Bioconcrete as an alternative sustainable construction material

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Abstract. The overall aim of the present research project is to examine the feasibility of industrialising a disruptive, carbon negative bio-concrete technology (developed by Biozeroc). The innovative technology uses bacteria to synthesise limestone which is used to bind aggregates. This eliminates the need for the high-temperature lime calcination process associated with ordinary Portland cement, the current preferred method for aggregate binding, which is responsible for 7~8 % of global green house gas emissions. This results in a concrete solution that can contribute to addressing the urgent need to address the climate emergency and help the construction industry achieve its NetZero targets. The main objective of the present study is to experimentally examine the material and structural performance of the newly-developed Microbially Induced Calcite Precipitation (MICP) bio-concrete and compare it to traditional ordinary Portland cement (OPC) concrete. This will be mainly based on examining the fresh and hardened properties of MICP and OPC concrete. The aim is to establish data-based guidelines for the uptake of an innovative and sustainable MICP concrete product within the construction industry. The outcome of these studies will be useful to manufacturers, practicing engineers, particularly designers and specifiers and to the concrete sector as a whole.

1 Introduction

1.1 Overview

With the current climate emergency, there is an urgent need to decarbonise the construction industry, one of the largest emitters of Greenhouse Gas Emissions (GHG) worldwide. Concrete is the most widely used building material worldwide due to its strength, durability, and versatility. Cement is traditionally the main binder in a concrete mix. It is primarily made of clinker, a residue produced by firing limestone and clay in a furnace heated up to 1,450 ^{o}C and therefore the manufacturing process produces large amounts of CO_2. Yet, without concrete, many of the world's most impressive buildings and structures would not be here. Meeting future societal population growth and urbanisation needs will not be viable without concrete. Therefore, one of the biggest challenges facing the construction sector is to reduce concrete's carbon footprint whilst retaining its benefits (especially in terms of durability and affordability).

The disruptive technology considered within the present project is highly original, since it aims to remove cement altogether from the concrete mix. Biozeroc's technology uses bacteria to precipitate calcium carbonate crystals akin to limestone. The crystals act to bind aggregate together, just like cement does, but storing carbon instead of releasing it. Limestone is one of the world's most time-tested building materials. One added benefit is the fact that limestone absorbs and releases heat efficiently, helping keep spaces cool in summer, and warm in winter, reducing energy costs and carbon footprints.

Fig. 1. Bioconcrete samples.

The present article reports on a collaborative research and development project between Biozeroc (a biomaterial science company aiming to provide access to low-cost, carbon-neutral construction materials) and the University of East London (UEL), which is providing research and technical expertise on the use of concrete and relevant performance requirements. Biozeroc's disruptive innovation uses biotechnology to make concrete without the need for cement. Traditional cement production is responsible for around 7~8 % of global GHG and as a result is an urgent target for large-scale decarbonisation in alignment with the Paris Agreement and the UK's Net Zero commitments. Biozeroc's low carbon technology functions at room temperature and pressure, without any inherent CO_2 emissions from the process. By replacing ordinary Portland cement with bacteria and feed media Biozeroc can manufacture a construction material called Bioconcrete that eliminates traditional cement entirely. This has enormous global decarbonisation potential. Recently, Biozeroc made a breakthrough in developing novel processes to create larger and thicker sections of Bioconcrete sufficient for use as concrete paving slabs. In order to produce concrete products, the material and structural performance of the Microbially Induced Calcite Precipitation (MICP) based Bioconcrete must be assessed. The main objective of the UEL research team is therefore to examine the material and structural performance of the Bioconcrete and compare it to traditional Ordinary Portland Cement (OPC) concrete. This will be mainly based on examining the fresh and hardened properties of MICP and OPC concrete. The aim is to establish data-based guidelines for the uptake of an innovative and sustainable MICP concrete product within the construction industry. A mix of laboratory experiments and field studies is currently underway.

The work is expected to provide critical insight into the material responses and structural performance of this novel MICP Bioconcrete construction material. This will accelerate the adoption of these innovations in construction materials and structural engineering applications, which will be vital in addressing the climate emergency. There is increasing research and innovation being carried out to develop low-carbon concrete materials (with the ultimate aim of producing a viable carbon-neutral/carbon-negative alternative to conventional cement-based concrete that is responsible for considerable CO2 emissions). More importantly, the work is expected to contribute considerably towards demonstrating that these MICP Bioconcrete materials can meet performance requirements.

1.2 Self-healing concrete

Initial developments in the field of MICP were focused on providing self-healing of concrete cracks using micro-organisms. Concrete is the most widely used building material worldwide due to its strength, durability, and versatility. However, despite these advantages, concrete structures are prone to cracking over time, primarily due to shrinkage, temperature fluctuations, and mechanical stress. These cracks compromise the structural integrity and longevity of buildings, allowing moisture and chemicals to penetrate, which can lead to corrosion of reinforcement bars and further degradation. To address this problem, the concept of Bioconcrete, also known as self-healing concrete, has emerged as an innovative solution in modern construction.

