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Scientific Article

Biomineralization of calcium carbonate in concrete by the action of *Bacillus pumilus*

Biomineralização de carbonato de cálcio no concreto pela ação do Bacillus pumilus

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ABSTRACT

The present study evaluated the viability of the bacterium *Bacillus pumilus* as a biological agent in the process of calcium carbonate precipitation on a concrete surface. This evaluation was carried out in a curing tank of concrete samples, applying a nutrient solution enriched with *B. pumilus* for 48 h. During the experimental period, a urease test was performed to determine whether the microorganisms could hydrolyze urea by the action of the urease enzyme. The results revealed that *B. pumilus* is susceptible to converting urea into ammonium and increasing the medium pH. There was also a 0.03 g cm^2 reduction in water absorption by capillarity in specimens biomineralized with *B. pumilus* compared to conventional specimens. Due to the degree of surface protection, microorganisms have reduced the material's porosity, causing an increase in tensile strength by diametric compression of approximately 9.0 MPa. The lower height of capillary rise observed was 1.83 cm in biomineralized specimens and 3.83 cm for conventional specimens. The results obtained with the scanning electron microscope and energy dispersive spectroscopy indicate the presence of $CaCO_3$ precipitated by the bacteria. In general, the results obtained in this study show that *B. pumilus* may improve its mechanical properties when it is applied superficially to concrete.

Keywords: self-healing; *Bacillus pumilus*; calcium carbonate; biomineralization; bioconcrete.

RESUMO

O presente estudo avaliou a viabilidade da bactéria *Bacillus pumilus* como agente biológico no processo de precipitação de carbonato de cálcio na superfície do concreto. Tal avaliação foi conduzida em um tanque de cura de amostras de concreto aplicando-se uma solução nutriente enriquecida com *B. pumilus* durante 48 horas. Durante o período experimental, foi realizado teste de uréase para determinar se *B. pumilus* é capaz de hidrolisar ureia por ação da enzima uréase. Os resultados revelaram que *B. pumilus* é suscetível a converter ureia em amônia, além de elevar o pH do meio. Constatou-se também a redução de 0,03 g cm^2 na absorção de água por capilaridade nos corpos de prova biomineralizados com *B. pumilus*, quando comparados aos corpos de prova convencionais. Dado o grau de proteção superficial, *B. pumilus* reduziu a porosidade do material ocasionando aumento da resistência à tração por compressão diametral de aproximadamente 9,0 MPa. A menor altura de ascensão capilar observada foi de 1,83 cm nos corpos de prova biomineralizados e de 3,83 cm nos corpos de prova convencionais. Os resultados obtidos no microscópio eletrônico de varredura e espectroscopia dispersiva de energia indicam a presença de $CaCO_3$, que foi precipitado pelas bactérias. De maneira geral, os resultados obtidos mostram que *B. pumilus* aplicado superficialmente no concreto pode melhorar suas propriedades mecânicas.

Palavras-chave: autocicatrização; *Bacillus pumilus*; carbonato de cálcio; biomineralização; bioconcreto.

INTRODUCTION

The construction industry overuses natural resources and energy, causing numerous environmental impacts (ENSHASSI; KOCHENDOERFER; RIZQ, 2014; MORA-BARRANTES *et al*., 2018; AKINTAYO *et al*., 2020). The variability of the combination of cement, water, and aggregates used in a concrete mixture allows its use in a range of applications (GAGG, 2014; JERZY, 2020). Cracks inevitably occur during the wear process of concrete structures after exposure to weathering. In the absence of repairs, cracks can increase and damage concrete structures due to easy moisture inflow (SING WONG, 2015). Although the presence of cracks in concrete often does not significantly damage the strength properties

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of the structure, they promote porosity and permeability, favoring the action of aggressive physical, chemical, and biological agents that can degrade the concrete and cause premature steel corrosion, impairing the structure's durability in the long term (JONKERS; SCHLANGEN, 2008; SING WONG, 2015).

