the materials used

Types of structure	Socio-technical objectives	Materials
Coastal defense structures (protection of coastlines and management of wave action effects)		
<i>Offshore breakwater</i>	Coastal defense structure built near the coast to protect it from the actions of the sea by reducing wave-action intensity	Rock fill Concrete blocks
<i>Groin</i>	Coastal defense structure to protect the coast from erosion and sediment transport	Rock fill
<i>Harbor breakwater, jetty</i>	Structure to protect a harbor area from wave action and currents	Rock fill and blocks of concrete (blocks, tetrapodes, accropodes)
Harbor structures		
<i>Finger pier</i>	Mooring structure for loading and unloading boats	Reinforced or prestressed concrete apron on caisson or gabion-type piles
<i>Boom wharf</i>	Structure on piles making up a finger pier (wharf perpendicular to the coast)	Reinforced concrete apron on metal or reinforced concrete piles
<i>Quay</i>	Continuous open-platform structure for mooring, loading and unloading boats	Reinforced concrete caissons, metal sheet-pile gabions, curtain walls and screens in metal or reinforced concrete
<i>Floating dock</i>	Floating structure enabling docking and mooring of boats in a harbor	Metal or reinforced concrete, held in place by piles or reinforced concrete moorings
<i>Floating breakwater</i>	Floating structure to protect a harbor from wave action	Reinforced concrete, held in place by piles or reinforced concrete moorings
<i>Lock / gate</i>	Structure enabling boats to change level and/or to keep a dock filled with water	Infrastructure in reinforced concrete, equipment in steel

Harbor structures for maintenance and services

<i>Dry dock</i>	Waterproof basin that can be drained or filled with water to enable maintenance and repair of boats/caissons	Unreinforced concrete, reinforced concrete / reinforced concrete, prestressed concrete
------------------------	--	--

<i>Slipway</i>	Slope enabling a boat to be launched or landed for maintenance	Reinforced concrete
-----------------------	--	---------------------

<i>Self-elevating platform, jack-up barge</i>	Floating deck using a wet dock to raise boats out of the water for maintenance or refitting	Infrastructure in reinforced concrete, equipment in steel
--	---	---

Open-sea structures

<i>Offshore structure</i>	Structure out as sea such as an oil rig or wind turbine	Reinforced concrete and steel
----------------------------------	---	-------------------------------

<i>Anchorage, ballast</i>	Underwater structure for anchoring boats or floating infrastructure	Reinforced concrete
----------------------------------	---	---------------------

<i>Artificial reef</i>	Underwater structure for protecting or hosting fauna and flora or for leisure activities	Reinforced concrete, metal, diverse materials
-------------------------------	--	---

94

95 Pragmatically, most current coastal concrete infrastructure cannot be readily removed. But there is
96 now increasing research efforts into innovative ways that future new infrastructures can be
97 designed and built to meet engineering requirements, while also increasing its value as an
98 ecological habitat for marine life (Dafforn *et al.*, 2015; Firth *et al.*, 2014; Lacroix and Pioch, 2011;
99 Naylor and Coombes, 2015; Patranella *et al.*, 2017; Perkol-Finkel and Sella, 2014; Phan, van Thiel
100 de Vries and Stive, 2015; Pioch and Souche, 2021). This “win-win” approach, should ensure
101 benefits both for human society and nature (Chapman and Underwood, 2011; Ferrario *et al.*, 2014;
102 Perkol-Finkel *et al.*, 2018; Pioch *et al.*, 2018, 2011; Temmerman *et al.*, 2013). This paradigm
103 support the idea that we have to construct structures with a minimal ecological impact on the
104 existing environment, maximizing their potential for colonization, and restore original habitats or
105 create new habitats adapted for local species ecological requirements (Browne and Chapman,
106 2011; Souche *et al.*, 2018). In this way, combining engineering techniques with ecological
107 understanding can provide, with a cost-effective ways, the maintenance or development of native
108 biodiversity (Airoldi *et al.*, 2020; Martins *et al.*, 2010; Pioch *et al.*, 2018; Scheres and Schüttrumpf,
109 2019; Souche *et al.*, 2019).

110 Artificial marine structures modify, positively or negatively, the natural environment (Azevedo *et*
111 *al.*, 2006) to become part of a new ecosystem (Giraudel, Garcia and Ledoux, 2014). Then to avoid
112 high negatives impacts, as we have seen, the ecological mechanism of settlement on concrete needs
113 to be assessed before their implementation (Baine, 2001; Bulleri and Chapman, 2010). Impacts
114 parameters are divided in five main fields: localization for the immersion zone, implantation
115 (Giraudel, Garcia and Ledoux, 2014), seasons and immersion time (Firth *et al.*, 2014; Vaz-Pinto *et*
116 *al.*, 2014), design of the structure (Baine, 2001; Pioch *et al.*, 2011), and the type of materials used

117 (Anderson and Underwood, 1994; Fitzhardinge and Bailey-Brock, 1989; Lee *et al.*, 2008). There
118 are also interdependent relationships that change over time between the type of structure, exposure
119 conditions, substrate, seasonality and colonization by living organisms (Anderson and Underwood,
120 1994; C. Choi *et al.*, 2006; Somsueb, Ohno and Kimura, 2001).

121 The way to associate civil engineering and ecological consideration is now a common subject of
122 research with eco-engineering, and specifically within the construction field the eco-design
123 strategies. Recent research applications, have demonstrated that it's possible to integrate
124 environmental objectives in the design of functional concrete marine infrastructures (Bulleri and
125 Chapman, 2010; Lacroix and Pioch, 2011; Pioch *et al.*, 2011; Pioch and Souche, 2021). Thus,
126 understanding the interactions between microorganisms and cementitious materials is a crucial step
127 toward constructing more durable, safer and more ecological structures (Lors, Feugeas and
128 Tribollet, 2019; Ottel  *et al.*, 2011; Perini and Ottel , 2014; Perkol-Finkel and Sella, 2014). As the
129 colonization of cementitious material by microorganisms is an essential step for the adhesion of
130 other organisms (Mieszkin, Callow and Callow, 2013; Rajitha *et al.*, 2020; Salta *et al.*, 2013), the
131 aim is to favor this colonization in order to reduce the ecological impact of the structure and
132 consequently increase biodiversity, without impacting the structure's strength and durability. Then,
133 additional studies are necessary to determine the different factors that can influence the
134 colonization of cementitious materials in the marine environment, but the main parameters seem
135 to be the water pH, the materials chemical composition and surface roughness or topography
136 (Grosseau *et al.*, 2015; Hayek *et al.*, 2020a, 2021; McManus *et al.*, 2018; Miller *et al.*, 2009, 2012).

137 The objective of this study was to identify key parameters to take into account to promote the
138 bioreceptivity of concrete structures in coastal and marine environments to identify key parameters
139 to take into account in order to promote the bioreceptivity of concrete structures.

140 **Scope and research significance**

141 The interaction of cement-based materials with microorganisms has been widely studied in
142 building and sewer network. To the best of our knowledge, in the marine environment, the present
143 literature review is the first one in the field of concrete bioreceptivity and concrete biocolonization
144 by marine bacteria. In this review, a significant amount of research has been performed on the first
145 stage of colonization of concrete in seawater with significant research on this topic including i) the
146 early colonization process and the detailed mechanisms involved in the biofilm formation on the
147 surface of marine concrete ii) the colonizing organisms of cement-based materials and iii) the
148 physicochemical factors influencing the colonization of cement-based materials in marine
149 environments.

150 Afterward, to achieve the purpose of this paper, i) some of the most significant quantitative results
151 about the bioreceptivity of concrete in the marine environment are presented ii) the ecological
152 impact and the effect of biological colonization on the durability of concrete are discussed and iii)
153 the perspectives to design a more bioreceptive concrete (green concrete) are mentioned.

154 Web of science and google scholar are the two databases used in this study for collecting the
155 relevant materials (211 studies) from the literature. The keywords used were: Biofilm formation,

156 Concrete biocolonization, Ecological impact, Eco-engineering *practices* Artificial reef, Marine
157 environment, Concrete Durability, Bioreceptivity and marine biodiversity.

158

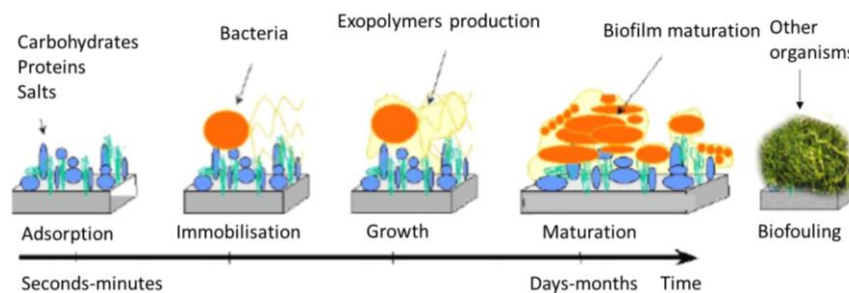
159 METHODS: BIOLOGICAL FACTORS AFFECTING THE 160 COLONIZATION OF CONCRETE IN THE MARINE 161 ENVIRONMENT

162 **Colonization and the development of biofilm on surface concrete**

163 From the first hours of the immersion of an object in seawater, a cement-based material is covered
164 with a biofilm consisting of one or more microbial communities (Dang and Lovell, 2015;
165 Dobretsov, Teplitski and Paul, 2009). By definition, the biofilm is considered to be a sessile
166 microbial community irreversibly attached to a substrate or an interface and included in a coating
167 of extracellular polymeric substances (EPS). Biofilm cells have modified phenotypes compared to
168 plankton cells that float freely in the environment (Donlan and Costerton, 2002).

169 The biofilm is the first stage in colonization, which enables the establishment of other marine
170 organisms via the EPS synthesized on the surface (Hinsa and O'Toole, 2006; Pasmore and
171 Costerton, 2003; Wood *et al.*, 2016). Bacteria (bacterial biofilm) are the first colonizers, which
172 facilitate the adhesion of other micro- and macro-organisms such as fungi, microalgae, macroalgae
173 and invertebrates (Briand *et al.*, 2018; Brian-Jaisson *et al.*, 2014; Dobretsov and Rittschof, 2020;
174 Salta *et al.*, 2013) (Figure 1).

175 After immersion, an induction phase allows the surface to be conditioned (through the formation
176 of the conditioning film), resulting in exponential accumulation, characterized by the adhesion and
177 growth of bacteria and other microorganisms on the surface. The length of the induction phase
178 depends on both the environmental parameters and the intrinsic parameters of the host material
179 (Hayek *et al.*, 2019; Karunasagar *et al.*, 1996; Katsikogianni and Missirlis, 2004). A submerged
180 solid object adsorbs organic and inorganic molecules and ions, leading to a modification of the
181 physicochemical properties of the surface, thus forming a nutrient-rich micro-niche (on a small
182 scale in comparison to the material) that favors the adhesion of bacterial cells. In this way, surface
183 conditioning impacts the adhesion of bacterial cells (Loeb and Neihof, 1975), which can be
184 stimulated or inhibited by the nature of the adsorbed molecules. This is why the conditioning of
185 the surface is considered a key step in biofilm formation (Herrmann *et al.*, 1988; Tang *et al.*, 2006).



186

187

Figure 1. Biofouling in the marine environment (Ogunola and Onada, 2016).

188 Therefore, the main stages of biofilm formation are (i) reversible and irreversible adhesion of
189 bacterial cells to the surface of the cement-based material; (ii) growth and maturing of the biofilm
190 with the secretion of EPS; and (iii) partial detachment of the biofilm and the dispersion of bacterial
191 cells (Hinsa and O'Toole, 2006; O'Toole, Kaplan and Kolter, 2000).

192 The adhesion of bacteria to a surface first requires that they move toward the surface to be
193 colonized. This movement can be due to environmental phenomena (gravitational and
194 hydrodynamic forces in the surrounding fluid) and/or by appendages on the bacteria that assist their
195 movement, such as flagella or pili (Ha and O'Toole, 2015; Katsikogianni and Missirlis, 2004).

196 Once a bacterium is within a critical distance of the object (generally < 1 nm), low-intensity
197 interactions take place between the bacterium and the surface, e.g. electrostatic forces, Van der
198 Waals forces and hydrophobic interactions (Carpentier and Cerf, 1993; Dunne, 2002). Depending
199 on these various interactions, the bacterium may either adhere or be repelled by the effect of
200 hydrodynamic actions. If the interactions are favorable, the bacterium adheres to the surface and
201 this step is then considered the reversible adhesion phase (An and Friedman, 1998; Berne *et al.*,
202 2018; Busscher and Weerkamp, 1987; van Loosdrecht *et al.*, 1989). The factors that influence this
203 phase concern interactions between the bacterial cells and the surface of the cement-based material:
204 (i) the specific characteristics of the bacteria, such as its cell surface charge, cell surface
205 hydrophobicity and the chemical composition of the cell wall; (ii) the intrinsic parameters of the
206 host surface, such as its physicochemical nature, polarity, porosity and roughness; and (iii) the
207 environmental conditions, such as pH level, temperature and flow conditions (Bunt *et al.*, 1993;
208 Scheuerman *et al.*, 1998; Speranza *et al.*, 2004). According to Carpentier and Cerf (1993), host
209 surface porosity and roughness are believed to increase bacterial adhesion, while a negatively
210 charged surface may have a repulsive effect as most bacteria are negatively charged.

211 Adhesion subsequently becomes irreversible when strong covalent interactions are established
212 between the bacteria and the surface of the cement-based material. The covalent interactions are
213 formed by macromolecules on the bacteria surface and include polysaccharides, proteins or
214 lipopolysaccharides (Berne *et al.*, 2018).

215 Once established on the object, the bacteria multiply and the EPS they secrete develop a three-
216 dimensional structure to form colonies that cover all or part of the surface. This varies depending
217 on the bacteria present and (i) their capacity to communicate with each other, i.e. their cell-to-cell
218 communication, or quorum sensing, system (Branda *et al.*, 2005; Dobretsov *et al.*, 2011); (ii) the
219 intracellular concentration of cyclic di-GMP (a high intracellular concentration of c-di-GMP
220 promotes the expression of genes involved in biofilm formation) (Barraud *et al.*, 2009; Chao *et al.*,
221 2013; Dang and Lovell, 2015); (iii) environmental conditions, and (iv) the properties of the host
222 material, especially hydrophobic properties (O'Toole, Kaplan and Kolter, 2000).

