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Bioreceptive concrete: State of the art and potential benefits

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Implementing nature in cities has great potential to improve urban liveability by providing ecosystem services, which can help mitigate heat stress, improve air quality, attenuate noise, and reduce rainwater run-off. However, widespread adoption of urban nature and green building typologies is still limited due to their costs, environmental impact, and space constraints. Bioreceptive concrete can form the basis of a new green building typology, where the concrete mixture is adjusted to allow for biological growth, specifically mosses, to occur on its surface.

This literature review aims to give an overview of the current state of the art on bioreceptive concrete as a material in general and specifically the (potential) ecosystem services provided by the mosses growing on this bioreceptive concrete.

This review shows that bioreceptivity can be achieved in concrete in several ways, including minor adjustments to standard concrete recipes. While quantitative data on the ecosystem services provided by mosses in an urban context is still limited, potential gains appear significant. The main challenges lie in the durable long-term development of mosses on the bioreceptive concrete and the valuation through quantification of the ecosystem services they provide. However, moss-receptive concrete shows promise as a new green building typology if these challenges are bridged.

Keywords: Bioreceptivity, bioreceptive concrete, ecosystem services, moss

1 Introduction

The urban population is steadily increasing; by 2050, it is expected to reach 6.68 billion people [1]. Cities worldwide already face several urbanisation-related issues, such as air and noise pollution and their associated health risks [2-4]. Furthermore, changes in land use caused by urbanisation have already increased flood risks and thermal stress experienced by urban inhabitants, as well as a loss of local biodiversity, which is expected to be compounded by the effects of climate change [5-7]. To combat these problems, policymakers, designers and urban planners are increasingly shifting towards using the ecosystem services urban biodiversity provides [8, 9]. While the value of ecosystem services has been recognised for a long time, it truly gained traction in 1997 when two seminal publications on the significance of ecosystem services were published. In the first of these publications, Daily [10] describes ecosystem services as "the conditions and processes through which ecosystems, and the species that make them up, sustain and fulfill life"(p. 3). In the second, Costanza, et al. [11] calculated the value of all global ecosystem services to be between 16 and 54 trillion USD a year, with an average of 33 trillion USD a year more than the annual global gross national product at the time. For this calculation, ecosystem services were grouped into seventeen main categories (Table 1).

Based on this list, it can be concluded that, at least conceptually, ecosystems could provide solutions to location-specific sets of socio-environmental problems in urban areas. As a review by Manso, et al. [12] shows, urban ecosystems such as green walls and vegetated roofs can provide several ecosystem services on either a building or urban scale (Table 2). However, while urban ecosystems based on vascular plants have received much attention from researchers, one category of plants is often overlooked in this research: mosses.

Like vascular plants, mosses (*Bryophyta*) belong to the Kingdom of Plants; nevertheless, they differ from vascular plants in several aspects. For example, they possess rhizoids

List of abbreviations

Abbreviation	Definition
CEC	Crushed Expanded Clay
GBFS	Granulated Blast-Furnace Slag
MPC	Magnesium-Phosphate Cement
OPC	Ordinary Portland Cement
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
UHI	Urban Heat Island
UHPC	Ultra-High Performance Concrete
SAP	Super Absorbent Polymer

rather than roots, which they mostly use to attach to a surface rather than to uptake water and nutrients [13]. Furthermore, unlike most plants, mosses reproduce not through seeds but through spores, vegetative propagules or fragmentation [14]. However, their relationship to water is arguably the most important difference between vascular plants and mosses. Most land plants have a desiccation avoidance strategy, employing various measures, such as stomata and a cuticle (the waxy layer around leaves), to ensure desiccation does not occur. If they do desiccate, these plants inevitably die. Mosses, however, employ a desiccation tolerance strategy instead. Rather than avoiding

Table 1. Overview of the categories of ecosystem services as defined by Costanza, et al. [11]

Ecosystem service	Ecosystem function
Gas regulation	Regulation of atmospheric chemical composition
Climate regulation	Regulation of global temperature, precipitation, and other biologically mediated climatic processes at global or local levels
Disturbance regulation	Capacitance, damping and integrity of ecosystem response to environmental fluctuations
Water regulation	Regulation of hydrological flows
Water supply	Storage and retention of water
Erosion control and sediment retention	Retention of soil within an ecosystem
Soil formation	Soil formation processes
Nutrient cycling	Storage, internal cycling, processing, and acquisition of nutrients
Waste treatment	Recovery of mobile nutrients and removal or breakdown of excess or xenic nutrients and compounds
Pollination	Movement of floral gametes
Biological control	Trophic-dynamic regulations of populations
Refugia	Habitat for resident and transient populations
Food production	The portion of gross primary production extractable as food
Raw materials	The portion of gross primary production extractable as raw materials
Genetic resources	Sources of unique biological materials and products
Recreation	Providing opportunities for recreational activities
Cultural	Providing opportunities for non-commercial uses

desiccation, mosses have evolved to tolerate it, ceasing metabolic function when desiccated and resuscitating themselves upon rehydration, an ability called poikilohydry [15]. Because of this ability, mosses have a thin cuticle compared to other plants [16] and can therefore obtain water and nutrients directly through the surface of their leaves and stems [13, 17]. This combination of traits has led mosses to be one of the most ubiquitous land plants, able to grow in most of Earth's aquatic and terrestrial biomes.

