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DOI
10.1016/j.jobe.2021.102545

Publication date
2021

Document Version
Final published version

Published in
Journal of Building Engineering

Journal of Building Engineering 44 (2021) 102545

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Making bioreceptive concrete: Formulation and testing of bioreceptive concrete mixtures

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ARTICLE INFO

Keywords:
Bioreceptivity
Concrete
Crushed expanded clay
Bone ash
wcf
Surface retarder

ABSTRACT

Increased urbanisation will put an increasing strain on our green spaces, which is expected to have a significant effect on our physical and mental health, as well as the health of our ecosystems. As such it is important to integrate more green spaces in our urban fabric. One way of doing this is by making use of so-called bioreceptive concrete on our façades and other structures, which allows for biological growth to take place on the concrete substrate itself, without requiring any additional systems or maintenance. However, the challenge is to create an affordable concrete mixture that is sufficiently bioreceptive for biological growth to take place. As such, in our research we test four possible measures to make concrete more bioreceptive: changing the aggregate to CEC (crushed expanded clay), adding bone ash to the mixture, increasing the wcf (water cement factor) and using a surface retarder on the concrete. Of these measures, changing the aggregate to CEC ($p = 0.024$), the addition of bone ash ($p = 0.022$) and the use of a surface retarder ($p < 0.001$) were found to significantly increase bioreceptivity. Increasing the wcf factor, however, was not found to significantly increase bioreceptivity ($p = 0.429$). It was also found that whereas it was previously though a pH below 10 is necessary for biological growth to take place, this does not appear to be the case. Although further research under natural conditions is necessary, the creation of an inexpensive bioreceptive concrete looks to be feasible.

1. Introduction

By 2050 over 68% of the world population will live in urban areas, constituting an increase of 2.5 billion people to the worldwide urban population [1]. If no measures are taken, this increased urbanisation will likely lead to a further reduction of the amount of green areas in and around our cities. This reduction in green spaces brings with it several problems, including but not limited to, a loss in biodiversity, heat stress, increased air pollution and more, bringing with them concerns for ecological and public physical and mental health [2–4]; McKinney, 2008). This means that the addition of extra green spaces in our cities is necessary in order to mitigate these problems. However, the addition of green spaces on ground level is not always possible in cities, due to spatial constraints. (see Figs. 4 and 5)

As such, more and more designers, planners and inhabitants of cities include green in the buildings within the cities themselves through the use of green roofs and façades. However, whilst green roofs and façades do provide plenty of benefits, they require a separate system that attaches them to the building. This means that these systems incur additional costs both in construction and maintenance, while they also put higher structural demands on the buildings they are attached to Refs. [5, 6].

Recently a new type of green building material has been touted in the form of bioreceptive materials. Originally coined by Ref. [7]; bioreceptivity is defined as: “the aptitude of a material to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration” (p. 216). This means that if a bioreceptive material were to be used as a façade cladding, the material itself could support biological growth, without the need of having an additional technical system, greatly simplifying green roof and façade systems, thus

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https://doi.org/10.1016/j.jobe.2021.102545
Received 13 January 2021; Received in revised form 26 March 2021; Accepted 12 April 2021
Available online 2 May 2021

potentially reducing their costs.

In nature, these bioreceptive surfaces are inhabited by stress-tolerant species from several domains of organisms, namely bacteria, algae, fungi, lichen and mosses, which together will form biofilms [8]. However, whilst these species are very stress-tolerant, they do still have some requirements that need to be met in the substrate they inhabit in order for them to survive and thrive. The most commonly found material characteristics improving bioreceptivity found by previous observational experiments are high surface roughness, high open porosity, high capillary water content and an abrasion pH below 10 [9]. Some research has also suggested that the addition of phosphorus to the substrate could improve bioreceptivity [10].

There are several options for bioreceptive materials, however concrete appears to be the most promising starting point. Not only because it is the most used material in the building industry [11]; and a bioreceptive variant could therefore have widespread applications, but also because its physiological make-up is similar to that of natural stone. However, normal concrete does not meet the requirements for biological growth to take place, or only in a very limited amount. Hence, such a concrete mixture would have to be developed, for widespread application in the built environment.

Some research has already been done to improve the bioreceptivity of concrete (e.g. Ref. [12]; Fábio et al., 2018; [13,14,60]. However, whilst their results did yield possible bioreceptive concrete mixtures, Fábio et al. (2018) and [14] only focused on aquatic concrete structures, whereas [12,13] used expensive (magnesium phosphate) cements in their mixtures, which will limit its applicability. The aim of this research is therefore to develop and test a bioreceptive concrete mixture based on widely available and commonly used materials to boost their prospect for use in building cladding.

The research question of this research can thus be formulated as follows: "*what changes can be made to a concrete mixture in order to make it more bioreceptive?*" We will formulate a variety of possible measures which might increase the bioreceptivity of concrete, after which their effectiveness will be tested in an experimental test set-up.

2. Materials and methods

2.1. Concrete mixtures

In order to achieve the required material characteristics, it was necessary to perform several changes to a common concrete mixture. Previous research used either magnesium phosphate cement or carbonation chambers to reduce the pH of their concrete samples [13]. However, whilst we did use magnesium phosphate cement (MPC) as a comparison, in this research we aimed to reduce the pH of the concrete through the addition of blastfurnace slag to regular Portland cement (OPC), as this is a common additive in the concrete industry and has been found to reduce the pH of the resulting concrete through increased carbonation [15,16].

Increased surface roughness was achieved through the use of a surface retarder on the samples. This is a commonly used method and not very labour intensive.

Open porosity and associated capillary water content were increased in two ways. First of all, the water/cement factor (wcf) was increased. Any water in the mixture that is not used in the hydration of the cement will evaporate, leaving behind an increased pore structure [17]. Additionally, the large diameter aggregate of the concrete was changed for crushed expanded clay, as this has been found to successfully increase the porosity of concrete [18]. As a wcf of 0.6 is the maximum allowed by code NEN EN 206, this was used as the upper limit, whereas the samples with a lower wcf used a wcf of 0.5.

The addition of phosphorus is more complicated, as the added phosphorus has to be both in a biologically available form and not deteriorate the concrete. As such, we settled on bone ash, an organic material made out of burned cattle bones, that consists mainly of CaO and P_2O_5 [19]. It has also been successfully used as a partial cement replacement in concrete [20].

As we did not only want to determine whether or not this would result in a bioreceptive concrete measure, but also whether individual measures were effective or not, all possible combinations of mixtures were used, resulting in 16 different mixtures per cement type (see Table 1).

2.2. Concrete samples

Of each mixture 4 samples were produced, measuring 50 × 50 × 30mm. Two samples were used for the measurement of the mixture's characteristics, and the other two were used for the bioreceptivity testing. In addition, two extra mixtures were used, using our partner's standard concrete mixture, to act as a reference.

An overview of the exact ingredients per mixture can be found in Table 2. For the MPC samples river gravel was used as the regular aggregate instead of limestone, as limestone might react with the MPC cement. All ingredients were mixed in a Hobart 5 L mixer with a flat mixer head. The resulting mixtures were then poured into plywood moulds (Fig. 1). For those samples were a surface retarder was used, either Pieri DRC 6/01 (OPC samples) or a combination of sugar and liquid citric acid (MPC samples) was applied to the bottom of these moulds. All mixtures were compacted using a vibrating table. The samples were demoulded after a period of 24 h in the case of OPC samples, or 45 min in the case of the MPC samples. They were then left to harden for another 25 ± 3 days before the inoculation with the algae for the OPC samples, or 4 days for the MPC samples.

2.3. Biofilm extraction and cultivation

For the extraction and cultivation of the biofilm an adapted version of the methods as described by Refs. [21,22] was used. An existing biofilm was collected from the faculty building of Architecture and the Built Environment in Delft (see Fig. 2) by means of a sterilised scalpel, equal to an area of 50 × 50mm. After this, the extracted biofilm was added to an Erlenmeyer containing BG11 liquid growth medium. The Erlenmeyers were exposed to optimal growing conditions at a 12h day/night cycle at a light intensity of 40 μmol $m^{-2}s^{-1}$ at room temperature, and a relative humidity around 95% for a period of 28 days [22–25]. The lighting was provided by a 40 Watt full spectrum LED panel, placed 65 cm above the samples and the humidity was maintained by a Medisana AH665 humidifier. In order to ensure a proper aeration and mixing of the culture, air was pumped into the mixture intermittently by a VT AP-40 air pump. The OPC samples were inoculated with the resulting biofilm 4 weeks after initial extraction and the MPC samples 8 weeks after initial extraction. After 4 and 6 weeks, 50 mL of the liquid biofilm was added to a fresh BG11 solution, to ensure sufficient nutrients were available (see Fig. 3).

2.4. Biofouling of samples and experimental test setup

The concrete samples were biofouled by adding drops of the liquid biofilm to the concrete samples using a pipette. Due to the fact that the OPC and MPC samples were innoculated at different times, a different total volume was added, since the algae density was higher at time of innoculation for the MPC samples. To the OPC samples 4 mL of liquid

Table 1
Overview of the used abbreviations within this paper.

Abbreviation	Meaning
CEC	Crushed expanded clay
MPC	Magnesium Phosphate cement
OPC	Ordinary Portland cement
Wc	water/cement factor

Table 2
Overview of all samples that will be made and their composition. The code in brackets behind the sample number denotes the shortcode that will be used to identify the samples in the rest of the research.

Sample	Aggregate	Cement additive	W/C ratio	Surface retarder
1 (Reg-BA-LW-R)	Regular	Bone ash (10%)	0.5	yes
2 (Reg-BA-LW-S)	Regular	Bone ash (10%)	0.5	no
3 (Reg-BA-HW-R)	Regular	Bone ash (10%)	0.6	yes
4 (Reg-BA-HW-S)	Regular	Bone ash (10%)	0.6	no
5 (Reg-No-LW-R)	Regular	None	0.5	yes
6 (Reg-No-LW-S)	Regular	None	0.5	no
7 (Reg-No-HW-R)	Regular	None	0.6	yes
8 (Reg-No-HW-S)	Regular	None	0.6	no
9 (CEC-BA-LW-R)	Crushed exp. clay	Bone ash (10%)	0.5	yes
10 (CEC-BA-LW-S)	Crushed exp. clay	Bone ash (10%)	0.5	no
11 (CEC-BA-HW-R)	Crushed exp. clay	Bone ash (10%)	0.6	yes
12 (CEC-BA-HW-S)	Crushed exp. clay	Bone ash (10%)	0.6	no
13 (CEC-No-LW-R)	Crushed exp. clay	None	0.5	yes
14 (CEC-No-LW-S)	Crushed exp. clay	None	0.5	no
15 (CEC-No-HW-R)	Crushed exp. clay	None	0.6	yes
16 (CEC-No-HW-S)	Crushed exp. clay	None	0.6	no

Fig. 1. The plywood moulds used for the creation of the concrete samples (left).

biofilm and to the MPC samples 2 mL of liquid biofilm was added. After they were fouled, they were placed in container with distilled water (with a water level slightly below the sample surface) and kept under the same optimal growing conditions as discussed before. All samples were kept under these conditions for 8 weeks, after which their bioreceptivity index was determined.

2.5. Measuring concrete characteristics

Determination of the pH of the concrete samples was done using the method as described by [61]. 10 Grams of the samples was crushed and ground up in a mortar and pestle, which was washed with distilled water

Fig. 2. Photograph showing origin of the original biofilm used in the experiment (right).

and dried before each measurement. After grinding for 2.5 min, 20 mL of distilled water was added and mixed with the ground concrete. After this, the mixture was allowed to settle for 2 min, after which 7.5 mL of the supernatant liquid was extracted and its pH determined using a Metrohm 827 pH meter, calibrated using a 10.01 and 7.00 pH solution.