Concrete self-healing is the process by which the material regenerates, repairing internal fissures through autogenous healing by carbonation and/or continuous hydration, or autonomous healing, with specific agents to produce self-healing, such as bacteria (ROIG-FLORES; FORMAGINI; SERNA, 2021). In order to create a sustainable and cost-effective alternative, MICP (microbially induced calcium carbonate precipitation) has been studied to be used in concrete fissure healing (SHARMA *et al.*, 2017). The chemical alternative through microbial action that results in mineral precipitation is biomineralization, a widespread event in nature (DHAMI; REDDY; MUKHERJEE, 2013) that significantly improves concrete properties such as durability (TITTELBOOM *et al.*, 2010). Biomineralization, a biological process by which living organisms act in the minerals' synthesis and structure, is considered a confluence of materials science, biophysics, proteomics, and evolutionary biology (SHASTRI, 2015). This natural process of calcium carbonate precipitation through urea hydrolysis is related to a wide range of marine environment bacteria, such as *Sporosarcin* sp., *Bacillus* sp., and *Brevundimonas* sp., which influence the marine carbonate cycle in natural environments (WEI *et al.*, 2015). Bacteria of the genus *Bacillus* were isolated from samples of mangrove sediments in China (ZHANG *et al.*, 2016), having the ability to maintain a high calcium precipitation activity at pH 9.5–11. In a study with *B. megaterium* (ANDALIB *et al.*, 2016), the authors reported higher calcite precipitation and increased compressive strength by 24% when embedded into the concrete. On the other hand, *B. subtilis*, a freshwater and soil bacterium, has shown an increase in concrete compressive strength (KALHORI; BAGHERPOUR, 2017) and good performance in mineral precipitation and growth at high pH (FENG *et al.*, 2021). To protect bacteria from concrete conditions, encapsulation of bacteria is preferable (WANG *et al.*, 2018). The compressive strength only decreased by approximately 5% with the addition of hydrogel; this process resulted in a greater reduction in water flow (81–90%) and higher crack sealing efficiency since more than 30% of fissure sites were completely interconnected (WANG *et al.*, 2018). This alternative was also addressed in a recent study with *B. sphaericus* that has been shown to be viable for insertion into self-healing concrete after hydrogel encapsulation (ZHU *et al.*, 2021).

The bacteria and nutrients insertion in the concrete repair process is paramount to its functioning in smart concretes through autogenous healing or concrete fissure self-healing (JONKERS; SCHLANGEN, 2008). Combined with the biomineralization concept, calcium carbonate biodeposition is a promising technique for improving aggregate quality, leading to a reduction in the water absorption capacity of the material. Biodeposition is a microbial-induced process characterized by the precipitation of a protective layer of calcium carbonate on the surface of construction materials such as limestone and cement. This technique's application aims to block the surface pores of the material, preventing water or other aggressive liquids from penetrating inside the material and causing early structure damage (DE MUYNCK; DE BELIE; VERSTRAETE, 2010; GRABIEC *et al.*, 2012).

Concrete is conducive to microcracks due to its fragile nature and durability issues when subjected to loading, requiring an effective method of healing cracks. Calcite precipitation by microorganisms can improve performance and repair cementitious materials (SODA; MINI, 2022). Different strains of bacteria may be able to precipitate calcite and can be incorporated into concrete, effectively promoting the self-healing of microcracks (PROŠEK *et al.*, 2022). Rapid microcrack repair gives concrete structures a long service life and a sustainable approach. Recent research shows that it may be possible to develop a material able to repair fissures by MICP (SANDALCI; TEZER; BASARAN BUNDUR, 2021). Aerobic bacteria induce the precipitation of calcium carbonate inside the cracks, increasing the strength and durability of the structure (SARKAR *et al.*, 2019; KASHIF UR REHMAN *et al.*, 2022). In order to solve such problems, we seek to contribute with studies that involve the use of biological agents in surface treatments of concrete, using methods that help repair certain types of cracks.

This alternative is advantageous for concrete industries due to its efficiency and sustainability and is considered a biotechnological and environmentally friendly option (MARÍN *et al.*, 2021). The main motivation to support this study lies in the importance of new sustainable materials in civil construction.