Table 2. Possible ecosystem services provided by green walls and green roofs (based on [12])

Building-scale ecosystem services	Urban-scale ecosystem services
Energy consumption reduction	Urban Heat Island (UHI) mitigation
Improved photovoltaic performance	Urban noise attenuation
Sound transmission reduction	Improved water management
Greywater treatment	Improved air quality
Increased in-service life Increased property value Reduced fire risk	Other (qualitative) benefits (health and well-being, biodiversity, aesthetic value, recreational use of space and urban farming)

More relevant for the urban context, the unique set of traits moss possesses—desiccation tolerance, many possibilities for reproduction, and the ability to gain nutrients from the air—enables them to colonise the very xeric, nutrient-poor, disturbance-prone surface of urban concrete structures, something which most other plants cannot do. As cement is still the second-most used material in the world (after water) [18] and makes up most of our cities (most often in the form of concrete), mosses' ability to colonise concrete could provide a large potential to add more green to our cities. To further encourage moss's colonising abilities, a new type of concrete, so-called bioreceptive concrete, had to be created to be more hospitable for biological growth.

Several researchers have since developed different iterations of this bioreceptive concrete, which can support biological growth on its surface under optimal conditions [19-22]. As growth can take place directly on the surface of the material, and moss can survive periods of drought, no additional technical systems would potentially be necessary. This could reduce the high initial and maintenance costs and the often high environmental impact compared to the materials used in contemporary green walls and roofs [12, 23-25]. Bioreceptive concrete could therefore be a cheaper and virtually maintenance-free alternative to currently available green structures. However, perhaps the most promising application is in infrastructure, where, next to the lower cost, the lower maintenance and lack of the need for irrigation could be a major advantage.

This review paper comprises two parts; the first of which provides an overview of the state of the art of bioreceptive concrete in marine and terrestrial settings, while the second part will discuss potential measures for the development of moss-receptive concrete and the benefits it could provide if applied in the urban environment. The overall focus will be on the use of bioreceptive concrete in an urban context, although other potential uses will also be discussed briefly.

2 Bioreceptivity

Bioreceptivity was initially defined by Guillitte [26] as "the aptitude of a material (or any object) to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration." While this suggests that there is one type of bioreceptivity, in reality, there are multiple ways of achieving, and many types of bioreceptivity in a material such as concrete. This part will discuss these different types of bioreceptivity, the main characteristics of bioreceptive building materials, and how these characteristics can be achieved in a concrete mixture.

2.1 ***Different types of bioreceptivity***

When Guillitte [26] originally defined the term "bioreceptivity", three categories of bioreceptivity were proposed: primary, secondary and tertiary. Primary bioreceptivity is defined as the susceptibility of a material to biological colonisation when its properties are very similar or identical to its initial state (i.e., its properties right after production). Secondary bioreceptivity denotes the bioreceptivity of a material after the material properties have changed naturally over time (i.e., due to colonising organisms or other (environmental) factors). Tertiary bioreceptivity is the bioreceptivity of a material after its properties have been changed due to human activity (i.e. due to cleaning or application of a coating). Guillitte [26] also made a further distinction in whether the material itself is bioreceptive (intrinsic bioreceptivity) or whether a material is bioreceptive due to the deposition of foreign materials, such as soil particles, on the surface (extrinsic bioreceptivity). Guillitte [26] also designated an in-between category called semi-intrinsic bioreceptivity for bioreceptivity that relies on a combination of the material itself and foreign material. Twenty-five years later, Sanmartin, et al. [27] proposed some changes to this initial categorisation of bioreceptivity and its definitions. The main difference is the splitting of tertiary bioreceptivity into two separate categories. The first of these is called tertiary bioreceptivity, and it is meant solely for the bioreceptivity that occurs after cleaning a material. The second of these categories is called quaternary bioreceptivity, and it is intended for bioreceptivity that occurs after adding new materials (such as coatings) to the surface of the original material. The argument Sanmartin, et al. [27] propose for this change is that, while both can be defined as human activity when following Guillitte's [26] definition, cleaning the material or adding chemicals to it are fundamentally different in the way they affect a material's bioreceptivity. Furthermore, they propose disposing of the terms intrinsic, semi-intrinsic, and extrinsic bioreceptivity and suggest using intrinsic and extrinsic factors instead. These terms express whether a material's bioreceptivity is associated with its material properties (intrinsic factors) or external circumstances, such as foreign materials or the microclimate (extrinsic factors). An overview of the differences in categories and definitions between Guillitte [26] and Sanmartin, et al. [27] is listed in Table 3. This paper will use the updated definitions proposed by Sanmartin, et al. [27].