Bioconcrete is an advanced type of concrete that integrates a biological component to autonomously repair cracks. The primary mechanism behind this self-healing process involves bacteria, which are capable of precipitating calcium carbonate ($CaCO_3$) when exposed to water and certain nutrients. This calcium carbonate acts as a natural sealant, filling in the cracks that develop over time. The use of bacteria in concrete is advantageous because these microorganisms can survive in dormant spore form for extended periods and are activated only when cracks occur, making the repair process efficient and long-lasting.

Subsequent studies have expanded on the range of materials used to encapsulate the bacteria, as encapsulation is essential for protecting bacterial spores during the mixing process and ensuring their activation only when needed. Van Tittelboom et al. (2011) [1] explored the use of various encapsulation methods, including porous aggregates, hydrogels, and clay pellets, to optimize the release of bacteria and nutrients. The effectiveness of these methods was evaluated based on their ability to seal cracks and their influence on the overall strength and workability of the concrete. Porous aggregates, in particular, have shown promise as a carrier for bacteria, as they provide ample space for the spores and nutrients while maintaining structural integrity within the concrete mix.

The self-healing process in Bioconcrete relies on bacteria converting calcium lactate into calcium carbonate, which fills the cracks and restores the material's impermeability. Jonkers (2011) [2] demonstrated that Bioconcrete could heal cracks up to 0.8 mm wide, effectively sealing cracks that would otherwise allow water and harmful substances to penetrate the structure. The study also emphasized that Bioconcrete showed improved durability, particularly in aggressive environments such as marine or industrial settings where traditional concrete would rapidly degrade.

The healing process has been confirmed through numerous experimental studies, where Bioconcrete specimens were subjected to controlled cracking and then exposed to water. In most cases, cracks were fully sealed within a few weeks of bacterial activation. Beskopylny et al. (2024) [3] found that Bioconcrete not only sealed surface cracks but also reduced the permeability of concrete, which is critical for preventing further degradation. Their research indicated that Bioconcrete could significantly extend the service life of structures, particularly those exposed to harsh environmental conditions.

More recent work by De Belie et al. (2018) [4] explored the long-term performance of Bioconcrete and its ability to repeatedly heal cracks. Their study showed that Bioconcrete retained its self-healing capacity even after multiple cycles of cracking and healing. The research also highlighted that Bioconcrete could reduce maintenance costs over time, as less manual intervention would be required for repair and restoration. Furthermore, De Belie et al. (2018) [4] suggested that advancements in encapsulation technologies could further improve the efficiency of the self-healing process by extending the lifespan of bacteria within the concrete matrix.

The self-healing properties of Bioconcrete help mitigate the damage caused by such exposure, as documented by Wiktor and Jonkers (2011) [5], who tested Bioconcrete in marine environments. The sustainability benefits of Bioconcrete are also gaining attention. One of the major environmental issues associated with conventional concrete production is the high carbon footprint, primarily due to the energy-intensive cement manufacturing process. By reducing the frequency of repairs and extending the lifespan of concrete structures, Bioconcrete contributes to lower CO_2 emissions over the lifecycle of a building. Other researchers like Stanaszek-Tomal, E. (2020) [6] advocate for Bioconcrete as a sustainable alternative that aligns with global efforts to reduce the environmental impact of construction. Research by Ersan et al. (2016) [7] has suggested that improving the scalability of Bioconcrete production and developing more cost-effective encapsulation methods could help bring down these costs, making Bioconcrete more competitive in the market.

Hoffmann, et.al. (2021) [8] reported that bacterial activity is widespread in our landscapes and throughout the geological record, playing a crucial role in shaping Earth's mineral deposits. This process, known as Bacteria-Induced Mineral Precipitation (BIMP), contributes to the formation of various mineral structures. These include stalactites, stalagmites, microbialites, stromatolites, and thrombolites, as well as large-scale sedimentation. In recent years, the capacity of bacteria to facilitate mineral formation has garnered interest in biotechnological applications. Notably, the precipitation of calcium carbonate as calcite, the primary component of limestone, has been utilized in pioneering civil engineering technologies. The first patented use of this process is believed to have been by Adolphe et.al. (1990) for the biological treatment of deteriorating stone surfaces [9].

The bacterial metabolic process known as Microbially Induced Calcium Carbonate Precipitation (MICP) has gained attention as a sustainable alternative to reduce costs and environmental impacts. Bioconcrete production utilizes bacteria capable of inducing mineral formation (biomineralization) within the cement matrix. This process is driven by the infiltration of water, CO_2, and other chemical substances such as SO_4 and NO_3^-, among others [11-14]. MICP not only enhances the self-healing properties of concrete but also improves its physical and mechanical characteristics. While several reviews have explored the biotechnological aspects of Bioconcrete [15,16], the microbiological and molecular mechanisms of MICP, as well as the role of different microbial groups, remain underexplored. This review focuses on the types of biomineralization processes, the metabolic pathways utilized by various microbial groups, and the genetic factors related to urease and carbonic anhydrase activities involved in MICPCastro-Alonso (2019) [10].