Bioconcrete

Bioconcrete, or self-healing concrete, has bacteria in its formula, which can induce calcium carbonate precipitation in the empty spaces between cement and aggregates, reducing the porosity and improving the efficiency of concrete (HUANG, KAEWUNRUEN, 2020). Calcium carbonate acts as a biological fixer, binding the particles of materials and helping in the self-repair of fissures and cracks in their initial phase (TITTELBOOM *et al.*, 2010; ACHAL; LI; ZHANG, 2014). The formation of calcium carbonate by bacteria results in the physical closure of microcracks. Experiments showed that the closure of cracks occurred up to 0.46 mm wide, resulting from the metabolic activity of the bacteria (WIKTOR; JONKERS, 2011).

When the cracks appear after molding, the endospores in the cracked zone will be activated upon contact with nutrients, oxygen, and water. The metabolic activity, whether it is urease production and/or heterotrophic carbon oxidation, passively initiates the precipitation of calcium carbonate, which will heal the cracks in situ (ZHU *et al.*, 2021). Therefore, these microorganisms can potentially increase the durability of concrete materials in humid environments (WIKTOR; JONKERS, 2011). Cracking is one of the leading causes of concrete aging, allowing pollutants to infiltrate and damage structures and reducing the physical and mechanical strength of concrete structures (KASHIF UR REHMAN *et al.*, 2022). Table 1 shows examples of bacteria used by different researchers for studying cementitious materials.

Precipitation of calcium carbonate induced by microorganisms

The calcium carbonate precipitation is quite direct and regulated by the following four factors influencing the chemical reaction: calcium ions concentration, dissolved inorganic compound concentration, the potential of hydrogen (pH), and nucleation site availability (HAMMES, VERSTRAETE, 2002; KASHIF UR REHMAN *et al.*, 2022). There are several mechanisms by which bacteria precipitate calcium carbonate; some are applied in concrete for crack healing (MONDAL; (DEY) GHOSH, 2019). Bacteria of the genus *Bacillus* can synthesize enzymes (AIRES *et al.*, 2020). Precipitation via ureolysis involves the synthesis of the enzyme urease using the bacterial metabolism in the formation of ammonia (NH_3) and dissolved inorganic carbon (DIC) (according to Equation 1) and causes an increase in alkalinity in the bacterial cells (Equations 2 and 3).

Table 1 – Bacteria insertion into concrete.

Bacteria	Mechanism	Material	References
Bacillus cereus	Urea or uric acid degradation	Concrete	(MONDAL; DAS; KUMAR CHAKRABORTY, 2017)
Bacillus holodurans	Metabolic conversion of organic compound	Concrete	(KUNAL; SIDDIQUE; RAJOR, 2014)
Bacillus megaterium	Metabolic conversion of organic compound	Concrete	(ANDALIB *et al*., 2016)
Bacillus pasteurii	Urea or uric acid degradation	Concrete	(QIAN *et al*., 2010)
Bacillus pseudofirmus	Metabolic conversion of organic compound	Concrete	(SHARMA *et al*., 2017)
Bacillus subtilis	Urea or uric acid degradation	Concrete	(FENG *et al*., 2021; MONDAL; DAS; KUMAR CHAKRABORTY, 2017)
Saposarcina pasteurii	Urea or uric acid degradation	Concrete	(ABO-EL-ENEIN *et al*., 2013)

The formation of carbonate precipitation on bacterial cell surfaces in the presence of a calcium source precipitates calcium carbonate, according to Equation 4 (JIANG *et al*., 2016).

$$(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2 \quad (1)$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^- \quad (2)$$

$$CO_2 + 2OH^- \leftrightarrow HCO_3^- + OH^- \leftrightarrow CO_3^{2-} + H_2O \quad (3)$$