2.2 ***Bioreceptivity of materials***

Most building materials, especially porous materials (e.g., concrete) and those based on biological materials, possess the intrinsic factors necessary for bioreceptivity. However, in their original state, these intrinsic factors are often insufficient to induce biological colonisation. Over time, the physical structure, chemical composition or both changes, either through natural weathering or human intervention, changing the material so that bioreceptivity is achieved. As such, primary bioreceptivity is low for most building materials, but secondary, tertiary, and quaternary bioreceptivity can and does occur (Figure 1).

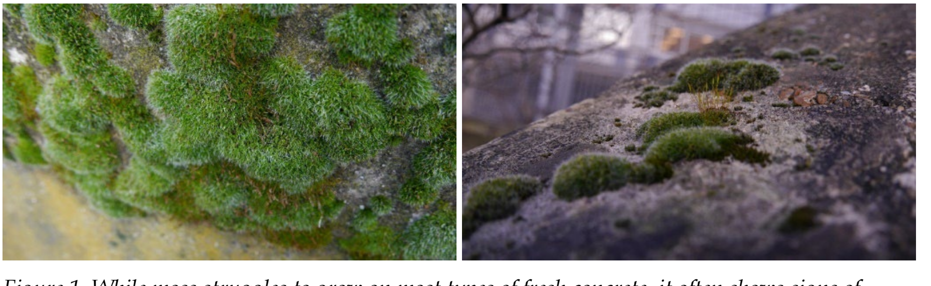

Figure 1. While moss struggles to grow on most types of fresh concrete, it often shows signs of secondary bioreceptivity once the concrete has sufficiently carbonated and weathered.

Table 3. Overview of the categories of bioreceptivity and their definitions as proposed by Guillitte [26] and Sanmartin, et al. [27]

Categories as per [26]	Categories as per [27]	Definitions as per [26]	Definitions as per [27]
Primary bioreceptivity	Primary bioreceptivity	The bioreceptivity of a material when its properties are very similar or identical to its initial state	The bioreceptivity of a material after it has been manipulated (e.g., carved) to perform its final function
Secondary bioreceptivity	Secondary bioreceptivity	The bioreceptivity of a material after its properties have changed naturally over time	The bioreceptivity of a material weathered by environmental factors and/or colonisers
Tertiary bioreceptivity	Tertiary bioreceptivity	The bioreceptivity of a material after its properties have been changed due to human activity	The bioreceptivity of a material after its properties have been changed due to mechanical cleaning
	Quaternary bioreceptivity	-	The bioreceptivity of a material after its properties have been changed due to the permanent or semi-permanent integration of chemicals into the original material
Intrinsic bioreceptivity	Intrinsic factors	Bioreceptivity caused by the properties of the material itself	Factors related to the material itself induce bioreceptivity
Extrinsic bioreceptivity	Extrinsic factors	Bioreceptivity caused by the properties of foreign material	External factors that induce bioreceptivity
Semi-Intrinsic bioreceptivity	Disposed	Bioreceptivity caused by a combination of the properties of the material itself and a foreign material	

The increase of bioreceptivity during a material's lifecycle is often seen as unfavourable due to its deleterious effects on the material. This is often called “biodeterioration”, defined by Hueck [28] as: “any undesirable change in the properties of a material caused by the vital activities of organisms”. Most initial research on bioreceptivity primarily focused on understanding what causes bioreceptivity in stony building materials, intending to avoid biological growth and its associated biodeterioration. Researchers found that the hydraulic properties [29-32], surface roughness [29, 30, 33], substrate pH [31, 33-35], and phosphorus content [36] all play a role in the bioreceptivity of these materials.

*2.3 **Bioreceptive concrete***

In the last two decades, a new field of research has emerged, which, rather than mitigating biological growth on materials, aims to use the knowledge of its intrinsic factors to produce building materials that have an improved (primary) bioreceptivity. Although some work has been done on other building materials, including glass [37], wood [38], and brick façades [39], most of this research has focused on concrete. The reason for this is two-fold. Firstly, concrete is the most used construction material worldwide, with global cement production equating to an estimated 4.1 billion tonnes in 2022 [18]. Secondly, concrete already possesses some of the inherent factors necessary for bioreceptivity. It is (generally) a porous material with a rough surface that can retain water. Moreover, as the concrete naturally becomes colonised by organisms over time, its mineralogical nature seems suitable for the growth of at least certain organisms. As such, research has started on improving the bioreceptivity of concrete in order to create concrete with a high (primary) bioreceptivity. These bioreceptive concretes can be roughly divided into three categories. The first is concrete for use in marine environments, which is meant to be used underwater or in intertidal zones. The second and third are both meant for use in a terrestrial setting. The former consists of traditional concretes, similar to the concrete most often used in construction, and the latter of permeable or highly porous concretes, which have much higher porosity and are water permeable. All categories have different requirements and use cases, which will be discussed below.

