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ORIGINAL ARTICLE

Understanding bioreceptivity of concrete: material design and characterization

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Abstract The climate crisis is driving an increasing demand for ecologically oriented concepts. In the building sector, this demand includes not only the use of environmentally friendly materials but also the greening of urban areas. One promising approach is the development of bioreceptive concrete façades, which support the growth of green biofilms directly on their surfaces. These innovative façades are anticipated to deliver benefits comparable to those of macroscopically greened façades, such as enhanced biodiversity and improved air quality, while offering the advantages of being more self-sustaining and stable systems once fully established.
However, the development of bioreceptive concrete presents substantial challenges. Due to the interdisciplinarity and novelty of this field, standardized methods for material characterization and bioreceptivity assessment are currently lacking. This study proposes an approach for evaluating surface properties crucial for bioreceptivity, developed on differently structured samples of ultra-high-performance concrete (UHPC). Existing methods and standards from concrete technology are critically reviewed and, where necessary, modified to meet the unique requirements of measuring bioreceptive material properties. Special attention is given to the surface pH value and water retention characteristics, as these are essential for promoting microbial growth and ensuring the long-term stability of green biofilms. The observed surface characteristics vary according to the imprinted surface structures, offering a spectrum of material properties and enabling the evaluation of their impact on bioreceptivity. The findings presented form the foundation for subsequent laboratory weathering experiments, which will be discussed in a complementary publication.

Keywords Bioreceptivity · Concrete · Material characterization · Surface pH-value · Water retention · Method development

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1 Introduction

Concrete is the most widely used building material in the world and its versatility allows it to be used

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in a wide range of applications [1]. For a long time, material adaptations mainly focused on increasing strength and durability, however, in recent years a trend towards more sustainable and environmentally friendly mix designs is observed. Research is increasingly focusing on reducing CO_2 emissions and lowering the consumption of raw materials, e.g. through alternative binders and recycled materials [1–4]. Another growing area of interest is the development of green façade systems, which promote biodiversity and create new urban green spaces [5–7]. These systems commonly rely on higher plants and their high cost and maintenance requirements limit their use [8, 9].

An alternative approach involves microbial greening using mosses [10, 11] or self-sustaining, algae-dominated biofilms [6, 12]. In case of the latter, microbial biocolonization of building materials describes the growth of biofilms on man-made surfaces [13] and is governed by bioreceptivity, the capacity of a material to support biological growth [14, 15]. Bioreceptivity is a complex concept influenced by material properties as well as biological and environmental factors. Environmental boundary conditions such as the amount of water available, temperature, and intensity and spectrum of solar radiation influence the microbial growth and can be considered on different scales, namely climate, weather, and microclimate. The inclination and orientation of the facades, as well as the proximity to green areas also play a role [15–17]. From a biological perspective, the abundance and diversity of microorganisms are decisive factors for microbial growth on a materials surface. Bioreceptivity as a material intrinsic parameter is determined by a combination of properties such as roughness, pH value, and water retention capacity [15]. These properties dictate how easily microorganisms, water, and nutrients can adhere to a surface and are sustained there to promote biofilm formation. Moreover, bioreceptivity is not a static property but evolves over time, especially due to weathering processes [14, 15].

As the most reproducible and controllable of the three factors influencing bioreceptivity, the building material is the primary focus in developing a microbially greened façade. Concrete's widespread use and versatility make it a suitable candidate for microbially greened facades, as concretes properties can be tailored to enhance its intrinsic bioreceptivity. While there has been significant research on bioreceptive concrete for marine infrastructure and costal renaturation [18–20], the findings from marine environments are not fully transferable to subaerial biofilms. Differences in environmental factors, such as exposure to air versus seawater, along with variations in concrete mixtures and target organisms, limit the applicability of marine research findings to the topic of subaerial bioreceptive concrete.

However, understanding fundamental interactions between the substrate and subaerial biofilm formation is crucial for designing concrete with increased bioreceptivity. So far, several studies offer insights into the role of concrete material characteristics on bioreceptivity. Sandra Manso established a foundation for evaluating how concrete chemistry and mix design influence its bioreceptivity, particularly by modifying the pH value of the bulk material [6]. Concrete is a highly alkaline material, with the fresh material often reaching pH levels above 12, making it a key material property in concrete bioreceptivity research [6, 17]. Over time, carbonation gradually reduces the pH value starting from the surface and migrating into the material, making concrete more bioreceptive. However, these initial high pH values create an inhospitable environment for microorganisms, as biofilms ideally require pH values below 10 to support photosynthetic activity and growth [17, 21]. Photosynthetic biofilms need sufficient light and moisture to grow with growth periods being significantly shortened if the pH value of the surface rises too fast when in contact with water. However, microorganisms may survive unfavorable conditions in a dormant state, but the duration of the preceding growth period is crucial.

