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Bioreceptivity of concrete: A review

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ABSTRACT

Materials that support natural biodiversity on their surfaces can compensate for human activities that have a negative impact on nature and thus contribute to a carbon-neutral and nature-positive world. Specifically designing bioreceptive materials which favor the growth of biofilms on their surface is an approach complementing conventional, macroscopic green façades. But what exactly characterizes a bioreceptive substrate and how do biofilm and substrate interact? How and why does a spontaneous colonization and the formation of biofilms take place? What are biofilms and how can they be established in a laboratory setting? How can this existing knowledge be transferred to the artificial stone concrete so that this material can be tuned to increase (or decrease) its bioreceptivity?

This review paper aims at summarizing the existing state of knowledge on bioreceptive concrete and pointing out inconsistencies and contradictions which can only be removed by more interdisciplinary research in the field.

1. Introduction

Functionalization tailors a material according to a specific application and the respective properties required. In most cases, it allows a more effective usage of resources and/or increases the performance of the material in the set environment. When it comes to building materials, there is still a high potential for improvement. This paper will focus on one particular case, namely controlling the bioreceptivity of concrete. By understanding the fundamentals of concrete as well as biological processes involved in its biocolonization, we aim towards a functionalized building material with set bioreceptivity. We are currently conducting basic research in this field while simultaneously adapting testing methods and standardizing an approach to measure bioreceptivity of concrete. This paper summarizes the extensive body of literature that builds the foundation for this project and emphasizes on the interdisciplinary approach needed. With that in mind, this review aims to create a common knowledge base. To achieve this, first the basics of biofilms are explained, followed by basics on concrete as a substrate. In addition, both subject areas are linked to another and concluding proposals are made on how to design a concrete mix with set bioreceptivity. Extensive tables enable the reader to gain a structured insight into several approaches that were collected in literature.

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2. Definition of bioreceptivity

Starting with the biological part, biological colonization was first mentioned as a neutral term “hylobiology” (Hueck, 1965) with a quick change to by the terms “biodeterioration” and “biodegradation” in the late-60s [1,2]. Biological colonization of building material was perceived mainly negatively but did not get much attention in the scientific community. This began to change with Guillette’s research 1995 [1]. In his paper “Bioreceptivity: a new concept for building ecology studies”, he defined the term bioreceptivity to introduce a neutral, objective way to describe this phenomenon. He defines bioreceptivity as “the aptitude of a material (or any other inanimate object) to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration” or put differently, “the totality of material properties that contribute to the establishment, anchorage, and development of fauna and/or flora.”.

Even though the definition of bioreceptivity mentioned above seems simple at first, the concept is quite complex. First of all, there are different kinds of bioreceptivity since it is a dynamic parameter changing over time [1,3]. For example, the primary or intrinsic bioreceptivity of a new material will always change after being exposed to the environment and associated weathering mechanisms. These result in the so called secondary bioreceptivity. Adding coatings as a measure of maintenance results in a tertiary bioreceptivity. Accumulation of material like dust on the surface leads to an extrinsic bioreceptivity. For further information regarding definitions of the various types of bioreceptivity, see Guillitte [1] and Sanmartín et al. [3].

Bioreceptivity is dependent on the material, but considerably impacted by environment and biosphere [4,5] (Fig. 1). A material that is highly bioreceptive in a particular environment does not necessarily exhibit a high biocolonization at every location. Here, even small factors like inclination, orientation, or a switch from urban to rural regions can have an immense impact on the bioreceptivity. Implementing the same material in different climate zones can even amplify that effect [6–11]. As bioreceptivity and biocolonization are the result of many uncontrollable and intertwined factors, they are quite complex and especially biocolonization is hard to predict.

3. Impact and potential of bioreceptivity

Since the first mention of biological colonization a lot of research was conducted. In the beginning, most of it focused on the destructive potential of biofilms and how to avoid them [12–20]. With rising awareness regarding climatic change, environmental pollution and sustainability, there was not only an increase in research but also a shift to a more positive view on biofilms [5,21–24]. Instead of mainly focusing on detrimental material – biofilm interactions, current research often includes potential positive environmental effects like air purification and improved microclimate [3,5,22,24]. Sheweka and Mohamed [25] evaluated the advantages of green façades in urban regions. They addressed macroscopic plants instead of biofilms, but most aspects are also applicable to biofilm façades. In general, a green building envelope protects the building material from direct solar radiation and lowers the internal temperature. They also report a not yet quantifiable adsorption of pollutants, CO_2 fixation and O_2 production. Moreover, biofilms are expected to increase biodiversity and compared to conventional green façades, need less maintenance and irrigation [22]. Sandra Manso [5] chose a new approach of vertical greening to tackle the deficiency of green spaces in urban regions. She did pioneer work as she was the first to develop a bioreceptive concrete with a structured approach. To answer fundamental questions, she aimed for the establishment of microbial biofilms as an alternative to conventional green façades with higher plants [5]. Since then, the focus has shifted more and more to the development of materials that deliberately produce an overall net gain in biodiversity and biomass in accordance with the term nature positive, defined as follows:

“We need to halt and reverse nature loss measured from a baseline of 2020, through increasing the health, abundance diversity and resilience of species, populations and ecosystems so that by 2030 nature is visibly and measurably on the path of recovery” [26].

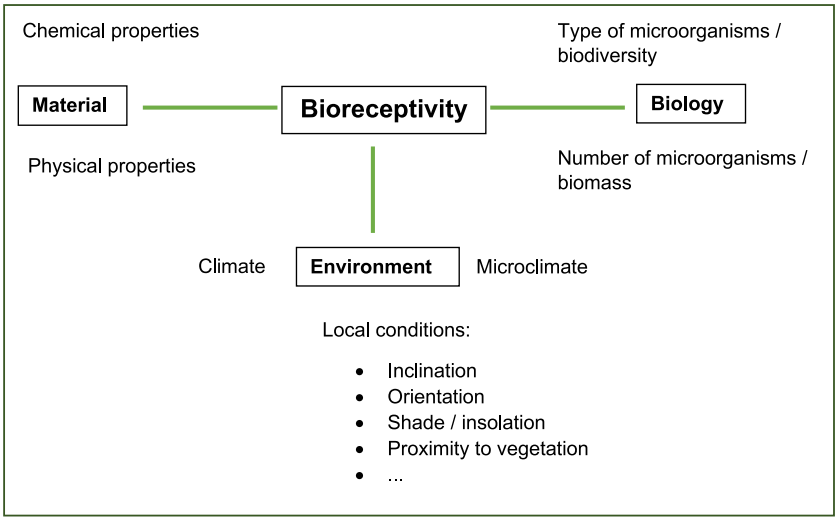

Fig. 1. Parameters influencing bioreceptivity, adapted from Manso, 2014.

With the paradigm shift from avoiding biological growth on building surfaces to facilitating it, research regarding biological colonization of building materials is increasing and the general concept of bioreceptivity becomes more important. A basic understanding of bioreceptivity enables development and production of purpose-oriented building materials.