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3(s) \quad (4)$$

Due to the medium's alkaline solutions, there is an unusual increase in the electronegative potential of cell surface membranes in bacterial metabolism. The composition and structure of the bacterial surface are responsible for the following processes: biomineralization, bacteria adherence, and biofilm formation. The calcium adsorption on the cells' surface suggests that the bacteria, as a defense to calcium adsorption, induce the precipitation of calcium carbonate $CaCO_3$ on the cell wall surface (BUNDELEVA *et al*., 2011). Microorganisms formed on specific substrates contain a diversity of species able to degrade a wide-ranging group of chemical compounds (CANEVAROLI *et al*., 2021). Initially, the bacterium produces the enzyme urease that catalyzes the urea hydrolysis, releasing electrons and dissolved inorganic carbon ions and ammonia, which are released into the bacteria's microenvironment (which dissociates in an aqueous medium) in the presence of calcium cations. The result is site oversaturation and, therefore, heterogeneous precipitation of calcium carbonate in the bacterial cell wall. This precipitation occurs since the membrane that covers the electronegatively charged bacteria attracts calcium ions. After a period, the cell is fully encapsulated, limiting the passage of nutrients and resulting in cell death (DE MUYNCK; DE BELIE; VERSTRAETE, 2010). Thus, the main aim of this study is to evaluate the role of *Bacillus pumilus* bacteria in the curing of concrete and verify its influence in determining concrete's permeability to liquids and mechanical properties.

MATERIALS AND METHODS

Microorganisms and growth conditions

Bacillus pumilus (ATCC 6633), obtained from the Mineral Processing Laboratory (LAPROM) of the Federal University of Rio Grande do Sul was used in the study. The *B. pumilus* sample (Figure 1A) was replicated in Petri dishes (Figure 1B) containing the solid culture medium Tryptic Soy Agar (TSA). These dishes were previously sterilized in an autoclave at 120°C for 20 min and kept in a culture oven at 30°C.

Urease test

The urease test was used to determine whether the microorganisms could hydrolyze urea into two ammonia molecules by the action of the enzyme urease. The resulting ammonia alkalizes the pH, causing the medium to become red, as indicated by the phenol red (VERMELHO *et al*., 2019). The nutrient broth used was *Urea Broth Base*; the typical chemical composition for this culture medium is monobasic potassium phosphate 9.10 (g L^{-1}), dibasic potassium phosphate 5.0 (g L^{-1}), yeast extract 0.10 (g L^{-1}), and phenol red 0.01 (g L^{-1}).

The indicator has a yellow-orange color at low pH of 8.4 and a red color at a pH of above 8.4. The test medium was developed to determine the microbial ability to convert urea into ammonia. The broth was sterilized in an autoclave at 121°C for 20 min. *B. pumilus* was inoculated in a test tube using a sterile loop, followed by inoculation at 30°C for 48 h for further analysis for color change. The urea hydrolyzes enzymes in alkaline products that promote an increase in the medium pH, causing a color change in the indicator to pink, representing a positive result for the test. No color change represents a negative urease test (VERMELHO *et al*., 2019).

The nutrient solution used in the curing of concrete is composed by adding an aqueous solution of 3.0 g L^{-1} of nutrient broth, 5.0 g L^{-1} of peptone, and 2.4 g L^{-1} of urea. This solution was sterilized in an autoclave at 121°C for 25 min. The biological material was evaluated by the rate of water absorption by capillarity. The methodology of concrete biodeposition is proposed by Qian *et al*. (2010), where it is sought to investigate the bacteria with the calcium carbonate crystal secretion induced by the presence of microorganisms.

Biodeposition in concretes

Ten cylindrical specimens with a 10 cm diameter and 20 cm height were prepared and coated internally with a thin layer of lubricant non-reagent to concrete for each sample to determine the influence of calcium carbonate formation in the presence of bacteria on the concrete surface. The molding procedures for the specimens were performed according to NBR 5738 (ABNT, 2016).

The biodeposition technique involved placing the samples in a nutrient solution enriched with the bacterium. A total of 10^9 mL of activated microorganism solution was added to the molds receiving specimens to be biomineralized (WANG *et al*., 2018). The specimens remained in contact with a water film in the solution for 48 h and were then removed and kept for another 26 days at room temperature for drying. The specimens in this experiment were produced and treated to test water absorption by capillarity.

Water absorption by capillarity tests in concrete samples and tensile strength by diametral compression tests

Capillarity tests were performed according to NBR 9779 (ABNT, 2012). The permanent contact area with water is equivalent to a circumference area, resulting in 78.5 cm^2.