2.3.1 Marine concrete

Bioreceptive concrete for use in a marine or intertidal environment is the most researched category, as it holds great potential for constructing artificial reefs and improving coastal biodiversity. It also has the least stringent material requirements for biological colonisation. Where organisms on concrete in a terrestrial environment are constantly exposed to drought and harsh (UV) lighting conditions, organisms growing on concrete in a marine or intertidal environment usually have an abundant water supply and, depending on the growing depth, have to deal with little to no direct sunlight. Therefore, the material does not need to act as a water source, nor does it need to provide shading from UV radiation. Instead, marine bioreceptive concrete must protect from shearing stress and impact caused by oceanic water flow.

As such, the most investigated set of measures for improving the bioreceptivity of marine bioreceptive concrete, and the one that has a positive impact in all studies, is either increasing the surface roughness at an mm-scale or the application of a surface pattern at a cm-scale (Table 2). By doing so, microhabitats are created, which aquatic organisms can more easily colonise. Furthermore, a more complex surface pattern creates many different microhabitats, increasing species richness in the organisms colonising the concrete [40, 41]. However, Coombes, et al. [42] did find that there appears to be an optimum in the degree of surface roughness which is applied to the concrete, with the best results obtained with an intermediate degree of surface roughness (grooves cut in concrete) and diminishing biological growth—compared to intermediate samples—with higher degrees (exposed aggregate).

Another set of measures that has been closely examined, is changing the chemical composition of the concrete, with most researchers focusing on the partial replacement of Ordinary Portland Cement (OPC) with granulated blast-furnace slag (GBFS), a pozzolanic waste material from the metal industry. Most researchers found that this measure increased bioreceptivity compared to pure OPC mixtures (Table 4), which is usually attributed to the lower surface pH this causes [43]. Guilbeau, et al. [44] also found that adding amorphous silica and accelerating carbonation reduce the concrete surface's pH, which was found to improve bioreceptivity. However, Hsiung, et al. [45] found little evidence that a lower pH improves bioreceptivity, although this was only tested in a saltwater environment. Overall, the partial replacement of OPC with a pozzolanic material, particularly GBFS, generally seems to improve bioreceptivity. This is often attributed to the lowering of the material its alkalinity, however, the exact pathway through which this occurs is still contentious. Using pure GBFS or fly ash (a pozzolanic waste material produced by the coal industry) in combination with an alkaline activator, also known as alkali-activated cement or geopolymer concrete, has seen mixed results, with Guilbeau, et al. [44] finding that alkali-activated cement types performed better than pure OPC or OPC mixed with GBFS or fly ash. However, Ly et al. [46] found the opposite, with pure alkali-activated cement types performing worse than a mixture of OPC with GBFS. Other possible improvements to bioreceptivity include using alumina-rich cement [46] and green formwork oil on the concrete surface [43]. In contrast, one study found that the use of a plasticiser may have a negative effect [43].

A third set of measures that can improve the bioreceptivity of marine concrete is increasing the porosity of the concrete, with a high porosity found to be beneficial to growth by Guilbeau, et al. [44] and Perkol-Finkel and Sella [46]. However, Morin, et al. [47] found no such benefit. It should be noted that rather than being used for increased water retention or the inclusion of other substrates, as is often the case for terrestrial bioreceptive concrete, this porosity is mainly meant to create microhabitats for marine organisms to settle into.

The final set of measures that has been tested is the use of different aggregates, with predominantly mixed results. The use of crustose coralline algae yielded no lasting benefits [48]. The use of seashells was found to be beneficial by Dennis, et al. [49]; however, Potet, et al. [50] and Hanlon, et al. [51] found no significant effect. The use of hemp fibres [49] and ceramic waste [52] improved bioreceptivity, which could be attributed to the increased surface roughness caused by the aggregate.

In conclusion, increasing the surface roughness is the primary way of improving the bioreceptivity of marine concrete, followed by the partial replacement of OPC with GFBS or possibly amorphous silica, the latter of which may be due to reduced alkalinity. Other measures that may increase bioreceptivity but are only have limited research available are the use of porous or even foamed concrete, alumina-rich cement, green formwork oil, and ceramic waste or hemp fibres as an aggregate material. Based on limited research, plasticisers should be avoided. The effect of pH on biological growth is not yet apparent and may depend on the water conditions and species of colonising organisms.