While surface pH value is primarily a chemical property, it is closely linked to physical characteristics, such as surface roughness, which can accelerate carbonation and thus lower the pH value [22, 23]. Accurately monitoring concrete's surface pH value is crucial, but current standards focus on measuring the carbonation depth or the pH value of the bulk material, which does not fully reflect surface properties relevant to microbial colonization.

Moreover, comparable in-depth studies on the influence of surface texture on bioreceptivity are scarce. Tran et al. investigated factors such as porosity, roughness, and surface pH value. They concluded, that while porosity did not affect colonization due to constant moisture present during the experiment, roughness facilitated algal attachment, and a lower surface pH accelerated algal growth [17]. Dalod et al. researched the influence of mortar chemistry and carbonation, and observed that surface roughness had little impact, but pH value and chemical properties were decisive for colonization [24]. Grosseau et al. combined laboratory and outdoor weathering experiments on various mortar mixes and curing conditions but did not study physical surface characteristics [25].

While there is a consensus of which surface parameters are influencing concrete bioreceptivity, there is no clear understanding of why, how, and to which degree a surface parameter influences microbial growth. Especially the influence of physical surface alterations, such as imprinting structures or treatments like sandblasting, remains underexplored. This is further complicated by the fact that results regarding the impact of physical surface properties are highly dependent on the type of growth experiment conducted and the test set-ups often vary greatly [26]. Laboratory weathering simulates environmental conditions but depending on the experimental design important boundary conditions like relative humidity or presence of liquid water on the tested material may not be reflected correctly. Tran et al. for example reports that the influence of concrete porosity could not be assessed in his experiments because of his testing methods led to a constantly high humidity during the growth [17]. Contradictory results illustrate that for assessing the influence of physical surface properties on bioreceptivity, not only the material characterization must be standardized, but also the growth experiments themselves [27].

As the first part of a two-part study, this work presents an experimental approach to evaluate the surface properties of concrete in a bioreceptive context. It addresses the gap in research regarding the influence of surface structure on biocolonization by using a fixed concrete mix and samples with varying surface structures. The emphasizes is on key surface properties known to affect bioreceptivity, including roughness, water retention, and surface pH value. A follow-up publication will link this data to a complementary laboratory growth experiment which allows to assess the impact of the thoroughly characterized surface structures on bioreceptivity with special attention to microbial attachment and growth [28].

2 Material and methods

Four differently structured concrete surfaces based on the same ultra-high-performance concrete (UHPC) mixture were produced and characterized. As the bulk material defining the material chemistry is the same for all samples, differences in material properties are the result of the surface structure.

2.1 UHPC mix

The concrete used in this study is the commercially available NANODUR® Compound 5941 (Dyckerhoff GmbH, Germany) in combination with fine-grained sand (0–2 mm). The small aggregate size made it possible to imprint very fine structures onto the surface. The w/c ratio of 0.19 was achieved using a superplasticizer (MasterGlenium ACE 394, BASF SE, Germany). The mix design and processing are summarized in Table 1.

2.2 UHPC samples

UHPC quality and workability were confirmed by measuring the temperature after mixing using a penetration thermometer (Testo 720, Testo SE & Co. KGaA, Germany) and by determining the spreading of the fresh UHPC on a flow table. UHPC prisms with the dimensions of 40 mm × 40 mm × 1600 mm were produced and subjected to a loading rate of 2.4 kN/s (MTS 1MN Hydraulic Universal Testing Machine, MTS System GmbH, Germany) to measure flexural and compressive strength after 1, 7 and 28 days (DIN

Table 1 Overview of the concrete mix composition and processing. Ingredients are in [kg/m^3] of concrete

Concrete recipe	Amount [kg/m^3]
Sand (0–2 mm)	1150
UHPC Mix NANODUR® Compound 5941	1050
Superplasticizer	18.1
Water	178.5

Mixing procedure	Time [min]
Dry ingredients	0–1
Water	1–2
Superplasticizer	2–8
End	8

EN 196). The porosity of the bulk material was evaluated with mercury intrusion porosimetry (MicroActive AutoPore V 9600, Micromeritics, USA).

Concreting was carried out in formwork with steel grid inserts, which allowed the production of 10 cm × 10 cm × 1 cm samples on a large scale. No formwork oil was used to produce the samples. Four surface structures with a range of different surface properties linked to bioreceptivity were created. One surface is a conventional concrete surface without imprinted surface structure, which serves as a reference. Two other surfaces were produced with textured molds, one with a texture milled directly into the bottom of the formwork and one by concreting onto a textile. The fourth surface was produced by applying expanded clay on top of the curing concrete. The expanded clay has a grain size of 1—2 mm and a total porosity of 41.7% with a water absorption of 10.3%.