Throughout the test, the samples were kept in contact with a water layer covering approximately 5 mm of the cylinder's bottom base, as shown in Figure 2A. The specimens were tested at a 48-h interval. After the test, the specimens were removed from the water, dried with a damp cloth, and weighted on the scale. Water absorption was calculated according to Equation 5.

$$C = \frac{A - B}{S} \quad (5)$$

where:

C: absorption of water by capillarity (g cm^{-2});

A: specimens' mass that remains with one face in contact with water for a specified period (g);

B: dry concrete body mass as soon as it reaches 23°C (g);

S: cross-sectional area (g).

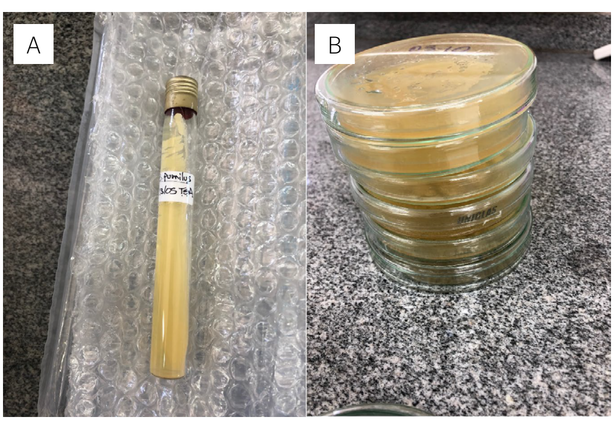

Figure 1 – Biological agent – (A) *B. pumilus*; (B) distribution of the medium in Petri dishes.

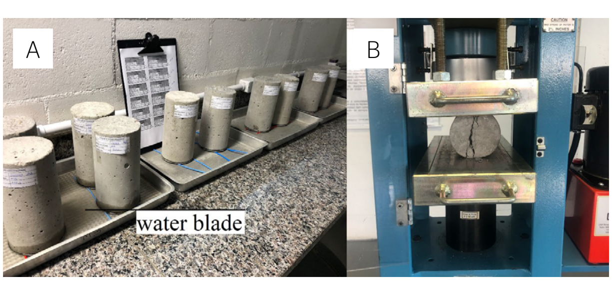

Figure 2 – Specimens prepared for the (A) capillarity test and (B) tensile strength by diametral compression test.

In the tensile strength by diametral compression test, the specimens were placed in the center of the press so that the axial plane defined by opposite generatrixes received the compression load, as shown in Figure 2B. According to NBR 7222 (ABNT, 2011), the load is applied continuously until the rupture of specimens.

The materials used in the concrete were Portland cement CP II Z 32, with a specific mass of 2.92 g cm^{-3}, which has the addition of pozzolanic material. Fine aggregate was obtained from the southern region of Santa Catarina and consisted of two types with different granulometry: fine river sand with a fineness modulus of 1.17 and a specific mass of 2.63 g cm^{-3}, and industrial sand with a fineness modulus of 2.85 and a specific mass of 2.60 g cm^{-3}. Gneiss aggregate with a maximum diameter of 19 mm was used as coarse aggregate, available in the Rio do Sul/SC region. The material has a specific mass of 2.51 g cm^{-3}. The local water utility supplied the water. Table 2 shows the material dosage in kilograms per cubic meter (kg m^{-3}).

The dosage developed by the ABCP method (Brazilian Association of Portland Cement) was considered for the specimens. The method is simple; in addition to defining the mix proportion, the methodology allows for laboratory adjustments regarding consistency (slump) and/or cohesion by modifying certain calculation parameters. The characteristic compressive strength (Fck) used to calculate the concrete mix design was 25 MPa, and the slump test considered was 10 ± 2 cm (for columns and beams).

Microstructural analysis

To analyze the samples, images were obtained using a field emission scanning electron microscope (SEM) model JSM-6701F coupled with an energy dispersive spectrometer (EDS) with an atomic resolution of 0.05%.