4. Biofilm basics

Biofilms are ubiquitous, meaning they can be found almost everywhere in earth [27,28]. They form complex microbial ecosystems that contain a multitude of different organisms as well as extracellular polymeric substances (EPS) secreted by the cells [29]. The microorganisms in question are bacteria, fungi, algae and cyanobacteria [6,8,19,27,30]. Bacteria can be autotrophic or heterotrophic. Fungi are heterotrophic and thrive on organic nutrients to survive. They are mainly made responsible for the negative image of biofilms since they are often associated with mold [31] - which is rarely justified taking into account biodiverse biofilm communities. Algae and cyanobacteria are photoautotroph, meaning they do not depend on organic nutrients but metabolize CO_2 and H_2O into organic compounds and O_2 [5,6,32].

The organisms within a biofilm are usually embedded in a matrix of extracellular polymeric substances (EPS), consisting of for instance polysaccharides, proteins, lipids, and humic substance. EPS in its complexity is crucial for the wellbeing of a biofilm, since it acts not only as a protection, but also as a water retention and communication tool [29,33].

The term subaerial biofilm (SAB) was introduced by Gorbushina and Krumbein [28]. SABs differ considerably from water-submerged biofilms and grow on all air-exposed surfaces. The colonizing organisms must be poikotolerant, meaning they can withstand strong fluctuations of e.g., daily ±60 °C in temperature, as well as high solar radiation and strongly varying water content [9,27,28,30,34]. Ragon et al. [35] investigated the influence of Chernobyl ionizing radiation on microbial communities. They concluded that SABs exhibit a natural resistance to the ionizing radiation and are barely influenced by it. This is explained by the intense UV-radiation and desiccation cycles these communities must deal with on a regular basis, selecting them also towards a high ionizing radiation resistance.

Moreover, the habitat on the rock-atmosphere interface offers only the bare minimum of protection and nutrients and is rightly classified as an extreme habitat. The environmental pressure on the organisms makes competition within a biofilm almost impossible and led to the development of a series of symbiotic and protective mechanisms, individually and as a community. Considering this, it is no surprise that avoiding or long-term removal of once established biofilms is nearly impossible. Summarizing, atmosphere-exposed material biofilms are highly specialized, synergistic and resilient ecosystems [27].

4.1. *Biofilm formation*

The development of a bioreceptive material requires a fundamental understanding not only of materials science but also of basic biological processes. In case of biofilm formation, a series of possible mechanisms is described. Osorio et al. [36], focused on the formation of algal biofilms and reported the following process, visualized in Fig. 2. First, the cell needs to attach to the substrate. This initial attachment is reversible since wind or water currents can tear of the organisms easily. If that does not happen, EPS is formed and acts as a kind of glue. The adhered cells gain additional resistance, especially to mechanical stress. The attachment of further cells is facilitated to a point when the attachment is irreversible. As the biofilm grows, it develops and finally reaches a mature state (Fig. 2). In

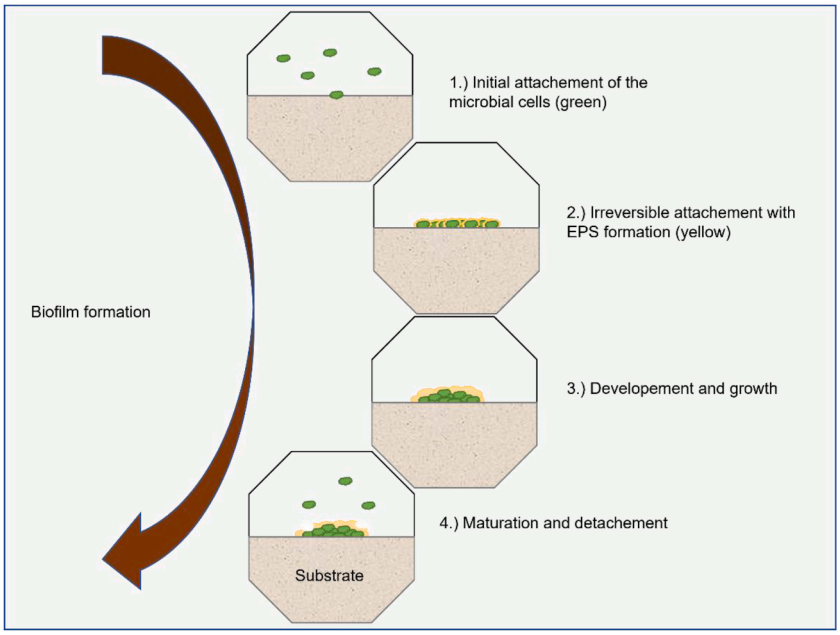

Fig. 2. Biofilm formation adapted from Moreno Osorio et al., 2021.

this state the biofilm may form spores and detach cells to find new settlements. Ledwoch et al. [37] even describes a preliminary conditioned film and a lag phase after the initial attachment. Although the exact description of the biofilm formation processes often slightly differs, there is a basic pattern visible. At least two different stages can be distinguished, initial attachment and permanent attachment with EPS formation [33,38–41]. A bioreceptive building material should allow irreversible attachment of the desired organisms as quickly as possible.

4.2. Biofilm – substrate interactions

Biofilm – substrate interactions are crucial and widely disputed. They influence the chance of microbial attachment, survival, and biofilm formation, while at the same time they may also change the durability of a building material. For permanent adhesion to the surface, biofilms must be able to interact with the substrate, altering the surface and impacting the underlying material. So far, there have been several approaches to describe and classify these processes. One example is the definition of biodeterioration by Hueck [2] as "any undesirable change in the properties of a material caused by the vital activities of organisms". Biodeterioration can be split further into three categories: (i). physical or mechanical, (ii). chemical and (iii). aesthetic [3,42,43]. The degradation processes can also be divided in geophysical and geochemical weathering [8,44]. Both can, but do not have to be enhanced by the presence of a biofilm. Biogeochemical weathering includes every chemical reaction between the material and its environment in combination with a biological organism. Biofilms can enhance the chemical weathering through the excretion of reactive metabolites like corrosive acids. This is also known as biocorrosion [43]. In the case of concrete this is primarily caused by chemolithotropic bacteria [6]. The chemical composition of the building material and binding matrix play a crucial role here since certain materials are more susceptible to chemical attack.

Biogeophysical deterioration processes are dependent on physical surface parameters. Existing pores and cracks are points of attack and widen with time. The weathering mechanisms consist of exerted pressure due to freeze thaw and corresponding volume changes of water in building material and biomass [43,45]. Some microorganisms, mainly fungi, are known to directly penetrate the given substrate with their hyphae, slowly deteriorating it physically and decreasing material durability [15,27,43,46,47]. For further information, see the review on influence of biological deterioration by Ferrari et al. [6].

However, in some cases opposite results were observed. Depending on the subjective point of view, biological colonization can be viewed as aesthetically pleasing [21,23]. Some researchers also promote an air cleaning effect of SABs, filtering pollutants and metabolizing CO_2 to O_2 [5,22]. The destructive potential of biofilm is very well researched in the field of heritage conservation [48, 49], but in recent years the view has become somewhat more nuanced. Every case should be reviewed independently to assess exactly which kind of relationship substrate and biofilm have [50]. Sometimes biofilms do not seem to influence the weathering at all, neither positive nor negative [51]. Sometimes even the opposite effect was documented. Instead of damaging the surface, a positive impact of biofilms on the substrate was reported [52–55]. The biofilm, in this context often called patina, stabilizes the substrate by forming a protective layer, shielding the surface from the harsh environment. Gerrits [56] summarized the multitude of processes with the terms bioweathering, bioprotection and biomineralization. Whether biofilms have a negative, neutral, or positive effect on their substrate seems to be dependent on the substrate, organisms in question and specific boundary conditions. The initial durability of the building material also defines its resistance to weathering processes and dictates the biofilm – substrate interactions.