223 A mature biofilm has a three-dimensional structure surrounded by a matrix made up of mineral
224 elements and EPS: proteins, polysaccharides, nucleic acids, lipids and other cellular components.
225 This matrix forms a barrier that protects biofilm microorganisms against external threats (Ha and
226 O'Toole, 2015; Soleimani *et al.*, 2013).

227 The last step in the development of the biofilm is the dispersion of cells in the environment after
228 detaching from the surface. This dispersion is an essential part of the biofilm cycle as it enables the
229 bacteria to colonize new surfaces and develop new biofilms (Kaplan, 2010). In general, biofilm
230 dispersion mechanisms can be divided into two broad categories: (i) active dispersion based on
231 mechanisms initiated by the bacteria; and (ii) passive dispersion due to external forces, such as
232 shearing forces caused by hydrodynamic conditions (Lawrence *et al.*, 2002). Several factors are
233 involved in the complex process of biofilm dispersion, such as environmental signals, quorum
234 sensing systems, and the bacteria's production of extracellular enzymes that can degrade the matrix
235 of biofilm components and facilitate dissociation (Boyd and Chakrabarty, 1994; Kaplan, 2010).

236 **Colonizing organisms of cement-based materials**

237 In the marine environment, there are many ubiquitous colonizing microorganisms likely to form a
238 biofilm on the surface of objects under suitable conditions. The main colonizing microorganisms
239 of cement-based materials are bacteria, fungi, cyanobacteria and algae (Gaylarde and Gaylarde,
240 2005).

241 **Bacteria**

242 Bacteria are medium-sized unicellular microorganisms that vary in size from 0.5 to 1.5 μm (Yañez
243 *et al.*, 2010) and develop on all types of surface materials; they are generally pioneers in the
244 colonization process (Meng *et al.*, 2020; Romani *et al.*, 2019; Scatigno *et al.*, 2016).

245 The deterioration of cement-based materials by microbial induced corrosion has been known since
246 1945 following the work of Parker, who was the first to isolate from concrete samples a sulfuric
247 acid-producing bacterium species initially called *Thiobacillus concretivorus*, then subsequently
248 called *Acidithiobacillus thiooxidans* (Parker, 1945). This phenomenon has mainly been studied in
249 sanitation networks, where the sulfate- and nutrient-rich environment provides optimal conditions
250 for the development of microbial fauna belonging to the genus *Thiobacillus* (Yuan *et al.*, 2015).
251 *Thiobacilli* are bacteria that oxidize sulfur compounds into sulfuric acid, a substance that is
252 particularly aggressive to concrete (De Belie, 2010). However, the biochemical processes leading
253 to the degradation of concrete under the influence of bacteria are essentially based on the synthesis
254 (bacterial metabolism) of acids such as sulfuric acid (H_2SO_4) and nitric acid (HNO_3) (Cwalina,
255 2008). These acids dissolve calcareous components, resulting in a loss of cohesion in the material
256 and the appearance of cracks or corrosion of the reinforcement bars in the concrete (Chatterjee and
257 Goyns, 2013; Poonguzhali *et al.*, 2008). These effects are common in the sulfate- and ammoniac-
258 rich environment of sanitation networks.

259 Despite the large number of concrete structures present in the waters of seas, rivers and lakes,
260 studies concerning the colonization of cementitious materials by bacteria in these environments
261 remain relatively rare (Chlayon, Iwanami et Chijiwa, 2020; Cooke *et al.*, 2020; Costa and
262 Appleton, 2001; Rica *et al.*, 2016; Scheres and Schüttrumpf, 2019; Sosa *et al.*, 2011; Souche *et al.*,
263 2016).

264 **Algae and cyanobacteria**

265 Microscopic algae (microalgae) and cyanobacteria are unicellular or multicellular species,
266 generally between 0.5 μm and 1 mm in size. These microorganisms are characterized by their
267 capacity to perform oxygenic photosynthesis (Leclerc, 1975).¹ As algae and cyanobacteria are
268 capable of generating their own organic matter from mineral elements, they are autotrophic
269 organisms (Harper and Pendleton, 1993; Krumbein, 1979; Subashchandrabose et al., 2011).

270 According to the literature, green algae (Chlorophyta) and cyanobacteria (Cyanophyta) produce
271 greenish, reddish or blackish stains on concrete, depending on the composition of the biofilm. In
272 addition, the secretion of organic acids, resulting from the metabolism of these organisms, can lead
273 to the dissolution of the calcium-rich phases of calcareous stones, concrete and mortar. In this way,
274 algae and cyanobacteria can cause the alteration or degradation of cementitious materials
275 (Escadeillas *et al.*, 2008, 2007).

276 Cyanobacteria are prokaryotic microorganisms, whereas microalgae are eukaryotic. Microalgae
277 are divided into several phylogenetic groups, such as chlorophytes, rhodophytes and diatoms (Al-
278 Handal and Wulff, 2008). Chlorophytes mainly develop in freshwater, such as rivers, and are the
279 largest group of green algae (Lueangthuwapranit, Sampantarak and Wongsai, 2011). Rhodophytes
280 are mainly macroscopic multicellular marine organisms and are known as red algae (Bengtson *et*
281 *al.*, 2017). Diatoms are microscopic unicellular organisms characterized by a silica cell wall, called
282 a ‘frustule’, that surrounds them. They are abundant in the marine environment (Robert *et al.*,
283 2004).

284 The colonization of cement-based materials in situ by cyanobacteria and algae has been confirmed
285 in various studies by measuring the quantity of chlorophyll and/or by the appearance of different-
286 colored stains on the samples tested (Silva and Naik, 2013; Souche *et al.*, 2016; Tran, 2011;
287 Vishwakarma *et al.*, 2014). However, in most of these studies, the colonizing species were not
288 identified and described, calling for further research to obtain a deeper understanding of the
289 interactions between cement materials and microorganisms in the marine environment.

290 **Fungi**

291 Micro-fungi, whose size varies from 1 to 100 μm , are chemotrophic eukaryotes. They are not
292 capable of photosynthesis to produce their own organic matter. Fungi require wet or moist
293 environments to develop, and their energy is provided by redox reactions. They are not very
294 sensitive to pH variation but develop more easily in acidic conditions.

295 Fungi are heterotrophs. They can only synthesize their cellular components from a source of
296 organic carbon. Thus, fungal colonization of a cement-based material requires an accumulation of
297 organic matter on the surface. In the case of successful colonization, fungi can then lead to the
298 alteration or deterioration of the colonized material. Certain fungi produce pigments (for example,
299 melanin) that cause dark stains on the cement-based material (Giannantonio et al., 2009). In
300 addition, fungi produce a large quantity of organic acids (acetic, formic, oxalic and tartaric acid),

¹ Photosynthesis is the reaction enabling certain living organisms to synthesize organic matter from CO₂ and an electron donor under the effect of sunlight.

301 which are responsible for the dissolution of lime in mineral matrices and the chelation of calcium
302 ions, leading to the deterioration of the material.

303 The marine environment is considered to contain a large number of fungal organisms (Escadeillas
304 *et al.*, 2007). However, only a few studies have focused on the colonization by fungi of cement-
305 based materials in the marine environment. Submerged surfaces are often covered by one or more
306 layers of algae and other protozoan organisms (Dürr and Thomason, 2009), which makes it difficult
307 to identify and isolate sessile fungi colonizers in the marine environment without the use of
308 advanced molecular biology techniques such as the extraction and sequencing of 18S rRNA.

309 **METHODS: PHYSICOCHEMICAL FACTORS INFLUENCING** 310 **THE COLONIZATION OF CEMENT-BASED MATERIALS IN** 311 **MARINE ENVIRONMENTS**

312 The biological colonization of a surface is governed by the interaction of three main factors: the
313 type of material, the microorganisms and the environment (Lors, Feugeas and Tribollet, 2019).
314 Then, two types of bioreceptivity are defined: (i) intrinsic bioreceptivity, linked only to the
315 physicochemical properties of the concrete surface, such as porosity, roughness and chemical
316 composition; and (ii) extrinsic bioreceptivity, related to the environment (Lors, Feugeas and
317 Tribollet, 2019).

318 **Intrinsic bioreceptivity (Material factors)**

319 **Chemical composition**

320 Depending on its chemical composition, a material can contain substances that favor or inhibit the
321 development of biofilm (Ly *et al.*, 2021). For example, the presence of certain heavy metals, in
322 sufficient quantities, can inhibit the growth and development of microorganisms (Dalod *et al.*,
323 2014; Dubosc, Escadeillas and Blanc 2001). In a comparison of the bacterial colonization of
324 Portland cement (CEM I) and slag cement (CEM III) in seawater, CEM III mortar was shown to
325 be more bioreceptive than CEM I mortar (Hayek *et al.*, 2020a, 2020b). Thus, the type of cement
326 influences the kinetics and the level of development of bacterial biofilm on a concrete surface. The
327 chemical composition of a concrete can also influence other important parameters, such as
328 roughness, porosity and pH (Veeger *et al.*, 2021).

329 **Surface roughness or topography**

330 The roughness of the surface of a material is one of the main physical factors influencing its
331 bioreceptivity. Roughness consists of bumps and irregularities on the surface of the material. These
332 irregularities can act as anchoring sites and micro-refuges for microorganisms, thus favoring
333 colonization (Ammar *et al.*, 2015). These micro-refuges protect microorganisms from the
334 hydrodynamic forces that tend to detach them during the highly precarious reversible adhesion
335 phase (Bellon-Fontaine *et al.*, 2016). Kerr *et al.* (1999) had observed an increase in bacterial
336 adhesion on glass and acrylic samples immersed in natural seawater when roughness was raised
337 from 0.25 to 30 μm . Teughels *et al.* (2006) had showed that the formation of dental plaque is
338 favored by a rough surface. Concerning cement-based materials, several studies have demonstrated

339 the effect of surface roughness on biofilm formation (Govin *et al.*, 2013; Hayek *et al.*, 2021; Manso
340 *et al.*, 2014; Manso and Aguado, 2016; Miller *et al.*, 2009; Souche *et al.*, 2019; Tomaselli *et al.*,
341 2000; Tran *et al.*, 2014, 2012). These studies show that rough cement-based materials have higher
342 bioreceptivity than smooth surfaces under both laboratory and natural conditions. To enhance
343 colonization, the target is to obtain multiscale rugosity; it is possible to reach the required quality
344 using special elastomeric formworks (Souche *et al.*, 2019).²

345 In addition to its effect on the adhesion of microorganisms, surface roughness also influences water
346 flow rates and the adsorption of organic matter (Dubosc, Escadeillas and Blanc 2001; El-Naggar
347 *et al.*, 2010). This directly impacts the formation of the conditioning film during the induction
348 phase. Some studies nuance the effect of roughness on the bioreceptivity of a material, specifying
349 that this depends on the characteristics of the microorganisms involved, e.g. the type of
350 microorganism, geometry, size and shape (Whitman *et al.*, 1998). For example, filamentous algae
351 such as *Klebsormidium flaccidum* attach to rough surfaces, whereas algae with thick cell walls
352 adhere to smooth surfaces (Lors, Feugeas and Tribollet, 2019; Rindi, Guiry and López-Bautista,
353 2008; Tran, 2011).

354 **Total porosity to water**

355 In the case of surfaces not immersed in water, bacteria preferentially colonize porous surfaces. This
356 can mainly be explained by the influence of porosity on the absorption and retention of water by
357 the material, a determining factor for the development of microorganisms (Nuhoglu *et al.*, 2006).
358 Crevasses that are the same size as the microorganism concerned appear to be ideal. Smaller pits
359 assist anchoring but do not protect from flows, while pits that are too large do not enable the
360 optimum transfer of nutrients.

361 In the case of submerged concrete, it is difficult to determine the effect of porosity on bioreceptivity
362 (Govin *et al.*, 2013; Tran *et al.*, 2014, 2012). This difficulty has been explained by the permanent
363 saturation of samples tested under water and therefore the high humidity throughout the
364 experiment.

365 **Surface pH**

366 The pH of the surface of the material can influence the type of microorganism and its capacity to
367 adhere to the material (Shi and Zhu, 2009). Generally, each species has an optimum pH for growth
368 and can develop within a more or less limited range around this value. Based on these pH ranges,
369 microorganisms are classed as acidophilic (pH < 6), neutrophilic (6 < pH < 8) or basophilic (pH >
370 8).

371 The metabolic activities, growth and adhesion of microorganisms and the synthesis of EPS are
372 influenced by the pH of the surface of the material. The reduction of the surface pH of concrete
373 after immersion in seawater (from 13 to about 9) accelerates colonization of the surface and
374 improves the bioreceptivity of the material (Dalod *et al.*, 2014; Hayek *et al.*, 2020b; Roberts *et al.*,
375 2002; Tran *et al.*, 2014; Vincke *et al.*, 2001). However, even concrete with a highly basic surface

² <http://www.grouplib.com/les-moules-et-produits-en-elastomeres.html>

376 could be colonized by extremophilic bacteria that can resist environmental conditions such as
377 extreme temperature, pH or pressure.

378 **Surface hydrophobicity**

379 Surface hydrophobicity is one of the factors that affect the patterns and nature of bacterial
380 colonization of a surface, especially during the early stages of biofilm formation (Dang and Lovell,
381 2015; Scheuerman *et al.*, 1998). Unsurprisingly, hydrophilic microorganisms attach more easily to
382 hydrophilic surfaces, whereas hydrophobic microorganisms prefer hydrophobic surfaces (Shi and
383 Zhu, 2009). As hydrophobicity and surface charge depend on the material's chemical composition
384 (Katsikogianni and Missirlis, 2004), this is one of the ways that composition influences the types
385 and diversity of colonizing microorganisms (Giannantonio *et al.*, 2009; Guillitte, 1995; Miller *et*
386 *al.*, 2012).