All samples including the prisms for flexural and compressive strength were demolded 24 h after concreting and then stored in water for 6 days, followed by air storage in a climatic room with 50% rH and 23 °C. A visual documentation of the different surface types was done with scans (Scanmaker 1000 XL Plus, Mikrotek, Taiwan) of the whole sample surface (10 cm × 10 cm) and digital microscopy images (VHX 7000, Keyence, Japan) of respective cylindric samples with a diameter of 30 mm.

2.3 Roughness

Surface roughness was measured with a laser-based system (SRC-LS, Form + Test Seidner&Co. GmbH, Germany). The 10 cm × 10 cm samples were measured in a grid-like structure, with 5 measurements each horizontally and vertically at regular intervals of 20 mm. The raw data were evaluated, and arithmetic roughness (Ra) values were determined.

2.4 pH measurements

The surface pH value of the structured concrete samples in contact with water was measured using an in-situ approach adapted from Sagüés et al. [29]. Cylinders with a diameter of 30 mm were drilled out of the samples and inserted into small polymer bottles. The sides were sealed off with synthetic resin so that only the surface of the samples was in exchange with the environment. Deionized water (10 g) was poured into the polymer bottles and changes in the pH value of the water was monitored over time (0,5 h, 1 h, 2 h, 3 h, 5 h, 1d, 2d, 3d, 4d, 5d and 7d) with a pH probe (InLab Micro, Mettler-Toledo GmbH, Germany).

2.5 Water retention

The interactions between water and the various sample surfaces were tested using several methods. Water contact and roll-off angles were measured with an optical contact angle goniometer (OCA 35XLH, DataPhysics, Germany). Contact angles were recorded for 10 µl water droplets placed on horizontally positioned samples, with measurements taken over the course of one minute. For the roll-off angle, the samples were gradually tilted from a horizontal 0° position to a vertical 90° position within 70 s.

The water absorption capacity of the surfaces was measured using a modified gravimetric approach, following the guidelines of DIN EN 13057. Samples were dried to achieve mass constancy, and the back and sides were sealed to ensure water uptake occurred only through the structured surface. Before testing, the samples were weighed and then placed face down on a saturated sponge cloth, allowing for capillary absorption without direct immersion in water. The samples were weighed repeatedly, measuring the capillary water uptake over time. The sorption coefficient was calculated for both short-term water uptake (2 h) and long-term wetting scenarios (3 d).

The water retention capabilities of the different surfaces were assessed further with nuclear magnetic resonance (NMR). A NMR-Mobile Universal Surface Explorer (NMR-MOUSE) device developed by Blümich et al. [30] was used to determine water penetration depth. Preliminary tests were carried out to assess the T1 time and suitable measurement settings were chosen. The number of scans was set to 1000, along with six echoes and a repetition time of 350 ms. The measurement set-up is inspired by Orlowsky et al. [31], and involves placing a wetted sponge textile on the NMR-MOUSE, followed by a dried concrete sample and a plastic foil on top to reduce evaporation. The water uptake is measured in-situ.

3 Results

3.1 UHPC mix

The temperature of the fresh UHPC mix stayed within the recommended range and averaged at 24.0 ± 1.8 °C. The spreading was uniform and with a value of 31.5 cm ± 0.5 cm within the expected range. The average pore size of the bulk material is 12.0 nm.

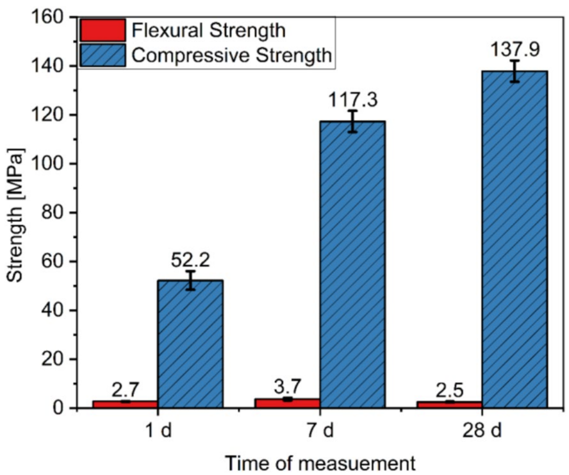

Fig. 1 Compressive and flexural strength of UHPC measured on prisms (40 × 40 × 160 mm) after 1, 7, and 28 days. The compressive strength increases steadily over time and reaches levels typical for UHPC

The resulting UHPC strength measured according to DIN EN 196 increases over time to a 28 day compressive strength of 137.9 ± 4.3 MPa and a flexural strength of 2.5 ± 0.2 MPa (Fig. 1).