2.3.2 Terrestrial concrete

Bioreceptive concrete for terrestrial use adds one major challenge to the challenges faced by bioreceptive concrete for a marine environment: the lack of water. In a marine or intertidal environment, water is abundant, and if dry periods do happen, they are usually short in scope. However, water on concrete surfaces is often very scarce in terrestrial environments and is only abundantly available during or directly after precipitation

Table 4. Different measures tested by researchers to improve the bioreceptivity of concrete in a marine environment

Measure		Positive effect	Negative effect	Mixed/No effect
Surface texture	Increasing surface roughness	[40, 42, 47, 48, 50, 53-55]		
	Applying surface pattern	[40, 41, 46, 51, 53, 54]		
(Chemical) composition	Partial replacement of OPC with GBFS	[43, 47, 53, 56, 57]		[44]
	Partial replacement of OPC with fly-ash			[44]
	Partial replacement of OPC with amorphous silica	[44]		
	Use of alumina-rich cement	[46]		
	Use of alkali-activated cement	[44]	[57]	
	Use of plasticiser			[43]
	Use of green formwork oil	[43]		
pH	Lowering pH	[44]		[45]
Porosity	Use of highly porous/foamed concrete	[44, 46]		[47]
Aggregate/filler	Use of seashells	[49]		[50, 51]
	Use of ceramic waste	[52]		
	Use of hemp fibres	[49]		
	Use of crustose coralline			[48]
	Algae			

events. While mosses (and most other terrestrial colonising organisms) are highly drought-tolerant, they do require water for the initial establishment and growth on the concrete surface. As such, the water retention capacity of bioreceptive concrete becomes a concern.

Several measures have therefore been proposed and investigated to improve the amount of water that can be stored in the concrete, as well as ways of retaining said water (Table 5). This can be achieved by increasing the aggregate's porosity, the water-to-binder ratio, or both. Two types of coarser aggregate investigated are crushed expanded clay (CEC) [20] and vermiculite [39], both of which improved bioreceptivity. Similarly, the addition of superabsorbent polymers (SAPs) to the concrete mixture can increase water retention [21, 58]. Using a non-optimal aggregate packing by employing a coarser aggregate has also been found to improve bioreceptivity, likely due to the increased porosity this causes in the overall concrete structure [21]. Increasing the porosity of the cement paste, on the other hand, has given mixed results. Veeger, et al. [20] found no significant increase in bioreceptivity when increasing the water/cement factor (wcf) from 0.5 to 0.6. Lubelli, et al. [39], on the other hand found that more porous mortar mixtures – achieved by changing the binder aggregate ratio, aggregate type and aggregate size – performed better in terms of bioreceptivity.

Another method to increase water capacity and retention is by changing the surface texture. Veeger, et al. [20] found that increasing the surface roughness of the concrete by employing a surface retarder increased the water absorption of the concrete. Furthermore, the rougher surface provided organisms with protected microhabitats, thereby improving establishment and survival. However, research by Manso, et al. [19], [59] shows that increasing the surface roughness by reducing the amount of binder in the mixture has no clear effect. Furthermore, Mustafa, et al. [22] found that applying a surface pattern also improved bioreceptivity by directing the water flow on bioreceptive concrete panels and that this can be used to control where growth occurs. The latter was also observed by Veeger, et al. [60], who demonstrated that a panel in which bioreceptive concrete and ultra-high performance concrete (UHPC) were combined developed biological growth solely on its bioreceptive parts.

Lastly, the effect of changes to the chemical composition of the concrete on its bioreceptivity is an area that has been investigated. Nowadays, most concrete is made on the basis of Ordinary Portland Cement (OPC). However, the pH of concrete containing

Table 5. Different measures tested by researchers to improve the bioreceptivity of concrete in a terrestrial environment

Measure		Positive effect	Negative effect	Mixed/No effect
Surface texture	Increasing surface roughness (surface retarder)	[20, 60]		
	Increasing surface roughness (binder/aggregate ratio)			[19, 59]
	Applying surface pattern	[22]		
(Chemical) composition	Use of MPC cement	[19]	[20, 59]	
	Use of lime-trass cement	[39]		
	Use of hydraulic lime	[39]		
	Use of bone ash	[20]		
Porosity	Increased wcf			[20]
	Porous binder	[39]		
Aggregate/filler	Use of SAPs	[21, 58*]		
	Use of CEC	[20]		
	Use of vermiculite	[39]		
	Use of coarser sand fraction	[21]		