4.3. Methods for assessing bioreceptivity and biocolonization

As early as 1998, Tiano [42] described bioreceptivity of building materials as an interdisciplinary field, combining microbiology and engineering. Research done so far mostly focused on one of these fields, sometimes resulting in questionable experimental design. The lack of an integrative approach is also the reason for still missing standardized test setups, bioreceptivity indices or even comparable measurement methods. Even though Guillitte [1] pointed out the need for a bioreceptivity index together with his initial definition of the term bioreceptivity in 1995, up to today there is none for concrete. This review paper aims to summarize the current research in the field and to highlight the need for interdisciplinary and standardized approaches in the future.

When testing the bioreceptivity of a material, two general approaches can be distinguished. First, outdoor weathering experiments are either carried out by making and weathering new samples, or by sampling existing structures. Since natural biofilms usually take several years to develop, the duration of experiment is comparatively long. Environmental conditions always vary, and results may not be reproducible. Since the environment cannot be controlled, but only partially monitored, it is also difficult to attribute occurring effects to specific environmental factors.

For the experimental design a n on-site approach is required. This should include continuous monitoring of as many climatic and environmental parameters as possible [5,11,30]. Sample analysis and documentation in the field often involves semi-quantitative and qualitative assessments. Visual methods such as color measurements, digital image analysis and PAM measurements can be used to monitor and quantify biofilm formation over time [5,57,58]. Identifying the species, on the other hand, is more challenging. The surface can be sampled, but only a fraction of the extracted microorganisms can be cultivated and isolated in the laboratory [16,30]. While biochemical methods help to identify and distinguish the types of organisms [5], the species itself is often determined by microscopic observations. Another possibility is the use of molecular techniques such as DNA extraction and PCR amplification [16] or genetic barcoding [30]. In summary, outdoor weathering requires a comprehensive set of methods consisting of quantitative and qualitative methods to assess the biofilm and a continuous monitoring of the environment.

The second approach are laboratory experiments, that usually last 2–4 months and simulate natural weathering scenarios. These are highly simplified and accelerated systems that provide rapid results and take place in a controlled environment. Performed correctly, laboratory experiments are reproducible and allow accurate conclusions to be drawn about how different boundary conditions affect biocolonization. In contrast to outdoor weathering tests, they focus exclusively on quantitative methods, e.g., visual

Table 1
Overview of laboratory set ups testing bioreceptivity of concrete.

	Laboratory set up			Documentation of biological staining				
	dynamic	Static	Strains	EPS analysis	Microscopic investigation	Colorimetry	Image Analysis	Chlorophyll based measurements
Alum et al., 2008 [71]	Horizontal samples		Natural biofilm				x	Chlorophyll extraction method
Barberousse et al., 2006 [11]	X		Algae: *Klebsormidium flaccidum* (ALCP 749B); *Stichococcus bacillaris* (ALCP 772B); *Chlorella* cf. *mirabilis* (ALCP 171A)	x	x		x	
Dubosc et al., 2001 [64]	X		Mixture of pioneer colonizing algal diaspores				x	
De Muynck et al., 2009 [66]		Viability assay	Bacteria*: Escherichia coli; L. monocytogenes; Salm. Enterica; Staph. aureus*		x			
De Muynck et al., 2009 [13]	x		*Algae: Chlorella vulgaris* var. *viridis chodat* (CCAP 211/12)			x	x	
Escadeillas et al., 2007 [31], Escadeillas et al., 2008 [14]	x	x	Algae: *Chroococcidiopsis, Chlorella and Chlorhormidium genera*			x	x	Chlorophyll extraction method
Giannantonio et al., 2009 [15], Giannantonio et al., 2009 [16]	Horizontal samples		Fungi: *Alternaria; Cladosporium; Epicoccum; Fusarium; Mucor, Penicillium; Pestalotiopsis; Trichoderma*		x		x	Chlorophyll extraction method
Guillitte und Dreesen, 1995 [65]	x		Algae: *Chlorella* spp.*; Stichococcus bacillaris; Klebsomidium flaccidum; Oocystis* sp. filamentous Cyanobacteria: *Lyngbya diguetii; Anabeana variabilis; Oscillatoria* sp. Diatoms: *Gleocapsa* Primordia and Protonema: *T. muralis; Bryum capillare;* Nitrophous species: *Desmococcus viridis; Scenedemus* sp.		x		X	
Kondratyeva et al., 2006 [46]	Unclear		Fungi: ubiquitous isolate, the spores of which are frequently found in air.		x			
Manso, 2014 [5]	X		Algae: *Chlorella vulgaris* var. *viridis Chodat* (CCAP 211/12)			x	X	PAM-F
Maury-Ramirez et al., 2013 [57]	X		*Algae: Chlorella vulgaris* var. *viridis Chodat* (CCAP 211/12)			x	X	
Perkol-Finkel and Sella, 2014 [72]	X		Soft coral: Heteroxenia fuscescens; Dendronephthya hemprichi Bryozoan: Bugula neritina				X	
Shirakawa et al., 2003 [60]		X	Fungi: *Cladosporium sphaerospermum (K2-19)*		x			

(*continued on next page*)

Table 1 (*continued*)

	Laboratory set up			Documentation of biological staining				
	dynamic	Static	Strains	EPS analysis	Microscopic investigation	Colorimetry	Image Analysis	Chlorophyll based measurements
Thu Hien et al., 2012 [20]	x		*Algae*: *Klebsormidium flaccidum* (ALCP 749B9)			x	X	
Veeger et al., 2021 [73], Veeger et al., 2021 [24]		X	Natural biofilm				x	
Wiktor et al., 2009 [68] Wiktor et al., 2011 [74]		X	Fungi: *A. alternata (MC342); Exophiala* sp. *(MC843); C. uncinatum (MC557)*	x	x			

inspections such as surface coverage by image analysis or microscopy (Table 1). Not only varying set-ups but also experimental parameters used make a comparison of the results challenging. These are for example different irrigation and light settings, as well as differences in sterility. The impact of experimental parameters on the resulting biocolonization can be seen in the work of Fuentes and Prieto [59]. They assessed the bioreceptivity of granite under different temperatures (18 and 24 °C) and levels of water availability (1, 3 and 7 days a week). This approach resulted in a different biofilm growth for the various settings. It was concluded, that bioreceptivity is an important material intrinsic property facilitating attachment of organisms, while the subsequent biocolonization is modulated by environmental factors. Furthermore, there are multiple measurement methods (Table 1) available for quantifying the biofilm formation, and each group of researchers select their own range of methods with their own measurement settings. Table 1 gives an overview in the current state of research and which methods are commonly used in laboratory set ups. For reasons of clarity, related research of the same author has been merged into one entry.

According to Fuentes et al. [4], there are two main types of laboratory weathering set ups, dynamic and static ones. In a static design, the samples are usually stored horizontally and regularly wetted via condensation, spraying or capillary suction. This is often combined with an initial inoculation instead of a continuous exposure to new organisms [4]. If the biological stain grows over time, one can be sure the substrate is bioreceptive and enables biological growth. The dynamic design – or run off experiment, models a façade like application, in which the sample is stored in a tilted position between 30° and 45° [4]. In defined time intervals, water flows over the surface and exerts shear stress to simulate rain events. These set ups tend to continuously introduce new microorganisms with every irrigation cycle.