3.2 UHPC samples

The different surface structures manufactured were visually documented (Fig. 2). A smooth surface called "Blanco" was selected as a reference to conventional concrete facades. The second surface structure was named "Expanded Clay" after the granulates additionally used in its production. For the "Vinidur" structure, crevasses with a depth of 0.5 mm and an offset of 1.0 mm were milled directly into the bottom of the formwork. Despite the implemented structure, the surface has a smooth and sealed appearance. Porous surfaces were represented by the structure "Textile". Concreting directly on a textile and ripping the textile off the UHPC surface after demolding led to small pores in the near-surface area.

3.3 Roughness

The reported values describe the microroughness of the different implemented surfaces. The unstructured Blanco surface shows the lowest roughness of 25.53 ± 8.5 µm. The Textile structure exhibits a roughness of 62.38 ± 7.0 µm, followed by

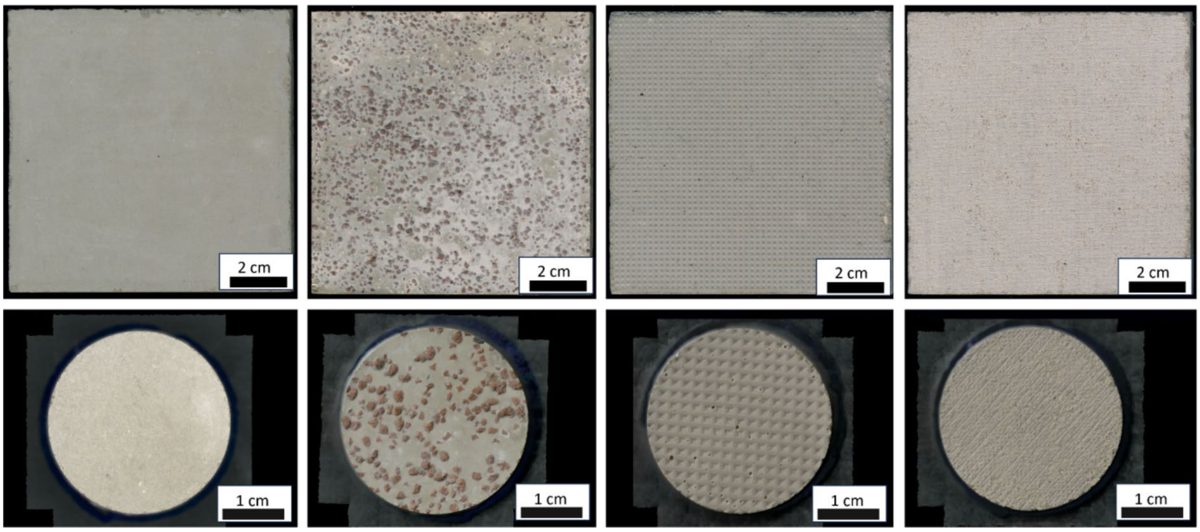

Fig. 2 Overview over the structured surfaces. From left to right: Blanco, Expanded Clay, Vinidur, Textile. On the top row scans of the 10 × 10 cm samples, on the bottom row the respective digital microscopy images of cylinders with a diameter of 3 cm

Vinidur with 65.92 ± 25.6 µm and Expanded Clay with 98.53 ± 23.9 µm.

3.4 pH measurements

The pH measurements of deionized water in contact with the various surface structures reveals a correlation between surface structure and the recorded pH values (Fig. 3). The initial pH value of the deionized water is at 6.5 and upon contact with the UHPC, its pH value increases, with the rate of increase dependent on the specific sample structure. After 30 min, the Textile surface exhibits the lowest pH value at 9.35 ± 0.1, followed by Blanco at 9.75 ± 0.2, Vinidur at 10.00 ± 0.4, and Expanded Clay at 10.45 ± 0.4.

Within the first 24 h, the Expanded Clay surface shows the most significant increase in pH value to values of 11.25 ± 0.25. The Blanco and Vinidur surfaces also show a strong increase in pH value to 11.0 ± 0.1 and 10.7 ± 0.4 respectively. The Textile surface exhibits the lowest increase in pH value within 24 h, with a value of 10.45 ± 0.05.

While the different surface structures initially have an impact on both pH value and rate of pH value increase, over time the underlying UHPC mix used for all samples leads to similar pH values recorded.