1.3 MICP Bioconcrete

Bioconcrete offers an innovative approach where aggregates are bound together by calcium carbonate crystals formed through microbially induced calcium carbonate precipitation (MICP). This biomineralization process is CO_2-negative, as carbon dioxide is sequestered within carbonate compounds. With a chemical composition akin to calcite-cemented sandstone, Bioconcrete can be moulded into diverse shapes and reinforced, making it a promising candidate for manufacturing larger building components. By utilizing renewable energy sources and adhering to circular economy principles in the production of raw materials, Bioconcrete has the potential to serve as a CO_2-neutral alternative to traditional Portland cement-based concrete [17]. Smirnova et.al. (2023) studied a combination of techniques such as utilizing urease-active calcium carbonate powder (UACP) in place of free bacterial cells, optimizing aggregate packing density, and applying an automated stop-flow pressure injection method. In their study, various cementation parameters were tested to identify the optimal conditions for producing uniformly cemented, high-strength Bioconcrete. Reproducibility and optimization studies were also conducted using selected parameter combinations. The results highlighted that achieving homogeneous compaction with adequate aggregate packing density was essential for consistent and high-quality cementation outcomes. These findings open new possibilities for using Bioconcrete in the production of prefabricated load-bearing building components, potentially replacing traditional concrete in certain applications [17].

Yang et.al. (2022) review examined the strength of biocemented soils under various conditions, including compression, tension, and both static and cyclic shear, focusing on unconfined compressive strength, splitting tensile strength, yielding, shear, and cyclic resistance strengths. Particle-scale mechanisms were detailed to explain the improvement processes in biotreatment and the failure patterns observed in biocemented samples under external loads. Additionally, the challenges associated with biocementation were addressed, and potential directions for future research were outlined [18].

Ray Harran (2022) investigated experimentally two types of sands treated with microbially induced carbonate precipitation (MICP), each with distinct initial properties. Samples containing varying calcite contents were tested under uniaxial and incremental loading, as well as long-term monotonic loading, to assess their compressibility and understand their deformation mechanisms. Additionally, the porosity-to-cement ratio, initially developed for artificially bonded soils, was evaluated as a parameter to describe the behaviour of MICP-treated sands. Results from the incremental loading tests showed that for calcite contents ranging between 3% and 8% and applied stress levels up to 1,000 kPa, MICP treatment significantly improved the stiffness of the geomaterials and reduced their overall deformability. Medium-grained sand required lower calcite content to achieve comparable compressibility to fine-grained sand and aligned better with the porosity-to-cement ratio. Long-term tests under sustained monotonic loads (over 75 days) revealed that under high stresses exceeding the apparent preconsolidation stress, the coefficient of secondary compression increased up to three times compared to untreated samples. The study demonstrated that stress and time effects are interdependent. The cementation from MICP shifted a portion of the immediate settlement to delayed deformation after bond breakage, influenced by loading conditions and bond quality (deposition and imperfections), as confirmed by microstructural analysis [19].

Fouladi et al. (2023) investigated the advantages of employing the MICP technique in construction materials, highlighting its potential as an effective method for converting waste into valuable and sustainable applications. In their research, they provided a comprehensive analysis of the environmental benefits and engineering uses of MICP technology, emphasizing the role of waste streams. Additionally, the study provides researchers with insights and strategies for identifying and addressing potential challenges when implementing MICP technology with waste streams [20].

Fu et.al. (2023) researched the use of MICP to improve the engineering properties of soils. Their research aimed to provide a thorough review of over a decade of research on the use of Microbially Induced Calcite Precipitation (MICP) for soil strengthening. By explaining the fundamental mechanisms, compiling and analyzing experimental results, and discussing critical aspects with reference to key published studies, it presents a comprehensive overview of the current state of MICP-based soil strengthening. The review identifies existing knowledge gaps and offers recommendations for future research, while also highlighting the opportunities and challenges associated with the practical implementation of this technique in real-world geotechnical applications [21].

Cheng et.al. (2020) explored bio-cementation using microbially induced calcite precipitation (MICP) to produce sandstone-like "bio-bricks" under 50% treatment saturation. The bio-bricks formed under these partially saturated conditions achieved a compressive strength of 9 MPa, double the strength typically obtained using the conventional fully saturated approach. Various mechanical properties were assessed, including water absorption (approximately 10%), resistance to salt attack (mass loss of about 0.5 g), and fire resistance. The findings indicated that these bio-bricks are a viable construction material, offering the added advantage of being a more environmentally friendly alternative to traditional fired clay or cement bricks [22].