The closest thing to a standardized test for concrete bioreceptivity is currently a standardized set up for evaluating fungal bioreceptivity of indoor mortars, developed by Shirakawa et al., in 2003 [60]. They promote a static approach using only the fungus *Cladosporium sphaerospermum* as inoculum. However, this approach is not suitable for testing a façade-type application of concrete, especially if one aims for a green biofilm consisting at least partly of algae and/or cyanobacteria. A consequence of this is that each research group decides individually on an experimental set-up, which ultimately leads to hardly comparable, if not contradictory, results. For more information on laboratory experiments in general, see the methodological review on laboratory development of subaerial biofilms commonly found on buildings by Fuentes et al. [4].

M any runoff experiments tend to neglect the interaction between substrate and biofilm. While often used visual methods like scans or colorimetric measurements give a good quantitative information, they cannot distinguish between a simple accumulation of biomass on the surface and actual attachment, or even biofilm formation. To thrive long term, grow and reproduce, the latter must be the case. For testing this specifically, additional methods like for instance EPS staining [27,61–63] and microscopic investigation [5,10,11,16,46,64–68] should be implemented. In this context, PAM-Fluorometry is another common method to study photosynthetic organisms in particular [5,6,30,58,59,69,70].

At the current state, most researchers choose their experiment design primarily based on their own background even though an interdisciplinary approach would be needed. This is especially true when developing a new material. Material scientists can contribute to standardized tests, ensuring quality and durability of a material and making sure it is suitable for the desired field of application. On the other hand, selection of microorganisms and monitoring methods profit from microbiological expertise. Fuentes et al. [4] differ between three types of microbial cultures, model monospecies cultures, ubiquitous monospecies and multispecies cultures obtained from natural occurring biofilms. While in general monospecies approaches are preferred, in the context of building materials like concrete multispecies cultures are used predominantly [4]. The organisms should be chosen in regard to their representativeness, growth rapidity and ease of liquid culture [31]. Here the complexity of the topic bioreceptivity becomes evident once again, as the microorganisms fulfilling these criteria change with location and must be chosen accordingly [22]. Rindi [9] described two major algal assemblages, prasiolalean and klebsormidium, in Europe alone, depending on the subordinate climate of the region. Gaylarde and Gaylarde [10] analyzed over 1500 biofilms all over Latin America and Europe. In accordance to Rindi [9], they frequently reported *Klebsormidium* in Europe as well as an continental difference in biofilm compositions: While algae are generally the dominant species in Europe, cyanobacteria were dominant in Latin America. Barberousse [11] sampled 71 biofilms in France and her findings aligned with those of Gaylarde and Gaylarde [10]. In 49% of her samples, a dominant species stood out. In 97% of these cases, the dominant species was algae. She also noticed a local dependency of microorganisms, mainly the proximity to the coastline seemed to affect biofilm

composition.

Using different microorganisms in laboratory settings also complicates comparability of results. Table 1 collects the organisms used in various laboratory set ups testing the bioreceptivity of concrete. It should provide the reader with an overview to enable the selection of comparable scenarios.

As can be seen in this paragraph, there are many ways to test for bioreceptivity and the need to structure and standardize set ups. In order to execute this well, all relevant disciplines must be taken into account. Gorbushina and Broughton [34], summarize the requirements for reflecting SAB development as follows: “The experimental framework must include

- (a). all known physical influences on the subaerial environment,
- (b). different substrates in various stages of exposure to the atmosphere,
- (c). permutations of possible atmospheric conditions, and
- (d). likely members of the biofilm consortium."

This aims to simplify and model biofilm formation under controlled conditions while still being relevant for the actual field of application. A standardized laboratory test would make it possible to quickly test different building materials – including different concrete mixes – for their bioreceptivity and facilitate material development.

5. Concrete basics

Concrete is a widely used building material. It is cheap, easy to produce and useable raw materials like clay, limestone, sand, or mineral waste materials can be found nearly anywhere on earth. As an artificial and shapeable stone, it is incredibly versatile. Concrete is made of cement (or an alternative binder), differently grained aggregates like gravel or sand, and water. Usually, it contains additional additives and admixtures to further tune specific properties. By extension this can be also done for bioreceptivity. If the key parameters determining bioreceptivity of concrete are identified, this can be used to design a material with set bioreceptivity. This might be a high bioreceptivity, resulting in accelerated biocolonization and a green façade, or a low bioreceptivity, minimizing maintenance costs and biocide use.

The concrete mix is processed in viscous state and hardens in the formwork either directly at the construction site or in a factory for precast concrete elements. Currently no building material can match the property profile and the availability of concrete, making it the most used building material in the world [75–77]. Each year, around 4 billion tons of cement are produced, and these amounts are even expected to rise due to expanding and developing countries like China and the African continent [78,79].

Concrete also has its downsides, mainly due to the properties of its traditional main binder, ordinary portland cement (OPC). During production of binder, limestone is deacidified and 590–1000 kg CO_2 per ton of cement is released into the atmosphere. The production of the global demand on cement is accounting for 6–8% of the global CO_2 emissions, responsible for the high carbon footprint of concrete as most of them contain OPC clinker in various amounts [75,80,81]. By using supplementary cementitious materials, the clinker content of a cement can be reduced up to 80%, drastically reducing emissions [82,83]. Nevertheless, the growing demand in concrete for construction leads to a compensation of this saving potential.

Concrete mixes with a low carbon and/or environmental impact can be realized by for example using supplementary cementitious materials and/or recycled aggregates. They are often called green concrete. However, an important distinction must be made because green concrete is not the same as a bioreceptive concrete [84]. While bioreceptive concrete will become literally green, the material itself may still have a high carbon footprint and is not necessarily saving resources.

To ensure concrete elements can safely withstand the expected stresses over decades, proper design, dimensioning, construction, and selection of building materials is required. Specifications for durability according to EN 1992-1-1 (“Eurocode 2”) form the basis for this requirement. EN 206-1 and DIN 1045-2 specify the necessary properties, compositions, and conformity procedures [85]. Certain durability requirements must be met in correspondence to the loading and exposure conditions. This might for example be the flexural and compressive strength but can also include resistance to sulfur or acid attack as well as freeze thaw resistivity. Façade panels of exposed concrete must also meet aesthetic standards, often resulting in defined values for maximal allowed visible pores per square meter [86]. Additionally, requirements regarding building protection against driving rain and thermal insulation must be considered

Table 2
Overview of surface parameters tested on concrete samples in the context of bioreceptivity.

Reference	Porosity	Surface roughness	Water retention	Surface pH	Chemical or mineralogical composition	Strength
Barberousse et al. (2006) [11]	x	x	x			
De Muynck et al. (2009) [13]	x	x	x	x		
D. J. Giannantonio et al. (2009) [15]		x		x	x	
Escadeillas et al. (2007) [31]	x	x	x		x	x
Guillitte and Dreesen (1995) [65]	x				x	
Manso (2014) [5]	x	x	x	x	x	x
Maury-Ramirez et al. (2013) [57]	x	x	x	x		x
M. Veeger et al. (2021) [73]		x	x	x		
Perkol-Finkel and Sella (2014) [72]			x	x		x
Shirakawa et al. (2003) [60]			x	x	x	
Thu Hien et al. (2012) [20]	x	x		x		
Wiktor et al. (2011) [74]	x	x			x	

[30]. Concrete is versatile enough to meet nearly every expectation with adaptations in recipe, resulting in its ubiquitous use.