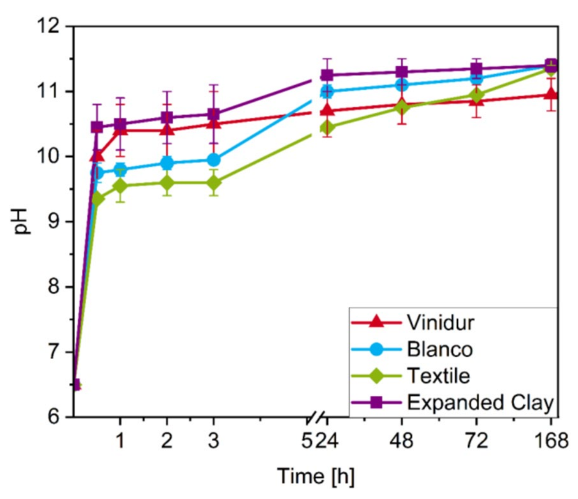

Fig. 3 Surface pH values of the four differently structured samples over time. The pH values of 10 ml deionized water in contact with the different surface structures is measured over time. In the initial phase of up to five hours, the surface structures impact leaching which leads to differences in pH values recorded. Eventually, all samples approached pH levels above 10, which are potentially inhibitory to biological growth, reflecting the influence of the shared cementitious base material

3.5 Water retention

Water contact angles measurements allow a distinction between hydrophilic and hydrophobic surfaces. The surfaces Blanco and Vinidur exhibit a water contact angle below 90°. They do not absorb the water, but hold it on the surface, classifying them as hydrophilic surfaces (Fig. 4). Expanded Clay as a combination of two materials is a special case, as the material properties of the added aggregates differ strongly from the surrounding, almost Blanco like UHPC surface, and results may differ depending on where droplets are placed. In the measurements, Expanded Clay performed similar to the Textile structure and both surface structures were not able to hold the water droplet on the surface, completely absorbing the water. The roll-off measurements yielded similar data and in case of Blanco and Vinidur, the droplet adhered to the structure even in a vertical position.

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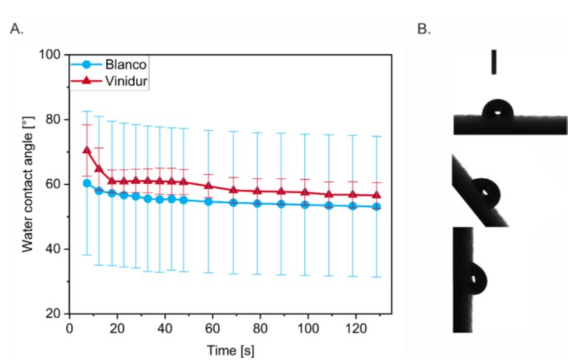

Fig. 4 Water contact measurements. 3A.: Water contact angles of the non-absorbent surfaces Vinidur and Blanco. Samples were stored horizontally. 3B.: Roll off angles of a Blanco sample. The sample was tilted 0°, 45° and 90° (top to bottom) and able to hold the droplet on its surface during the experiment duration of 70 s

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The water absorption capacity and linear sorption coefficients vary across the different structures (Fig. 5). The calculated 2 h value simulates short-term moisture accumulation possible during an extended rain or condensation event. Blanco and Vinidur show minimal water uptake, whereas the structures Expanded Clay and Textile show a comparatively high-water uptake in the beginning (Fig. 5A). Over a longer duration, the differences between the structures average out and the underlying material properties of the dense UHPC dominate the coefficients calculated (Fig. 5B).

The NMR results complete the water retention characterization of the different surfaces and show where absorbed water is stored within the concrete samples (Fig. 6). A distinction between wet sponge cloth, UHPC saturation zone and dry UHPC bulk material can be made, with their specific depths depending on the surface structure. The UHPC saturation zone indicates the extent and location of water storage within the material. The signal amplitude corresponds to the quantity of absorbed water, while the signal depth reflects how deeply the water penetrates the material. All observed UHPC saturation zones, including those of the two absorbent surfaces, Textile and Expanded Clay, are relatively thin, demonstrating that water storage is primarily confined near the surface. A sharp decrease in water absorption marks the transition from the surface structure to the bulk UHPC zone.

4 Discussion

The ultra-high-performance concrete (UHPC) used in this study was, due to its fine particle size distribution, well suited for accurately imprinting delicate microstructures. Four different surface structures (Blanco, Vinidur, Expanded Clay, and Textile) were specifically designed to enhance the UHPC's bioreceptivity and to represent a broad range of potentially suitable surface characteristics (Fig. 2). To avoid confounding effects, the samples were cast without a release agent, as conventional formwork oils can introduce organic residues to the surface, potentially inhibiting biofilm formation or promoting heterotrophic growth during early stages of planned biofilm growth experiments