OPC is very high, at least initially, which has been linked to a decreased bioreceptivity in other stony materials [31, 33-35]. In bioreceptive concrete and mortar, changing to other binders has seen mixed results. Lubelli, et al. [39] did find that lime-trass and hydraulic lime cements improved the bioreceptivity of mortar, as both are characterised by a high rate of carbonatation (thus reducing pH) and improved water absorption and retention as compared to OPC-based mortars. Another binder option investigated for improving bioreceptivity is magnesium phosphate cement (MPC), which has been suggested to be more bioreceptive due to its lower pH than regular OPC [61]. Manso, et al. [19] indeed saw improved bioreceptivity when using MPC compared to OPC when testing under interior conditions; however, they found the opposite in a later outdoor experiment [59]. Similarly, Veeger, et al. [20] found that MPC-based concrete mixtures performed worse than CEMIII/B-based ones, although the latter had significantly higher pH levels at time of inoculation with the biofilm (11.49 - 12.18 for the CEMIII/B samples and 10.26 - 10.89 for the MPC samples). Whilst this suggests that pH might not be an inhibitor for the growth of at least some species of organisms growing on the bioreceptive concrete, no research has been conducted that directly investigates the effect of pH on the effectiveness of bioreceptive concrete.

The effect of the addition of nutrients to the concrete mixture has so far not been extensively investigated, although Veeger, et al. [20] did find that the addition of bone ash (a pozzolanic material containing phosphorus) did improve bioreceptivity.

In summary, the main measures that can be taken to improve the bioreceptivity of concrete in a terrestrial setting relate to improving its hydrological properties, either by changing to a more porous aggregate, filler, binder, or a combination of these and by changing the surface texture of the material. The addition of nutrients to bioreceptive concrete mixtures appears to be another promising measure, though research on this is limited. Finally, the effect of pH on bioreceptivity requires further investigation.

An important constraint of most research on bioreceptive concrete in a terrestrial environment is that most experiments are done in a laboratory setting. Research done in an outdoor environment has shown that natural colonisation is very slow [39, 59], suggesting that it may be necessary to establish initial growth under a more controlled environment. However, when mosses and algae are grown under controlled indoor conditions (stable room temperature, high humidity, controlled lighting conditions and no environmental stressors), subsequent outdoor survival is often poor, as they seemingly do not develop the protection mechanisms necessary for survival under these harsher conditions [60, 62]. As such, cultivation and a regime for adaptation to outdoor conditions needs to be developed to ensure both rapid growth and long-term survival, research into which is currently ongoing by Veeger (Figure 2).

Figure 2. test set-up used to stress-test different growing regimes

2.3.3 Permeable concrete

The last type of bioreceptive concretes is not a bioreceptive concrete in the strictest sense. Instead, it is concrete that has extrinsic factors which make it bioreceptive. This typology uses extremely porous concrete, often with a highly irregular surface, which is usually achieved by combining a non-optimal aggregate packing with a low binder content. The large pores are then filled with a growing substrate. So far, all iterations of this concrete use an irrigation system to keep the substrate wet [63-67]; therefore, it is not currently considered self-supporting.

Both Riley, et al. [63] and Jakubovskis, et al. [64] combined this permeable concrete typology with a bio-based growth substrate and a structural concrete backing to successfully create growth on the surface of their panels. The latter is necessary as the porous concrete's strength is significantly reduced compared to regular concrete.

Jakubovskis, et al. [64] also used expanded clay as an aggregate, potentially allowing for water storage in the porous concrete itself. Other cases did not apply a structural backing, such as that explored by Bao, et al. [67], who achieved positive results using bioreceptive porous concrete as a green soil slope stabiliser. In another study, Hitti, et al. [65] investigated bioreceptive porous concrete as an alternative to rock wool in a hydroponic system. They concluded that bioreceptivity was mainly related to the pH and electrical conductivity of the substrate, as high pH and EC levels can negatively affect nutrient availability and uptake. Similarly, Zhao, et al. [66] found that the lower pH of MPC-based bioreceptive porous concrete led to improved growth compared to OPC-based samples.

Overall, this typology of bioreceptive concrete appears promising, as it allows for a wider variety of plants to grow on and in the concrete, as the concrete itself is no longer the growing substrate. However, structural backing will be necessary in most use cases, as its strength is significantly reduced, even compared to regular bioreceptive concrete. Furthermore, pH appears to play a more prominent role in this typology than the other terrestrial bioreceptive concrete type. This might be caused by the higher sensitivity of the plants used or a higher leaching potential due to the higher exposed surface area of the concrete.

3 Benefits of bioreceptive materials

Whilst bioreceptive concrete as a material has been gathering increased scientific attention in the past decade, research on the benefits of the mosses growing on said concrete is lagging. Nevertheless, quantifying the ecosystem services provided by these mosses is essential in determining the value and thus, the viability of bioreceptive concrete as a green building typology. Based on the ecosystem services provided by other plants, some inferences can be made on which ecosystem services mosses can be expected to provide. However, the differences in physiology and morphology compared to most other plants will cause the extent to which these services are provided to differ. As of yet, little quantitative research has been done on the ecosystem services mosses provide in the urban environment. Therefore, this part aims to explore the mechanisms through which other plants provide their ecosystem services and what impact the differences in physiology and morphology of mosses may have on the number and rate of ecosystem services. The focus in this review will be on the four urban-scale, quantifiable ecosystem services provided by green building structures (improved air quality, UHI mitigation, urban noise attenuation and stormwater retention) as defined by [12] and summarised in Table 2.