6. Concrete properties affecting bioreceptivity

When adjusting the bioreceptivity of concrete, it is important to understand which material properties influence its bioreceptivity. Guillitte [1] was one of the first to acknowledge the crucial role the physical material properties of the substrate have on biofilm formation. Their effect is generally applicable and not dependent on the material of the substrate. Therefore, some of the references used in this chapter cover the topic of surface properties influence on biofilm growth without explicit relation to concrete.

While there are many interesting and possibly influential properties, in existing literature certain characteristics are tested for more frequently than others. Table 2 shows the six most common concrete properties usually investigated in the context of bioreceptivity, namely strength, porosity, surface roughness, water retention, surface pH and chemical or mineralogical composition. Even though researchers acknowledge the importance of these properties, small differences regarding the ranking of importance are made [5,13,20,37,87–89].

With respect to experimental design and measurement methods for the parameters listed in Table 2, literature strongly varies. As mentioned before in the context of laboratory set-ups, this makes a comparison of research results difficult or even impossible. Elaborating on this, the following chapters will go into detail how certain properties influence the bioreceptivity, introduce common measurement methods and their limitations.

6.1. Roughness

The here mentioned roughness is on the microscale (μm), macroscopic features are described in the next chapter. Roughness is directly linked to bioreceptivity as it increases the available surface area and thereby the anchorage of microorganisms as well as nutrient and water adhesion. Roughness facilitates both the initial attachment phase and the subsequent biofilm formation as discussed in chapter 4.1, as it continues to support the biofilm by protecting it from shear stresses build up by wind and water flow [8,23,24].

Generally speaking, the ideal roughness should be slightly bigger tha n the cell size of the organisms in question [37,39,44]. The ideal roughness of a surface is mostly dependent on the microorganisms and their morphology. While single celled organisms are usually up to 10 μm in size, filamentous growing species can be as large as multiple hundred μm [11,30,90]. Outside of concrete research, a lot of thought has been put into answering the question of the perfect structure and substrate to grow large amount of biofilm. Huang et al. [91] for example tested surfaces made from polydimethylsiloxane with different artificial roughness and concluded that with the same roughness factor the shape of the microstructure defining the roughness can have a considerable influence.

Measurement methods often used for the assessment of microroughness are confocal or digital microscopy and laser-based set ups like profilometers [5,11,13,15,20,57,70,73].

6.2. Texture

Adjusting the substrate on the macro scale (mm – cm) adds a specific texture and pattern to a surface. This can be used to control the water flow and shade specific areas. By designing local differences in bioreceptivity the pattern of biological growth can be controlled [21,23,24]. The texture of a substrate can be characterized with 3D scans or photographs, as well as surface models.

6.3. Porosity and permeability

In hydraulic binders, mixing the powdered binder with water leads to an exotherm hydration reaction and hardening of the mix. The hydration of concrete always results in a solid body incorporating an internal pore system [92]. Porosity and pore size distribution vary strongly depending on the mixture, mainly water/binder ratio, binder composition, mixing procedure and intensity of compacting. The degree of hydration increases with time after setting. In the first days, the hydration reaction is very strong, slowing down successively over time but never coming to a final standstill. This leads to a corresponding decrease of porosity and a characteristic change in pore structure with concrete age, related to an increase of mechanical properties and higher durability regarding weathering or chemical attack. Usually, high porosity should be avoided since it reduces the compressive strength of the material and increases susceptibility to freeze-thaw damage [24]. Various kinds of pores are defined by either their size or the different processes of involved

Table 3
Overview pore type classifications.

Reference	Gel pores	micropores	mesopores	capillary pores	macropores
Adilkhodjaev et al. (2021) [Pore size] [96]	0.5–2.5 nm between crystals	<0.5 nm, interlayer		2.5 nm - 15 μm	>15 μm
Gong et al. (2013) [Pore size] [94]		1–100 nm	100 nm - 10 μm		100 μm - 1 cm
Jennings (2004) [97]	<0.5 nm–5 nm			75 nm	
Kumar and Bhattacharjee, (2003) [92]	0.5–10 nm, mostly of 1.5–2.0 nm		5–5000 nm		x
Li and Li (2014) [Diameter] [98]	<10 nm	Transitional pores: 10–100 nm		100–1000 nm	>1000 nm
Mindess (2002) [Diameter] [99]	Interlayer micropores/gel pores: Ø < 0.5 nm Micropores/gel pores: 0.5 < Ø < 2.5 nm			Big capillary pores/macropores 50 nm < Ø < 10 μm	
	Small capillary pores/small mesopores/gel pores: 2.5 < Ø < 10 nm		Medium capillary pores//large mesopores: 10 < Ø < 50 nm		
Schober (2011) [Size range/Diameter] [100]		<50 μm, different formation process			100–3000 μm

in their formation. The available measuring methods are based on different underlying approaches, leading once again to hardly comparable results. This can be easily seen when attempting to directly compare a pore size distribution measured by image analysis with one determined by mercury intrusion porosimetry. Thus, it is quite difficult to classify typical pore types by their size, as can be seen from the diverse definitions collected in Table 3.

Gel pores influence autogenous shrinkage but have no relevance regarding bioreceptivity. While gel pores do not yet affect the strength of the concrete, pore sizes above do [92]. Since bioreceptivity requires a certain degree of porosity, the challenge is to increase bioreceptivity without compromising too much on the mechanical strength of the material. Capillary pores are expected to have the biggest influence on bioreceptivity as they control the vapor and fluid transfer through the material and provide water for the organisms [93]. They exhibit capillary suction and can hold humidity against the force of gravity [94]. Capillary pores are also responsible for draining the water away from the surface into deeper layers and with that extracting water from the biofilm. Further, they are also important regarding freeze thaw resistance. Manso [5] refers to capillary pores as the most interesting pore size magnitude regarding bioreceptivity and expects them to enhance water absorption. Lastly, macropores improve the general water retention capabilities of concrete. Snoeck et al. [95], combined cementitious materials with super absorbent polymers and reported a positive correlation between macropores and high bioreceptivity.

Next to size, the connectivity of pores is important. As visualized in Fig. 3, closed pores within the material have no effect on the water retention capability. Permeable materials have interconnected pore systems of a certain size, allowing the movement of e.g., capillary water in liquid or gaseous form through a tunnel like pore system. The network of interconnected pores therefore defines the transport processes which are again decisive for water absorption, water retention and drying of the substrate [101,102].

There are different approaches when it comes to measuring porosity and permeability. Two common methods are mercury porosimetry and water absorption. Mercury porosimetry measures the open and accessible pores. Since the penetration of pores is dependent on the applied pressure, results may differ based on the experimental parameters. Closed pores will not be captured by these procedures. For this, the difference between bulk density and true density must be evaluated [5,103]. Porosity measurements differ with respect to the standard used, e.g. determining the percentage of voids according ASTM C642-13 [5] and measuring the permeable porosity of the concrete specimens by means of vacuum saturation according to ASTM C 1202 [13,57].

Both porosity and permeability are crucial parameters for bioreceptivity and therefore should be evaluated [104].