387 However, a hydrophobic surface exhibits low wettability and low surface energy, whereas a
388 hydrophilic surface exhibits high wettability and high surface energy. Water droplets on a
389 hydrophobic surface will 'bead up' while droplets on a hydrophilic surface will spread out evenly.
390 The degree of hydrophobicity is determined by contact angle measurements between water droplet
391 and surface; the surface is super-hydrophilic, hydrophilic, hydrophobic and superhydrophobic
392 when the contact angle is respectively less than 10°, between 10° and 90°, between 90° and 150°
393 and between 150° and 180° (Bixler and Bhushan, 2012).

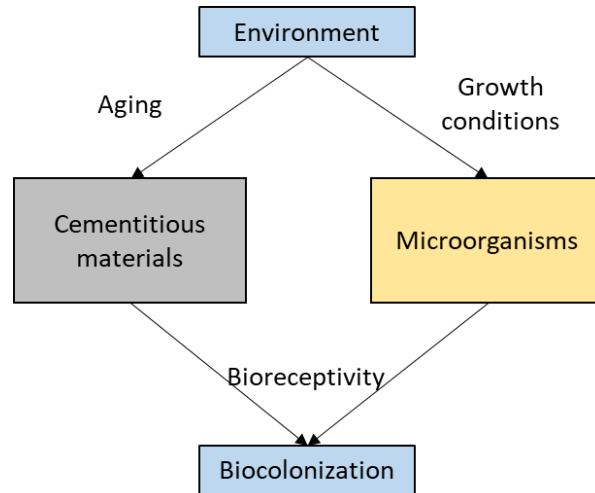
394 Despite the importance of this parameter on marine biodiversity as well as on the colonization of
395 submerged surfaces, studies that relate to the surface hydrophobicity of cementitious materials and
396 its effects on the biocolonization in the marine environment seem to be very rare. Hayek *et al.*,
397 (2021) showed that the use of curing compound inhibits the biocolonization of concrete surface in
398 seawater because of its effect on surface hydrophobicity (the cure compound forms a
399 superhydrophobic film on the concrete surface). This study is in agreement with the literature,
400 which has been proven that the use of a hydrophobic surface coating (low adhesive surface) is a
401 successful strategy to inhibit biofouling in the marine environment (Blainey and Marshall, 1991;
402 Huggett *et al.*, 2009; Razavi *et al.*, 2019).

403 **Extrinsic bioreceptivity (Environmental factors)**

404 Several studies have reported that the environment has a strong impact on the colonization of
405 cementitious materials in the marine context (Giraudel, Garcia and Ledoux, 2014; Lors, Feugeas
406 and Tribollet, 2019; Souche *et al.*, 2019). The medium influences the development and growth of
407 microorganisms as well as the aging of the material. Indeed, interactions between the environment
408 and microorganisms define the conditions in which microbial growth can occur (Figure 2).

409 Generally, the development of biofilm on the surface of a cement-based material is relatively slow
410 as concrete has a high pH of about 13 (Codina, 2007; Manso and Aguado, 2017). This high
411 alkalinity is unfavorable for biological colonization because few microorganisms can develop
412 under such basic pH conditions. For that reason, an initial induction step that reduces the pH from
413 13 to 9.5 will favor the colonization of cement-based materials (Roberts *et al.*, 2002). This
414 modification of the surface pH arises from the adsorption of mineral and organic compounds and

415 the interaction of the concrete with seawater, which contains high concentrations of several
416 dissolved species (Vavrenyuk, Efimenko and Vavrenyuk, 2020). De Weerd, Justnes and Geiker
417 (2014) have shown that, within about 20 days, cement-based binders immersed in seawater undergo
418 phase changes, whatever the type of binder tested (De Weerd, Justnes and Geiker, 2014; Jakobsen,
419 De Weerd and Geiker, 2016).



420
421 Figure 2. Interactions between the environment, microorganisms and cementitious materials
422 (Lors, Feugeas and Tribollet, 2019)

423 There are a number of environmental factors that act on the colonization of cementitious materials
424 in the marine environment, including luminosity, pH, temperature, nutrients and hydrodynamic
425 conditions (Azevedo, Carloni and Carvalheira, 2006; Choi *et al.*, 2006; Färber *et al.*, 2015; Firth *et*
426 *al.*, 2014; Qvarfordt *et al.*, 2006; Sherman, Giliam and Spieler, 2001; Witt *et al.*, 2012). Of these,
427 it seems that the availability of nutrients and the temperature are the most likely factors to differ
428 between marine environments. Thus, these are considered the major factors influencing the
429 extrinsic bioreceptivity of cementitious materials in these contexts (Färber *et al.*, 2015; Gong, Song
430 and Warren 2005; Salta *et al.*, 2013).

431 **Nutrients availability**

432 The medium is the means of propagation of nutrients allowing microorganisms to develop. The
433 environment can be the source of nutrients, as is the case in sanitation networks, where the
434 environment consists of wastewater rich in nutrients such as organic matter and sulfur compounds.
435 Or the medium can simply be a means of transporting nutrients through the dissolution of organic
436 matter. The concentration of nutrients present in the environment may favor the development of
437 certain bacterial species. In the case of cementitious materials, these do not provide nutrients to the
438 microorganisms, so the medium must be the source of nutrients to allow bacterial growth.

439 Seawater contains micro- and macronutrients essential for the growth of the cells of living
440 organisms. Macronutrients, which contain carbon (C), phosphorus (P), nitrogen (N) and silicon
441 (Si), provide the nutritive requirements indispensable to the metabolic functions of living
442 organisms. Micronutrients, containing iron (Fe), Zinc (Zn), Copper (Cu) or Manganese (Mn), while
443 consumed in much lower quantities, act as enzyme cofactors for metabolic reactions (de

444 Fommervault, 2016). The existence of these nutrients in seawater make it rich not only in macro-
445 organisms, but also microorganisms such as bacteria, cyanobacteria and microalgae (*Poli et al.*,
446 2017). The concentration and diversity of marine organisms also depend on other environmental
447 conditions, such as pressure, temperature and salinity. Biodiversity is lower where these conditions
448 are more drastic and hence more selective (Das, Lyla and Khan *et al.*, 2006; Sheehan, 2001;
449 Zeppilli *et al.*, 2018).

450 In laboratory tests, the use of artificial seawater as a culture medium has been shown to be sufficient
451 for marine bacteria to form a mature biofilm on a glass surface (Guillonneau *et al.*, 2018; Hayek *et*
452 *al.*, 2019; Mireille Ayé *et al.*, 2015). This medium lacks organic substances, indicating that marine
453 bacteria can form a biofilm without the need organic matter.

454 **Temperature**

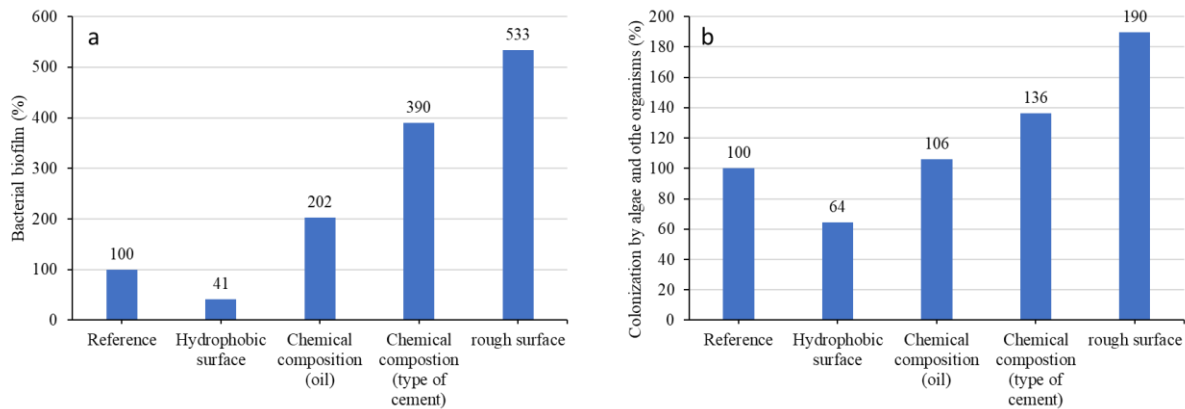
455 Temperature is one of the most important factors affecting the growth of microorganisms
456 (Mesquita *et al.*, 2020). The optimum temperature for most microorganisms is between 15°C and
457 35°C (Lors, Feugeas and Tribollet, 2019; Tran, 2011). A temperature that is too low reduces the
458 kinetics of the enzymatic reactions that condition the metabolism of microorganisms and thereby
459 their growth (González-Figueredo *et al.*, 2018; Huston, Krieger-Brockett and Deming, 2000;
460 Robinson, 2015). A temperature that is too high damages microbial cells by denaturing the enzymes
461 and proteins of transport systems (Shehadul Islam, Aryasomayajula and Selvaganapathy, 2017).
462 However, certain microorganisms can resist temperatures close to 0°C and greater than or equal to
463 70°C (Brock, 2012). Moreover, each microorganism has an optimum growth temperature
464 dependent on its original environment (Lors, Feugeas and Tribollet, 2019). For example, marine
465 bacteria isolated from sediment, water or biofilm samples (adhered to a surface) are mesophilic,
466 growing best in moderate temperatures. Their optimum growth temperatures are between 25°C and
467 30°C, but they can grow at 20°C and withstand a temperature of 4°C (Brian-Jaisson *et al.*, 2014;
468 Guillonneau *et al.*, 2018; Hau and Gralnick, 2007; Hayek *et al.*, 2019; Makemson *et al.*, 1997;
469 Mireille Ayé *et al.*, 2015).

470 Likewise, the temperature of the medium affects the bioreceptivity of cementitious materials
471 through the mechanisms of adhesion between microorganisms and material. The surface tension of
472 a liquid medium varies with temperature, which influences the three-way equilibrium between
473 material, medium and microorganism and can thus affect microorganism adhesion. In the same
474 effect category, Van der Waals forces also vary with temperature (Nedwell, 1999).

475 **RESULTS: BIOLOGICAL COLONIZATION AND THE** 476 **DURABILITY OF CONCRETE**

477 The effect of the materials factors (cited below) on the intrinsic bioreceptivity of cement-based
478 materials in the marine environment was studied in situ by Hayek *et al.*, (2021). In this paper, the
479 effect of several parameters in the two main stages (bacterial biofilm and colonization by algae and
480 other marine organisms) of cementitious material biocolonization in the marine environment was
481 tested. The main parameters studied were i) the surface roughness, ii) the surface hydrophobicity
482 and iii) the chemical composition. Figure 3 present the results obtained after 6 (Figure 3a) and 78

483 (Figure 3b) days of immersion in seawater. The results obtained in this study are in keeping with
 484 the literature cited above, in which a similar effect of materials factors on the intrinsic
 485 bioreceptivity has been reported. Based on the persistence of their significant effect (after 78 days
 486 of immersion in seawater), the intrinsic parameters that support greater biocolonization are
 487 classified from more to less effective in the following order; surface roughness (190 %) > chemical
 488 composition (slag cement instead Portland cement) (136 %) > chemical composition (presence of
 489 formwork oil) (106 %). Therefore, at the material scale, surface roughness is the most effective
 490 factor in designing bioreceptive concrete that enhances marine biodiversity (Browne and Chapman
 491 2011; Dafforn *et al.*, 2015; Hayek *et al.*, 2021).



492
 493 Figure 3. The effect of material factors on the intrinsic bioreceptivity of cement-based materials
 494 in the marine environment. Data collected from the study of Hayek *et al.* (2021). (a) colonization
 495 by bacteria after 6 days of immersion. (b) colonization by algae and other marine organisms after
 496 78 days of immersion in seawater.

497 Hayek *et al.* (2020a) also showed that the carbonation of cementitious materials before immersion
 498 in seawater plays a primary role in surface colonization by marine bacteria. Carbonated concrete
 499 and mortar were shown to be more bioreceptive (200 % after 6 days of immersion in seawater)
 500 than non-carbonated cement-based materials.

501 However, regarding the environmental factors, several authors have mentioned the importance of
 502 nutrients availability. For example, in the case of artificial reef structures whose objective is the
 503 colonization of the material, several ‘pro-biofouling’ coatings have been tried. The constituents of
 504 these coatings are today known as chemo-attractors that allow microorganisms to adhere and grow
 505 on the material (Lee *et al.*, 2008; Souche *et al.*, 2016). Lee *et al.* (2008) have found that the use of
 506 chemoattractant coatings such as ferrous sulfate, zinc oxide, ammonium nitrate, sodium phosphates
 507 and ferrous lactate increase the colonization of cementitious materials in the marine environment.
 508 A maximum biocolonization with green algae 25%, red algae 11.3% and brown algae 63.7% was
 509 estimated from ferrous lactate coating.

510 Moreover, the colonization of cementitious material differs depending on the season (temperature
 511 effect) (Choi *et al.*, 2006; Manso *et al.*, 2015). In a study carried out by Rica *et al.* (2016) focusing
 512 on the effect of temperature on the colonizing biomass of a concrete surface in a marine

513 environment, a decrease in temperature from 18°C to 13°C led to a regression (from 100% to 33%)
514 in the biomass of the biofilm formed on concrete immersed in seawater.

515 Biological colonization can have positive or negative effects on a structure, either protecting or
516 degrading the material (Coombes *et al.*, 2011; Georges *et al.*, 2021; Harshada, Desai and Gupta,
517 2017). Relatively little attention has been paid to the biodegradation of concrete in seawater, despite
518 the fact that the colonization of marine concrete structures is spontaneous. This can be explained
519 by the difficulty of separating biodeterioration from other processes that damage cementitious
520 materials in seawater (e.g. aging, chemical erosion by chlorides, sulfate, *etc.*). In 2018, a laboratory
521 experiment demonstrated that the colonization of cementitious materials by microorganisms such
522 as the diatom *Cylindrotheca closterium* allowed greater penetration of chloride and sulfate ions,
523 which accelerated the degradation of the material. The author posited that the creation of cracks in
524 the material by diatoms could explain this phenomenon (Ferrero, 2018).