Zhang et al. (2023) conducted a comprehensive review of the fundamentals and engineering applications of Microbial Induced Calcium Carbonate Precipitation (MICP) technology, drawing on existing studies. Their work addresses the practical needs of various fields, including geotechnical engineering, construction materials, hydraulic engineering, geological engineering, and environmental engineering. The study offers fresh insights into the feasibility and challenges of implementing MICP in real-world scenarios. The analysis and discussions are tailored to the specific considerations of each field. The study highlights three viable approaches for MICP implementation: bioaugmentation, biostimulation, and enzymatic methods. [23].

Konstantinou et al. (2021) presented microbially induced carbonate precipitation (MICP) as a technique for creating artificially cemented specimens with tailored properties that closely mimic those of soft carbonate sandstones. The study utilized materials with two distinct particle size distributions (PSDs) to explore a variety of strength and porosity combinations. While the MICP parameters, such as calcium carbonate crystal size and type, remained consistent across all samples, the injected volume was adjusted to achieve varying levels of cementation. Despite the challenges associated with uniformly cementing very coarse sands, the findings revealed that both fine and coarse sand specimens exhibited high uniformity and repeatability. The unconfined compressive strengths of the artificial specimens, which were below 3000 kPa, and their porosities, ranging from 0.25 to 0.4, aligned with values reported for natural rocks. The fine sand demonstrated greater strength gain compared to the coarse sand, as the larger void sizes in the coarse sand led to less effective precipitation locations, away from particle contacts. The strength and porosity values obtained for both sands in this study fell within the ranges documented in the literature for natural soft rocks, highlighting the MICP technique's ability to replicate realistic properties. This suggests that by adjusting grain sizes and potentially the width of the PSD, a full spectrum of properties can be achieved [24].

Yang Xiao (2021) conducted experimental one-dimensional compression tests on quartz sands treated with microbially induced carbonate precipitation (MICP) to assess the influence of gradation and calcium carbonate ($CaCO_3$) content on compression behavior. The findings indicate that specimen compressibility increases with a higher coefficient of uniformity or lower $CaCO_3$ content. The relationship between void ratio and vertical stress can generally be divided into three stages based on the underlying mechanisms. Bond breakage begins at approximately 0.036 MPa of vertical stress, while particle breakage becomes the dominant mechanism at around 8.3 MPa. Scanning electron microscope analyses reveal that the bonding and coating effects of $CaCO_3$ precipitation contribute to the reduced compressibility of MICP-treated specimens. Additionally, the presence of fine particles promotes the formation of interparticle $CaCO_3$ bonds, which, upon breaking, still allow the smaller particles to occupy the voids between coarser grains [25].

2 Experimental study

An extensive programme of testing is currently underway to optimise the performance of the developed Bioconcrete products for different construction applications.

2.1 Materials used

Various types of fine and coarse aggregates have been utilized in the present research studies. Classification and properties were investigated as well as analysing the Particle Size Distribution (PSD).

2.2 Testing Programme

Biozeroc innovated an MICP method to replace cement usage with a cement-free Bioconcrete alternative. The method is based on using bacteria that stimulate the precipitation of calcium carbonate, which acts as a binding agent, replacing cement's role in traditional concrete. The scope of the experimental study is focused on the testing of: compressive strength, tensile strength, flexural strength, durability, scanning electron microscope (SEM), X-ray diffraction (XRD), and skid resistance. A series of experiments were then conducted on the different mix designs using different specialist laboratory equipment.

3 Results and discussion

3.1 Aggregate packing density

In this research, the aggregate packing density was used to increase the volume ratio of aggregates to voids in the mixture. This not only enhances efficiency but also offers economic advantages by reducing the amount of cementation solution required. The optimization of packing density was conducted using a combination of aggregates used with different percentages. A grading curve was developed with an optimized packing density. This study explored the relationship between void fraction and density [26], with the goal of identifying mix designs that maximize packing density while maintaining desirable material properties. The void fraction is a measure of the empty spaces in a mixture, expressed as the ratio of the volume of voids to the total volume of the mixture. Packing density refers to the fraction of the total volume occupied by solid particles. A lower void fraction corresponds to a higher packing density, which is desirable for improving material performance.

In order to simulate the packing arrangement of particles in various mix designs, the following steps were followed:

1. Input Material Properties: The particle size distribution, shape, and density of each material were defined.
2. Define Mix Proportions: The relative proportions of materials in the mixture were specified.
3. Simulate Packing Arrangement: the packing of particles was simulated and calculated the void fraction and packing density.
4. Optimize Mix Design: the particle size distribution and material proportions were adjusted to minimize void fraction and maximize packing density.

The relationship between void fraction and density was analyzed for different mix designs. Consequently, the impact of particle size distribution, shape, and material proportions on packing density was evaluated.