3.1 *Improved air quality*

Perhaps the most promising ecosystem service mosses provide is removing pollutants from the air. Fine dust, or particulate matter (PM), is a type of pollution that consists of a mixture of organic pollutants (such as polycyclic aromatic hydrocarbons or PAHs) and inorganic pollutants (such as heavy metal ions). All plants can filter the air by adsorbing PM on their leaf surface and absorbing pollutants in their plant tissue. However, mosses are particularly well suited to this task due to a combination of several factors. They have a very high leaf-to-surface area ratio [68], meaning they have a comparatively large area to capture pollutants. They mostly lack the cuticle (a waxy layer protecting leaves from desiccation) that other plants have [16, 69], allowing for the easy absorption of foreign particles (such as heavy metal ions) into the moss tissue. Finally, their chemistry and physiology allow for a high retention of pollutants on their surface and tissue [70].

The combination of these factors has led mosses—often in the form of moss bags—to become one of the main bio monitors used in field experiments, with extensive research to prove their use [71]. However, while this type of research focuses on using mosses as indicators of current and past air quality, research on how they affect air quality themselves is very scarce. A study by Haynes, et al. [72] found that moss turfs growing by the roadside captured significantly more PM on their surface as compared to tree leaves (5.60 - 33.00 mg per gram of dry weight vs. 2.15 - 10.24 mg per gram of dry weight). Research on a moss-based filter concept using forced airflow, showed that filtered air had an 11-38% lower concentration of PM [73].

3.2 *UHI mitigation*

There are three main ways mosses can reduce heat stress in an urban environment, all identical to other plants, though they are expected to have a different impact. In regular green façades, the primary cooling effect can be attributed to the shading of the underlying material by the plants [74]. Rather than sunlight hitting the material surface, the plants reflect or absorb the light. In the case of bioreceptive concrete, this means that less sunlight is reflected overall, as the albedo of mosses is lower than that of bioreceptive concrete (0.10-0.40). However, this is offset by the lower thermal mass of moss, which causes less heat energy to be stored overall and the stored energy to dissipate more rapidly [75]. A lower proportion of the cooling effect of regular green façades can be attributed to evapotranspiration [74]. As water evaporates, heat energy is extracted from the green façade, thereby cooling it. This cooling pathway is particularly promising for mosses, as they can store large amounts of water, up to 4.7L per m^2 [75]. The final way plants can cool structures is through insulation [74]. By forming an insulating barrier between the air and the structure, less heat is transported to the structural material underneath. Regarding insulation, moss has excellent insulating properties [76, 77], even compared to other plants [78]. These insulating properties have led to the investigation of moss-based thermal insulation panels [e.g. 79, 80]. Initial experimental work has shown that the application of moss on concrete leads to a 0-5 degrees Celsius reduction when dry [75]. When wet, bare panels and moss-covered panels both showed a 5-10 degrees Celsius reduction in temperature, with the moss-covered panel still 2-5 degrees Celsius cooler, and the cooling effect of the water was present for longer due to the moisture retained by the mosses. It was also found that the surface temperature of the mosses was 2-3 degrees Celsius higher than that of the bare concrete, which can be explained by the lower albedo, low thermal mass, and high insulating properties of the moss. However, whether the moss-covered panels lost their heat faster during the night has not been investigated, nor has the effect of different moss species.

3.3 ***Urban noise attenuation***

Plants can attenuate noise by both scattering and absorbing sound energy [81, 82]. Noise scattering occurs mainly at the leaf surface, where the different angles of the leaves redirect sound in different directions, potentially leading to destructive interference [81]. Noise absorption can take place through two different processes. The first is through damped vibrations, where sound waves vibrate the plant leaves and part of this vibration is converted to heat energy. The extent of the absorption and the absorbed frequencies mainly depend on the size and orientation of the leaf compared to the sound source [83]. The second is through visco-thermal damping, where air between leaves and in the plant substrate acts as a viscous fluid, which, when moved by sound, is subjected to boundary layer effects which convert the sound energy to heat [81].