In order to determine the hydraulic properties of the samples, an adapted method of the one used by Ref. [26] was employed. The samples were prepared by first weighing the samples and then drying the samples in an oven at 37° Celsius for 24 h, after which they were weighed and dried for another 24 h. This process was repeated until there was no weight difference between successive measurements, as 24 h was not sufficient to completely dry all samples. After this the samples were submerged in tap water for 24 h to ensure full saturation of the samples and the surface water was removed using a damp towel. The samples were then exposed to a temperature of 37° Celsius, at low humidity for 48 h. During this process, the weight of the samples was measured after the drying process, after the saturation process, and after 1, 2, 4, 8 and 24 h during the secondary drying process. The weight difference between the fully dried and saturated samples shows the maximum amount of water that can be contained within the sample, whereas the weight measurements during the secondary drying process gives an indication of the sample's ability to retain water.

Surface roughness of the samples was originally to be determined by using White Light Optical Interferometry (WLOI) in Vertical Scanning Interferometry (VSI) mode, as described by Ref. [27]. However, due to the COVID-19 outbreak at the time of this research, the required equipment was not available, and as such a more low-tech approach had to be found. So instead the methodology as described by Ref. [28] was used. A negative of the sample surface is made using a 0.8 mm needle profilometer, which was then photographed using a Panasonic Lumix G6 camera against a white paper held in front of the sky. This photograph was then cropped and converted into a black and white bitmap using Adobe Photoshop CC. This bitmap was then analysed in Mathworks Matlab (version R2020a) using the script provided by Ref. [28]. This gives a Roughness Profile (R), which is defined as the ratio between the true length of the surface trace and its projected length in the surface plane [29]. It is calculated by using the following formula, as given by Ref. [28]:

$$Rp = \frac{\sum_{i=1}^{N-1} \sqrt{\Delta s^2 + (y_i - y_{i+1})^2}}{\Delta s(N-1)}$$

Where:

N = number of evenly spaced sampling points

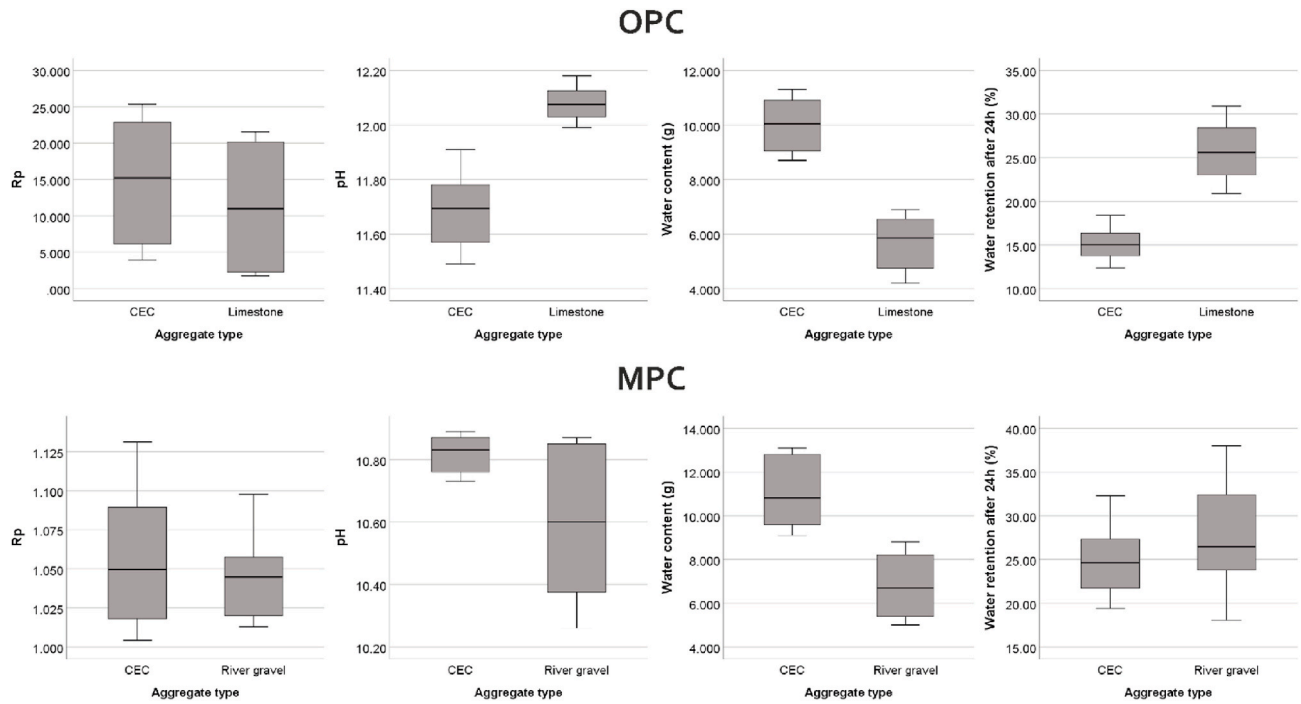

Fig. 3. Overview of the differences between the samples with CEC and regular aggregates for the tested concrete characteristics. In the case of the OPC samples, the group differences for pH ($p = 0.001$), capillary water content ($p = 0.001$) and capillary water retention ($p = 0.001$) were found to be significant. For the MPC samples, only the group difference for the capillary water content ($p = 0.001$) was significant.

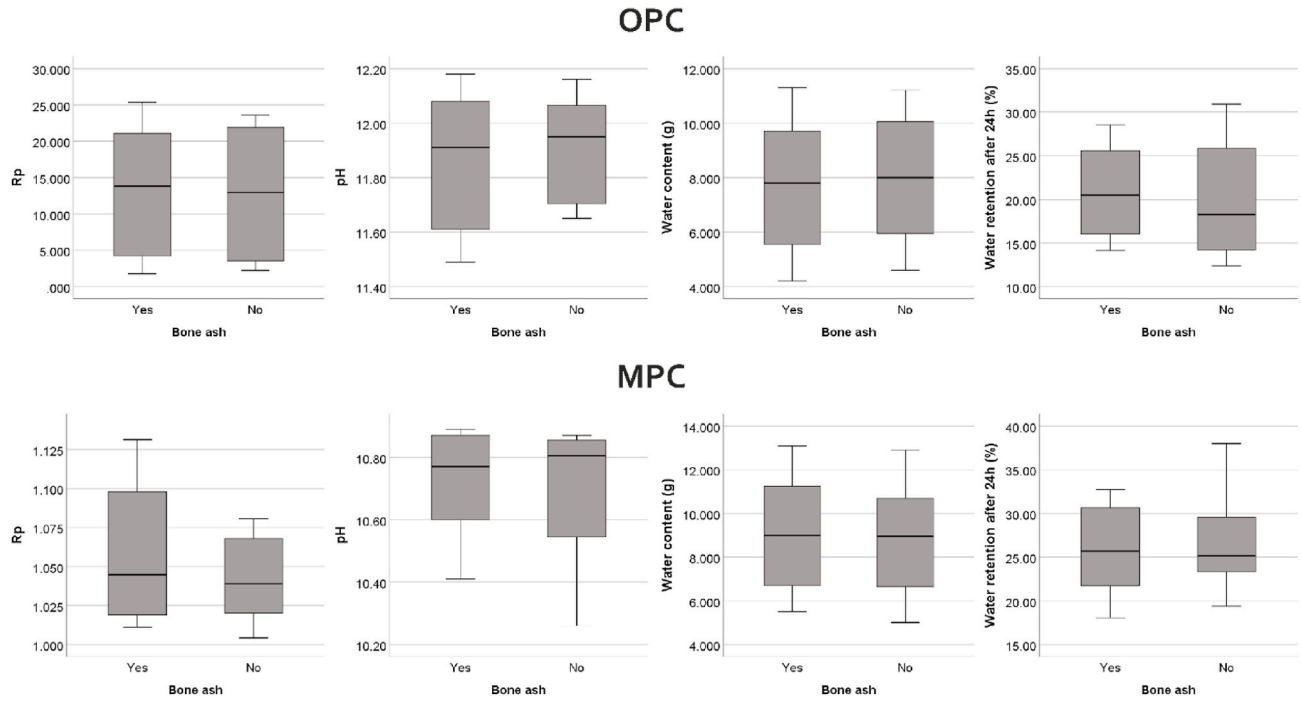

Fig. 4. Overview of the differences between the samples with and without bone ash for the tested concrete characteristics. None of the differences were found to be significant.

s = distance between points along sampling line
y = distance between points normal to sampling line

Therefore, a rougher profile will give a higher ratio. Whilst this method of measuring surface roughness is not the most precise as it is limited by the precision of the needle profilometer (giving a resolution of 0.8 mm), it requires no specialised equipment and has been proven to work well within the field of Geology.

The exact phosphorus contents was not measured, due to not having access to the necessary equipment caused by the COVID19 outbreak. However, it is to be expected that the effect of the measures on phosphorus contents will be straightforward, with bone ash increasing the phosphorus content and the other measures having a negligible effect. Using previous chemical analyses of bone ash done by Ref. [19] it is

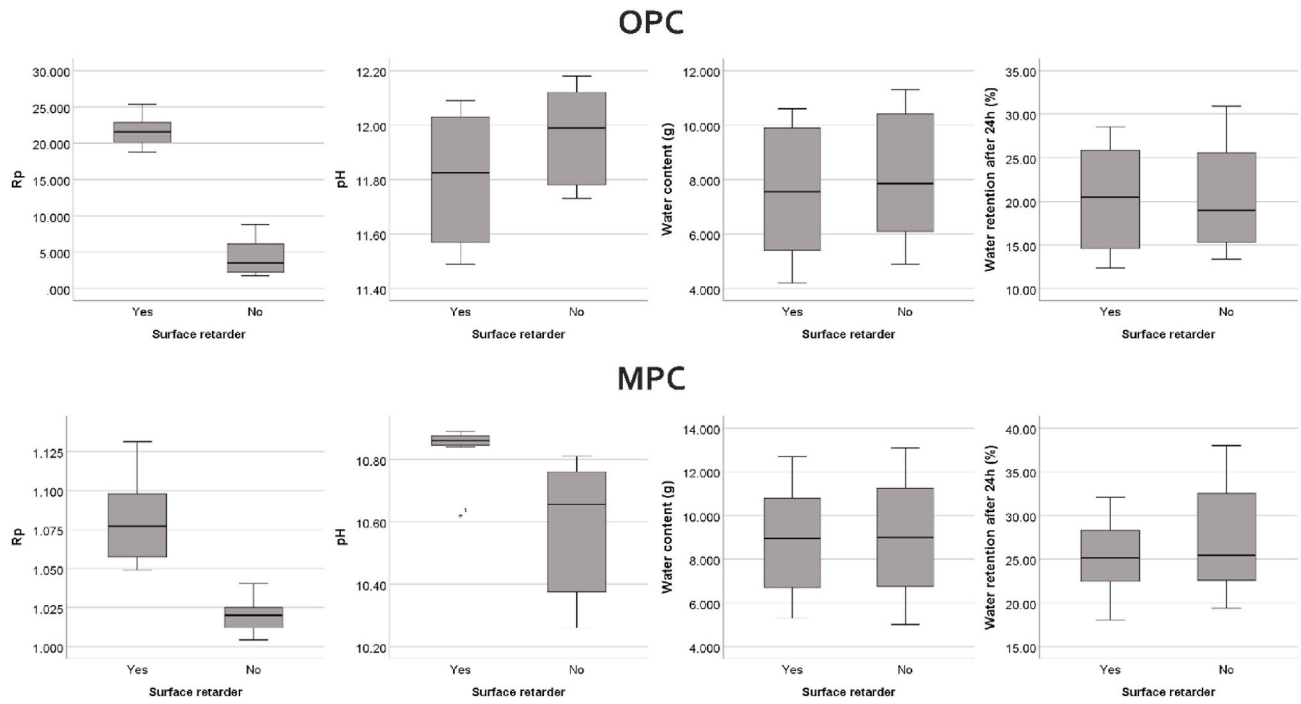

Fig. 5. Overview of the differences between the samples where a surface retarder was and was not used for the tested concrete characteristics. In the case of the OPC samples, the group difference for surface roughness ($p = 0.001$) was found to be significant. For the MPC samples, both the group differences for the surface roughness ($p = 0.001$) and pH ($p = 0.003$) were significant.

possible to make a rough estimate on the total amount of P available in the samples containing bone ash. Based on their findings that 41,7 wt% of bone ash consists of P_2O_5 and the 30 kg/m^3 of used bone ash in our samples, it is estimated that our samples containing bone ash have a P content of around 7 kg/m^3.