6.4. *Water absorption, water retention and drying characteristics*

Going one step further, different pore systems result in different water – surface interactions. This is especially true with respect to the final application of the material. A large scaled pore system for example could take in a lot of water if completely immersed or under hydrostatic pressure, but would not do so in a façade like application where only the surface is exposed to humidity. In contrast to that, a pore network of capillary pores is capable of sucking water into deeper layers of the substrate. A rapid water transport into deeper layers of the concrete could lead to a decreased bioreceptivity, in analogy to thick renders as part of external thermal insulation systems [105]. For an improved bioreceptivity, the pore system should be able to store rain- and dew water near the surface where it is accessible for the microorganisms, all while being in a vertical position.

Regarding moisture on material surfaces, the type of humidification is also important. High relative humidity can be favorable for microorganisms without even wetting the surface [58]. When it comes to natural humidification by driving rain or condensation, drop volume plays a significant role. While rain drop sizes vary between 0,5 mm and 6,4 mm, dew forming during condensation only ranges between 0,0015 mm and 0,1 mm [105]. Depending on the structure of a material, certain drop sizes can adhere easier through sitting in the recesses, wetting the surface longer [23,106].

With respect to bioreceptivity, moisture and time of wetness are crucial for biological growth [1,9,30,64]. When it comes to water availability, dew formation might be more important than rain. This is especially the case since because of the climate crisis rain events tend to get shorter, more intensive, and therefore the water is less available for plants of any size. Strength and angle of rain

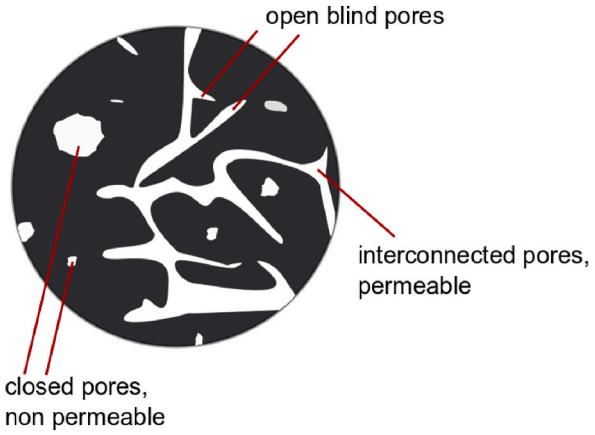

Fig. 3. Types of pores, pore system and permeability according to Li et al., 2021, and Ganat, 2020.

precipitation might also be a factor negatively impacting the adherence of rainwater. Research on precipitation concludes, that during extreme droughts or in deserts dew can be the main source of water, even exceeding rain [107]. Beysens et al. [108], examined rain and dew events in Paris and concluded, that despite low quantitative yields of dew, the contribution to the biosphere is important. Furthermore, evaporative spray and mist cooling is becoming increasingly popular in regions like Spain, Japan or Israel [109] and could act as an additional source of water for biofilm façades. As this environmental factor impacts bioreceptivity strongly, local climate and weather must be considered.

As described in the section on porosity, the network of interconnected pores together with the boundary conditions define the transient liquid and gaseous transport within the substrate. To differentiate between materials, a variety parameters for moisture storage and transport are defined. These include absorption coefficient, diffusion resistance coefficient, drying coefficient, sorption isotherm and the free water saturation. To measure them in a comparable way, the concrete industry has existing standards for measuring the water retention of concrete, e.g., ASTM C642-21 as used in an earlier version (C642 – 13) by Manso [5] in her dissertation. This method, as most procedures, is based on a gravimetric approach by completely immersing samples in water. For further information, see Meng and Müller [110].

In context of bioreceptivity assessment, these standards provide a first characterization of the material but lack a differentiation of the absorbed water. Immersing samples in water does not reflect a natural weathering regime but results in a value commonly registered as water content. From the absorbed water however cannot be inferred to the water that is held on or close to the surface and therefore available for the organisms. As to current knowledge there is no standardized test measuring the adherence of differently sized water droplets simulating dew and rain events on a surface, even though in context of bioreceptivity these would be the values sought after. A promising approach consists of NMR measurements, allowing the determination of moisture profiles in the material [111].

6.5. *Wettability*

The wettability, often measured via water contact angle (WCA) and roll-off angle, also influences the water availability. It is determined by the intrinsic material properties and surface morphology [112–114]. Water on a surface will try to achieve the lowest energy state possible, which means water droplets will spread out as far as they can [113]. As a result of this, the wettability of a surface is characterized by the water contact angle. Low WCAs are characterized by droplet spreading and large contact area between water and material. The surface is hydrophilic. Hydrophobic surfaces on the other hand have high WCAs and a low material – water contact surface. The water is not able to penetrate the material and rolls off [113–115]. Measuring WCAs allows to classify the properties, as can be seen in Fig. 4. Usually WCAs range from 10°, describing hydrophilic states, to 150°, describing hydrophobic regimes. From a nano engineering point of view, the extreme states below 10° and above 150° are especially interesting [113,116,117].

According to literature, wettability cannot only be described solely by WCAs but also by the contact mode between water and surface. Here, two main hydrophobic scenarios are imaginable: The Wenzel mode as wet-contact mode and the Cassie mode representing a non-wet state, where the droplets can roll of easily [106,112].

A lot of research has been done in this area, especially regarding mimicking existing biological structures. The most prominent case for this is the lotus leaf structure, found in e.g., lotus leaves or broccoli. Lotus leaves show a combination of macro and microstructure, making them superhydrophobic with WCAs >150° [106,113,116]. The plant is self-cleaning, as water droplets run off immediately and take dirt with them. Designing hydrophobic and at the same time adhesive surfaces could result in highly bioreceptive surfaces because they extend the duration of liquid water dwell time at the surface.

This lesser-known effect can also be found in nature and is called the petal effect. Like the lotus effect, it relies on a hierarchical surface structure, combining nano-und microstructure [106,112]. The superhydrophobicity gets combined with high adhesion, causing water to adhere to the surface even if the surface is turned upside down. Both effects are schematically shown in the Fig. 5.

As early as 1991, Ortega-Calvo et al. [45] reported the correlation between local water retention and occurring biological growth patterns, making this type of surface especially interesting. To manufacture such surfaces one needs low energy surfaces and a suitable surface structures that significantly increases hydrophobicity [115].

As previously hinted, the crucial parameter for these effects is drop volume. Small dew sized drops will be able to sit in small structures, while bigger raindrops will slide off. Moreover, smaller drops experience less gravity and have a higher surface tension, two favorable properties which makes them stay on the surface longer [106]. When it comes to designing materials with specifically set bioreceptivity this effect may play a huge role and the microstructure of surfaces must be adjusted accordingly.

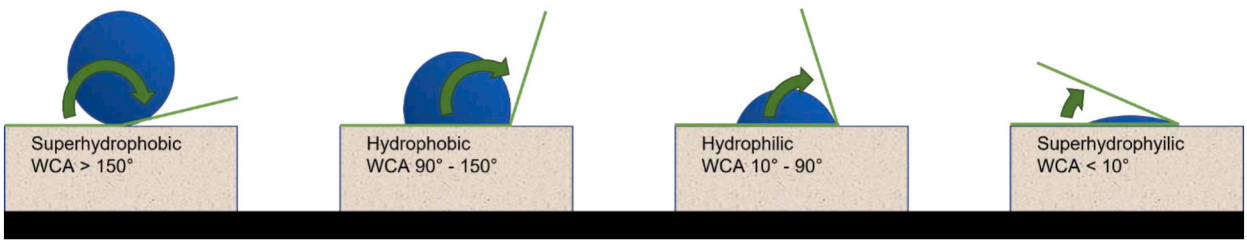

Fig. 4. Bioinspired superwetting surfaces for biosensing Zhu et al., 2021.