3.2 Strength testing

A large number of samples were prepared, with several specimens for each variation prepared and the average value was then considered. The compressive strength test was carried out according to (BS EN 12390-3: 2019 2022) [27]. Both cylindrical and cube samples, the latter with standard dimensions of 100 mm x 100 mm x 100 mm. Fig. 2 shows the evolution of Bioconcrete samples from small 16mm cylinders to the 100 mm cubes used for compressive strength testing. The strength of samples was measured at both 7 and 28 days. The results showed that the compressive strength was improved for each trial and well correlated with the conventional concrete counterpart.

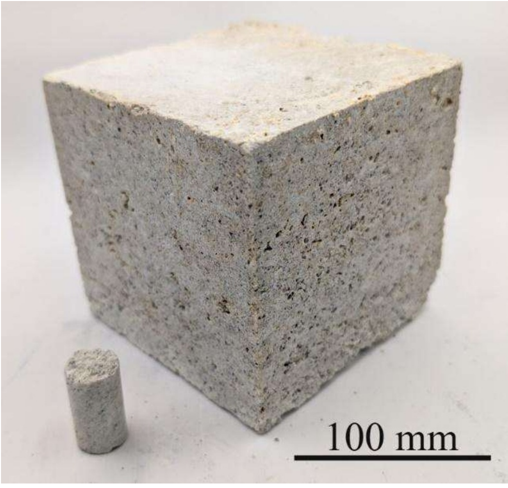


Fig. 2. Bioconcrete samples. Left, 16 mm cylinder, produced as an early test format. Right, 100 mm cube, for testing to British Standards.

Flexural testing was also carried out, following the method outlined in BS EN 1339 [28]. In brief, samples were prepared by cutting a bioconcrete paving slab of dimensions 300 mm x 300 mm x 50 mm. into sections of 150 mm x 50 mm x 50 mm. These samples were then tested using a 3-point bend test. The results of these tests are displayed in Fig. 3. The flexural strength, with a characteristic strength of 3.69 MPa exceeds the required characteristic strength value for BS EN 1339 of 3.5 MPa.

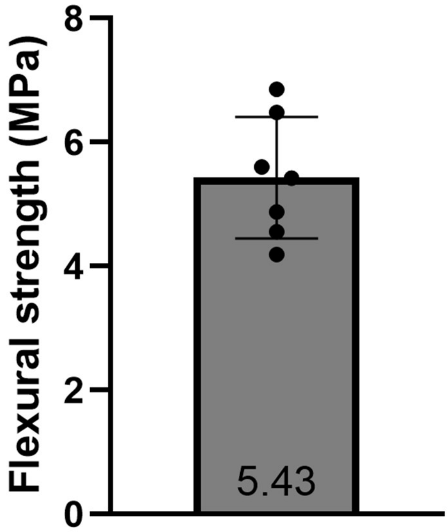


Fig. 3. Flexural strength of Bioconcrete paving slab slices. (n = 7, mean = 5.43 MPa, standard deviation = 0.98 MPa). For concrete paving slab standards BS EN 1339 [28], the characteristic strength of the slabs must exceed 3.5 MPa. The characteristic strength of these samples is 3.69 MPa.

3.3 Durability

The durability of the Bioconcrete samples was assessed by means of a freeze and thaw resistance testing using a de-icing salt method, as per the guidelines of BS EN 1339-2003 [28]. After curing of (168 ± 5) hours in a controlled climate chamber at 20 ± 2 °C, a layer of a 3% NaCl (sodium chloride) solution in potable water is poured on the test surface to a depth of 5 ± 2 mm, simulating exposure to moisture.

After 7 and 14 cycles, an additional 3% NaCl in potable water was added during the thaw period, if necessary, to ensure a (5 ± 2) mm layer was maintained on the surface of the samples.

After 28 cycles, the following procedure was carried out for each specimen:

a) Any material that had scaled off the test surface was collected by rinsing into a vessel using a spray bottle and brushing into the vessel until no further scaled material was removed.

b) The liquid and scaled material in the vessel were carefully poured through a filter paper. The material collected on the filter paper was washed with a minimum of 1 litre of potable water to remove any residual NaCl. The filter paper and collected material were dried for at least 24 hours at (105 ± 5) °C. The dry mass of the scaled material was determined to an accuracy of ± 0.2 g, with appropriate adjustment made for the weight of the filter paper.

The results from the freeze and thaw test in Fig. 4 show that the samples performed exceptionally well in terms of durability under the test conditions, indicating excellent resistance to freeze-thaw damage, beyond that of BS EN1339-2003 class 4, Extreme freeze-thaw resistance. Testing of further samples and analysis are under way.