525 Yet as marine environments are extremely diverse, the results of experiments carried out in the
526 laboratory do not always reflect reality. A colonization effect determined in the laboratory is highly
527 dependent on the choice of microorganisms, the studied material (concrete, mortar, cement paste,
528 Portland cement, *etc.*) and the experimental conditions. According to Lv *et al.* (2015), the
529 colonization of concrete may actually improve its lifespan depending on the substrate and
530 microorganisms involved. These authors showed that the biofilm formed by bacteria of the genus
531 *Pseudoalteromonas* on the surface of the cement-based material improved its durability by
532 reducing the quantity of aggressive ions such as Cl⁻ able to penetrate the material and cause
533 biodeterioration. This protective effect of biofilm has been identified not only in the laboratory
534 with bacteria, but also in situ with biofilm made up of other marine microorganisms and macro-
535 organisms such as cyanobacteria, algae, lichens and barnacles (Bertron, 2014; Coombes *et al.*,
536 2011; de la Rosa, Warke and Smith, 2013). In a number of studies, these living organisms have
537 been found to reduce the permeability of the cement-based material, resulting in greater durability
538 (Chlayon, Iwanami and Chijiwa, 2018; Coombes *et al.*, 2017; Patil *et al.*, 1994; Perkol-Finkel and
539 Sella, 2014; Soleimani *et al.*, 2013).

540 In this way, the biological colonization of concrete could provide structures with additional
541 protection against chemical or even mechanical degradation, through the effects of the physical
542 barrier offered by living organisms colonizing the surface of cementitious material (Ariño *et al.*,
543 1995; Bartoli *et al.*, 2014; Carter and Viles, 2003; Chlayon, Iwanami and Chijiwa, 2020;
544 Mottershead and Lucas, 2000; Viles and Cutler, 2012). According to the literature, a beneficial
545 biofilm (bioprotection) can protect the material by reducing the quantity of water and nutrients
546 available, synthesizing anti-microbial agents (thus inhibiting the growth of other microorganisms
547 having a harmful effect on cementitious materials) or forming a protective layer of synthesized
548 exopolysaccharides (Chlayon *et al.*, 2018; Soleimani *et al.*, 2013).

549 A microbial biofilm can also facilitate the attachment of other living organisms to the surface of
550 the structure. In the case of cementitious materials, the attachment of living organisms such as
551 oysters, tubeworms, barnacles and corals can lead to the formation of calcite precipitated in the
552 gaps of the cement matrix, making the concrete denser and stronger (Chlayon *et al.*, 2018; Joshi,
553 Goyal and Reddy, 2018; Risinger, 2012).

554

555

556

557

DISCUSSION: ECOLOGICAL CONSIDERATIONS AND PERSPECTIVES TO DESIGN MORE BIORECEPTIVE CONCRETE (GREEN CONCRETE)

558

559

560

561

562

563

564

565

It has been shown that the marine diversity decreases with the loss of coastal wetlands and nearshore communities when marine infrastructure such as seawalls are constructed. The loss of horizontal extent of coastal communities occurs with seawalls, contributing to poor ecological performance, exacerbated by increased land-based sources of pollution. One of the major reasons for the poor ecological performance of the marine infrastructure is the structural design which is less complex than the natural communities replaced (Hosseinzadeh *et al.*, 2022). However, if the marine infrastructure is designed considering ecological features, natural marine habitats could be replicated which supports some species of marine life (Dyson and Yocom, 2015).

566

567

568

569

570

571

572

573

574

575

576

577

While ideally coastal development should be minimized or avoided, as artificialization is the primary cause of biodiversity loss in the world (IPBES, 2019), in the short term the global demand for this is set to continue. To reduce the environmental impact and the disturbance of coastal ecosystems, we recommend using a new design method for coastal and marine structures. One way to do this is to consider the use of bioreceptive concrete at the site of impact, conceived with the optimal surface characteristics for the local ecosystem. This new design approach would aim to enhance biological colonization of coastal engineering structures and should be considered at the project outset (Pioch *et al.*, 2018). The geometry or the physical shape of marine infrastructure is one of the parameters that show a direct ecological effect; fishes and benthic invertebrates populate and interact in greater numbers on materials with rugose and irregular surfaces rather than a smooth, flat wall (Hosseinzadeh *et al.*, 2022; Koraim, 2013; Perkol-Finkel and Sella, 2014; Yip, Zhang and Chwang, 2002).

578

579

Moreover, based in the present paper and the literature cited above, the following recommendations aim to meet the objective of the new design approach:

580

581

582

583

584

585

586

587

588

589

590

591

1. Map the ecosystem at the site where the structure will be built and identify sensitive species.
2. Test the compatibility of the proposed concrete composition with the ecosystem where the project is planned, using the test method proposed by Hayek *et al.* (2020a).
3. Design surface roughness to ensure adhesion.
4. Pretreat the surface (e.g. carbonation), if possible, to accelerate growth.
5. Adjust the timing of the project (e.g. season) so that the biophysical conditions (dependent on the area) are favorable for the ecosystem to start colonization quickly.
6. Develop a monitoring plan to ensure the reestablishment of the ecosystem after construction, as well as a solution to fight against invasive species if needed.
7. Do not apply a hydrophobic coating such as the curing product on the concrete surface.
8. Use slag cement (CEM III) instead of Portland cement (CEM I) to prepare the concrete.

592

593

CONCLUSIONS

594 This review of literature presents some of the latest research results that contributes to enhancing
595 the colonization of marine infrastructure built with concrete. Biological colonization can reduce
596 negative impacts on natural and local ecosystems and lower ubiquitous exotic species invasion. To
597 encourage surface colonization by marine microorganisms, the carbonation of cementitious
598 materials before their immersion in seawater play the primary role. The type of cement influences
599 the kinetics and the level of surface colonization. Moreover, latest findings clearly indicate that
600 slag cement (CEM III) enhances marine biodiversity as compared to Portland cement (CEM I). At
601 the material scale, surface roughness is the most effective factor in designing bioreceptive concrete
602 that enhances marine biodiversity. Based on the persistence of their significant effect (after 78 days
603 of immersion in seawater), the intrinsic parameters that support greater biocolonization are
604 classified from more to less effective in the following order; surface roughness, CEM III as binder,
605 chemical composition (presence of formwork oil).

606 But, adopting new methods of construction often requires overcoming a certain inertia: insurance
607 and construction companies, as well as resource managers, tend to try to avoid technical issue or
608 legal repercussions by repeating historically proven methods, ignoring the ecological aspect or
609 hiding negatives impacts. Nonetheless, there is no question that coastal areas need to be considered
610 as tremendous reservoirs of biodiversity (IPBES, 2019). Ecological engineering inspiration to eco-
611 design concrete infrastructures, is one way to mitigate negative impact from human construction,
612 and should help to restore marine biodiversity which could be saved by 2050, if appropriate policies
613 and projects in the field start quickly (Duarte *et al.*, 2020). This review highlights some of the most
614 significant results demonstrating that concrete can be an appropriate support for biological
615 colonization, making it a candidate for green design strategies. Of course, such an approach should
616 not be used as a ‘greenwashing’ excuse to allow unregulated construction anywhere, thus becoming
617 a Trojan horse to ongoing massive artificialization (Firth *et al.*, 2020). For real and fair progress to
618 be made, it will be essential to develop robust assessment methods to measure the ecological gains
619 of bioreceptive designed infrastructure and prove their potential benefits.

620 However, to increase the understanding of biofilm formation on concrete surfaces in the marine
621 environment and to analyses the ecological benefits of this biocolonization, further investigation is
622 needed using the molecular biology tools such as the amplicon sequencing of the 16S rRNA gene
623 in order to investigate succession of the biofilm communities and their interaction with the concrete
624 material and the flowing water.

625

626

ACKNOWLEDGMENTS

627 The authors are grateful to IMT Mines d’Alès and University of Paul Valéry Montpellier 3 for
628 their participation and support.

629

LITERATURE CITED

- 632 Al-Handal, A.Y., Wulff, A., 2008. Marine epiphytic diatoms from the shallow sublittoral zone in
633 Potter Cove, King George Island, Antarctica. *Bot. Mar.* 51, 411–435.
634 <https://doi.org/10.1515/BOT.2008.053>
- 635 Ammar, Y., Swailes, D., Bridgens, B., Chen, J., 2015. Influence of surface roughness on the initial
636 formation of biofilm. *Surf. Coat. Technol.*, The 42nd International Conference on
637 Metallurgical Coatings and Thin Films 284, 410–416.
638 <https://doi.org/10.1016/j.surfcoat.2015.07.062>
- 639 An, Y.H., Friedman, R.J., 1998. Concise review of mechanisms of bacterial adhesion to biomaterial
640 surfaces. *J. Biomed. Mater. Res.* 43, 338–348. [https://doi.org/10.1002/\(SICI\)1097-4636\(199823\)43:3<338::AID-JBM16>3.0.CO;2-B](https://doi.org/10.1002/(SICI)1097-4636(199823)43:3<338::AID-JBM16>3.0.CO;2-B)
- 642 Anderson, M.J., Underwood, A.J., 1994. Effects of substratum on the recruitment and development
643 of an intertidal estuarine fouling assemblage. *J. Exp. Mar. Biol. Ecol.* 184, 217–236.
644 [https://doi.org/10.1016/0022-0981\(94\)90006-X](https://doi.org/10.1016/0022-0981(94)90006-X)
- 645 Ariño, X., Ortega-Calvo, J.J., Gomez-Bolea, A., Saiz-Jimenez, C., 1995. Lichen colonization of
646 the Roman pavement at Baelo Claudia (Cadiz, Spain): biodeterioration vs. bioprotection.
647 *Sci. Total Environ.*, The Deterioration of Monuments 167, 353–363.
648 [https://doi.org/10.1016/0048-9697\(95\)04595-R](https://doi.org/10.1016/0048-9697(95)04595-R)
- 649 Azevedo, Flávia Beatriz Beserra, Carloni, G.G., Carvalheira, L.V., 2006. Colonization of benthic
650 organisms on different artificial substratum in Ilha Grande bay, Rio de Janeiro, Brazil. *Braz.*
651 *Arch. Biol. Technol.* 49, 263–275. <https://doi.org/10.1590/S1516-89132006000300012>
- 652 Azevedo, F. B B, Carloni, G.G., Carvalheira, L. V., 2006. Colonization of benthic organisms on
653 different artificial substratum in Ilha Grande Bay, Rio de Janeiro, Brazil. *Braz. Arch. Biol.*
654 *Technol.* 49, 263–275. <https://doi.org/10.1590/S1516-89132006000300012>
- 655 Baine, M., 2001. Artificial reefs: a review of their design, application, management and
656 performance. *Ocean Coast. Manag.* 44, 241–259. [https://doi.org/10.1016/S0964-5691\(01\)00048-5](https://doi.org/10.1016/S0964-5691(01)00048-5)
- 658 Barraud, N., Schleheck, D., Klebensberger, J., Webb, J.S., Hassett, D.J., Rice, S.A., Kjelleberg, S.,
659 2009. Nitric Oxide Signaling in *Pseudomonas aeruginosa* Biofilms Mediates
660 Phosphodiesterase Activity, Decreased Cyclic Di-GMP Levels, and Enhanced Dispersal. *J.*
661 *Bacteriol.* 191, 7333–7342. <https://doi.org/10.1128/JB.00975-09>
- 662 Bartoli, F., Municchia, A.C., Futagami, Y., Kashiwadani, H., Moon, K.H., Caneva, G., 2014.
663 Biological colonization patterns on the ruins of Angkor temples (Cambodia) in the
664 biodeterioration vs bioprotection debate. *Int. Biodeterior. Biodegrad.* 96, 157–165.
665 <https://doi.org/10.1016/j.ibiod.2014.09.015>
- 666 Bellon-Fontaine, M.-N., Benezech, T., Boutroux, K., Hermon, C., 2016. Conception hygiénique
667 de matériel et nettoyage-désinfection. p. 12.
- 668 Bengtson, S., Sallstedt, T., Belivanova, V., Whitehouse, M., 2017. Three-dimensional preservation
669 of cellular and subcellular structures suggests 1.6 billion-year-old crown-group red algae.
670 *PLOS Biol.* 15, e2000735. <https://doi.org/10.1371/journal.pbio.2000735>
- 671 Berne, C., Ellison, C.K., Ducret, A., Brun, Y.V., 2018. Bacterial adhesion at the single-cell level.
672 *Nat. Rev. Microbiol.* 16, 616–627. <https://doi.org/10.1038/s41579-018-0057-5>

673 Bertron, A., 2014. Understanding interactions between cementitious materials and
674 microorganisms: a key to sustainable and safe concrete structures in various contexts.
675 Mater. Struct. 47, 1787–1806. <https://doi.org/10.1617/s11527-014-0433-1>

676 Bixlar Gregory, D., Bhushan, B., 2012. Biofouling: lessons from nature. Math. Phys. and Eng. Sci.
677 370, 2381–2417. <https://doi.org/10.1098/rsta.2011.0502>

678 Blainey, B.L., Marshall, K.C., 1991. The use of block copolymers to inhibit bacterial adhesion and
679 biofilm formation on hydrophobic surfaces in marine habitats. Biofouling 4, 309–318.
680 <https://doi.org/10.1080/08927019109378221>

681 Boyd, A., Chakrabarty, A.M., 1994. Role of alginate lyase in cell detachment of *Pseudomonas*
682 *aeruginosa*. Appl. Environ. Microbiol. 60, 2355–2359.