2.6. Measuring biological growth

During this experiment, pictures were taken of the samples to show the progression of biological growth throughout the experiment. These pictures were taken at the start of the experiment and after 1, 2, 4 and 8 weeks. All pictures were taken using a Panasonic Lumix G6 camera using fixed settings (35 mm focal length, 1/200s, f/5.0, ISO 200, 6500K WB) under studio lighting (6500K).

In order to determine the bioreceptivity of the concrete samples, it was planned to determine the total biomass present on the samples. Originally, chlorophyll *a* was to be extracted using the peryphiton pigment extraction protocol, as described by Vollenweider, Talling & Westlake, [62] and Miller et al. [30].

However, due to the COVID-19 outbreak at the time of this experiment, as with the measurement of the surface roughness, the necessary equipment to measure the chlorophyll *a* content of the samples was not accessible. Instead, the pictures of the samples taken at the beginning and end of the experiment were used to determine the total coverage of biofilm present on the sample surface at the end of the experiment. First, the images were cropped and aligned in Adobe Photoshop CC 2020. Then, the differences between the layers were highlighted using the 'differences' layer blend option. The resulting images can already be used for analysing growth patterns, however in order to gain quantitative data on the biofilm coverage percentage these were then exported to ImageJ (version 1.8.0).

In ImageJ, the images were first converted to 8-bit grayscale and then to a black-and-white bitmap. For this last conversion a threshold of 40 was used, as this was found the be a good balance between eliminating false positives caused by minor colour differences between the before and after images, and still correctly highlighting biological growth. The percentage of white pixels was then calculated, as this shows which percentage of the sample surface was covered with growth at the end of the experiment.

It should be noted that false positives due to colour differences not caused by biological growth cannot be completely mitigated. However, the impact of these false positives is minor in most cases. Also, it does underestimate biological growth that has a similar colour to the original underlying substrate or that is located inside the pores of the concrete. However, its low-tech nature and relative reliability made the described method the best available option of quantitatively comparing biological growth between concrete samples at the time of testing.

2.7. Statistical analysis

To determine the effect the different additions to the concrete have on the characteristics that are to be modified in the concrete and the resulting bioreceptivity, all samples were split into two groups, based on whether or not a measure was taken, resulting in four pairs of groups based on aggregate type, bone ash, water/cement factor and surface retarder. The resulting data sets were tested for normality using a Shapiro-Wilk test. As several datasets showed a significant variance from normal distribution, all data analyses were done using a Mann-Whitney *U* test.

All data analysis, as well as the creation of the bar plots was done in SPSS (Version 25), using a significance level of 0.05.

3. Results

3.1. Concrete characteristics

We will first discuss the effect the proposed measures have on the concrete characteristics that are expected to be important for bioreceptivity: pH, surface roughness, capillary water content and capillary water retention. A full overview of these characteristics for all samples can be found in Table 3 and Table 4.

Table 3
Overview of the recipes for all OPC and MPC samples. Ingredients are in kg per m^3 of concrete.

Sample	CEMIII/A 52.5N	CEMIII/B 32.5N	ME T545	Sand (0-4 mm)	Limestone	River gravel	Argex AG4/8	Bone ash	Water
OPC									
1 (Reg-BA-LW-R)	150	150		761	1174			30	150
2 (Reg-BA-LW-S)	150	150		761	1174			30	150
3 (Reg-BA-HW-R)	150	150		749	1155			30	180
4 (Reg-BA-HW-S)	150	150		749	1155			30	180
5 (Reg-No-LW-R)	150	150		774	1193				150
6 (Reg-No-LW-S)	150	150		774	1193				150
7 (Reg-No-HW-R)	150	150		742	1144				180
8 (Reg-No-HW-S)	150	150		742	1144				180
9 (CEC-BA-LW-R)	150	150		762			578	30	150
10 (CEC-BA-LW-S)	150	150		762			578	30	150
11 (CEC-BA-HW-R)	150	150		730			554	30	180
12 (CEC-BA-HW-S)	150	150		730			554	30	180
13 (CEC-No-LW-R)	150	150		772			586		150
14 (CEC-No-LW-S)	150	150		772			586		150
15 (CEC-No-HW-R)	150	150		741			562		180
16 (CEC-No-HW-S)	150	150		741			562		180
MPC									
1 (Reg-BA-LW-R)			1191			774		30	149
2 (Reg-BA-LW-S)			1191			774		30	149
3 (Reg-BA-HW-R)			1124			731		30	196
4 (Reg-BA-HW-S)			1124			731		30	196
5 (Reg-No-LW-R)			1196			777			150
6 (Reg-No-LW-S)			1196			777			150
7 (Reg-No-HW-R)			1129			733			197
8 (Reg-No-HW-S)			1129			733			197
9 (CEC-BA-LW-R)			1191				393	30	149
10 (CEC-BA-LW-S)			1191				393	30	149
11 (CEC-BA-HW-R)			1124				371	30	196
12 (CEC-BA-HW-S)			1124				371	30	196
13 (CEC-No-LW-R)			1196				394		150
14 (CEC-No-LW-S)			1196				394		150
15 (CEC-No-HW-R)			1129				372		197
16 (CEC-No-HW-S)			1129				372		197

3.1.1. Aggregate type

For the OPC samples, changing the aggregate to CEC was found to have a significant impact on pH (U = 0.0, p = 0.001), capillary water content (U = 0.0, p = 0.001) and capillary water retention (U = 0.0, p = 0.001). PH was lower for the CEC samples (MDN = 11.70) than for the limestone samples (MDN = 12.08). And whilst the capillary water content was higher for the CEC samples (MDN = 10.05g) than for the limestone samples (MDN = 5.85g), the capillary water retention was lower for the CEC samples (MDN = 15.05%) than for the limestone samples (MDN = 25.58%). There was no significant difference in surface roughness between the CEC (MDN = 1.0543) and limestone (MDN = 1.0332) samples; U = 17.0, p = 0.115.

For the MPC samples, aggregate type had a significant effect solely on water content, with the CEC samples (MDN = 10.80g) having a higher capillary water content than the river gravel samples (MDN = 6.70g); U = 0.0, p = 0.001. The samples with CEC aggregate (MDN = 10.83) showed no significant difference in terms of pH as compared to those with river gravel (MDN = 10.60); U = 15.5, p = 0.083. There was also no significant difference between the CEC (MDN = 1.0495) and river gravel (MDN = 1.0446) samples in terms of surface roughness; U = 28.0, p = 0.674. The CEC (MDN = 24.63%) and river gravel (MDN = 26.45%) showed no difference in terms of capillary water retention either; U = 22.0, p = 0.294.

3.1.2. Bone ash

For the OPC samples, the addition of bone ash had no significant effect on any of the tested concrete characteristics. Surface roughness was similar for the samples with (MDN = 1.0410) and without (MDN = 1.0389) bone ash; U = 31.0, p = 0.916. Neither was there a significant difference in terms of pH between the samples with (MDN = 11.91) and without (MDN = 11.95) bone ash; U = 31.0, p = 0.916. There was no significant difference between the samples with (MDN = 7.80g) and without (MDN = 8.00g) bone ash in terms of capillary water content; U = 30.0, p = 0.834. There was also no significant difference between the samples with (MDN = 20.49%) and without (MDN = 18.26%) bone ash when it comes to capillary water retention; U = 28.0, p = 0.674.

The same holds true for the MPC samples. There was no significant difference in surface roughness for the samples with (MDN = 1.0446) and without (MDN = 1.0389) bone ash; U = 27.0, p = 0.600. There was also no difference in pH between the samples with (MDN = 10.77) and without (MDN = 10.81) bone ash; U = 29.5, p = 0.793. Samples with bone ash (MDN = 9.00g) showed no different capillary water content from those without bone ash (MDN = 8.95g); U = 28.5, p = 0.713. Lastly, there was also no significant difference between the samples with (MDN = 25.68%) and without (MDN = 25.12%) bone ash in terms of capillary water retention; U = 31.0, p = 0.916.

3.1.3. Surface retarder

For the OPC samples, the samples with a surface retarder (MDN = 1.0901) were found to have a significantly higher surface roughness than those without a surface retarder (MDN = 1.0046); U = 0.0, p = 0.001. The samples with a surface retarder (MDN = 11.83) were not significantly different in terms of pH as compared to those without surface retarder (MDN = 11.99); U = 18.0, p = 0.141. There was also no significant difference in terms of capillary water content between the samples with (MDN = 7.55) and without (MDN = 7.85) surface retarder; U = 25.0, p = 0.462. Surface retarder (MDN = 20.49%) or no surface retarder (MDN = 18.97%) did not make a significant difference for the capillary water retention either; U = 31.0, p = 0.916.

In case of the MPC samples, the use of a surface retarder had a significant impact on two characteristics. The pH of the samples with surface retarder (MDN = 10.86) was significantly higher than those

Table 4
| Results of concrete characteristics per test sample.

Sample	pH	Total water capacity (grams per sample)	Water remaining after 24h	Surface roughness (Rp)
OPC				
1 (Reg-BA-LW-R)	12.09	4.2 g	29%	1.0624 ± 0.0305
2 (Reg-BA-LW-S)	12.18	4.9 g	27%	1.0028 ± 0.0008
3 (Reg-BA-HW-R)	12.01	6.2 g	23%	1.0812 ± 0.0341
4 (Reg-BA-HW-S)	12.07	6.9 g	25%	1.0020 ± 0.0001
5 (Reg-No-LW-R)	11.99	4.6 g	28%	1.0684 ± 0.0222
6 (Reg-No-LW-S)	12.16	5.5 g	31%	1.0039 ± 0.0024
7 (Reg-No-HW-R)	12.05	6.4 g	23%	1.0911 ± 0.0215
8 (Reg-No-HW-S)	12.08	6.7 g	21%	1.0027 ± 0.0026
9 (CEC-BA-LW-R)	11.49	8.7 g	18%	1.0892 ± 0.0078
10 (CEC-BA-LW-S)	11.81	8.8 g	17%	1.0195 ± 0.0238
11 (CEC-BA-HW-R)	11.49	10.6 g	14%	1.2151 ± 0.0566
12 (CEC-BA-HW-S)	11.73	11.3 g	15%	1.0106 ± 0.0132
13 (CEC-No-LW-R)	11.66	9.3 g	15%	1.1295 ± 0.0968
14 (CEC-No-LW-S)	11.91	9.6 g	16%	1.0052 ± 0.0044
15 (CEC-No-HW-R)	11.65	10.5 g	12%	1.1337 ± 0.0193
16 (CEC-No-HW-S)	11.75	11.2 g	13%	1.0094 ± 0.0073
MPC				
1 (Reg-BA-LW-R)	10.62	6.2 g	29%	1.0490 ± 0.0135
2 (Reg-BA-LW-S)	10.58	5.5 g	33%	1.0403 ± 0.0139
3 (Reg-BA-HW-R)	10.86	7.2 g	18%	1.0977 ± 0.0586
4 (Reg-BA-HW-S)	10.41	8.4 g	24%	1.0129 ± 0.0097
5 (Reg-No-LW-R)	10.84	5.3 g	32%	1.0619 ± 0.0358
6 (Reg-No-LW-S)	10.26	5.0 g	38%	1.0196 ± 0.0021
7 (Reg-No-HW-R)	10.87	8.8 g	24%	1.0528 ± 0.0383
8 (Reg-No-HW-S)	10.34	8.0 g	24%	1.0206 ± 0.0093
9 (CEC-BA-LW-R)	10.88	9.8 g	28%	1.0981 ± 0.0176
10 (CEC-BA-LW-S)	10.73	9.6 g	32%	1.0110 ± 0.0090
11 (CEC-BA-HW-R)	10.89	12.7 g	22%	1.1313 ± 0.0693
12 (CEC-BA-HW-S)	10.81	13.1 g	21%	1.0249 ± 0.0128
13 (CEC-No-LW-R)	10.85	9.1 g	26%	1.0806 ± 0.0472
14 (CEC-No-LW-S)	10.75	9.6 g	27%	1.0042 ± 0.0008
15 (CEC-No-HW-R)	10.86	11.8 g	23%	1.0739 ± 0.0280
16 (CEC-No-HW-S)	10.77	12.9 g	19%	1.0251 ± 0.0158
REFERENCE				
No surface treatment	12.41	5.3 g	51%	1.0025 ± 0.0014
Surface treatment	12.21	5.0 g	42%	1.0413 ± 0.0161

without a surface retarder (MDN = 10.66); U = 4.0, p = 0.003. Once again there also was a significant difference between the samples with (MDN = 1.0772) and without (MDN = 1.0201) surface retarder, with the samples were a surface retarder was used showing a significantly rougher surface than those where a surface retarder was not used; U = 0.0, p = 0.001. The surface retarder had no significant impact on the capillary water content, with samples with (MDN = 8.95g) and without (MDN = 9.00g) a retarder showing a similar water content; U = 31.0, p = 0.916. There was also no significant difference in terms of water retention between the samples with (MDN = 25.12%) and without (MDN = 25.45%) a surface retarder; U = 27.0, p = 0.600.