As discussed previously, mosses are good thermal insulators, as they can trap small pockets of stagnant air between their leaves. Whilst good for thermal insulation, this will also induce visco-thermal damping of sound energy. Combined with the high leaf surface area of mosses, which leads to sound scattering, it can thus be expected that mosses are proficient sound absorbers. This expectation was confirmed by Li, et al. [84], who found that noise absorption of tree bark was higher when moss was present. Similarly, Reethof, et al. [85] found that forest floors with moss covering had higher acoustic absorption than those with leaf litter or bare soils. Like moss-based thermal insulation panels, moss-based acoustic solutions have also been investigated. Kim, et al. [86] used a mixture of moss and either beer or buttermilk to achieve noise reduction coefficients of up to 0.189 in the 250-2000Hz frequency range. Similarly, Sleinus, et al. [87] achieved sound absorption coefficients of 0.1 at 250Hz and up to 0.95 at 4000Hz with a mixture of flax, organic lake sediment and *Sphagnum* moss. Overall, mosses can function as noise absorbers, with higher absorption values achieved at higher frequencies. However, as the substrate is the primary source of noise absorption in other green building systems [81], it remains to be seen how mosses will perform when grown on bioreceptive concrete, where no such porous substrate is present.

3.4 ***(Storm)water retention***

The main problems caused by extreme rainfall are two-fold. Peaks in rainwater run-off may cause local flooding by overwhelming drainage capacity, and large amounts of total rainwater run-off can overwhelm the treatment capacity of wastewater treatment plants, leading to combined sewer overflows, where untreated wastewater is discharged directly into surface water [88]. Plants can help mitigate this problem by retaining rainwater, reducing the total amount of water that needs to be processed by wastewater treatment plants, and delaying and attenuating peak rainwater run-off rates responsible for overwhelming the local drainage system [12]. In contemporary green building systems, most of the water is stored in the substrate. The plants are responsible for the evaporation of this stored water, thereby recovering the water storage capacity of the substrate [89].

Mosses lack this substrate, which is usually responsible for most of the water storage in other green building systems. However, unlike the plants used in these other systems, mosses have evolved to hold on to large amounts of water either on their shoots or in their colony structure. An experiment on the water retention of 13 arctic moss species by Gimingham and Smith [90] found that these moss species could retain between 1.769 and 11.707 times their body weight in water. Porter [91] even describes how the bog species *Sphagnum papillosum* can hold between 20 and 22 times its body weight in fluids. Brandão, et al. [92] have found that mosses, when added to green roof vegetation, can both increase total water retention as well as speed up recovery of the water storage capacity after a rainfall event due to evapotranspiration.

When looking more specifically at moss species growing on concrete in an urban environment, *Bracchytecium rutabulum* can absorb 16.1 times its body weight in water [93]. Verhoeven [75], when testing moss species growing on bioreceptive concrete, found that *Rhynchostegium confertum* could absorb 3.11 times its weight, *Bryum capillare* 3.54 times, *Syntrichia ruralis* 7.88 times, and *Eurhynchium striatum* 11.73 times. For *Bryum capillare*, the best-performing moss on a per surface area basis, this would mean a total absorption of 4.7L water per m^2. Theoretically, this moss species could therefore mitigate 4.7mm of water run-off. In practice, however, absorption rates and water retention differ per species [90]. Where the former determines whether the rainwater can be absorbed quickly enough to retain all the rainwater falling on the plant. the latter is relevant for how quickly water is evaporated after a rain shower, thus resetting the moss's water absorption potential. This can also be seen in green roofs, where the so-called antecedent dry weather period determines the effectiveness of green roofs in rainwater retention and run-off reduction [94]. In conclusion, while mosses are able to retain large amounts of water, further investigation into their rate of absorption and evaporation are needed to determine their performance in terms of (storm)water retention.

4 Conclusions and future outlook

This review provides an overview of past and ongoing research on bioreceptive concrete and the mosses that grow on it. Bioreceptive concrete as a material has already seen success when used in a maritime setting and shows promise for use in a terrestrial setting, mainly because the measures that can be taken to make concrete more bioreceptive are relatively straightforward and inexpensive. Most measures that improve the water retention properties of the concrete, increase surface roughness, or add nutrients to the concrete do indeed improve bioreceptivity, the role of pH is unclear as of yet. The biological component is currently the main challenge in the large-scale application of bioreceptive concrete in an urban context. Natural outdoor colonisation is slow, whereas indoor controlled growth is fast but has poor long-term survivability when transferred from indoor to outdoor conditions. The development of a growing regime that optimises growth and induces environmental hardening to outdoor conditions of the mosses is therefore necessary.

When it comes to the ecosystem services provided by mosses, very little quantitative data on their effect in an urban setting is currently available. Based on the ecosystem services provided by other plants and their mechanisms as well as the ecosystem services provided by mosses in natural ecosystems, the extent of the services provided by mosses seems promising. Preliminary experimental results also support this notion.

Overall, bioreceptive concrete holds great potential, as it removes the need for technical systems, such as irrigation, or additional structures, whilst likely maintaining many of its benefits in terms of ecosystem services. Therefore, future research on both the development of a moss layer on the bioreceptive concrete and on quantifying the ecosystem services provided by mosses will have to show whether bioreceptive concrete has the potential to be a new urban typology and be a viable alternative to other green structures.

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