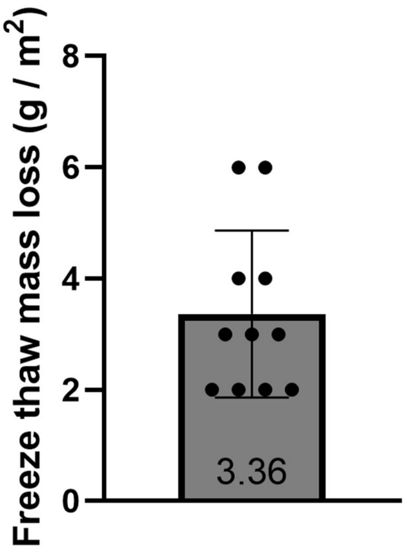


Fig. 4. Graph of freeze-thaw resistance of Bioconcrete samples, showing extreme resistance to freeze-thaw. (n = 11, mean = 3.36 g / m^2, standard deviation = 1.50 g / m^2).

In addition to freeze thaw resistance testing, water absorption may be used as a proxy measure of the resistance of concrete to freeze thaw. For concrete paving slab standards [28], a threshold of 6 % water absorption is used to assess freeze thaw durability. Bioconcrete samples produced using MICP were shown to be capable of meeting the freeze thaw durability standard, as shown in Fig. 5. The results show an average water absorption of 5.39 % (n = 6, mean = 5.39, standard deviation = 0.28), with all sample below the 6% threshold required by the paving slab standards.

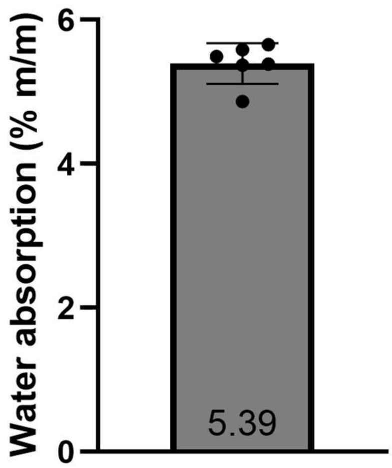


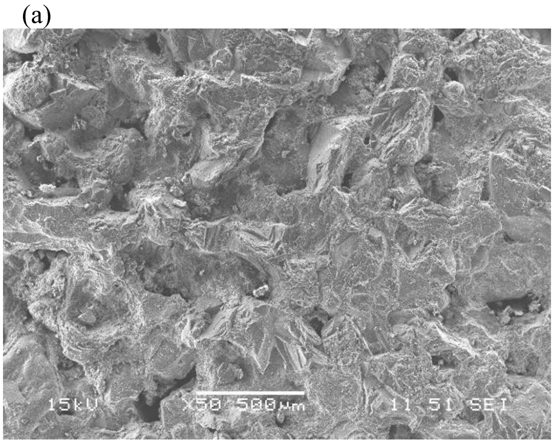
Fig. 5. Water absorption of Bioconcrete (%w/w), measured using 100mm cubes (n = 6, mean = 5.39, standard deviation = 0.28). For concrete paving slab standards BS EN 1339, a threshold of 6 % water absorption is used to assess freeze-thaw durability.

1.1 Scanning Electron Microscope (SEM)

Scanning Electron Microscopy (SEM) tests were performed to examine the surface morphology and microstructural features of the Bioconcrete. SEM is commonly used in materials science, geology, and engineering to investigate surface characteristics, particle sizes, fracture patterns, and other microscale details.

The results in Fig. 6 show the fracture surface of a Bioconcrete sample. The calcium carbonate deposition is visible across most of the surface, with aggregate chip out resulting in a rough, uneven surface. From Fig. 5 (b) the fracture of the calcium carbonate layer may be observed, as well as the flaking off of calcium carbonate from the underlying aggregate. It is also possible to observe the layering of calcium carbonate from deposition of multiple MICP layers. The deposition of calcium carbonate appears to be relatively uniform across the surface of the aggregate, suggesting a relatively homogeneous deposition during the production process.

(a)



(b)

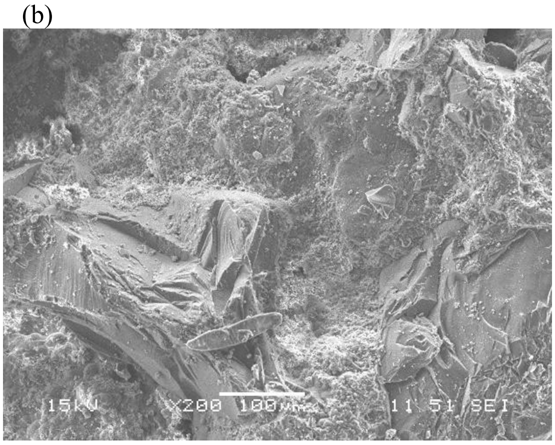


Fig. 6. SEM images of Bioconcrete fracture surface. (a) x50 magnification, showing chip out of aggregate. (b) x200 magnification showing fracture of calcium carbonate layer.

1.2 X-ray diffraction (XRD)

X-ray Diffraction (XRD) tests were performed to identify the crystalline phases, the crystallite size, assess purity, or analyze the texture present in a material. Each pattern provides a plot of intensity (counts) versus 2θ (degrees), where 2θ represents the diffraction angle, and intensity corresponds to the abundance of a particular crystallographic plane in the sample.