683 Branda, S.S., Vik, S., Friedman, L., Kolter, R., 2005. Biofilms: the matrix revisited. Trends
684 Microbiol. 13, 20–26. <https://doi.org/10.1016/j.tim.2004.11.006>

685 Briand, J.-F., Pochon, X., Wood, S.A., Bressy, C., Garnier, C., Réhel, K., Urvois, F., Culioli, G.,
686 Zaiko, A., 2018. Metabarcoding and metabolomics offer complementarity in deciphering
687 marine eukaryotic biofouling community shifts. Biofouling 34, 657–672.
688 <https://doi.org/10.1080/08927014.2018.1480757>

689 Brian-Jaisson, F., Ortalo-Magné, A., Guentas-Dombrowsky, L., Armougom, F., Blache, Y.,
690 Molmeret, M., 2014. Identification of Bacterial Strains Isolated from the Mediterranean
691 Sea Exhibiting Different Abilities of Biofilm Formation. Microb. Ecol. 68, 94–110.
692 <https://doi.org/10.1007/s00248-013-0342-9>

693 Brock, T.D., 2012. Thermophilic Microorganisms and Life at High Temperatures. Springer
694 Science & Business Media.

695 Browne, M.A., Chapman, M.G., 2011. Ecologically Informed Engineering Reduces Loss of
696 Intertidal Biodiversity on Artificial Shorelines. Environ. Sci. Technol. 45, 8204–8207.
697 <https://doi.org/10.1021/es201924b>

698 Bugnot, A.B., Mayer-Pinto, M., Airoidi, L., Heery, E.C., Johnston, E.L., Critchley, L.P., Strain,
699 E.M.A., Morris, R.L., Loke, L.H.L., Bishop, M.J., Sheehan, E.V., Coleman, R.A., Dafforn,
700 K.A., 2020. Current and projected global extent of marine built structures. Nat. Sustain. 1–
701 9. <https://doi.org/10.1038/s41893-020-00595-1>

702 Bulleri, F., Airoidi, L., 2005. Artificial marine structures facilitate the spread of a non-indigenous
703 green alga, *Codium fragile* ssp. *tomentosoides*, in the north Adriatic Sea. J. Appl. Ecol. 42,
704 1063–1072. <https://doi.org/10.1111/j.1365-2664.2005.01096.x>

705 Bulleri, F., Chapman, M.G., 2010. The introduction of coastal infrastructure as a driver of change
706 in marine environments. J. Appl. Ecol. 47, 26–35. <https://doi.org/10.1111/j.1365-2664.2009.01751.x>

707

708 Bulleri, F., Chapman, M.G., 2004. Intertidal assemblages on artificial and natural habitats in
709 marinas on the north-west coast of Italy. Mar. Biol. 145, 381–391.
710 <https://doi.org/10.1007/s00227-004-1316-8>

711 Bunt, C.R., Jones, D.S., Tucker, I.G., 1993. The effects of pH, ionic strength and organic phase on
712 the bacterial adhesion to hydrocarbons (BATH) test. Int. J. Pharm. 99, 93–98.
713 [https://doi.org/10.1016/0378-5173\(93\)90350-O](https://doi.org/10.1016/0378-5173(93)90350-O)

714 Busscher, H.J., Weerkamp, A.H., 1987. Specific and non-specific interactions in bacterial adhesion
715 to solid substrata. FEMS Microbiol. Rev. 3, 165–173. <https://doi.org/10.1111/j.1574-6968.1987.tb02457.x>

716

717 Carpentier, B., Cerf, O., 1993. Biofilms and their consequences, with particular reference to
718 hygiene in the food industry. *J. Appl. Bacteriol.* 75, 499–511.
719 <https://doi.org/10.1111/j.1365-2672.1993.tb01587.x>

720 Carter, N.E.A., Viles, H.A., 2003. Experimental investigations into the interactions between
721 moisture, rock surface temperatures and an epilithic lichen cover in the bioprotection of
722 limestone. *Build. Environ., Building Stone Decay: Observations, Experiments and*
723 *Modeling* 38, 1225–1234. [https://doi.org/10.1016/S0360-1323\(03\)00079-9](https://doi.org/10.1016/S0360-1323(03)00079-9)

724 Chao, L., Rakshe, S., Leff, M., Spormann, A.M., 2013. PdeB, a cyclic Di-GMP-specific
725 phosphodiesterase that regulates *Shewanella oneidensis* MR-1 motility and biofilm
726 formation. *J. Bacteriol.* 195, 3827–3833. <https://doi.org/10.1128/JB.00498-13>

727 Chapman, M.G., Underwood, A.J., 2011. Evaluation of ecological engineering of “armoured”
728 shorelines to improve their value as habitat. *J. Exp. Mar. Biol. Ecol., Global change in*
729 *marine ecosystems* 400, 302–313. <https://doi.org/10.1016/j.jembe.2011.02.025>

730 Chatterjee, A., Goyns, A., 2013. Cementitious Materials Performance in Aggressive Aqueous
731 Environments – Engineering Perspectives, in: Alexander, M., Bertron, A., De Belie, N.
732 (Eds.), *Performance of Cement-Based Materials in Aggressive Aqueous Environments:*
733 *State-of-the-Art Report, RILEM TC 211 - PAE, RILEM State-of-the-Art Reports.* Springer
734 Netherlands, Dordrecht, pp. 391–449. https://doi.org/10.1007/978-94-007-5413-3_16

735 Chlayon, T., Iwanami, M., Chijiwa, N., 2020. Impacts from concrete microstructure and surface
736 on the settlement of sessile organisms affecting chloride attack. *Constr. Build. Mater.* 239,
737 117863. <https://doi.org/10.1016/j.conbuildmat.2019.117863>

738 Chlayon, T., Iwanami, M., Chijiwa, N., 2018. Combined protective action of barnacles and biofilm
739 on concrete surface in intertidal areas. *Constr. Build. Mater.* 179, 477–487.
740 <https://doi.org/10.1016/j.conbuildmat.2018.05.223>

741 Choi, C., Ohno, M., Sohn, C., 2006. Algal succession on different substrata covering the artificial
742 iron reef at Ikata in Shikoku, Japan. *Algae* 21, 305–310.
743 <https://doi.org/10.4490/ALGAE.2006.21.3.305>

744 Choi, C.G., Ohno, M., Sohn, C.H., 2006. Algal Succession on Different Substrata Covering the
745 Artificial Iron Reef at Ikata in Shikoku, Japan. *ALGAE* 21, 305–310.
746 <https://doi.org/2006.21.3.305>

747 Codina, M., 2007. *Les bétons bas pH - Formulation, caractérisation et étude à long terme (Theses).*
748 INSA de Toulouse.

749 Cooke, S.J., Bergman, J.N., Nyboer, E.A., Reid, A.J., Gallagher, A.J., Hammerschlag, N., Van de
750 Riet, K., Vermaire, J.C., 2020. Overcoming the concrete conquest of aquatic ecosystems.
751 *Biol. Conserv.* 247, 108589. <https://doi.org/10.1016/j.biocon.2020.108589>

752 Coombes, M.A., Naylor, L.A., Thompson, R.C., Roast, S.D., Gómez-Pujol, L., Fairhurst, R.J.,
753 2011. Colonization and weathering of engineering materials by marine microorganisms: an
754 SEM study. *Earth Surf. Process. Landf.* 36, 582–593. <https://doi.org/10.1002/esp.2076>

755 Coombes, M.A., Naylor, L.A., Viles, H.A., Thompson, R.C., 2013. Bioprotection and disturbance:
756 Seaweed, microclimatic stability and conditions for mechanical weathering in the intertidal
757 zone. *Geomorphology* 202, 4–14. <https://doi.org/10.1016/j.geomorph.2012.09.014>

758 Coombes, M.A., Viles, H.A., Naylor, L.A., La Marca, E.C., 2017. Cool barnacles: Do common
759 biogenic structures enhance or retard rates of deterioration of intertidal rocks and concrete?
760 *Sci. Total Environ.* 580, 1034–1045. <https://doi.org/10.1016/j.scitotenv.2016.12.058>

761 Costa, A., Appleton, J., 2001. Concrete carbonation and chloride penetration in a marine
762 environment. *Concr. Sci. Eng.* 3, 8.

763 Crutzen, P.J., 2006. The “Anthropocene,” in: Ehlers, E., Krafft, T. (Eds.), *Earth System Science in*
764 *the Anthropocene*. Springer, Berlin, Heidelberg, pp. 13–18. [https://doi.org/10.1007/3-540-](https://doi.org/10.1007/3-540-26590-2_3)
765 [26590-2_3](https://doi.org/10.1007/3-540-26590-2_3)

766 Cwalina, B., 2008. Biodeterioration of concrete. *Archit. Civ. Eng. Environ.* 4, 133–140.

767 Dafforn, K.A., Glasby, T.M., Airoidi, L., Rivero, N.K., Mayer-Pinto, M., Johnston, E.L., 2015.
768 *Marine urbanization: an ecological framework for designing multifunctional artificial*
769 *structures*. *Front. Ecol. Environ.* 13, 82–90.

770 Dalod, E., Govin, A., Guyonnet, R., Grosseau, P., Lors, C., Damidot, D., 2014. t, in: Fentiman,
771 K.L., C.H.; Mangabhai, R.J.; Scrivener (Ed.), *International Conference on Calcium*
772 *Aluminates*. IHS BRE Press, Palais des Papes, Avignon, France, pp. 523–534.

773 Dang, H., Lovell, C.R., 2015. *Microbial Surface Colonization and Biofilm Development in Marine*
774 *Environments*. *Microbiol. Mol. Biol. Rev.* MMBR 80, 91–138.
775 <https://doi.org/10.1128/MMBR.00037-15>

776 Das, S., Lyla, P.S., Khan, S.A., 2006. Marine microbial diversity and ecology: importance and
777 future perspectives. *Curr. Sci.* 90, 1325–1335.

778 De Belie, N., 2010. Microorganisms versus stony materials: a love–hate relationship. *Mater. Struct.*
779 43, 1191–1202.

780 De Fommervault, O.P., 2016. *Dynamique des nutriments en Méditerranée: des campagnes*
781 *océanographiques aux flotteurs Bio-Argo*.

782 De Fraiture, C., Wichelns, D., Rockstrom, J., Kemp-Benedict, E., Eriyagama, N., Gordon, L.J.,
783 Hanjra, M.A., Hoogeveen, J., Huber-Lee, A., Karlberg, L., 2007. Looking ahead to 2050:
784 scenarios of alternative investment approaches.

785 De la Rosa, J.P.M., Warke, P.A., Smith, B.J., 2013. Lichen-induced biomodification of calcareous
786 surfaces: Bioprotection versus biodeterioration. *Prog. Phys. Geogr. Earth Environ.* 37, 325–
787 351. <https://doi.org/10.1177/0309133312467660>

788 De Weerd, K., Justnes, H., Geiker, M.R., 2014. Changes in the phase assemblage of concrete
789 exposed to sea water. *Cem. Concr. Compos., Special issue: Durability of concrete* 47, 53–
790 63. <https://doi.org/10.1016/j.cemconcomp.2013.09.015>

791 Dobretsov, S., Rittschof, D., 2020. Love at First Taste: Induction of Larval Settlement by Marine
792 Microbes. *Int. J. Mol. Sci.* 21, 731. <https://doi.org/10.3390/ijms21030731>

793 Dobretsov, S., Teplitski, M., Bayer, M., Gunasekera, S., Proksch, P., Paul, V.J., 2011. Inhibition
794 of marine biofouling by bacterial quorum sensing inhibitors. *Biofouling* 27, 893–905.
795 <https://doi.org/10.1080/08927014.2011.609616>

796 Dobretsov, S., Teplitski, M., Paul, V., 2009. Mini-review: quorum sensing in the marine
797 environment and its relationship to biofouling. *Biofouling* 25, 413–427.
798 <https://doi.org/10.1080/08927010902853516>

799 Donlan, R.M., Costerton, J.W., 2002. Biofilms: Survival Mechanisms of Clinically Relevant
800 Microorganisms. *Clin. Microbiol. Rev.* 15, 167–193.
801 <https://doi.org/10.1128/CMR.15.2.167-193.2002>

802 Doody, J.P., 2004. ‘Coastal squeeze’— an historical perspective. *J. Coast. Conserv.* 10, 129–138.
803 [https://doi.org/10.1652/1400-0350\(2004\)010\[0129:CSAHP\]2.0.CO;2](https://doi.org/10.1652/1400-0350(2004)010[0129:CSAHP]2.0.CO;2)

804 Duarte, C.M., Agusti, S., Barbier, E., Britten, G.L., Castilla, J.C., Gattuso, J.-P., Fulweiler, R.W.,
805 Hughes, T.P., Knowlton, N., Lovelock, C.E., Lotze, H.K., Predragovic, M., Poloczanska,
806 E., Roberts, C., Worm, B., 2020. Rebuilding marine life. *Nature* 580, 39–51.
807 <https://doi.org/10.1038/s41586-020-2146-7>

808 Dubosc, A., Escadeillas, G., Blanc, P.J., 2001. Characterization of biological stains on external
809 concrete walls and influence of concrete as underlying material. *Cem. Concr. Res.* 31,
810 1613–1617. [https://doi.org/10.1016/S0008-8846\(01\)00613-5](https://doi.org/10.1016/S0008-8846(01)00613-5)

811 Dunne, W.M., 2002. Bacterial Adhesion: Seen Any Good Biofilms Lately? *Clin. Microbiol. Rev.*
812 15, 155–166. <https://doi.org/10.1128/CMR.15.2.155-166.2002>

813 Dürr, S., Thomason, J.C., 2009. *Biofouling*. John Wiley & Sons.

814 Dyson, K., Yocom, K., 2015. Ecological design for urban waterfronts. *Urban. Ecosyst.* 18, 189–
815 208. <https://doi.org/10.1007/s11252-014-0385-9>

816 El-Naggar, M.Y., Wanger, G., Leung, K.M., Yuzvinsky, T.D., Southam, G., Yang, J., Lau, W.M.,
817 Neals, K.H., Gorby, Y.A., 2010. Electrical transport along bacterial nanowires from
818 *Shewanella oneidensis* MR-1. *Proc. Natl. Acad. Sci.* 107, 18127–18131.
819 <https://doi.org/10.1073/pnas.1004880107>

820 Escadeillas, G., Bertron, A., Blanc, P., Dubosc, A., 2007. Accelerated testing of biological stain
821 growth on external concrete walls. Part 1: Development of the growth tests. *Mater. Struct.*
822 40, 1061–1071. <https://doi.org/10.1617/s11527-006-9205-x>

823 Escadeillas, G., Bertron, A., Ringot, E., Blanc, P.J., Dubosc, A., 2008. Accelerated testing of
824 biological stain growth on external concrete walls. Part 2: Quantification of growths. *Mater.*
825 *Struct.* 42, 937. <https://doi.org/10.1617/s11527-008-9433-3>

826 Evans, K., Bax, N., Bernal, P., Corrales, M.B., Cryer, M., Forsterra, G., Gaymer, C.F.,
827 Haussermann, V., Rice, J., 2016. D. South Pacific Ocean.