3.1.4. Water/cement factor (wcf)

For the OPC samples, there was no difference in pH between the samples with a high (MDN = 11.88) and low (MDN = 11.95) wcf; U = 25.5, p = 0.495. There was also no difference between high (MDN = 1.0459) and low (MDN = 1.0410) wcf in terms of surface roughness; U = 30.0, p = 0.834. Whilst there does appear to be a difference in water content between high (MDN = 8.70g) and low (MDN = 7.10g) wcf, their difference was not significant; U = 16.0, p = 0.093. For the water retention there also appears to be a difference between high (MDN = 17.97%) and low (MDN = 22.46%) wcf, but the difference was again not significant; U = 16.0, p = 0.093.

For the MPC samples, the difference between high (MDN = 22.46%) and low (MDN = 30.55%) wcf was significant for the capillary water retention; U = 0.0, p = 0.001. For the capillary water content, the difference between high (MDN = 10.30g) and low (MDN = 7.65g) wcf was still not significant; U = 16.0, p = 0.093. Like with the OPC samples, there was again no significant difference between high (MDN = 10.84) and low (MDN = 10.74) wcf in terms of pH; U = 23.0, p = 0.344. There was also no significant difference between high (MDN = 1.0389) and low (MDN = 1.0446) wcf for the surface roughness; U = 27.0, p = 0.600.

3.2. Bioreceptivity

An overview of the extent of biological growth per samples, as well as total biofilm coverage, can be found in Fig. 7 (reference), 8 (OPC) and 9 (MPC) (see Fig. 6). In the case of the OPC and reference samples, the left two images show the sample at the beginning and at the end of the experiment. The third highlights the differences between the two images to show where biological growth has taken place and the last is a bitmap version of the third image, used to determine total biological coverage. In the case of the MPC samples, due to the minor amount of growth and high amounts of salt precipitation, using the method used for the OPC samples to determine growth patterns and total coverage of biofilm produced very inaccurate results, due to the salt precipitation being recognised as biological growth. As such, for these samples only the surface at the beginning and end of the experiment is shown. Also, since no coverage percentage could be reliably calculated, results from the MPC samples are not taken into account when determining the effectiveness of the proposed measures (see Fig. 8).

3.2.1. Amount and type of growth

Whereas the MPC samples only show minor growth on some samples, the OPC samples, with the exception of sample 2-2 and 6–2, all show biological growth to some extent. Maximum coverage of the OPC samples reaches up to 43.17% of the surface in the case of sample 3–2. On the other hand, the untreated reference samples show no, and the surface treated reference samples show only very minor biological growth.

OPC mixtures 3, 9 and 11 show the most growth overall, with mixture 3 showing the highest growth on a single sample (43.17% on samples 3–2). Whereas mixtures 9 and 11 show a more consistent high amount of growth (37.13% and 40.40% for mixture 9 and 33.36% and 34.73% for mixture 11) (see Fig. 9).

Overall, three different types of growth can be seen on the OPC samples. Green growth is the most common and present to some extent

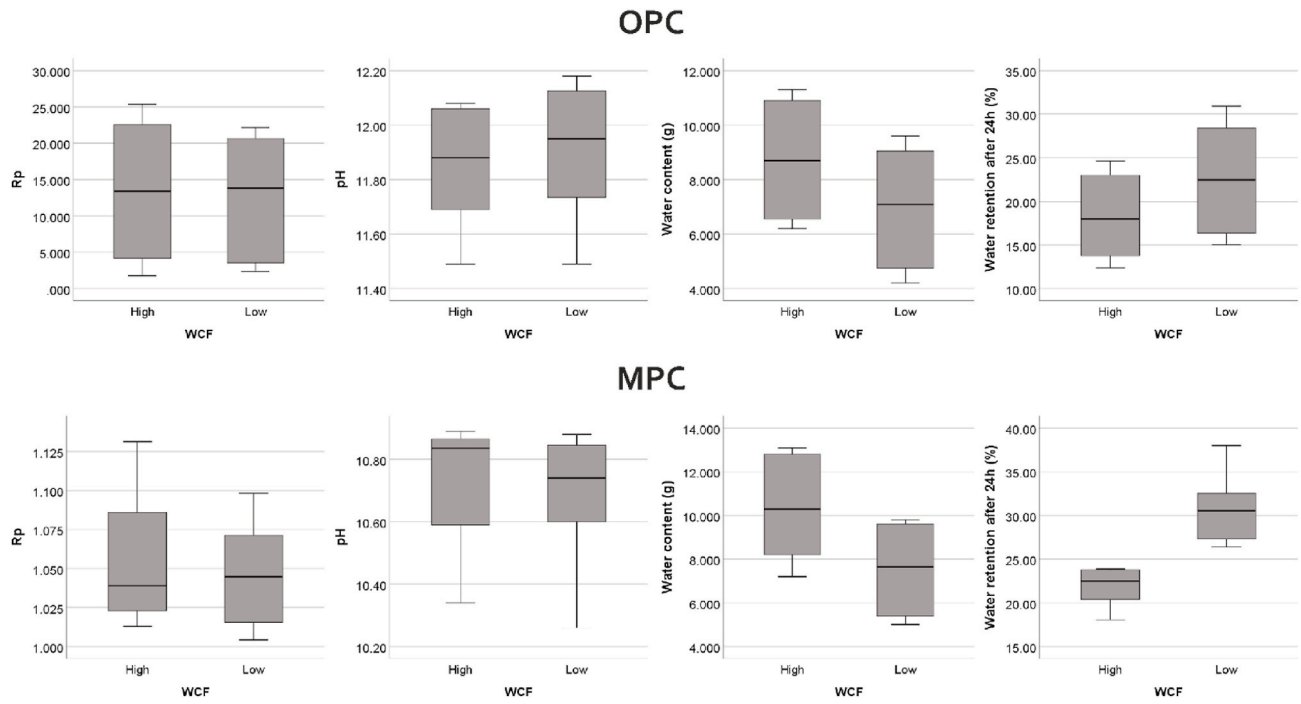

Fig. 6. Overview of the differences between the samples with a high and low wcf for the tested concrete characteristics. The only group difference that is significant is for the water retention in the MPC samples ($p = 0.001$).

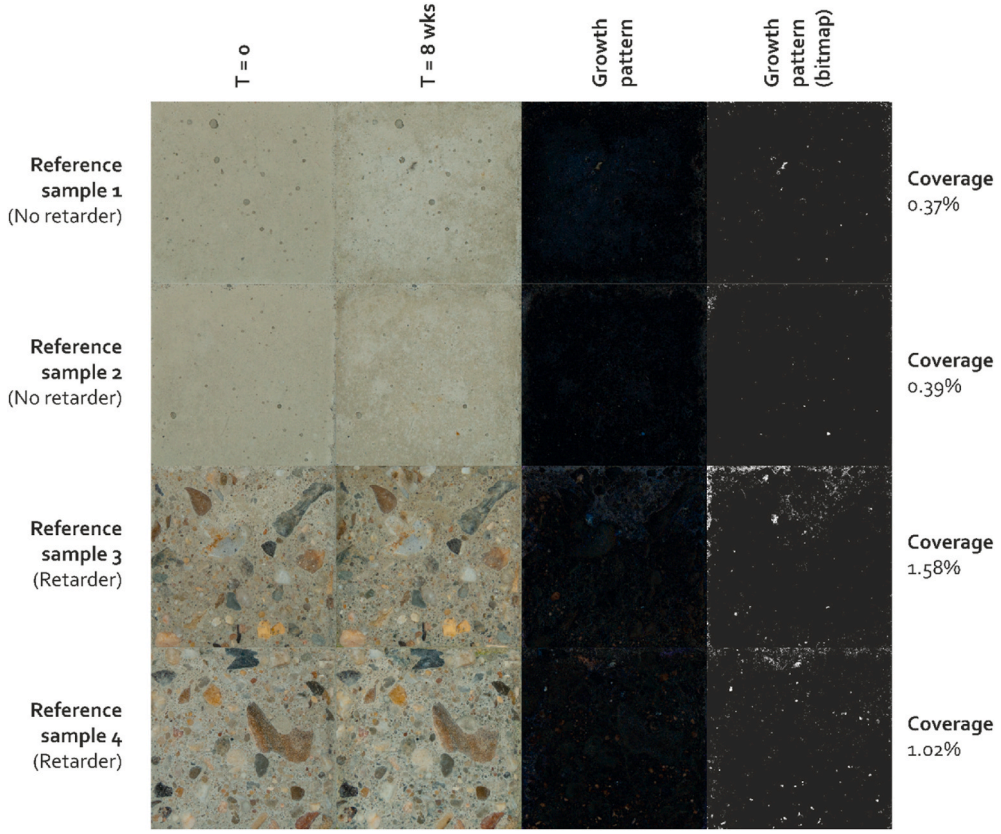

Fig. 7. Overview of the growth pattern on the reference samples.

on all samples that show biological growth. Blue growth is the second most prevalent and is particularly prominent on mixtures 4 and 16. Red growth is the rarest, and only visibly present on sample 10–2. On the MPC samples, however, only an orange-brown growth can be observed on some samples. An overview of these types of growth is shown in Fig. 10.