In XRD, the positions and intensities of peaks correspond to the specific crystal structures in the material. For example, in Fig. 7, peaks corresponding to the Quartz (101) reflection, the Vaterite (110) reflection and the Calcite (104) reflection are highlighted. The Quartz (101) reflection is as a result of the underlying aggregate, but the Vaterite and Calcite peaks are as a result of MICP deposition of calcium carbonate, and the subsequent crystalline phases that it develops into. The quantification of different phases by the intensity of the different peaks can give a rough indication of the proportion of the different phases, allowing analysis of the effect of curing of Bioconcrete under different conditions.

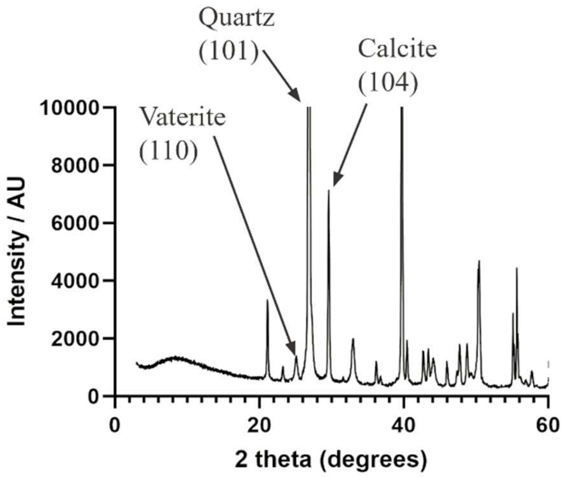


Fig. 7. XRD spectrum of Bioconcrete. Peaks corresponding to Vaterite (110) and Calcite (104) produced by the MICP process have been identified, alongside the Quartz (101) peak from the aggregate used.

1.3 Skid resistance

The skid resistance of bio-concrete samples has been tested using the portable skid resistance tester. The test procedure followed the EN 1339:2003 [28] standard. The friction test equipment and slider are kept in a room at a controlled temperature of (20 ± 2) °C for at least 30 minutes prior to testing. The specimen is immersed in water at the same temperature, (20 ± 2) °C, for a minimum of 30 minutes immediately before testing. The friction tester is placed on a stable, level surface, and the levelling screws are adjusted to ensure the pendulum support column is vertical.

This process is repeated five times, with the specimen rewet each time, and the mean of the last three readings is calculated. The specimen is then rotated 180°, repositioned, and the procedure is repeated. The skid resistance initial results indicate that the majority of the samples perform adequately. Further evaluation and improvements are currently underway.

Fig. 8. Skid resistance test.

2 Conclusions

The experimental research investigations described in the present article were aimed at examining the performance of the novel Bioconcrete mixes, which result in cement-free concrete. The behaviour was investigated by performing compressive, tensile and flexural tests as well as durability investigations (using an environmental chamber to apply freeze and thaw cycles as well as skid resistance testing). This was complimented by an examination of the microstructure using Scanning Electron Microscope (SEM) and X-ray diffraction (XRD). The initial results confirm the potential for Bioconcrete to be used as an alternative sustainable construction material.