828 Evans, K., Bax, N.J., Smith, D.C., 2018. Enhancing the robustness of a national assessment of the
829 marine environment. *Mar. Policy* 98, 133–145.
830 <https://doi.org/10.1016/j.marpol.2018.08.011>

831 Färber, C., Wisshak, M., Pyko, I., Bellou, N., Freiwald, A., 2015. Effects of Water Depth, Seasonal
832 Exposure, and Substrate Orientation on Microbial Bioerosion in the Ionian Sea (Eastern
833 Mediterranean). *PLOS ONE* 10, e0126495. <https://doi.org/10.1371/journal.pone.0126495>

834 Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C., Airoidi, L., 2014. The
835 effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nat. Commun.*
836 5, 3794. <https://doi.org/10.1038/ncomms4794>

837 Ferrero, M.-A., 2018. Colonisation et biodétérioration des bétons en milieu marin : mise au point
838 d'essais en laboratoire et influence de la composition chimique du matériau cimentaire
839 (phdthesis). Normandie Université.

840 Firth, L.B., Airoidi, L., Bulleri, F., Challinor, S., Chee, S.-Y., Evans, A.J., Hanley, M.E., Knights,
841 A.M., O'Shaughnessy, K., Thompson, R.C., Hawkins, S.J., 2020. Greening of grey
842 infrastructure should not be used as a Trojan horse to facilitate coastal development. *J.*
843 *Appl. Ecol.* 57, 1762–1768. <https://doi.org/10.1111/1365-2664.13683>

844 Firth, L.B., Thompson, R.C., Bohn, K., Abbiati, M., Airoidi, L., Bouma, T.J., Bozzeda, F.,
845 Ceccherelli, V.U., Colangelo, M.A., Evans, A., Ferrario, F., Hanley, M.E., Hinz, H.,
846 Hoggart, S.P.G., Jackson, J.E., Moore, P., Morgan, E.H., Perkol-Finkel, S., Skov, M.W.,
847 Strain, E.M., van Belzen, J., Hawkins, S.J., 2014. Between a rock and a hard place:
848 Environmental and engineering considerations when designing coastal defence structures.
849 *Coast. Eng., Coasts@Risks: THESEUS, a new wave in coastal protection* 87, 122–135.
850 <https://doi.org/10.1016/j.coastaleng.2013.10.015>

851 Fitzhardinge, R.C., Bailey-Brock, J.H., 1989. Colonization of artificial reef materials by coral and
852 other sessile organisms. *Bull. Mar. Sci.* 44, 567–579.

- 853 Gaylarde, C.C., Gaylarde, P.M., 2005. A comparative study of the major microbial biomass of
854 biofilms on exteriors of buildings in Europe and Latin America. *Int. Biodeterior. Biodegrad.*
855 55, 131–139. <https://doi.org/10.1016/j.ibiod.2004.10.001>
- 856 Georges, M., Bourguiba, A., Chateigner, D., Sebaibi, N., Boutouil, M., 2021. The study of long-
857 term durability and bio-colonization of concrete in marine environment. *Environ. Sustain.*
858 *Indic.* 10, 100120. <https://doi.org/10.1016/j.indic.2021.100120>
- 859 Giannantonio, D.J., Kurth, J.C., Kurtis, K.E., Sobecky, P.A., 2009. Effects of concrete properties
860 and nutrients on fungal colonization and fouling. *Int. Biodeterior. Biodegrad.* 63, 252–259.
861 <https://doi.org/10.1016/j.ibiod.2008.10.002>
- 862 Giraudel, C., Garcia, N., Ledoux, S., 2014. Single-layer breakwater armouring : feedback on the
863 accropode™ technology from site experience., in: *Coastal Engineering 2014*. pp. 1–15.
- 864 Gong, J., Song, W., Warren, A., 2005. Periphytic ciliate colonization: annual cycle and responses
865 to environmental conditions. *Aquat. Microb. Ecol.* 39, 159–170.
866 <https://doi.org/10.3354/ame039159>
- 867 González-Figueredo, C., Flores-Estrella, R.A., Rojas-Rejón, O.A., 2018. Fermentation:
868 Metabolism, Kinetic Models, and Bioprocessing. *Curr. Top. Biochem. Eng.*
869 <https://doi.org/10.5772/intechopen.82195>
- 870 Govin, A., Tran, T.H., Guyonnet, R., Grosseau, P., Lors, C., Damidot, D., Devès, O., Ruot, B.,
871 2013. Ability in biofouling by *Klebsormidium flaccidum* of mortars: Influence of the
872 intrinsic characteristics. *First Int. Conf. Concr. Sustain. ICCS S3-3-6* pp. 914–919.
- 873 Gowell, M.R., Coombes, M.A., Viles, H.A., 2015. Rock-protecting seaweed? Experimental
874 evidence of bioprotection in the intertidal zone. *Earth Surf. Process. Landf.* 40, 1364–1370.
875 <https://doi.org/10.1002/esp.3736>
- 876 Grosseau, P., Dalod, E., Govin, A., Lors, C., Guyonnet, R., Damidot, D., 2015. Effect of the
877 Chemical Composition of Building Materials on Algal Biofouling.
- 878 Guillitte, O., 1995. Bioreceptivity: a new concept for building ecology studies. *Sci. Total Environ.*,
879 *The Deterioration of Monuments* 167, 215–220. [https://doi.org/10.1016/0048-](https://doi.org/10.1016/0048-9697(95)04582-L)
880 [9697\(95\)04582-L](https://doi.org/10.1016/0048-9697(95)04582-L)
- 881 Guillitte, O., Dreesen, R., 1995. Laboratory chamber studies and petrographical analysis as
882 bioreceptivity assessment tools of building materials. *Sci. Total Environ.*, *The Deterioration*
883 *of Monuments* 167, 365–374. [https://doi.org/10.1016/0048-9697\(95\)04596-S](https://doi.org/10.1016/0048-9697(95)04596-S)
- 884 Guillonneau, R., Baraquet, C., Bazire, A., Molmeret, M., 2018. Multispecies Biofilm Development
885 of Marine Bacteria Implies Complex Relationships Through Competition and Synergy and
886 Modification of Matrix Components. *Front. Microbiol.* 9, 1960.
887 <https://doi.org/10.3389/fmicb.2018.01960>
- 888 Ha, D.-G., O’Toole, G.A., 2015. c-di-GMP and its Effects on Biofilm Formation and Dispersion:
889 a *Pseudomonas Aeruginosa* Review. *Microbiol. Spectr.* 3, MB-0003-2014.
890 <https://doi.org/10.1128/microbiolspec.MB-0003-2014>
- 891 Harper, K.T., Pendleton, R.L., 1993. CYANOBACTERIA AND CYANOLICHENS: CAN THEY
892 ENHANCE AVAILABILITY OF ESSENTIAL MINERALS FOR HIGHER PLANTS?
893 *Gt. Basin Nat.* 53, 59–72.
- 894 Harshada, M.K., Desai, P.M.M., Gupta, D.A.K., 2017. Deterioration of Concrete in Marine
895 Structure.
- 896 Hau, H.H., Gralnick, J.A., 2007. Ecology and Biotechnology of the Genus *Shewanella*. *Annu. Rev.*
897 *Microbiol.* 61, 237–258. <https://doi.org/10.1146/annurev.micro.61.080706.093257>

898 Hayek, M., Baraquet, C., Lami, R., Blache, Y., Molmeret, M., 2019. The Marine Bacterium
899 *Shewanella woodyi* Produces C8-HSL to Regulate Bioluminescence. *Microb. Ecol.*
900 <https://doi.org/10.1007/s00248-019-01454-z>

901 Hayek, M., Salgues, M., Habouzit, F., Bayle, S., Souche, J.-C., De Weerd, K., Pioch, S., 2020a.
902 In vitro and in situ tests to evaluate the bacterial colonization of cementitious materials in
903 the marine environment. *Cem. Concr. Compos.* 113, 103748.
904 <https://doi.org/10.1016/j.cemconcomp.2020.103748>

905 Hayek, M., Salgues, M., Habouzit, F., Bayle, S., Souche, J.-C., Weerd, K.D., Pioch, S., 2020b.
906 L'influence de la carbonatation sur la biocolonisation de matériaux cimentaires dans le
907 milieu marin. *Matér. Tech.* 108, 202. <https://doi.org/10.1051/mattech/2020020>

908 Hayek, M., Salgues, M., Souche, J.-C., Cunge, E., Giraudel, C., Paireau, O., 2021. Influence of the
909 Intrinsic Characteristics of Cementitious Materials on Biofouling in the Marine
910 Environment. *Sustainability* 13, 2625. <https://doi.org/10.3390/su13052625>

911 Herrmann, M., Vaudaux, P.E., Pittet, D., Auckenthaler, R., Lew, P.D., Schumacher-Perdreau, F.,
912 Peters, G., Waldvogel, F.A., 1988. Fibronectin, fibrinogen, and laminin act as mediators of
913 adherence of clinical staphylococcal isolates to foreign material. *J. Infect. Dis.* 158, 693–
914 701.

915 Hins, S.M., O'Toole, G.A., 2006. Biofilm formation by *Pseudomonas fluorescens* WCS365: a
916 role for LapD. *Microbiol. Read. Engl.* 152, 1375–1383.
917 <https://doi.org/10.1099/mic.0.28696-0>

918 Hosseinzadeh, N., Ghiasian, M., Andiroglu, E., Lamere, J., Rhode-Barbarigos, L., Sobczak, J.,
919 Sullivan-Sealey, K., Suraneni, P., 2022. Concrete seawalls: A review of load
920 considerations, ecological performance, durability, and recent innovations. *Ecol. Eng.* 178,
921 106573. <https://doi.org/10.1016/j.ecoleng.2022.106573>

922 Huggett, M.J., Nedved, B.T., Hadfield, M.G., 2009. Effects of initial surface wettability on biofilm
923 formation and subsequent settlement of *Hydroides elegans*. *Biofouling* 25, 387–399.
924 <https://doi.org/10.1080/08927010902823238>

925 Huston, A.L., Krieger-Brockett, B.B., Deming, J.W., 2000. Remarkably low temperature optima
926 for extracellular enzyme activity from Arctic bacteria and sea ice. *Environ. Microbiol.* 2,
927 383–388. <https://doi.org/10.1046/j.1462-2920.2000.00118.x>

928 Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J.,
929 Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., Hughes, T.P., Kidwell, S., Lange,
930 C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H., Steneck, R.S., Tegner, M.J., Warner,
931 R.R., 2001. Historical Overfishing and the Recent Collapse of Coastal Ecosystems. *Science*
932 293, 629–637. <https://doi.org/10.1126/science.1059199>

933 Jakobsen, U.H., De Weerd, K., Geiker, M.R., 2016. Elemental zonation in marine concrete. *Cem.*
934 *Concr. Res.* 85, 12–27. <https://doi.org/10.1016/j.cemconres.2016.02.006>

935 Joshi, S., Goyal, S., Reddy, M.S., 2018. Influence of nutrient components of media on structural
936 properties of concrete during biocementation. *Constr. Build. Mater.* 158, 601–613.
937 <https://doi.org/10.1016/j.conbuildmat.2017.10.055>

938 Kaplan, J.B., 2010. Biofilm dispersal: mechanisms, clinical implications, and potential therapeutic
939 uses. *J. Dent. Res.* 89, 205–218. <https://doi.org/10.1177/0022034509359403>

940 Karunasagar, I., Ota, S.K., Karunasagar, I., Indrani, K., 1996. Biofilm formation by *Vibrio harveyi*
941 on surfaces.

942 Katsikogianni, M., Missirlis, Y., 2004. Concise review of mechanisms of bacterial adhesion to
943 biomaterials and of techniques used in estimating bacteria-material interactions. *Eur. Cell.*
944 *Mater.* 8, 37–57. <https://doi.org/10.22203/eCM.v008a05>

945 Koraim, A.S., 2013. Hydrodynamic efficiency of suspended horizontal rows of half pipes used as
946 a new type breakwater. *Ocean. Eng.* 64, 1–22.
947 <https://doi.org/10.1016/j.oceaneng.2013.02.008>

948 Krumbein, W.E., 1979. Photolithotropic and chemoorganotrophic activity of bacteria and algae as
949 related to beachrock formation and degradation (gulf of Aqaba, Sinai). *Geomicrobiol. J.* 1,
950 139–203. <https://doi.org/10.1080/01490457909377729>

951 La Marca, E.C., Coombes, M.A., Viles, H.A., Naylor, L.A., 2014. THE BIO-PROTECTIVE ROLE
952 OF A BIOLOGICAL ENCRUSTATION. *Biol. Mar. Mediterr.* 21, 345.

953 Lacroix, D., Pioch, S., 2011. The multi-use in wind farm projects: more conflicts or a win-win
954 opportunity? *Aquat Living Resour EDP Sci.* 24, 129–135.
955 <https://doi.org/10.1051/alr/2011135>

956 Lawrence, J.R., Scharf, B., Packroff, G., Neu, T.R., 2002. Microscale evaluation of the effects of
957 grazing by invertebrates with contrasting feeding modes on river biofilm architecture and
958 composition. *Microb. Ecol.* 44, 199–207. <https://doi.org/10.1007/s00248-001-1064-y>

959 Leclerc, H., 1975. Microbiologie générale, in: *Microbiologie Generale*. Doin.

960 Lee, H.S., Sidharthan, M., Shim, C.S., Do Kim, Y., Lim, C.Y., Ko, J.W., Han, M.D., Rang, M.J.,
961 Bim, L.S., Cho, H.S., 2008. Screening and formulation of chemoattractant coatings for
962 artificial reef structures. *J. Environ. Biol.* 29, 605–612.

963 Loeb, G.I., Neihof, R.A., 1975. Marine conditioning films.

964 Lors, C., Feugeas, F., Tribollet, B., 2019. Interactions Materials - Microorganisms: Concrete and
965 Metals more Resistant to Biodeterioration. *EDP sciences*.