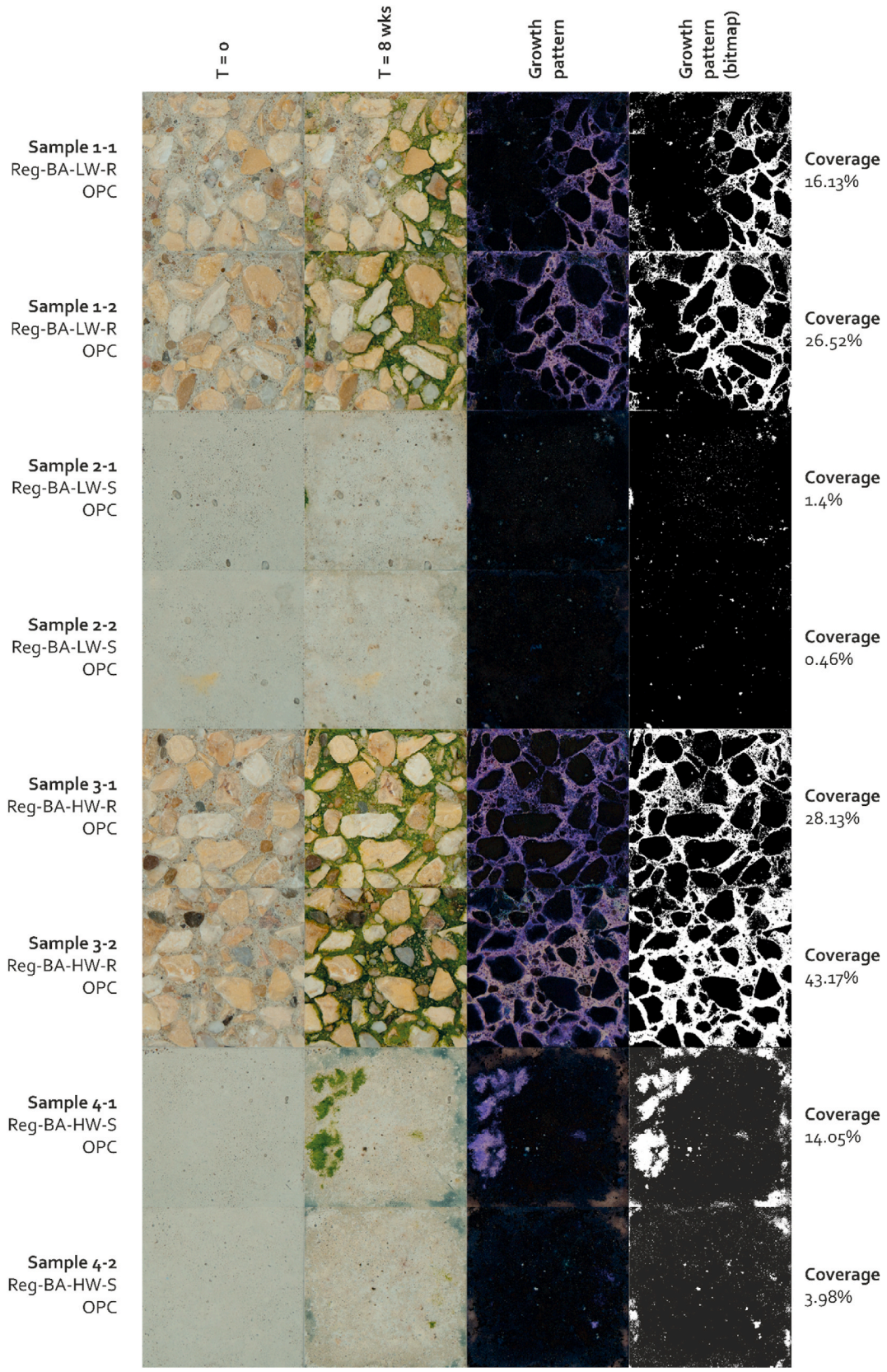

Fig. 8. Overview of the growth pattern on the OPC samples.

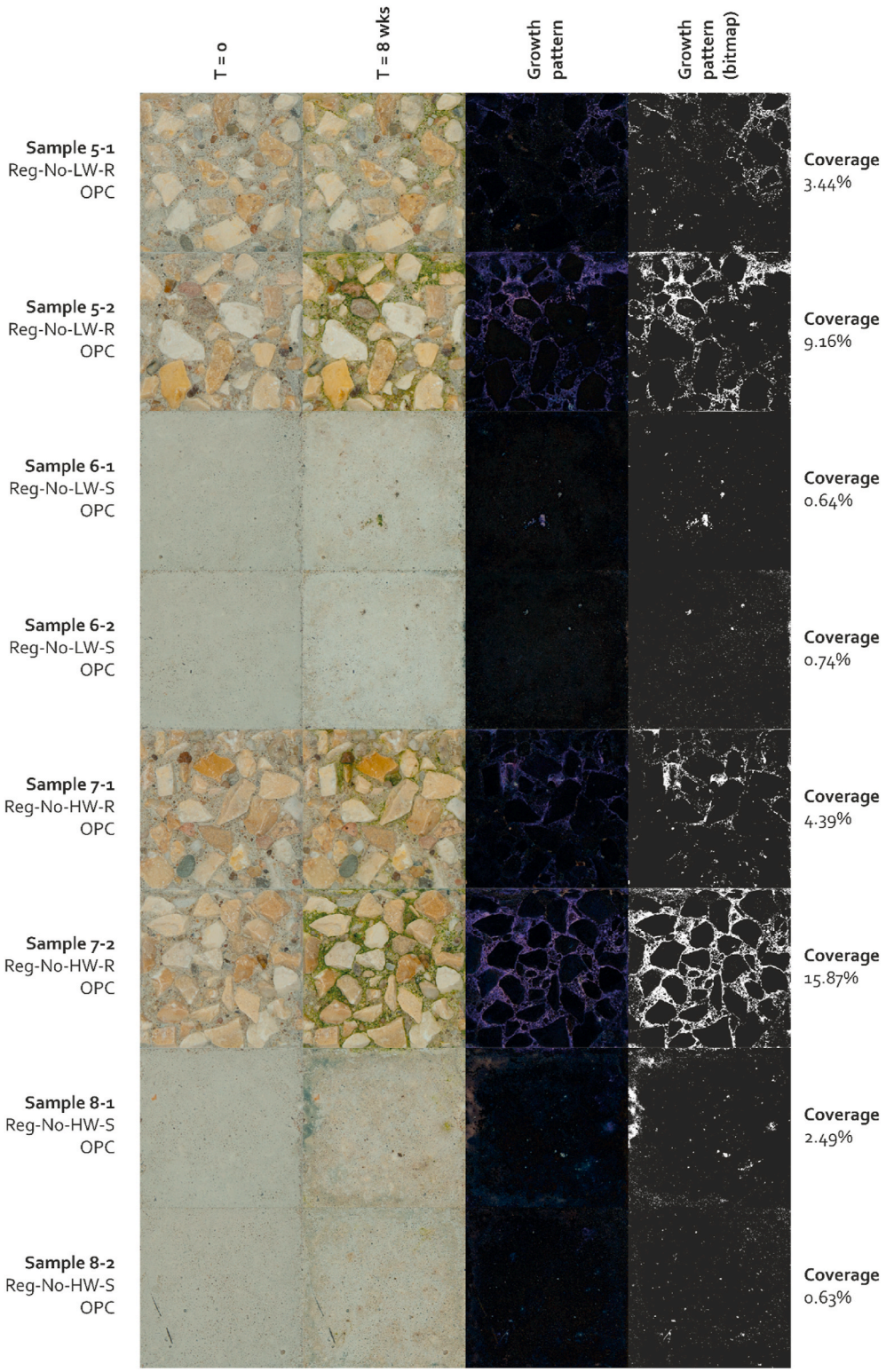

Fig. 8. (*continued*).

3.2.2. *Growth patterns*

For the OPC samples that were treated with a surface retarder, growth is mostly concentrated on the cement part of the surface, not the aggregate. This holds especially true for the samples with the regular limestone aggregate, where growth takes place exclusively on the cement. For the samples with CEC aggregate, growth is still mainly located on the cement, but also on part of the aggregate (see also Figs. 11–1,11-2).

For the OPC samples with an untreated surface, growth appears to mostly concentrate around the transition between undamaged and damaged parts of the surface (see for example samples 14–1 and 14–2). Corners that have broken off, such as is the case for samples 10–1, 10–2 and 12–2 appear to be particularly attractive to biological growth and can form a hotspot for said growth (see also Figs. 11–3,11-4).

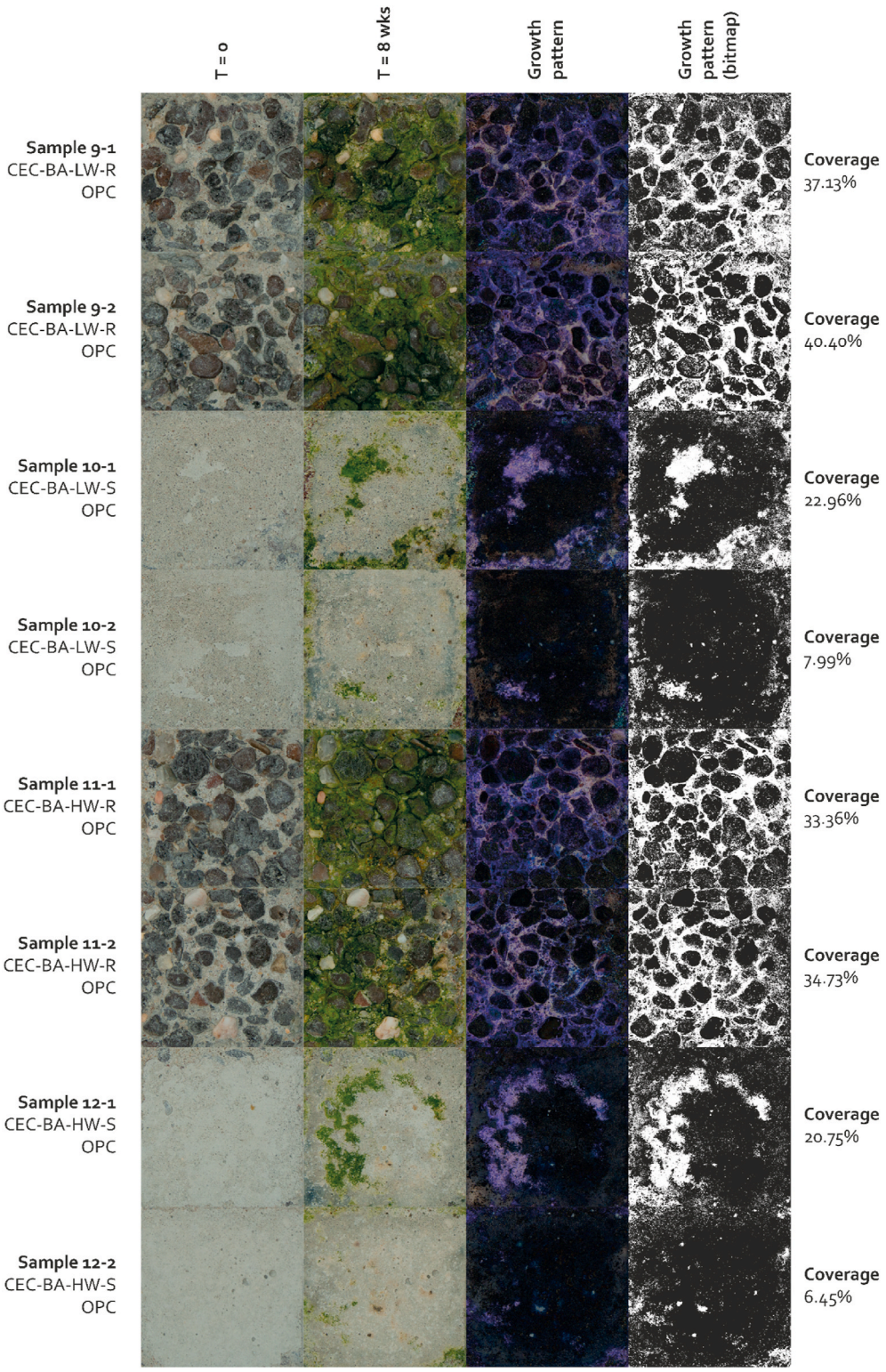

Fig. 8. (*continued*).

Also, while the OPC samples that have bone ash added to their mixture do show more biological growth overall after 8 weeks, after 2 weeks of biofilm development the differences in growth when compared to those samples without bone ash is not yet obvious. An comparison is shown in Fig. 12.