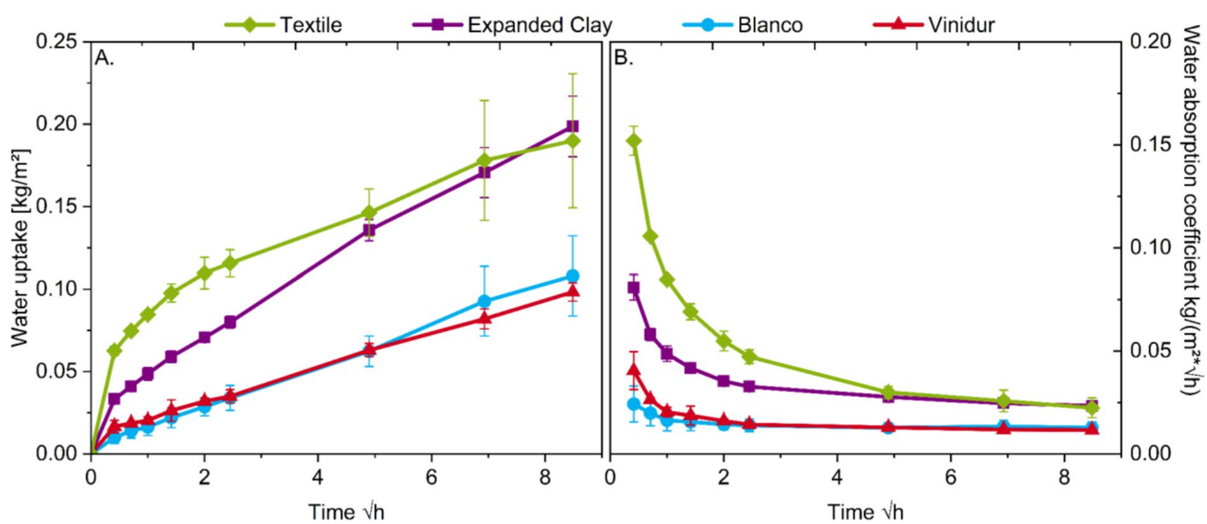

Fig. 5 Water retention experiments adapted from DIN EN 13057. A: Water uptake of the different surface structures in kg/m^2 over the experiment duration of 2 h ($\sqrt{8}$ h). B: Water absorption coefficient of the different surface structures in kg/(m.^{2}*$\sqrt{}$h) over the experiment duration of 2 h ($\sqrt{8}$ h)