966 Lueangthuwapanit, C., Sampantarak, U., Wongsai, S., 2011. Distribution and Abundance of
967 Phytoplankton: Influence of Salinity and Turbidity Gradients in the Na Thap River,
968 Songkhla Province, Thailand. *J. Coast. Res.* 27, 585–594.
969 <https://doi.org/10.2112/JCOASTRES-D-10-00123.1>

970 Ly, O., Yoris-Nobile, A.I., Sebaibi, N., Blanco-Fernandez, E., Boutouil, M., Castro-Fresno, D.,
971 Hall, A.E., Herbert, R.J.H., Deboucha, W., Reis, B., Franco, J.N., Teresa Borges, M.,
972 Sousa-Pinto, I., van der Linden, P., Stafford, R., 2021. Optimisation of 3D printed concrete
973 for artificial reefs: Biofouling and mechanical analysis. *Constr. Build. Mater.* 272, 121649.
974 <https://doi.org/10.1016/j.conbuildmat.2020.121649>

975 Makemson, J.C., Fulayfil, N.R., Landry, W., Van Ert, L.M., Wimpee, C.F., Widder, E.A., Case,
976 J.F., 1997. *Shewanella woodyi* sp. nov., an Exclusively Respiratory Luminous Bacterium
977 Isolated from the Alboran Sea. *Int. J. Syst. Evol. Microbiol.* 47, 1034–1039.
978 <https://doi.org/10.1099/00207713-47-4-1034>

979 Manso, S., Aguado, A., 2017. A review of sample preparation and its influence on pH
980 determination in concrete samples. *Mater. Constr.* 67, 108.
981 <https://doi.org/10.3989/mc.2017.08515>

982 Manso, S., Aguado, A., 2016. The use of bio-receptive concrete as a new typology of living wall
983 systems. *Matér. Tech.* 104, 502. <https://doi.org/10.1051/mattech/2016028>

984 Manso, S., Calvo-Torras, M.Á., De Belie, N., Segura, I., Aguado, A., 2015. Evaluation of natural
985 colonisation of cementitious materials: Effect of bioreceptivity and environmental
986 conditions. *Sci. Total Environ.* 512–513, 444–453.
987 <https://doi.org/10.1016/j.scitotenv.2015.01.086>

988 Manso, S., De Muynck, W., Segura, I., Aguado, A., Steppe, K., Boon, N., De Belie, N., 2014.
989 Bioreceptivity evaluation of cementitious materials designed to stimulate biological
990 growth. *Sci. Total Environ.* 481, 232–241. <https://doi.org/10.1016/j.scitotenv.2014.02.059>
991 Martins, G.M., Thompson, R.C., Neto, A.I., Hawkins, S.J., Jenkins, S.R., 2010. Enhancing stocks
992 of the exploited limpet *Patella candei* d'Orbigny via modifications in coastal engineering.
993 *Biol. Conserv.* 143, 203–211. <https://doi.org/10.1016/j.biocon.2009.10.004>
994 McManus, R.S., Archibald, N., Comber, S., Knights, A.M., Thompson, R.C., Firth, L.B., 2018.
995 Partial replacement of cement for waste aggregates in concrete coastal and marine
996 infrastructure: A foundation for ecological enhancement? *Ecol. Eng.* 120, 655–667.
997 <https://doi.org/10.1016/j.ecoleng.2017.06.062>
998 Meijer, J.R., Huijbregts, M.A.J., Schotten, K.C.G.J., Schipper, A.M., 2018. Global patterns of
999 current and future road infrastructure. *Environ. Res. Lett.* 13, 064006.
1000 <https://doi.org/10.1088/1748-9326/aabd42>
1001 Meng, H., Zhang, X., Katayama, Y., Ge, Q., Gu, J.-D., 2020. Microbial diversity and composition
1002 of the Preah Vihear temple in Cambodia by high-throughput sequencing based on genomic
1003 DNA and RNA. *Int. Biodeterior. Biodegrad.* 149, 104936.
1004 <https://doi.org/10.1016/j.ibiod.2020.104936>
1005 Mesquita, M.C.B., Prestes, A.C.C., Gomes, A.M.A., Marinho, M.M., 2020. Direct Effects of
1006 Temperature on Growth of Different Tropical Phytoplankton Species. *Microb. Ecol.* 79, 1–
1007 11. <https://doi.org/10.1007/s00248-019-01384-w>
1008 Mieszkin, S., Callow, M.E., Callow, J.A., 2013. Interactions between microbial biofilms and
1009 marine fouling algae: a mini review. *Biofouling* 29, 1097–1113.
1010 <https://doi.org/10.1080/08927014.2013.828712>
1011 Miller, A.Z., Dionísio, A., Laiz, L., Macedo, M.F., Saiz-Jimenez, C., 2009. The influence of
1012 inherent properties of building limestones on their bioreceptivity to phototrophic
1013 microorganisms. *Ann. Microbiol.* 59, 705–713. <https://doi.org/10.1007/BF03179212>
1014 Miller, A.Z., Sanmartín, P., Pereira-Pardo, L., Dionísio, A., Saiz-Jimenez, C., Macedo, M.F.,
1015 Prieto, B., 2012. Bioreceptivity of building stones: A review. *Sci. Total Environ.* 426, 1–
1016 12. <https://doi.org/10.1016/j.scitotenv.2012.03.026>
1017 Mireille Ayé, A., Bonnín-Jusserand, M., Brian-Jaisson, F., Ortaño-Magné, A., Culioli, G., Koffi
1018 Nevry, R., Rabah, N., Blache, Y., Molmeret, M., 2015. Modulation of violacein production
1019 and phenotypes associated with biofilm by exogenous quorum sensing N-acylhomoserine
1020 lactones in the marine bacterium *Pseudoalteromonas ulvae* TC14. *Microbiology*, 161,
1021 2039–2051. <https://doi.org/10.1099/mic.0.000147>
1022 Mottershead, D., Lucas, G., 2000. THE ROLE OF LICHENS IN INHIBITING EROSION OF A
1023 SOLUBLE ROCK. *The Lichenologist* 32, 601–609. <https://doi.org/10.1006/lich.2000.0300>
1024 Naylor, L., Coombes, M.A., 2015. Bioprotection: working with nature to manage coastal hazards.
1025 *Geogr. Rev.* 28, 37–41.
1026 Nedwell, D.B., 1999. Effect of low temperature on microbial growth: lowered affinity for
1027 substrates limits growth at low temperature. *FEMS Microbiol. Ecol.* 30, 101–111.
1028 <https://doi.org/10.1111/j.1574-6941.1999.tb00639.x>
1029 Nuhoglu, Y., Oguz, E., Uslu, H., Ozbek, A., Ipekoglu, B., Ocak, I., Hasenekoglu, I., 2006. The
1030 accelerating effects of the microorganisms on biodeterioration of stone monuments under
1031 air pollution and continental-cold climatic conditions in Erzurum, Turkey. *Sci. Total*
1032 *Environ.* 364, 272–283. <https://doi.org/10.1016/j.scitotenv.2005.06.034>

- 1033 Ogunola, O.S., Onada, O.A., 2016. Anti-Biofouling Defence Mechanism of Basibionts (A
1034 Chemical Warfare) - A Critical Review. *J. Environ. Anal. Toxicol.* 6, 1–6.
1035 <https://doi.org/10.4172/2161-0525.1000380>
- 1036 O’Toole, G., Kaplan, H.B., Kolter, R., 2000. Biofilm formation as microbial development. *Annu.*
1037 *Rev. Microbiol.* 54, 49–79. <https://doi.org/10.1146/annurev.micro.54.1.49>
- 1038 Ottel , M., Perini, K., Fraaij, A.L.A., Haas, E.M., Raiteri, R., 2011. Comparative life cycle analysis
1039 for green faades and living wall systems. *Energy Build.* 43, 3419–3429.
1040 <https://doi.org/10.1016/j.enbuild.2011.09.010>
- 1041 Parker, C.D., 1945. The corrosion of concrete: 1. The isolation of a species of bacterium associated
1042 with the corrosion of concrete exposed to atmospheres containing hydrogen sulphide. *Aust.*
1043 *J. Exp. Biol. Med. Sci.* 23, 81–90.
- 1044 Pasmore, M., Costerton, J.W., 2003. Biofilms, bacterial signaling, and their ties to marine biology.
1045 *J. Ind. Microbiol. Biotechnol.* 30, 407–413. <https://doi.org/10.1007/s10295-003-0069-6>
- 1046 Patil, B.T., Gajendragad, M.R., Ranganna, G., Wagh, A.B., Sudhakaran, T., 1994. Impact of
1047 biofouling on corrosion resistance of reinforced concrete.
- 1048 Patranella, A., Kilfoyle, K., Pioch, S., Spieler, R.E., 2017. Artificial reefs as juvenile fish habitat
1049 in a marina. *J. Coast. Res.* 33, 1341–1351.
- 1050 Perini, K., Ottel , M., 2014. Designing green faades and living wall systems for sustainable
1051 constructions. *Int. J. Des. Nat. Ecodynamics* 9, 31–46. [https://doi.org/10.2495/DNE-V9-](https://doi.org/10.2495/DNE-V9-N1-31-46)
1052 [N1-31-46](https://doi.org/10.2495/DNE-V9-N1-31-46)
- 1053 Perkol-Finkel, S., Hadary, T., Rella, A., Shirazi, R., Sella, I., 2018. Seascape architecture –
1054 incorporating ecological considerations in design of coastal and marine infrastructure. *Ecol.*
1055 *Eng.* 120, 645–654. <https://doi.org/10.1016/j.ecoleng.2017.06.051>
- 1056 Perkol-Finkel, S., Sella, I., 2014. Ecologically Active Concrete for Coastal and Marine
1057 Infrastructure: Innovative Matrices and Designs, in: *From Sea to Shore? Meeting the*
1058 *Challenges of the Sea.* ICE Publishing, pp. 1139–1149.
1059 <https://doi.org/10.1680/fsts.59757.124>
- 1060 Phan, L.K., van Thiel de Vries, J.S.M., Stive, M.J.F., 2015. Coastal Mangrove Squeeze in the
1061 Mekong Delta. *J. Coast. Res.* 31, 233–243. [https://doi.org/10.2112/JCOASTRES-D-14-](https://doi.org/10.2112/JCOASTRES-D-14-00049.1)
1062 [00049.1](https://doi.org/10.2112/JCOASTRES-D-14-00049.1)
- 1063 Pioch, S., Kilfoyle, K., Levrel, H., Spieler, R., 2011. Green Marine Construction. *J. Coast. Res.* 61,
1064 257–268. <https://doi.org/10.2112/SI61-001.1>
- 1065 Pioch, S., Relini, G., Souche, J.C., Stive, M.J.F., De Monbrison, D., Nassif, S., Simard, F.,
1066 Allemand, D., Saussol, P., Spieler, R., Kilfoyle, K., 2018. Enhancing eco-engineering of
1067 coastal infrastructure with eco-design: Moving from mitigation to integration. *Ecol. Eng.*
1068 120, 574–584. <https://doi.org/10.1016/j.ecoleng.2018.05.034>
- 1069 Pioch, S., Souche, J.-C., 2021. L’ coconception des infrastructures maritimes: vers un
1070 am nagement int gr    l’environnement. ISTE Group.
- 1071 Poli, A., Finore, I., Romano, I., Gioiello, A., Lama, L., Nicolaus, B., 2017. Microbial Diversity in
1072 Extreme Marine Habitats and Their Biomolecules. *Microorganisms* 5.
1073 <https://doi.org/10.3390/microorganisms5020025>
- 1074 Poonguzhali, A., Shaikh, H., Dayal, R.K., Khatak, H.S., 2008. A Review on Degradation
1075 Mechanism and Life Estimation of Civil Structures. *Corros. Rev.* 26, 215–294.
1076 <https://doi.org/10.1515/corrrev.2008.215>

- 1077 Qvarfordt, S., Kautsky, H., Malm, T., 2006. Development of fouling communities on vertical
1078 structures in the Baltic Sea. *Estuar. Coast. Shelf Sci.* 67, 618–628.
1079 <https://doi.org/10.1016/j.ecss.2006.01.004>
- 1080 Rajitha, K., Nancharaiah, Y.V., Venugopalan, V.P., 2020. Role of bacterial biofilms and their EPS
1081 on settlement of barnacle (*Amphibalanus reticulatus*) larvae. *Int. Biodeterior. Biodegrad.*
1082 150, 104958. <https://doi.org/10.1016/j.ibiod.2020.104958>
- 1083 Razavi, S.M.R., Oh, J., Haasch, R.T., Kim, K., Masoomi, M., Bagheri, R., Slauch, J.M., Miljkovic,
1084 N., 2019. Environment-Friendly Antibiofouling Superhydrophobic Coatings. *ACS Sustain.*
1085 *Chem. Eng.* 7, 14509–14520. <https://doi.org/10.1021/acssuschemeng.9b02025>
- 1086 Relini, G., Tixi, F., Relini, M., Torchia, G., 1998. The macrofouling on offshore platforms at
1087 Ravenna. *Int. Biodeterior. Biodegrad.* 41, 41–55. [https://doi.org/10.1016/S0964-](https://doi.org/10.1016/S0964-8305(98)80007-3)
1088 [8305\(98\)80007-3](https://doi.org/10.1016/S0964-8305(98)80007-3)
- 1089 Rica, H.C., Boutouil, M., Boudart, B., Claquin, P., Leroy, F., 2016. Colonisation et détérioration
1090 des bétons incorporant des coquilles pour récifs artificiels. *Matér. Tech.* 104, 503.
- 1091 Rindi, F., Guiry, M.D., López-Bautista, J.M., 2008. Distribution, morphology, and phylogeny of
1092 klebsormidium (*Klebsormidiales*, Charophyceae) in urban environments in europe 1. *J.*
1093 *Phycol.* 44, 1529–1540.
- 1094 Risinger, J., 2012. Biologically dominated engineered coastal breakwaters. LSU Dr. Diss.
- 1095 Robert, R., Chretiennot-Dinet, M.-J., Kaas, R., Martin-Jezequel, V., Moal, J., Le Coz, J.-R.,
1096 Nicolas, J.-L., Bernard, E., Connan, J.-P., Le Dean, L., 2004. Amélioration des productions
1097 phytoplanctoniques en éclosérie de mollusques: caractérisation des microalgues fourrage.
- 1098 Roberts, D.J., Nica, D., Zuo, G., Davis, J.L., 2002. Quantifying microbially induced deterioration
1099 of concrete: initial studies. *Int. Biodeterior. Biodegrad., Biodet.of Constr. Materials* 49,
1100 227–234. [https://doi.org/10.1016/S0964-8305\(02\)00049-5](https://doi.org/10.1016/S0964-8305(02)00049-5)
- 1101 Robinson, P.K., 2015. Enzymes: principles and biotechnological applications. *Essays Biochem.*
1102 59, 1–41. <https://doi.org/10.1042/bse0590001>
- 1103 Romani, M., Carrion, C., Fernandez, F., Intertaglia, L., Pecqueur, D., Lebaron, P., Lami, R., 2019.
1104 High bacterial diversity in pioneer biofilms colonizing ceramic roof tiles. *Int. Biodeterior.*
1105 *Biodegrad.* 144, 104745. <https://doi.org/10.1016/j.ibiod.2019.104745>
- 1106 Salta, M., Wharton, J.A., Blache, Y., Stokes, K.R., Briand, J.-F., 2013. Marine biofilms on artificial
1107 surfaces: structure and dynamics. *Environ. Microbiol.* 15, 2879–2893.
1108 <https://doi.org/10.1111/1462-2920.12186>
- 1109 Scatigno, C., Moricca, C., Tortolini, C., Favero, G., 2016. The influence of environmental
1110 parameters in the biocolonization of the Mithraeum in the roman masonry of casa di Diana
1111 (Ostia Antica, Italy). *Environ. Sci. Pollut. Res.* 23, 13403–13412.
1112 <https://doi.org/10.1007/s11356-016-6548-x>
- 1113 Scheres, B., Schüttrumpf, H., 2019. Enhancing the Ecological Value of Sea Dikes. *Water* 11, 1617.
1114 <https://doi.org/10.3390/w11081617>
- 1115 Scheuerman, T.R., Camper, A.K., Hamilton, M.A., 1998. Effects of Substratum Topography on
1116 Bacterial Adhesion. *J. Colloid Interface Sci.* 208, 23–33.
1117 <https://doi.org/10.1006/jcis.1998.5717>
- 1118 Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and
1119 direct impacts on biodiversity and carbon pools. *Proc. Natl. Acad. Sci.* 109, 16083–16088.
1120 <https://doi.org/10.1073/pnas.1211658109>
- 1121 Shearer, C.A., Descals, E., Kohlmeyer, B., Kohlmeyer, J., Marvanová, L., Padgett, D., Porter, D.,
1122 Raja, H.A., Schmit, J.P., Thornton, H.A., Voglymayr, H., 2007. Fungal biodiversity in