3.2.3. *Effectiveness of proposed measures*

Of the different measures that were taken to improve biological growth, three were shown to have a significant impact on the coverage of biofilm on the samples. First of all, the samples with the CEC aggregate (MDN = 19.95%) showed significantly more biofilm development than the samples with a regular limestone aggregate (MDN = 4.19%); U = 68.0, p = 0.024. As for the use of bone ash, samples with bone ash added (MDN = 21.86%) also showed significantly increased growth compared to the samples without bone ash (MDN = 6.59%); U = 67.0, p = 0.022. Finally, the samples where a surface retarder was used (MDN

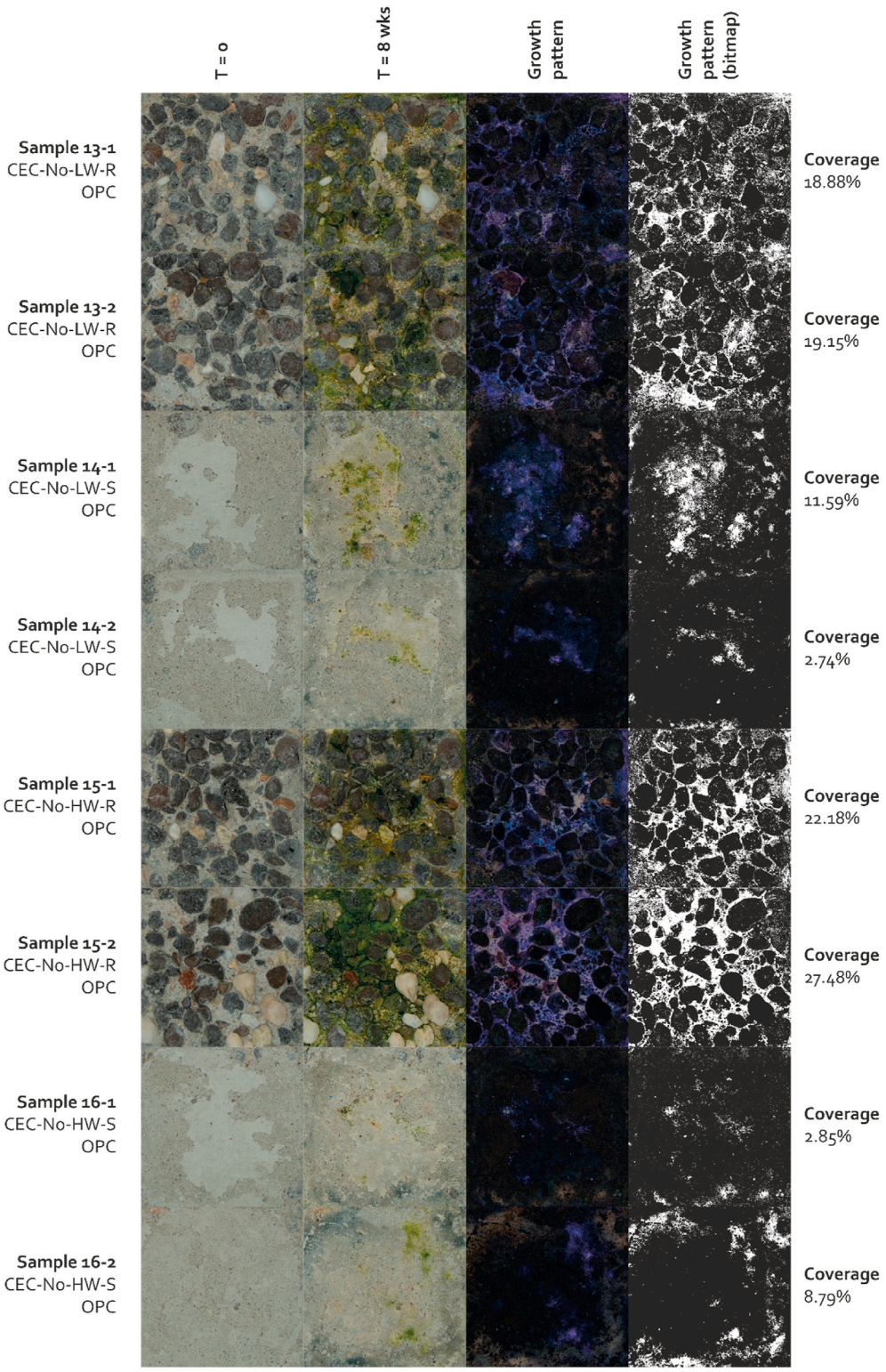

Fig. 8. (*continued*).

= 24.35%) had a significant increase in the amount of biofilm coverage as compared to those where no surface retarder was used (MDN = 3.42%); U = 28.0, $p < 0.001$. The difference between a high (MDN = 14.96%) and low (MDN = 10.38%) water/cement factor was not found to be significant; U = 107.0, p = 0.429.

4. Discussion

4.1. Influence of cement type and biofilm

Whilst coverage data for the MPC samples was not available, from a visual inspection it is clear that the OPC samples showed significant biofilm development in most instances, whereas their MPC counterparts showed little to no development. This is directly contrary to the findings

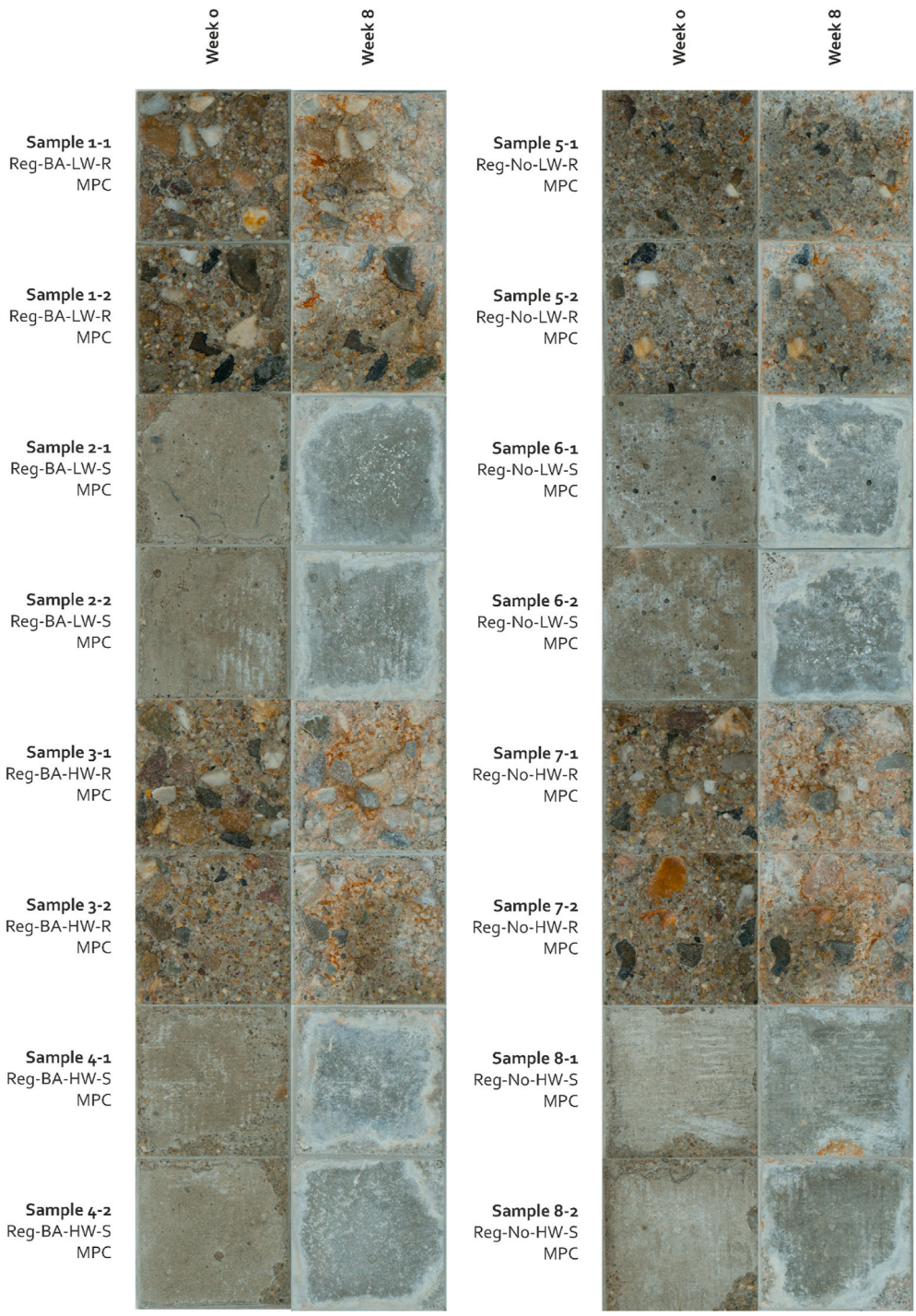

Fig. 9. Overview of the growth pattern on the MPC samples.

by Ref. [22]; who saw their MPC samples outperforming their OPC counterparts. Not only did my MPC samples show less growth, they also showed less diversity in the growth that was present. On the OPC samples three different types of growth were visibly present, whereas on the MPC samples this was limited to just one.

There are two possible explanations for this discrepancy. The first has to do with the mixture used for the MPC samples. Whereas [22] used their own MPC blend, in my experiment a pre-mixed MPC mortar (BASF MasterEmaco T545) was used. This mortar mixture has some unknown additives and it is possible that these play a deleterious role in the development of biofilm.

The other possible explanation has to do with the biofilm that was used to inoculate the samples [22]. used a single algae species (*Chlorella vulgaris* var. *viridis Chodat*) from an existing culture as their initial biofilm. In my research the initial biofilm was scraped of an existing (OPC) concrete structure. Given that [10] found that: "mineral/rock composition significantly influences microbial community structure, diversity, membership, phylogenetic variability, and biofilm growth in subsurface communities" (abstract). It therefore stands to reason that the biofilm used in our research is adapted to growth on OPC type concrete and would need to adapt in order to grow on MPC concrete, possibly contributing to the lack of biological growth and diversity on MPC

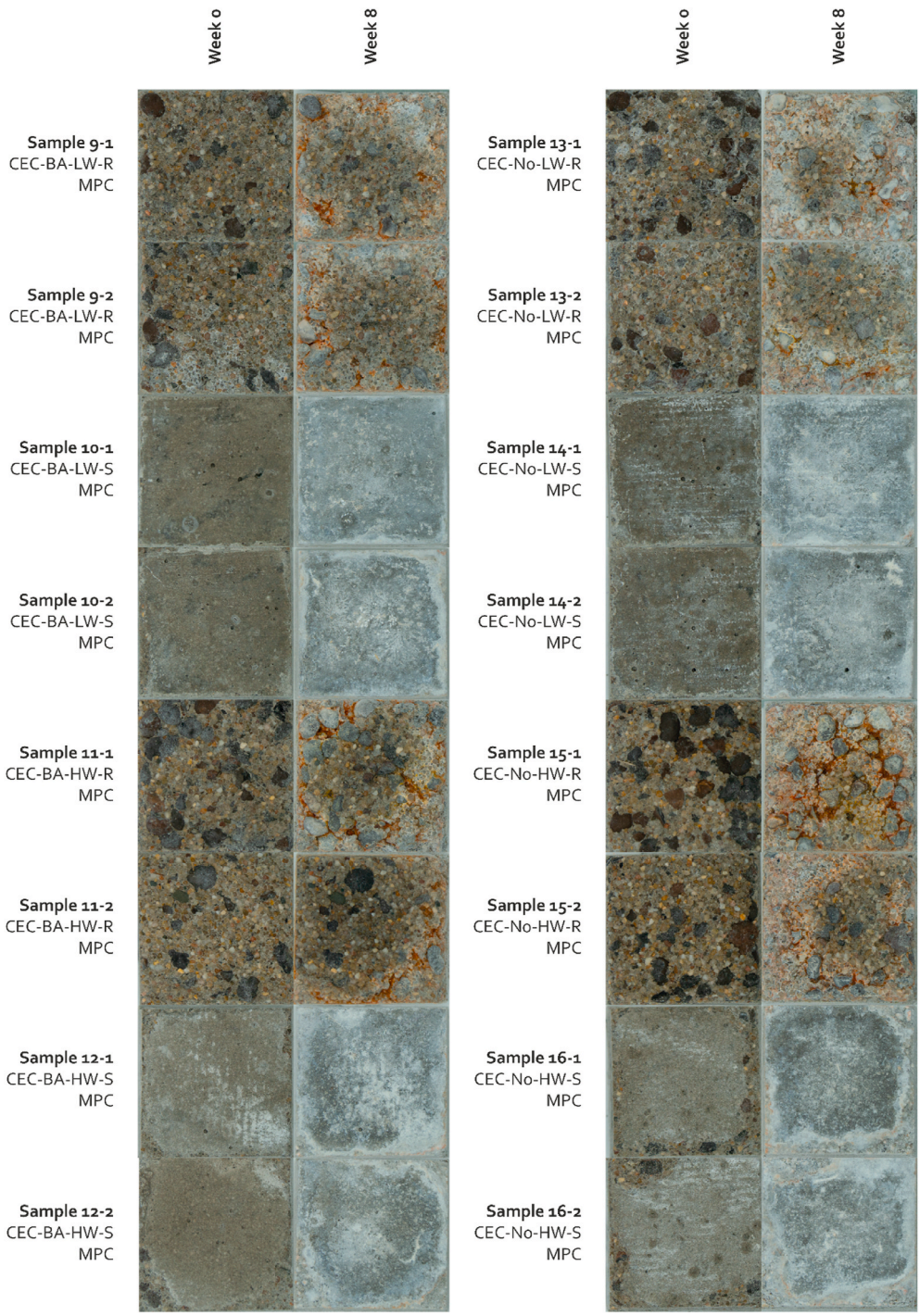

Fig. 9. (*continued*).