RESULTS AND DISCUSSION

Bacillus pumilus conservation medium

Bacillus pumilus had the best development in TSA (Figure 3), which corresponds to a culture medium, isolation, and maintenance of demanding microorganisms.

Urease test

B. pumilus was inoculated in a test tube with Urea Broth Base. Figure 4A shows the culture medium with the strain. Figure 4B shows the strain inoculation after 48 h. In Figure 4C, we can observe the addition of phenol red, indicating that the test was positive for urease determination.

Table 2 – Dosage of materials used to make concrete.

Composition	Quantity (kg m^{-3})
Portland cement	840
Fine sand	494
Industrial medium sand	970
Gravel	1,872
Water	420

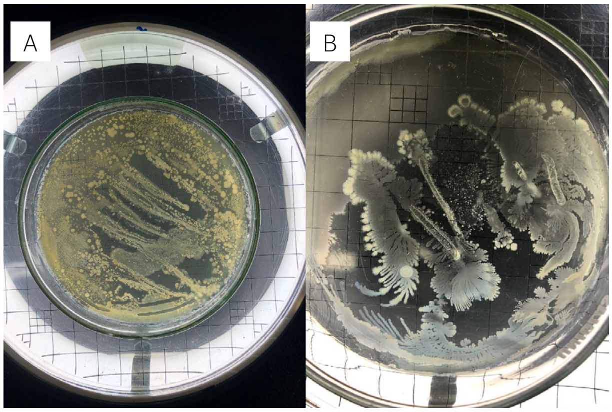

Figure 3 – Observing *Bacillus pumilus* in the colony counter – (A) after 7 days and (B) 14 days.

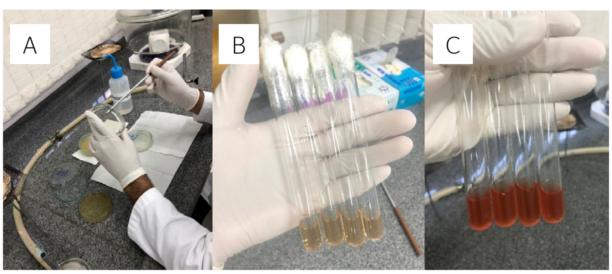

Figure 4 – Inoculation of (A) *B. pumilus*, (B) inoculated medium, and (C) urease test result.

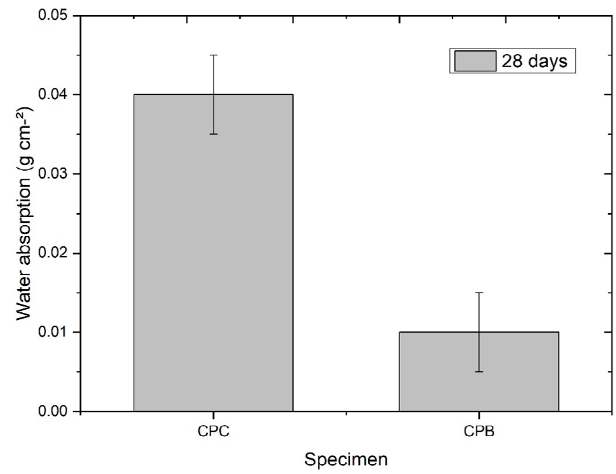

Figure 5 – Water absorption by capillarity test results.

Water absorption by capillarity tests in concrete samples and tensile strength by diametral compression tests

The water absorption by capillarity test was the experimental test applied to confirm the feasibility of using the biodeposition technique and demonstrate the strength, permeability, and modification of porosity in concrete materials (KALHORI; BAGHERPOUR, 2017). For this test, cylindrical concrete specimens were in contact with a water film for 48 h in a nutrient solution containing *B. pumilus*.

The reduction in water absorption by capillarity was noticeable in all tests, as shown in the graph in Figure 5, where specimens (biomineralized CPB) are samples cured with biological agents and specimens (conventional CPC) are the results of samples without the addition of microorganisms. For the values evaluated, there was an average reduction of approximately 0.03 g cm^{-2} for water absorption in specimens cured with *B. pumilus*.