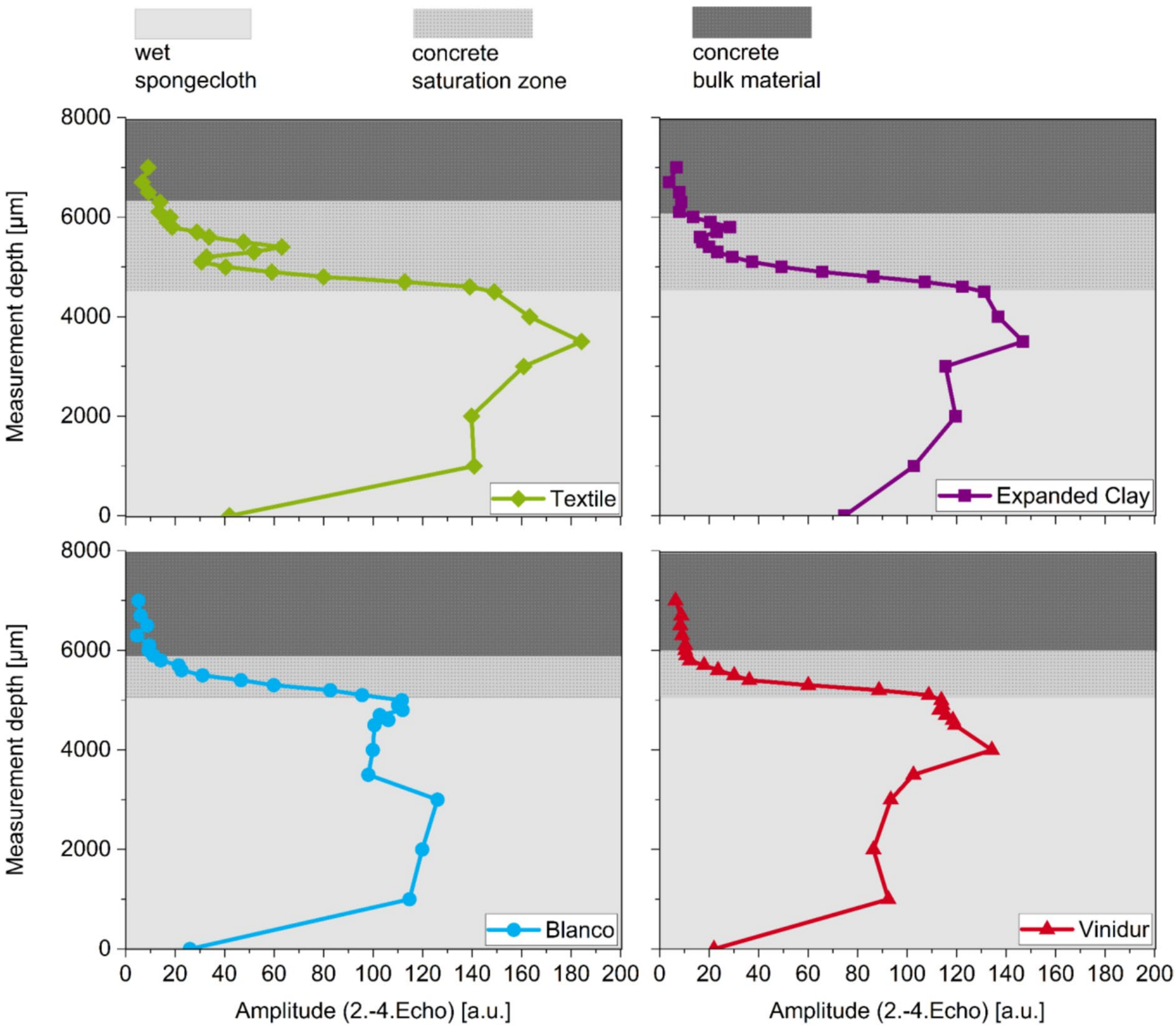

Fig. 6 NMR measurement of differently structured UHPC samples. Dry concrete samples with different surface structures are put on a wet spongecloth and measured with NMR. Differences in water retention capabilities are visible by water penetration depth (measurement depth) as well as amount of water retained in the sample (amplitude)

[32]. Formwork oils may further alter surface–water interactions until washed off or degraded, influencing material characterization results. These considerations during sample production ensured that the observed effects on bioreceptivity could be attributed primarily to the surface structure itself. Subsequent in depth surface characterization included roughness, surface pH values, and water retention capabilities.

Roughness values revealed comparatively high standard deviations (Paragraph 3.3). Not using a release agent led to the formation of pores, particularly on the Vinidur surface, which was produced using the most intricate formwork mold. Nevertheless, the number and size of these pores remained within acceptable limits and were considered preferable to the potential confounding effects of release agents. According to the literature, the size and shape of the surface structure has an influence on bioreceptivity [20] and ideally, the structures should be slightly larger than the colonizing microorganisms to facilitate adhesion [33]. Given the variability among potentially colonizing organisms, a range between 20 µm and 150 µm was aimed for and successfully achieved, resulting in roughness values comparable to those reported in previous studies [17, 24].

For measuring the surface near pH value, a specific experimental set-up adapted from Sagüés [29] was used, in which only the sample surface was continuously submerged in water, allowing close monitoring of changes in pH value. The set-up excludes potentially influential real-world effects, such as aerosol accumulation typically observed on façades, effectively isolating surface characteristics as the primary factor affecting pH value and enabling a direct comparisons between different surface structures.

Samples had been stored for one year at room conditions prior to testing, allowing some carbonation linked to physical surface parameters to occur. The results reveal significant differences in surface pH value across different UHPC surfaces tested. While the surfaces Vinidur and Expanded Clay exceeded a pH value of 10 within just 0.5 h of immersion, potentially limiting microbial growth, Textile and Blanco surfaces sustained more bioreceptive pH values for up to 3 h. After 24 h, all surfaces surpassed the pH threshold of 10, indicating limited suitability for microbial activity over extended wetting periods (Fig. 3). As noted in the introduction, excessively high pH values do not necessarily cause microorganisms to die but rather induce a dormant state, allowing them to survive the harsh environment. The timeframe during which a biofilm could remain active, along with the gradual increase in pH value that allows organisms sufficient time to adapt and shut down, is crucial and particularly promising on the Textile surface.

In the later stages of testing, atmospheric CO_2 likely influences results, as the shaking and opening of bottles allows CO_2 diffusion, causing a gradual decrease in pH value over time. This effect should be accounted for in long-term experiments. Overall, the experimental set-up provided meaningful insights, particularly for simulating shorter wetting periods that might occur naturally, and their impact on pH values present on a materials surface.

Another crucial factor for biological growth is water retention and availability [16, 27, 34]. Porosity, roughness, and texture influence the water absorption, water retention and wettability of a building material [16, 17, 35]. An important distinction between absorbed water and bioavailable water close to the surface must be made. In hydrophilic materials with high water retention capabilities, water is often absorbed into deeper layers, effectively reducing its bioavailability to microorganisms. On the other hand, hydrophobic surfaces may repel water, causing it to drain away and dry too quickly, also limiting bioavailability. For a material to be considered bioreceptive, it must retain water close to the surface over extended periods, ensuring it remains accessible to microorganisms and supports biological activity.

Water retention was assessed using a combination of techniques: water contact angle measurements to evaluate surface wettability, capillary sorption tests to quantify water uptake, and NMR to determine the distribution and bioavailability of water. This integrated approach provides a comprehensive understanding of water availability in the context of bioreceptivity.