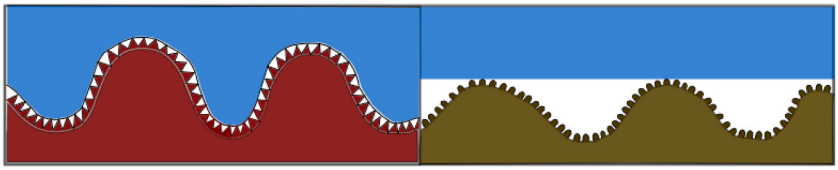

Fig. 5. Schematic adapted from (Feng et al., 2008). On the left: petal Effect with the cassie impregnating wetting state. Right the lotus effect with the cassies state.

6.6. Chemical properties: mineralogical composition, nutrients & pH

Even though chemical properties influence bioreceptivity, most agree that they play a minor role compared to the physical ones [10,21,23,118]. Photoautotrophic organisms do not need nutrient rich substrate but instead mainly CO_2, sunlight, and water [119]. The low amount of nutrients needed is usually accessible by the aerosol. These nutrients are mainly nitrogen and phosphate [37], plenty of which are in the air and thus can be transported onto the concrete surface [24,70]. This is in part because of the amount of fertilization done by the agriculture in modern society as well as a result of exhaust fumes produced by traffic [38,43]. An exception to the subordinate impact of chemical properties on bioreceptivity is the pH value [5,20]. This is especially true for concrete as an alkaline building material with initial pH values easily exceeding 12 and even 13. With time, carbonization lowers the surface pH value, via reaction of not only, but mostly portlandite and calcium silicate hydrates (C–S–H) with CO_2 in the atmosphere forming calcium carbonate [74,120,121]:

$$\textbf{I. Portlandite carbonation}: \mathbf{Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O}$$

$$\textbf{II. C - S - H carbonation}: \mathbf{(CaO)_x(SiO_2)(H_2}O\mathbf{)_z + xCO_2 \rightarrow} \; x\mathbf{CaCO_3 + SiO_2(H_2}O\mathbf{)_t} + (z-t)\mathbf{H_2O}$$

The carbonation process starts at the surface and then progresses into the material. Regarding durability this effect is not welcome as it enables corrosion when it reaches embedded steel reinforcements. In direct contradiction to that, most organisms prefer lower pH values [20,30,57]. Therefore, this reaction often gets utilized to bypass the problem of an initially too high surface pH value by accelerated carbonation [5,11,20,57,122]). But even regarding this aspect, some researchers achieved contradictory results. Veeger et al. [73] reports, pH values above 10 were colonized in his experiments and therefore the pH is not as important as so far thought. Wiktor [74] exposed concrete samples to accelerated weathering and reported a thin carbonated layer on the sample surface, closer to a carbonate composition than a cementitious one. On a suitable concrete, this phenomenon together with dust and nutrients accumulating on an engineered structure might facilitate a fast and natural occurring biological growth [105].

Moreover, porous concrete surfaces have a higher reactive surface than smooth ones. The carbonatation front proceeds faster, meaning the average pH of the material decreases more quickly. This links the physical properties to the chemical ones. Measuring the pH value of concrete in the context of bioreceptivity poses a challenge. Here, only the surface pH is important, and the pH of the bulk is negligible. A widespread method consists of milling the material and measuring the pH value of the powder in a solution [5,72,73]. While this provides exact values, it is does not reflect the relevant surface pH value. Milling a sample takes material from a cross section and not only from the surface. This means, the surface material gets mixed up with inner bulk material characterized by less carbonation and higher pH values. The resulting value reflects the entirety of the sample and therefore does not represent the conditions on the surface. The milling process of the sample which leads to a powder with higher surface area also might promote carbonation and distort the values further. Another option is the use of a phenolphthalein indicator [16,60] or a combination of water droplets and pH strips to check for carbonation [57,66]. However, this approach does not give an exact pH value but a general idea if a material is carbonized. Building on this, there is also the possibility of wetting the surface with a defined amount of water, letting it sit for a certain amount of time and then measuring the pH of that water with an electrode [20,60]. Regarding bioreceptivity, this is currently the most suitable method since it reflects the conditions a biofilm would have to live in. However, this method can produce vastly different results depending on the measurement procedure. Droplet volume, room temperature and soaking duration have a significant influence on the values reported. pH is considered one of the key parameters regarding bioreceptivity and should not only be evaluated once, but its changes monitored over time. The review of Behnood et al. [123] gives a summary about existing pH measurement methods. Long term, a test specifically for the context of bioreceptivity must be designed.

7. Adjusting the bioreceptivity of concrete

Integrated ability to interact with climate and biosphere is essential for modern materials in a carbon-neutral and nature-positive world. Since there is already a lot of research done in building materials optimization, this existing knowledge should be adapted for the development of bioreceptive materials. As described above, pH, porosity, roughness, texture, and water retention are not only key parameters but also strongly linked to another.

Concrete has the advantage of being an artificial material and therefore these key parameters can be designed to result in a set bioreceptivity. Multiple approaches for adjusting these properties can be summarized in two categories. First, they can be controlled by the concrete recipe itself. For example, to maximize strength in ultra-high-performance-concrete, the material is designed to be as compact as possible. This is done by minimizing water content, e.g., through the addition of superplasticizer and accordingly to the fuller curve, grain sized optimized aggregates [124]. Multiple researchers already used this approach and tested different water to cement ratios (w/c) [5,15,20,64,66,73], evaluated resulting material properties and bioreceptivity. Generally, a higher water content

results in increased porosity, fast carbonation and high bioreceptivity while simultaneously decreasing strength.

One might also take a closer look at the chemical components of the materials used in the concrete mix, as some are known for biocidal effects or aggressive pH values. This mainly includes photocatalytic additives like TiO2, but also metallic ones like Cu and Zn [57,71,125,126]. Furthermore, minimizing the cement content reduces the alkaline binder, which lowers the overall pH value and might facilitate biological growth. Regarding the type of cement, most researchers test different portland cements as they are the most frequently used building materials [11,20,73,74,93,127]. In smaller scales, magnesium-phosphate cement (Mg–P cement) was tested as well and seems to be quite suitable as it has a naturally low pH value as well as important nutrients for the habitants [73,93]. Here, the future field of application must be considered, as Mg–P cements are known for their comparatively lower strength.

Not only the cement used, but also the type and grain size distribution of aggregate can play a role in bioreceptivity. Aggregate filler options are for example sand, crushed lime, crushed expanded clay [5,20,64,75], recycled aggregate [75], or in case of marine research even crushed shells [84]. Different additives or alternative binders are also known to impact key properties. Fly ash for instance is known to lower the pH [128], other materials commonly used are blast furnace slags [104,129], silica fume [71] and bone ash [73]. Further information is summarized Table 4. It summarizes research done so far in the field of concrete bioreceptivity and includes detailed information regarding cement types, adjustments in recipe, and storage conditions.