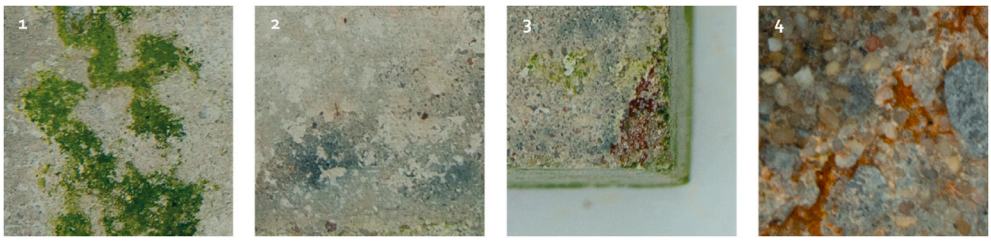

Fig. 10. Green growth is the most prevalent on the OPC samples (1), followed by blue growth (2) and red growth is very rare (3). On the MPC samples, only orange-brown growth is present (4). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

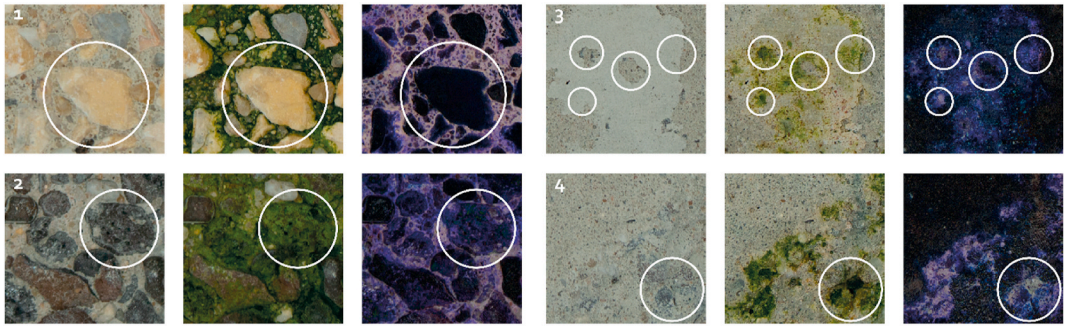

Fig. 11. For the samples where a surface retarder was used, growth was mostly located on the cement, not the aggregate for the limestone samples (1), whereas the CEC samples also showed growth on the aggregate (2). For the samples where no surface retarder was used, growth was mostly located around the edges of imperfections on the surface (3) or broken corners (4).

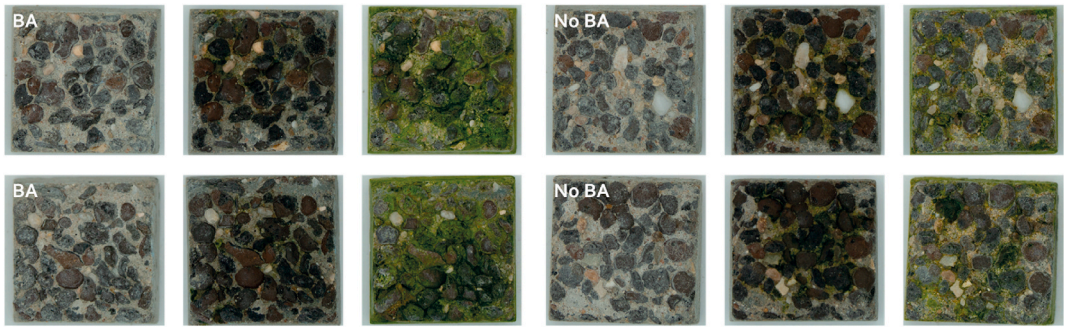

Fig. 12. When looking at samples that had the same mixture, apart from the addition of bone ash (samples 9 and 13), the samples with bone ash (BA) and no bone ash (no BA) showed similar amount of growth in week 2 (middle column), but the samples with bone ash showed significantly more growth at the end of the experiment (right column). The darker surface colour of the samples when photographed in week 2 is caused by higher moisture content, as the samples where not fully dried at this time, in order to minimise the impact on the rest of the experiment. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

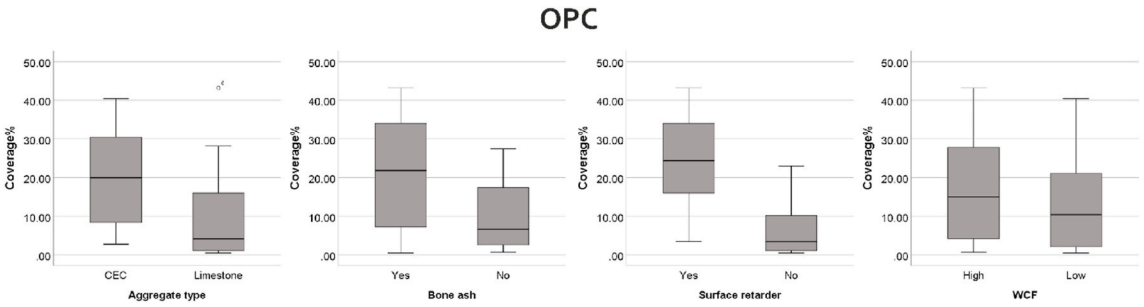

Fig. 13. Overview of the differences between the different samples and the resulting biological coverage. The group differences that were found to be significant are those for aggregate type ($p = 0.024$), bone ash ($p = 0.022$) and the use of surface retarder ($p < 0.001$).

concrete.

It is unknown which of these factors is the main contributor to the lack of biological growth on the MPC samples. However, the results obtained in our research show that it is possible to create a highly bioreceptive concrete using OPC cement and that it is possible that the biofilm used to inoculate the samples could play a large role in the results obtained from a bioreceptivity study.

4.2. The influence of pH on biological growth

The results obtained in this study are in direct contrast with the findings of other authors who found that no biological growth took place on cementitious materials with a pH above 10 (e.g. Refs. [31–34]. Given these previous results by other authors, none of the OPC samples used in our study should show any biological growth, with their pH in the 11.6–12.2 range. Yet a majority of them showed significant biological growth, in some cases after as little as 1 week. A possible explanation for this discrepancy is that it is not the pH value that determines the bioreceptivity, but the state of weathering of the concrete. Initial pH values of concrete are high, due to the presence of calcium hydroxide ($Ca(OH)_2$). Over time, under the influence of CO_2, the calcium hydroxide, but also other cement constituents such as portlandite and CSH react to calcite ($CaCO_3$), a process called carbonation.

In nature, carbonation is the main chemical reaction influencing the strength of cement-based materials, and, in conjunction with leaching, is the main cause of weathering [34]. It is therefore possible that the pH of a stony material merely correlates with its bioreceptivity and is not the determining factor. In fact, this explanation was also proffered by Ref. [27] when finding an inverse relationship between pH and bioreceptivity of granitic rocks. According to Ref. [27] one would expect

the relationship to be direct rather than reverse, as nutrients are more easily solubilised in higher pH environments. However, the inverse relationship can be explained by the correlation it has on weathering, as pH also acts as an indicator of weathering for natural rocks.

As such it is possible that a high pH does not directly influence bioreceptivity, but is merely a correlation. Nevertheless, it does not yet explain why the samples in our research do show biological growth at a pH this high, when such a high pH in general does correlate with no biological growth.

For a possible explanation, one first has to look at what changes physically in the concrete during the carbonation and subsequent leaching process. During the carbonation process, calcite minerals will precipitate on the surface and in the pores of the concrete matrix, and due to its larger volume than the original minerals, will end up clogging pores and leading to a reduction of the total porosity of the concrete matrix [33,35–37]. However, this reduction in porosity is not the same for all pore sizes. As the carbonation process progresses, and portlandite is depleted, CSH is decalcified to provide new portlandite for the carbonation reaction [34]. This leads to mostly the gel pores in the CSH gel and smaller capillary pores being reduced, with the larger capillary pores being largely unaffected or even increasing in size, the latter of which is especially true for blast furnace slag cements [36,37]. In fact, when comparing carbonation depth with the water absorption properties of the cement, a positive correlation can be found [38].

When this is combined with concrete leaching, a process through which ions are removed from the concrete, which in turn leads to a further dissolution of CSH and portlandite, porosity is further increased, likely leading to a further improvement of water absorption [34,35,39]. It would also mean that the water retention is lowered after a certain point, due to the larger pore diameter (an effect that can also be seen when comparing the water retention of the reference samples with the bioreceptive test samples). However, as a biofilm develops the biofilm itself can protect the concrete from desiccation. This higher porosity can then act as a large water reservoir. Also, because initial biofilm development, when water retention by the biofilm would be lowest due to a lack of EPS, took place in an environment with high water availability, the impact of lower water retention is further mitigated (seeFig. 13).

This carbonation and leaching process could also remove the top layer of the compacted concrete, which is not very permeable to water due to its high density and oil residue from the casting process. This low permeability was also observed during the inoculation process of the samples with no surface treatment, where the liquid from the liquid biofilm would lie on top of the concrete (see also Fig. 14), whereas on the samples with a surface treatment the liquid was quickly absorbed by the concrete. This is similar to the findings of [34] who saw the same effect on their non-carbonated samples, but not on their carbonated and carbonated and leached samples.

This would mean that it is the improved hydraulic properties caused by the weathering process that makes aged and carbonated concrete more bioreceptive, not the reduced pH. It would also explain why in our experiment, despite the samples' high pH, biological growth was still found. Due to the high porosity and water sorptivity caused by the high water/cement factor and used aggregate, in combination with the removal of the compacted top layer, the circumstances for biological growth were already sufficient for it to take place (this process is summarised in Fig. 15). Likewise, the latter would explain why the samples on which no surface retarder was used mainly showed growth around damaged areas of the surface and broken corners, as on these areas the compacted top layer and casting oil has also been removed. Although it would explain the obtained results, further research is necessary to prove or disprove this theory. It is also necessary to investigate whether the specific composition of the biofilms also plays a role in whether or not biological growth can take place at such a high pH, as perhaps this is limited to a select number of organisms.

Fig. 14. Contrary to the samples where a surface retarder was used, which absorbed water almost immediately, the ones without surface retarder showed a significant delay in water absorption, causing distinct welling of water applied to their surface. This effect was still visible on this sample 3 months after casting.

4.3. *The effectiveness of the proposed measures*

The results show a significant impact on bioreceptivity for three of the four proposed measures. The measure that had the largest effect on overall bioreceptivity was the use of a surface retarder on the concrete. This is unexpected, as increasing the surface roughness by means of a surface retarder was initially proposed as a means of protecting the biofilm against environmental factors and to increase the entrapment of microorganisms and macronutrients when exposed to a natural environment. As such, no difference was expected under laboratory circumstances, were no such protection is necessary, or entrapment can take place. [22]; for example, found that their samples with a lower roughness showed a similar result to those with a higher roughness. It should be noted, however, that all of their samples used a surface retarder and the difference in roughness was caused by differences in aggregate size between samples, not the use or lack of use of a surface retarder.

As to what it is that the surface retarder does to improve bioreceptivity under laboratory circumstances, one of the possible positive effects it has on bioreceptivity has already been discussed before the surface retarder removes the compacted top layer of cement and formwork oil left after casting, allowing water to better penetrate the surface. The permeability of the surface has already been proven to play an important role in the colonisation of microorganisms on natural stone monuments [40]; something, it would appear, that also holds true for concrete. The increased surface roughness caused by the surface retarder also increases the total surface area available to biological colonisation, possibly increasing biological growth even further [41].

The measure with the second largest effect on bioreceptivity was the use of bone ash in the mixture. As it had no effect on any of the other measured characteristics, it is likely that this is due to the increased availability of phosphorus. This corroborates the findings by Ref. [10] that the addition of phosphorus to a mineral substrate increases biological growth on said substrate. It can be seen, though, that during initial development the differences between samples with and without bone ash are not obvious, and only increase afterwards. This suggests that nutrient availability only becomes a limiting factor for growth during later stages of development. It also shows that using bone ash is a viable way of alleviating this limiting factor.