1123 aquatic habitats. *Biodivers. Conserv.* 16, 49–67. <https://doi.org/10.1007/s10531-006-9120->
1124 z

1125 Sheehan, P.M., 2001. History of marine biodiversity. *Geol. J.* 36, 231–249.
1126 <https://doi.org/10.1002/gj.890>

1127 Shehadul Islam, M., Aryasomayajula, A., Selvaganapathy, P.R., 2017. A Review on Macroscale
1128 and Microscale Cell Lysis Methods. *Micromachines* 8. <https://doi.org/10.3390/mi8030083>

1129 Sherman, R.L., Gilliam, D.S., Spieler, R.E., 2001. Site-dependent differences in artificial reef
1130 function: implications for coral reef restoration. *Bull. Mar. Sci.* 69, 5.

1131 Shi, X., Zhu, X., 2009. Biofilm formation and food safety in food industries. *Trends Food Sci.*
1132 *Technol., Natural and Safe Foods* 20, 407–413. <https://doi.org/10.1016/j.tifs.2009.01.054>

1133 Shukla Jang, B., Maninder, S., Arora Maitri, V., Arvind, M., Yasuhiro, T., 2021. The Impact of
1134 Sea Level Rise Due to Global Warming on the Coastal Population Dynamics: A Modeling
1135 Study. *Earth Systems and Environment.* 5, 909–926. <https://doi.org/10.1007/s41748-021->
1136 00246-1

1137 Silva, M.R., Naik, T.R., 2013. Biodeterioration of Concrete Structures in Coastal Zone. p. 8.

1138 Soleimani, S., Ormeci, B., Isgor, O.B., 2013. Growth and characterization of *Escherichia coli*
1139 DH5 α biofilm on concrete surfaces as a protective layer against microbiologically
1140 influenced concrete deterioration (MICD). *Appl. Microbiol. Biotechnol.* 97, 1093–1102.

1141 Somsueb, S., Ohno, M., Kimura, H., 2001. Development of seaweed communities on suspended
1142 substrata with three slope angles. *J. Appl. Phycol.* 13, 109–115.
1143 <https://doi.org/10.1023/A:1011180527959>

1144 Sosa, M., Pérez-López, T., Reyes, J., Corvo, F., Camacho-Chab, R., Quintana, P., Aguilar, D.,
1145 2011. Influence of the Marine Environment on Reinforced Concrete Degradation
1146 Depending on Exposure Conditions. *Int J Electrochem Sci* 6, 19.

1147 Souche, J.-C., Le Saout, G., Salgues, M., Pioch, S., 2016. Effets de bétons bio-actifs sur la
1148 colonisation marine en environnement méditerranéen. *Matér. Tech.* 104, 504.

1149 Souche, J.-C., Pioch, S., Salgues, M., Ienny, P., Le Saoût, G., 2018. interaction des ouvrages avec
1150 leur environnement. le milieu maritime, collection. ed. Paris.

1151 Souche, J.-C., Pioch, S., Salgues, M., Weerdt, K.D., Agostini, A., Hayek, M., 2019. De la
1152 conception à l'éco-conception des ouvrages maritimes: intégrer la nature au projet
1153 d'aménagement maritime. *Rev. Paralia* 12. <https://doi.org/10.5150/revue-paralia.2019.n01>

1154 Speranza, G., Gottardi, G., Pederzoli, C., Lunelli, L., Canteri, R., Pasquardini, L., Carli, E., Lui,
1155 A., Maniglio, D., Brugnara, M., Anderle, M., 2004. Role of chemical interactions in
1156 bacterial adhesion to polymer surfaces. *Biomaterials* 25, 2029–2037.

1157 Subashchandrabose, S.R., Ramakrishnan, B., Megharaj, M., Venkateswarlu, K., Naidu, R., 2011.
1158 Consortia of cyanobacteria/microalgae and bacteria: Biotechnological potential.
1159 *Biotechnol. Adv.* 29, 896–907. <https://doi.org/10.1016/j.biotechadv.2011.07.009>

1160 Tang, H., Wang, A., Liang, X., Cao, T., Salley, S.O., McAllister, J.P., Ng, K.Y.S., 2006. Effect of
1161 surface proteins on *Staphylococcus Epidermidis* adhesion and colonization on silicone.
1162 *Colloids Surf. B Biointerfaces* 51, 16–24. <https://doi.org/10.1016/j.colsurfb.2006.04.011>

1163 Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013.
1164 Ecosystem-based coastal defence in the face of global change. *Nature* 504, 79–83.
1165 <https://doi.org/10.1038/nature12859>

1166 Tomaselli, L., Lamenti, G., Bosco, M., Tiano, P., 2000. Biodiversity of photosynthetic micro-
1167 organisms dwelling on stone monuments. *Int. Biodeterior. Biodegrad.* 46, 251–258.

- 1168 Tran, T.H., 2011. Influence of the intrinsic characteristics of a mortar on its ability to resist to the
1169 biofouling (Theses). Ecole Nationale Supérieure des Mines de Saint-Etienne.
- 1170 Tran, T.H., Govin, A., Guyonnet, R., Grosseau, P., Lors, C., Damidot, D., Devès, O., Ruot, B.,
1171 2014. Influence of the intrinsic characteristics of mortars on their biofouling by pigmented
1172 organisms: Comparison between laboratory and field-scale experiments. *Int. Biodeterior.*
1173 *Biodegrad.* 86, 334–342. <https://doi.org/10.1016/j.ibiod.2013.10.005>
- 1174 Tran, T.H., Govin, A., Guyonnet, R., Grosseau, P., Lors, C., Garcia-Diaz, E., Damidot, D., Devès,
1175 O., Ruot, B., 2012. Influence of the intrinsic characteristics of mortars on biofouling by
1176 *Klebsormidium flaccidum*, in: *International Biodeterioration & Biodegradation*. pp. 31–39.
1177 <https://doi.org/doi.org/10.1016/j.ibiod.2011.10.017>
- 1178 Valipour, M., Sayed M.B., Changhyun, J., 2021. Global Surface Temperature: A New Insight.
1179 *Climate*, 9. <https://doi.org/10.3390/cli9050081>
- 1180 van Loosdrecht, M.C.M., Lyklema, J., Norde, W., Zehnder, A.J.B., 1989. Bacterial adhesion: A
1181 physicochemical approach. *Microb. Ecol.* 17, 1–15. <https://doi.org/10.1007/BF02025589>
- 1182 Vavrenyuk, S.V., Efimenko, Y.V., Vavrenyuk, V.G., 2020. On Standard Requirements to Cement
1183 for Concrete Used in Marine Environment. *IOP Conf. Ser. Mater. Sci. Eng.* 753, 022040.
1184 <https://doi.org/10.1088/1757-899X/753/2/022040>
- 1185 Vaz-Pinto, F., Torrontegi, O., Prestes, A.C.L., Alvaro, N. V., Neto, A.I., Martins, G.M., 2014.
1186 Invasion success and development of benthic assemblages: Effect of timing, duration of
1187 submersion and substrate type. *Mar. Environ. Res.* 94, 72–79.
1188 <https://doi.org/10.1016/j.marenvres.2013.12.007>
- 1189 Veeger, M., Otelé, M., Prieto, A., 2021. Making bioreceptive concrete: Formulation and testing
1190 of bioreceptive concrete mixtures. *J. Build. Eng.* 44, 102545.
1191 <https://doi.org/10.1016/j.jobbe.2021.102545>
- 1192 Viles, H.A., Cutler, N.A., 2012. Global environmental change and the biology of heritage
1193 structures. *Glob. Change Biol.* 18, 2406–2418. <https://doi.org/10.1111/j.1365-2486.2012.02713.x>
- 1195 Vincke, E., Boon, N., Verstraete, W., 2001. Analysis of the microbial communities on corroded
1196 concrete sewer pipes--a case study. *Appl. Microbiol. Biotechnol.* 57, 776–785.
- 1197 Vishwakarma, V., George, R.P., Ramachandran, D., Anandkumar, B., Mudali, U.K., 2014. Studies
1198 of detailed Biofilm characterization on fly ash concrete in comparison with normal and
1199 superplasticizer concrete in seawater environments. *Environ. Technol.* 35, 42–51.
1200 <https://doi.org/10.1080/09593330.2013.808249>
- 1201 Weilgart, L. s., 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for
1202 management. *Can. J. Zool.* 85, 1091–1116. <https://doi.org/10.1139/Z07-101>
- 1203 Whitman, W.B., Coleman, D.C., Wiebe, W.J., 1998. Prokaryotes: The unseen majority. *Proc. Natl.*
1204 *Acad. Sci.* 95, 6578–6583. <https://doi.org/10.1073/pnas.95.12.6578>
- 1205 Witt, M.J., Sheehan, E.V., Bearhop, S., Broderick, A.C., Conley, D.C., Cotterell, S.P., Crow, E.,
1206 Grecian, W.J., Halsband, C., Hodgson, D.J., Hosegood, P., Inger, R., Miller, P.I., Sims,
1207 D.W., Thompson, R.C., Vanstaen, K., Votier, S.C., Attrill, M.J., Godley, B.J., 2012.
1208 Assessing wave energy effects on biodiversity: the Wave Hub experience. *Philos. Trans. R.*
1209 *Soc. Math. Phys. Eng. Sci.* 370, 502–529. <https://doi.org/10.1098/rsta.2011.0265>
- 1210 Wood, T.L., Guha, R., Tang, L., Geitner, M., Kumar, M., Wood, T.K., 2016. Living biofouling-
1211 resistant membranes as a model for the beneficial use of engineered biofilms. *Proc. Natl.*
1212 *Acad. Sci.* 113, E2802–E2811. <https://doi.org/10.1073/pnas.1521731113>

1213 Yañez, F., Gomez-Amoza, J.L., Magariños, B., Concheiro, A., Alvarez-Lorenzo, C., 2010.
1214 Hydrogels porosity and bacteria penetration: Where is the pore size threshold? *J. Membr.*
1215 *Sci.* 365, 248–255. <https://doi.org/10.1016/j.memsci.2010.09.012>
1216 Yip, T.L., Zhang, D.H., Chwang, A.T., 2002. Environmental And Safety Considerations For
1217 Design of a Perforated Seawall. *OnePetro.*
1218 [https://onepetro.org/ISOPEIOPEC/proceedings/ISOPE02/All-ISOPE02/ISOPE-I-02-](https://onepetro.org/ISOPEIOPEC/proceedings/ISOPE02/All-ISOPE02/ISOPE-I-02-375/9056)
1219 [375/9056](https://onepetro.org/ISOPEIOPEC/proceedings/ISOPE02/All-ISOPE02/ISOPE-I-02-375/9056)
1220 Yuan, H., Dangla, P., Chatellier, P., Chaussadent, T., 2015. Degradation modeling of concrete
1221 submitted to biogenic acid attack. *Cem. Concr. Res.* 70, 29–38.
1222 Zeppilli, D., Leduc, D., Fontanier, C., Fontaneto, D., Fuchs, S., Gooday, A.J., Goineau, A., Ingels,
1223 J., Ivanenko, V.N., Kristensen, R.M., Neves, R.C., Sanchez, N., Sandulli, R., Sarrazin, J.,
1224 Sørensen, M.V., Tasiemski, A., Vanreusel, A., Autret, M., Bourdonnay, L., Claireaux, M.,
1225 Coquillé, V., De Wever, L., Rachel, D., Marchant, J., Toomey, L., Fernandes, D., 2018.
1226 Characteristics of meiofauna in extreme marine ecosystems: a review. *Mar. Biodivers.* 48,
1227 35–71. <https://doi.org/10.1007/s12526-017-0815-z>
1228 Zobel, R.W., 1974. Control of morphogenesis in the ethylene-requiring tomato mutant,
1229 *diageotropica*. *Can. J. Bot.* 52, 735–741.
1230
1231