The second way to adjust the material intrinsic bioreceptivity of concrete can be implemented during or after the concreting. A surface texture can be imprinted while concreting by using a structured formwork [23]. Applying an environmentally friendly

Table 4
Overview concrete adjustments.

Reference	Cement	Variables and/or methods investigated	storage conditions
Barberousse et al. (2006) [11]	Outdoor samples from existing building + own substrates: Laboratory-made mortar (PC) and four manufactured products	Cellulose ether; Organic finish or paint	Accelerated carbonation; Humidity chamber
De Muynck et al. (2009) [13]	White architectural (CEM II/A-LL 42.5 N) and autoclaved aerated concrete	Assessed water repellents, biocides, and combination thereof	Accelerated carbonation; Humidity chamber
De Muynck et al. (2009) [66]	Mortar prisms; REFERENCE SAMPLES. CEM I 52,5	Triclosan-incorporated fibers; silver copper zeolites; w/c	Accelerated carbonation; Humidity chamber; UV Light sterilization
Dubosc et al. (2001) [64]	OPC	Siliceous river sand; Superplasticizer; Densified silica fume; w/c	
D. J. Giannantonio et al. (2009) [15]	adjusted commercially available GU Type I/II cements; Essroc Type I/II and Essroc Type I/II doped with nano-anatase TiO_2	Different concentrations of SCMs: fly ash, slag, silica fume, metakaolin; Varying aggregate size; w/c; surface mechanically altered with: standard brush finish, 120 grit paper polish, 600 grit paper polish	Accelerated carbonation; Limewater curing; autoclaving (= sterilization method)
Escadeillas et al. (2007) [31]	Four different mortar compositions	Formwork oil	Accelerated carbonation; Humidity chamber; Artificial leaching; Water storage
Huang, X. et al. (2016) [129]	Own recipe created	Recipe: cement clinker, granulated blast furnace slag (powder) and steel slag (powder and coarse aggregates) and flue gas desulfurization gypsum, polycarboxylate superplasticizer; Particle size distribution was optimized according to Fuller's curve	Humidity chamber, Curing in artificial seawater
Manso (2014) [5]	Mg–P Cement with different P:M ratios, OPC 51,5	Small aggregates for flexural strength; C fly ash; Different mixtures with and without acid; Microporosity: w/c; Macroporosity: varying aggregates size and the cement paste content	Accelerated carbonation; Humidity chamber
Maury-Ramirez et al. (2013) [57]	TiO_2 white cement; Architectural white cement CEM II/A-LL 42.5 N; Autoclaved aerated concrete	different concentrations of TiO_2; TiO_2 coating; Water repellent coating	Accelerated carbonation; Humidity chamber
M. Veeger et al. (2021, 2021) [24,73]	OPC, UHPC, MPC, 16 different mixtures were evaluated; Two prototype panels were designed	Silica fume, limestone powder, blast furnace slag, bone ash; Aggregates: gravel + sand, expanded clay + sand; UHPC: Plasticiser; Open porosity and water capillary content: w/c; Capillary water content: coarse aggregates were changed to crushed expanded clay; Roughness: surface retarder (OPC & MPC)	Accelerated carbonation
Shirakawa et al. (2003) [60]	OPC, high calcium hydrated lime + standardised sand; two ready-mixed building mortars	w/c; Granulometry	Accelerated carbonation; Humidity chamber; autoclaving (=sterilization method)
Thu Hien et al. (2012) [20]	Portland cement CEM I 52.5 N (Holcim)	Cellulose ether; w/c; Finishing methods: smoothing with a ruler, scratching with different sponges	Accelerated carbonation; Humidity chamber
Wiktor et al. (2011) [74]	Ordinary white Portland cement CEM I 52.5 R	w/c	Accelerated carbonation; Humidity chamber; Accelerated weathering: combination of carbonation and leaching; UV light for sterilization

formwork oil may also decrease the risk of biocides or a surplus of nutrients resulting in fungal growth on the surface [15]. After demolding, a series of physical methods can alter the concrete surface, like scratching, sandblasting, acid washing or even milling [20,130]. Certain types of concrete like exposed aggregate concrete might also be worth a try. Here, a surface retarder keeps the upper layer of concrete soft and after demolding, the cement can be removed by pressure washing. This results in a low cement content and therefore a low surface pH. Additionally, the material shows exposed aggregates and a greater surface roughness than before [131]. This is especially promising if the aggregate itself is characterized by high porosity and roughness. Another already developed concrete from which one might draw inspiration is autoclaved aerated concrete, by nature a very porous material [13,57].

Finally, storage conditions and optional finishes can be used to adjust bioreceptivity. Storing the concrete in CO_2 chambers accelerates the carbonation and lowers the pH [41,132]. Adding surface finishes and coating alter the surface subsequently but must be renewed in regular intervals. Commonly used coatings are water repellents and biocides [18,30,57,71,126,127], but coatings with growth-promoting abilities might have a promising future.

8. Conclusion

Subaerial biofilms consist of a multitude of different organisms like fungi, algae, cyanobacteria, and bacteria, glued together by extracellular polymeric substances (EPS). Biofilms are complex and self-sustaining miniature ecosystems, dependent on environmental, biological, and material intrinsic parameters. The material intrinsic bioreceptivity is a crucial factor in the initial biocolonization and long-term establishment of biofilms. This bioreceptivity is governed by surface characteristics like roughness, porosity, pH value and water retention capabilities. Designing concrete with set bioreceptivity starts with choosing, adjusting, and testing concrete type and recipe. Further adjustments can be made during concreting and storage, with possible final touches like surface finishes.

9. Outlook

Until today, there are different perceptions on biofilms, ranging from deteriorating and harmful to more recently a means of design with added value. To fully understand the interactions between substrate and biofilm, combining both microbiological and material science fundamentals is crucial. Following an interdisciplinary approach, current knowledge can be used to develop purpose-oriented building materials, regardless of if the desired properties are bioreceptive or biocidal. This requires designing suitable and standardized measurement methods. Corresponding to the requirements of the application, structurally essential material properties like strength and durability must be tested. Additionally, set-ups to test relevant material properties like pH and water retention must be specifically adapted for the context of assessing bioreceptivity. Based on this initial characterization, a uniform laboratory measurement concept for evaluating bioreceptivity must be designed. Monitoring biofilm formation and growth must be standardized to make results comparable. Final examinations allow to determine and quantify occurring biofilm – substrate interactions like leaching or deteriorating. Going one step further, when developing bioreceptive concrete engineers and architects should also be included. Here additional factors like building heat flows can be considered, irrigation system planned, and an aesthetic rating system applied. In our working group a follow up project designing algae façade panels is not only utilizing the basic research done so far but also considering the previously discussed topics.

Purpose oriented concrete has the potential of positively impacting the environment. In case of aiming for low bioreceptivity the use of harmful and biocidal coatings can be reduced while bioreceptive materials create additional green spaces. Further research is reasonable and promising.

CRediT author statement

Leonie Stohl: Conceptualization, Investigation, Writing - Original Draft, Visualization, Writing - Review & Editing, Tanja Manninger: Conceptualization, Writing - Review & Editing, Julia von Werder: Conceptualization, Project administration, Frank Dehn, Writing - Review & Editing, Anna Gorbushina, Conceptualization, Writing - Review & Editing, Birgit Meng: Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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