The decrease in concrete surface porosity can be considered responsible for reducing water absorption. This blockage is superficial; in the biodeposition process, the microorganisms have their capacity limited to a few millimeters due to the need for a substrate for their active state and the induction of calcium carbonate precipitation. The porosity reduction occurs due to biomass formed by MICP in empty spaces. Due to these factors, water will hardly penetrate the material compared to samples not treated with biological agents.

The degree of surface protection in the form of $CaCO_3$ biodeposition reduces the open porosity of materials (SING WONG, 2015). It is noted that water absorption rates by capillarity become more evident over time.

In the tensile strength analysis tests, specimens were subjected to a diametral compression effort evenly applied over their entire length, allowing them to determine tensile strength. Compared to studies conducted by other researchers, the results are similar to the 28-day curing period. It is worth noting that in the control concrete specimens tested by Chen, Chen and Tang (2020), the strength values obtained were 26 MPa, whereas with the addition of bacteria, the values ranged from 29.96 to 30.96 MPa. In the studies conducted by Soda and Mini (2022), the results for the control concrete specimens were 18.05 MPa, while with the addition of bacteria, the strength increased to 20.67 MPa. The test helps check microstructural damage conditions, cracks, and weathering.

According to the values shown in Figure 6, the specimens (biomineralized CPB), samples cured with a biological agent, had an increase in tensile strength of 9.00 MPa on average compared to conventional specimens (conventional CPC), samples without the addition of microorganisms.

The results of the maximum capillary rise heights found after the diametral rupture of the specimens had standard deviations of 0.76 (CPC) and 1.04 (CPB). Figure 7A displays the samples (conventional CPC) with a percolation height 2.00 cm greater than the test specimens (biomineralized CPB), as depicted in Figure 7B.

Microstructural analysis

The microstructure image of the concrete samples is indicated in Figure 8. The resulting precipitations in the sample during the calcium carbonate precipitation (MIPC) were collected and analyzed with a SEM. Chemical reactions occurred to generate $CaCO_3$ crystals. The SEM test results in Figure 8B show that calcium's microbial and chemical precipitations are polygonal crystals (FENG *et al.*, 2021) combined with EDS analysis, as shown in Figure 9.

The EDS (Figure 9) spectrum of the precipitated material (point a) reveals carbon (C), oxygen (O), and calcium (Ca) as the main elements. The EDS spectrum of the precipitated material (point b) reveals carbon

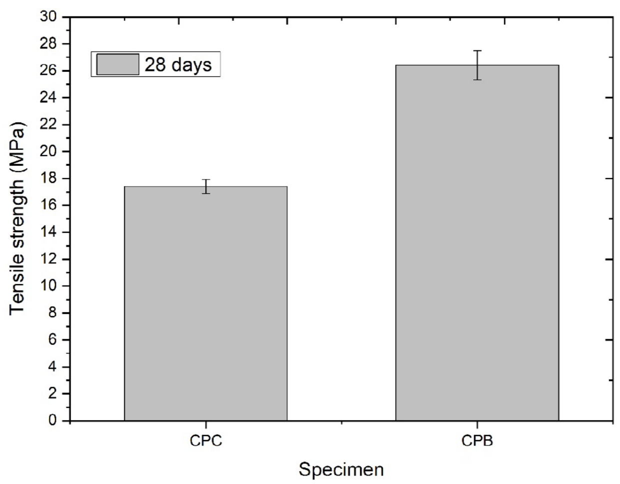

Figure 6 – Tensile strength by diametral compression test results.

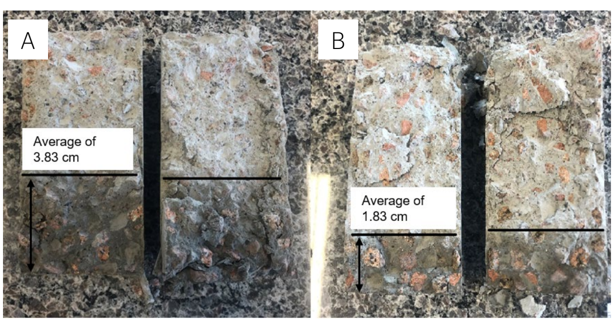

Figure 7 – Water percolation – (A) conventional CPC and (B) biomineralized CPB.