Water contact angle and roll-off measurements (Fig. 4), distinguished between absorbent (Expanded Clay, Textile) and hydrophilic (Blanco, Vinidur) surfaces. Notably, water droplets on both the Vinidur and the Blanco surface remained on the surface without rolling off, even in a vertical, façade-like application.

Capillary sorption tests (adapted from DIN EN 13057) revealed differences in water uptake linked to the surface structure (Fig. 5). Results were in line with those from the water contact angles, as a distinction between two absorbent samples (Expanded Clay, Textile) and two hydrophilic and therefore less absorbent surfaces could be made (Blanco, Vinidur). Importantly, capillary sorption tests also provide insight into which surface structures possess more capillary pores, a feature potentially relevant for the success of microbial attachment.

For the two non-absorbent surfaces Blanco and Vinidur, the NMR results (Fig. 6) indicated a stronger signal directly at the surface, but the amplitude was close to that of the bulk material, suggesting minimal water absorption as indicated by the previous results. In contrast, the absorbent Expanded Clay and Textile surfaces showed a higher amplitude in the uppermost layer, indicating greater water retention near the surface. Comparing all four types of surface structures, significant differences in amount and depth of water saturation can be observed. The inhomogeneity of the Expanded Clay surface made precise NMR measurements difficult, as the recorded signal was an average of both air and saturated expanded clay particles, leading to higher error margins.

Due to the material density typical for UHPC, even the absorbent surfaces Expanded Clay and Textile retained water near the surface as intended. Their combination of increased roughness and surface-near water retention makes them promising candidates for upcoming laboratory weathering tests. The two non-absorbent surfaces also performed well, displaying hydrophilic contact angles without allowing water droplets to roll off. This effect depends on the droplet size, if the droplet becomes too large, gravity will overcome adhesion, causing it to roll off. However, dew droplets and prolonged drizzle are likely to have a major impact on biofilm development and growth [36, 37]. Considering this, the 10 µl droplet size used in the water contact angle measurements represent the key moisture fraction, further supporting the relevance of the methodology.

Despite using the same base UHPC mix for all samples, a wide range of material-water interactions was achieved solely by altering the surface structure. overall, the methods implemented provided a thorough understanding of the surfaces' wetting behavior and their ability to retain bioavailable water, showing that varied water interactions can be effectively controlled through a materials surface structure.

The surface parameters discussed should not be viewed in isolation as they often influence each other [27], such as e.g. roughness and porosity affect ph values. The results show that the structure significantly affects material-environment interactions in the short term. The in-depth material characterization allows a preliminary estimation of the bioreceptive properties. building on insights from literature on bioreceptive concrete [6, 17, 38] and on laboratory weathering experiments [26], the UHPC samples will be inoculated and subjected to a dynamic laboratory weathering experiment with irrigation using deionized water. In this scenario, the surfaces Expanded Clay and Textile are expected to show bioreceptive properties due to their enhanced roughness and capillary sorption and linked to it, their ability to help microorganisms attach. moreover, the pH values of both surfaces appear promising. Textile demonstrates the lowest pH values during shorter wetting periods of up to 3 h. When distinguishing between the uhpc matrix and the aggregate, expanded clay provides aggregates with more favorable ph conditions compared to the uhpc surface. This thesis will be further evaluated in the subsequent weathering experiments testing the durability of the imprinted structures and the interaction between inoculated microorganisms and their substrates. The complementary study aims to develop a comprehensive understanding of how the assessed surface properties affect bioreceptivity under realistic weathering conditions [28].

5 Conclusion

Bioreceptivity of concrete surfaces is primarily influenced by roughness, water retention capacity, and surface pH value. In case of concrete, crucial material parameters can be finely tuned through thoughtful choices in concrete formulation, surface adjustments, and storage conditions, enabling the development of bioreceptive materials.

To improve comparability across studies, a comprehensive testing framework for concrete surfaces properties in relation to bioreceptivity is presented. A novel assessment of the surface near pH value to monitor water–material interactions was introduced and simulates the conditions experienced by biofilms during their photosynthetic activity. Water availability was evaluated using a combination of contact angle measurements, capillary absorption tests, and NMR, measuring total water uptake as well as the fraction of water accessible to biofilms. This study demonstrates that, using the same underlying bulk material, a wide range of surface properties can be achieved.

Future research will combine these material characterization insights with a dynamic laboratory weathering experiment aimed to facilitate biofilm growth on bioreceptive surfaces, providing deeper insights into the connection between surface properties and microbial colonization.

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Data availability Data sets generated during the study are available from the corresponding author on reasonable request.

Declarations

Conflict of interests The authors have no relevant financial or non-financial interests to disclose. The authors have no conflicts of interest to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

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