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References

1. Van Tittelboom, Kim, Nele De Belie, Willem De Muynck, and Willy Verstraete. "Use of bacteria to repair cracks in concrete." Cement and concrete research 40, no. 1 (2010): 157-166..
2. Jonkers, Henk M. "Bacteria-based self-healing concrete." Heron 56, no. 1/2 (2011): 1-12.
3. Beskopylny, Alexey N., Evgenii M. Shcherban', Sergey A. Stel'makh, Alexandr A. Shilov, Andrei Chernil'nik, Diana El'shaeva, and Vladimir A. Chistyakov. "Analysis of the Current State of Research on Bio-Healing Concrete (Bioconcrete)." Materials 17, no. 18 (2024): 4508.
4. De Belie, Nele, Elke Gruyaert, Abir Al-Tabbaa, Paola Antonaci, Cornelia Baera, Diana Bajare, Aveline Darquennes et al. "A review of self-healing concrete for damage management of structures." Advanced materials interfaces 5, no. 17 (2018): 1800074.
5. Wiktor, Virginie, and Henk M. Jonkers. "Quantification of crack-healing in novel bacteria-based self-healing concrete." Cement and concrete composites 33, no. 7 (2011): 763-770.
6. Stanaszek-Tomal, Elżbieta. "Bacterial concrete as a sustainable building material?." Sustainability 12, no. 2 (2020): 696..
7. Erşan, Yusuf Çağatay, Hilke Verbruggen, Iris De Graeve, Willy Verstraete, Nele De Belie, and Nico Boon. "Nitrate reducing CaCO3 precipitating bacteria survive in mortar and inhibit steel corrosion." Cement and Concrete Research 83 (2016): 19-30.
8. Hoffmann, Timothy D., Bianca J. Reeksting, and Susanne Gebhard. "Bacteria-induced mineral precipitation: a mechanistic review." Microbiology 167, no. 4 (2021): 001049.
9. Loubire, J. F., J. Paradas, J. P. Adolphe, and F. Soleillhavoup. "Procédé de traitement biologique d'une surface artificielle." (1990).
10. Castro-Alonso, María José, Lilia Ernestina Montañez-Hernandez, Maria Alejandra Sanchez-Muñoz, Mariel Rubi Macias Franco, Rajeswari Narayanasamy, and Nagamani Balagurusamy. "Microbially induced calcium carbonate precipitation (MICP) and its potential in Bioconcrete: microbiological and molecular concepts." Frontiers in Materials 6 (2019): 126.
11. De Muynck, Willem, Kathelijn Cox, Nele De Belie, and Willy Verstraete. "Bacterial carbonate precipitation as an alternative surface treatment for concrete." Construction and Building Materials 22, no. 5 (2008): 875-885.
12. Jonkers, Henk M., Arjan Thijssen, Gerard Muyzer, Oguzhan Copuroglu, and Erik Schlangen. "Application of bacteria as self-healing agent for the development of sustainable concrete." Ecological engineering 36, no. 2 (2010): 230-235.
13. Dhami, Navdeep Kaur, M. Sudhakara Reddy, and Abhijit Mukherjee. "Application of calcifying bacteria for remediation of stones and cultural heritages." Frontiers in microbiology 5 (2014): 304.
14. Bundur, Z., R. Ferron, and M. J. Kirisits. "Bacterial calcification in cement pastes and mortars containing mineral admixtures." Academic Journal of Civil Engineering 33, no. 2 (2015): 316-323.
15. Zhu, Tingting, and Maria Dittrich. "Carbonate precipitation through microbial activities in natural environment, and their potential in biotechnology: a review." Frontiers in bioengineering and biotechnology 4 (2016): 4.

16. Jain, Surabhi, and D. N. Arnepalli. "Biochemically induced carbonate precipitation in aerobic and anaerobic environments by Sporosarcina pasteurii." Geomicrobiology Journal 36, no. 5 (2019): 443-451.
17. Smirnova, Maiia, Christoph Nething, Andreas Stolz, Janosch AD Gröning, Daniele P. Funaro, Erik Eppinger, Manuela Reichert, Jürgen Frick, and Lucio Blandini. "High strength bio-concrete for the production of building components." npj Materials Sustainability 1, no. 1 (2023): 4.
18. Xiao, Yang, Xiang He, Musharraf Zaman, Guoliang Ma, and Chang Zhao. "Review of strength improvements of biocemented soils." International Journal of Geomechanics 22, no. 11 (2022): 03122001.
19. Harran, Ray, Dimitrios Terzis, and Lyesse Laloui. "Characterizing the deformation evolution with stress and time of biocemented sands." Journal of Geotechnical and Geoenvironmental Engineering 148, no. 10 (2022): 04022074.
20. Fouladi, Amir Sina, Arul Arulrajah, Jian Chu, and Suksun Horpibulsuk. "Application of Microbially Induced Calcite Precipitation (MICP) technology in construction materials: A comprehensive review of waste stream contributions." Construction and Building Materials 388 (2023): 131546.
21. Fu, Tianzheng, Alexandra Clarà Saracho, and Stuart Kenneth Haigh. "Microbially induced carbonate precipitation (MICP) for soil strengthening: A comprehensive review." Biogeotechnics 1, no. 1 (2023): 100002.
22. Cheng, Liang, Takamitsu Kobayashi, and Mohamed A. Shahin. "Microbially induced calcite precipitation for production of “bio-bricks” treated at partial saturation condition." Construction and Building Materials 231 (2020): 117095.
23. Zhang, Kuan, Chao-Sheng Tang, Ning-Jun Jiang, Xiao-Hua Pan, Bo Liu, Yi-Jie Wang, and Bin Shi. "Microbial-induced carbonate precipitation (MICP) technology: a review on the fundamentals and engineering applications." Environmental Earth Sciences 82, no. 9 (2023): 229.
24. Konstantinou, Charalampos, Giovanna Biscontin, Ning-Jun Jiang, and Kenichi Soga. "Application of microbially induced carbonate precipitation to form bio-cemented artificial sandstone." Journal of Rock Mechanics and Geotechnical Engineering 13, No. 3 (2021): 579-592.
25. Xiao, Yang, Chang Zhao, Yue Sun, Shun Wang, Huanran Wu, Hui Chen, and Hanlong Liu. "Compression behavior of MICP-treated sand with various gradations." Acta Geotechnica 16 (2021): 1391-1400.
26. EMMA Software User Manual. Elastic Mixture Model Analysis. (2023).
1. Standard EN 1168:2005+A3:2011 Precast concrete products – Hollow core slabs. European Committee for Standardization. 2024.