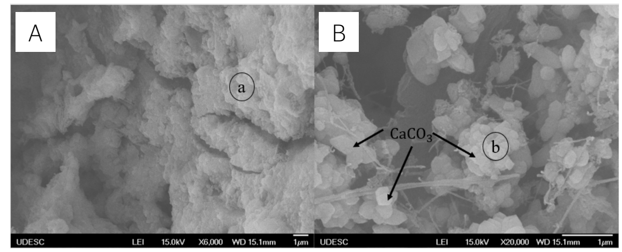

Figure 8 – (A) Conventional CPC and (B) biomineralized CPB calcium carbonate derived from MICP and chemical reaction in microscopic view.

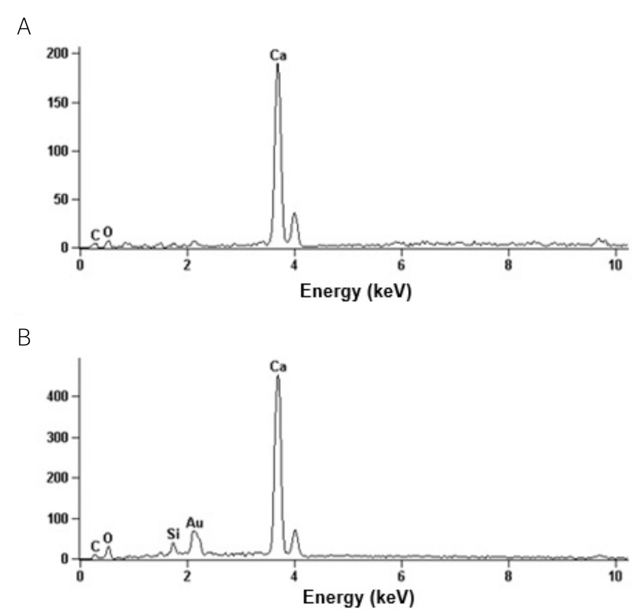

Figure 9 – Energy dispersive X-ray analysis (EDS) – (A) conventional CPC and (B) biomineralized.

(C), oxygen (O), and calcium (Ca), the compound silicon (Si) derived from Portland cement composition, and the analysis material contains gold (Au) (SHARMA *et al*., 2017).

The EDS (Figure 9B) indicates the precipitation of calcium carbonate by bacterial cells (ABO-EL-ENEIN *et al*., 2013). EDS revealed that the crystal is mainly composed of calcium (Ca), carbon (C), and oxygen (O) with a weight ratio similar to $CaCO_3$, thus indicating that the crystal is $CaCO_3$ (SU; ZHENG; QIAN, 2021; ZHANG *et al*., 2016).

CONCLUSION

The results from biodeposition in concrete were positive, confirming this technique as an alternative to traditional surface protection from external agents against water passage, thus protecting concrete structures.

B. pumilus is a microorganism capable of developing in alkaline media and inducing calcium carbonate formation, making it a legitimate bacterium for biotechnological uses. It contributes to the prompting of calcium carbonate crystals that act as a material sealant, decreasing the surface porosity, permeability, and consequently the water absorption by the concrete, thereby adding to the increase in the service life of structures against water and aggressive substances inflow, such as toxic materials like gases and other pollutants. The reduction of water absorption by capillarity was noticeable in the tests. For the evaluated values, there was an average reduction of approximately 0.03 g cm^{-2} of water absorption in specimens cured with *B. pumilus*. The water percolation test in the CPC and CPB samples had a percolation height difference of 2.00 cm.

The concrete specimens were submitted to SEM tests. The study of MICP showed that biomineralization is composed of calcium carbonate, as visualized by the spectrum (EDS).

Thus, it is possible to state that biomineralization can be applied in built environments, showing a positive efficiency in the surface coating of structures and effectiveness in repairing surface defects in cement-based materials. *Bacillus pumilus* improved the concrete properties, such as diametral tensile strength at 9.00 MPa after 28 days of self-healing and the consequent filling of gaps between the cement grains.

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