The final measure that had a significant effect on bioreceptivity is changing the aggregate from limestone to crushed expanded clay (CEC). Partly this is due to CEC's higher inherent bioreceptivity than limestone. This is shown by the fact that whereas part of the CEC aggregate was covered with a biofilm at the end of the experiment, no such growth was found on the limestone aggregate, thereby increasing total biofilm coverage. However, CEC also had a significant effect on all the measured concrete characteristics, with the highest changes in the hydraulic properties of the concrete. As the effect on pH and surface roughness is only minor, it is suggested that the changes in hydraulic properties play the most important role in the increased bioreceptivity.

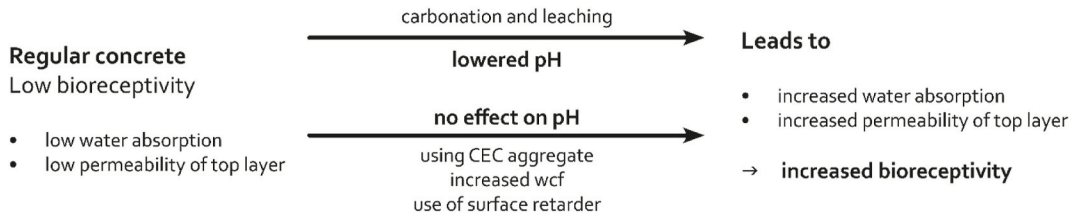

Fig. 15. Overview of the similar effect carbonation and leaching and the tested measures have on the properties and bioreceptivity of the concrete, while having a different effect on the concrete pH.

[42] already demonstrated that the water absorbing capacity of the concrete aggregate used is one of the main determining factors in the total water absorption by the concrete overall. As such, it is no surprise that the concrete samples containing CEC have a higher water absorbing capacity. The lower water retention is more unexpected, however does not appear to hamper biological growth under the used growing conditions. This is likely because water was freely available. Still, this unexpected deleterious effect on water retention might have a negative impact on biological growth under natural circumstances during initial growth, when desiccation occurs often and the biofilm has not yet fully developed an EPS matrix to protect itself. As for the reason why this water retention is so much lower, it is possible it is related to the increased porosity of the concrete with CEC aggregate, allowing for easier evaporation of water inside it, in combination with the water/-cement factor used.

In fact, increasing the water/cement factor was the only measure that was found not to have a significant impact on biofilm coverage. This is likely due to the fact that the different wcf factors used in this study (0.5 and 0.6) did not result in significantly different capillary water content and capillary water retention, although a small difference was visible in the graphs, and was expected. This might be due to the difference in wcf not being large enough between the "high" and "low" samples. As such, wcf might influence bioreceptivity, just not with the chosen wcf.

It is therefore prudent to adjust the water/cement factor based on the type of aggregate (and possibly other constituents) used. On top of that, this should also be tested under natural circumstances, as well as under different stages of biofilm development. As mentioned, under natural circumstances desiccation is more common and biofilms that are in early stages of development do not have a sufficient EPS layer surrounding needed to protect them against desiccation (Wolfaardt et al., 1999). As such, the findings from these future experiments could be different from those found in this experiment.

4.4. Application and durability

The recipes in their current iteration do not use a plasticiser. Additionally, the high wcf used and low cement content lead (intended) to an increased porosity and water absorption of the bioreceptive concrete. This has four effects on the material properties of the concrete:

4.4.1. Not self-compacting

Due to the lack of a suitable plasticiser, the current concrete recipes were not self-compacting, as compared to most modern concrete. A plasticiser was left out of the current recipes to simplify them, however future iterations could look into adding plasticisers to improve the workability.

4.4.2. Reduced compressive strength

Increased porosity has been found to have a negative effect on the compressive (and indirect tensile strength) of concrete [43]. As such, it is likely that the compressive strength of bioreceptive concrete is significantly lower than that of its regular counterpart. In some cases, this could limit its use in structural applications where it has to carry a high compressive load. However, as both the wcf and cement content are still within legal parameters, the reduced compressive strength is unlikely to play a major role in non-structural use.

4.4.3. Increased carbonation

Carbonation of concrete is dependent on the air permeability of the concrete and the amount of cement and pozzolanic materials in the concrete [44]. With its high porosity, low cement and high pozzolanic material content, bioreceptive concrete is very susceptible to carbonation. As explained before, this is likely to be inducive for biological growth. However, it also reduces the pH which can cause increased corrosion of the concrete rebar. Under high pH environments (pH > 12.5) γ-FeOOH is formed on the outer layer of the concrete rebar, forming a passive oxide film that is impermeable to water and oxygen, both of which are necessary for the corrosion of steel [45]. In low pH conditions, such as when concrete carbonation depth has reached the rebar, this layer is no longer present, thus making the rebar susceptible to corrosion. This, combined with the permeability of bioreceptive concrete (allowing for the ingress of water) makes corrosion of the rebar likely. Recently, progress has been made on concrete rebar that is more corrosion resistant, such as rebar made out of fibre reinforced polymers (FRP). However, whilst testing of the former has shown some promising initial results, including high corrosion resistance, which indicate it could act as a possible replacement for steel rebar, further research in this field is still required [46–48]. As such, the use of bioreceptive concrete as a structural concrete might be possible, but cannot be recommended when using standard steel rebar, due to the increased corrosion risk of the steel rebar.

4.4.4. Reduced durability

Carbonation and leaching are not the only factors that could negatively influence the durability of the concrete. There is also the possibility of deterioration of the concrete by the acids produced by the biofilm that is applied to the concrete. In fact, because of this, most early (and sometimes recent) research into the bioreceptivity of stone materials was done with the goal of reducing biological growth, since it deteriorates the stone surface (e.g. Refs. [27,30,32]. However, this damage is mostly superficial and only affects the skin of the concrete [49]. Thus giving rise to aesthetic considerations, but not to the structural integrity of the concrete. Finally, there is physical deterioration caused by environmental factors. The increased water absorption and weaker cement matrix makes the concrete more susceptible to freeze/thaw cycles and mechanical abrasion [44]. This in turn can lead to surface scaling (the loss of cement paste on the surface) or internal cracking, the former of which has only minimal impact on the concrete and no effect on the structural integrity of the concrete, whereas the latter does (Cho, 2007). It will need to be tested to what extent these factors affect the durability of the concrete in practice. It should also be noted that damage by freeze-thaw cycles can be mitigated, if need be, by the addition of fibres to the bioreceptive concrete, which can increase its freeze-thaw resistance whilst maintaining or even increasing the permeability of the concrete [50]. It is unlikely that the fibres will in turn negatively affect bioreceptivity in a significant manner.

Based on this, the use of just bioreceptive concrete in structural or

otherwise critical structures could be limited or require further adaptation. However, these factors should not influence the applicability of bioreceptive concrete as either a superficial layer on top of regular concrete or as a façade cladding.

4.5. Efficacy and sustainability

One of the main reasons for the inclusion of green façades in our buildings, apart from possible aesthetic considerations, is to mitigate the effects of urbanisation and anthropogenic climate change. When bioreceptive and regular green façades are compared in this manner it is likely their effects are very similar. The increased amount of water retained within the bioreceptive concrete panels will increase evapotranspiration, reducing the Urban Heat Island (UHI) effect around the building. However, it should be noted that some biofilms can also lower the surface albedo, negating some of the positive effect they have on the UHI effect [51]. At the same time, certain types of biofilm can also decrease thermal conductivity (thereby increasing insulation) of a surface. Although the effect bacteria, algae, funghi and lichen have one thermal conductivity are likely minimal, due to the fact that very little air is trapped within biofilms consisting of the organisms, mosses have been found to lower thermal conductivity of a surface and provide insulating effects [52–54].

As for their effect on air quality, just as with regular green façades, CO_2 sequestration will take place during photosynthesis. Not only that, biofilm induced calcite precipitation could lead to further carbon sequestration [55]. Additionally, some substances that are considered airborne pollutants by humans, can act as nutrient sources for biofilms [56]. In this way, bioreceptive façades could not only play a mitigating role in the larger climate change problem, but also help improve the air quality of our cities, similar to regular green façades.

However, one also has to consider the sustainability of the materials used. In this regard the concrete used in bioreceptive façades is not ideal, as the production of the used Portland cement causes the emission of significant amounts of both NOx and CO_2, and the limestone required for its production is becoming a scarce resource [57]. However, its properties in terms of water retention, surface texture and nutrient content make it the best candidate for bioreceptive façades. The only other common construction material that has these properties, wood is likely unsuitable due to its high susceptibility to biodeterioration [58]. Additionally, the low cement content and high amount of pozzolanic cement replacements in the bioreceptive concrete mixture also help to reduce the embodied energy of the façade panels significantly. As cement is the most expensive constituent in concrete, this should also help reduce construction costs of the bioreceptive concrete.

Furthermore, bioreceptive façades likely have an advantage when compared to traditional green façades, as not only do they also have an embedded energy associated with them (both for the technical system required for plant growth and the underlying façade material), their maintenance also has an associated energy requirement, the amount of which is dependent on the system that is used [59]. Seeing as regular green façades therefore have three main energy sinks (embedded energy of both the technical system and façade material and energy cost of maintenance), as compared to just the one for bioreceptive façades (embedded energy of the façade material, no technical system or additional maintenance is required), it is likely that a bioreceptive façade is more energy efficient, although an LCA comparison will have to be done to prove this. At the same time, the lack of required maintenance will lead to a reduced maintenance cost throughout the product its lifetime.

It can therefore be concluded that it is likely that bioreceptive façades have the same positive effects on the urban climate as current green façades, whilst reducing costs and possibly having a lower embedded and maintenance energy. However, further research will have to determine the exact effects on the urban climate and the embedded energy of bioreceptive façades, in order to make a final comparison, as this is beyond the scope of this research.

5. Conclusion

The aim of this research was to find what changes can be made to a concrete in order to make it more bioreceptive. In our research we tested the effect of addition of bone ash and a surface retarder to the mixture, as well as the effect of changing the aggregate to CEC (crushed expanded clay) and increasing the wcf (water cement factor). Based on our results we can conclude the following:

- Using a surface retarder did significantly increase the bioreceptivity of the concrete, likely due to both removing the hydrophobic top layer of the concrete and through increasing the available surface area
- The addition of bone ash did significantly increase the bioreceptivity of the concrete, by making more nutrients (specifically phosphorus) available within the substrate.
- Changing the aggregate to CEC did significantly increase the bioreceptivity of the concrete, likely due to a combination of CEC being inherently bioreceptive and CEC improving the hydraulic properties of the concrete for biological growth.
- Increasing the wcf did not significantly increase the bioreceptivity of the concrete. It is however possible that no effect was observed due to the increase in wcf (to 0.60) not being large enough as compared to the baseline value (0.50).

Additionally, it was found that:

- It is likely not necessary to create concrete with a pH below 10. Most of the samples showed moderate to extensive biological growth, despite their pH being significantly higher than 10.

Overall, these results show that relatively common materials and production methods can be used to create a bioreceptive concrete. And, whilst material properties and durability are worse than regular concrete, it is expected that these negative effects are neglible when this concrete is used in non-structural use cases. At the same time, the possible reductions in costs and energy usage as compared to contemporary green façades provide sufficient incentive to further explore bioreceptive concrete. It is recommended that future research focuses on the performance of this bioreceptive concrete under natural circumstances. This will introduce stressors hampering the growth of the biofilm, thereby possibly highlighting other factors that might influence the bioreceptivity of concrete when used on exterior structures. Additionally, it should be investigated how the positive external effects of bioreceptive façades compare to contemporary green façades.

Author Agreement

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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.

Acknowledgements

We would like to thank Byldis B.V. and in particular Ellen van Genechten, Koen Spijkers, and Gerard Brood for helping us with the production of the prototypes used in this research. We would also like to thank Noel de Brabander from BASF, for supplying us with the

magnesium phosphate based mortar used in this research. Laboratory measurements were performed at the Microlab of the Section Materials & Environment, Faculty of Civil Engineering, TU Delft.

This research was conducted as part of a MSc thesis for the Building Technology master at the TU Delft.

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