International Journal of Inventive Engineering and Sciences (IJIES)
ISSN: 2319-9598 (Online), Volume-11 Issue-11, November 2024

A Comprehensive Review of Biomaterials Synthesized Using the MICP Process for Sustainable Construction

Stuti Goyal

***Abstract:** Building materials and infrastructure contribute to approximately 13% of global CO_2 emissions annually, according to the International Energy Agency (IEA, 2022). This underscores the urgent need to transition to more sustainable construction materials. Emerging biomaterials, developed through innovative processes such as the Microbially Induced Calcium Carbonate Precipitation (MICP) process, are being explored as potential alternatives to conventional materials. These biomaterials, including bio-concrete, bio- cement, and bio-bricks, are produced using waste materials and biological processes, such as bacteria and plant-based resources that act as carbon sinks, offering an eco-friendly solution to construction challenges. Many researchers and companies are actively experimenting with these materials to solve pressing environmental problems, with promising results. However, challenges remain in optimizing these materials for large-scale production and ensuring their performance under real-world conditions. Despite these obstacles, ongoing research is continually pushing the boundaries of biomaterials' potential in construction, with numerous studies focused on improving their properties and addressing current limitations. This paper provides a comprehensive review of the advantages and disadvantages of biomaterials in comparison to traditional construction materials. It explores how these bio- based materials—synthesized through the MICP process—can offer significant benefits, such as self-healing properties, low-cost production, and reduced environmental impact. The review also discusses the challenges that still need to be overcome and the ongoing research aimed at making biomaterials a viable alternative to conventional materials. As part of the field of engineering, this paper highlights the critical role of biotechnology in advancing sustainable construction practices and the continued evolution of biomaterials in engineering applications.*

***Keywords:** Biomaterials, MICP, Bio-Concrete, Bio-Cement, Bio-Bricks, Construction*

I. INTRODUCTION

According to the 2022 Global Status Report for Buildings and Construction, the construction sector emitted around 10 gigatonnes of carbon dioxide (CO2) into the environment in 2021. Revaluating popular construction materials is an important measure that the AEC sector can take in the next years to help slow down climate change. The next frontier in biology and material science is bioengineered materials, which have the ability to grow, produce energy, and self-heal. These materials may pave the way for a new type of building.

Over the past ten years, construction biotechnology has developed at an exponential rate in both science and engineering.

The two main focuses of this field are the selection of microorganisms and the development of microbially mediated building processes and biotechnologies for the manufacture of construction biomaterials. Microbial bio concrete, bio cement, bio bricks and bio grouts, which are inexpensive, durable, and environmentally benign, are among the products of construction biotechnologies. Biotechnology and material science advancements may significantly alter the relationship between the built environment and the natural world. A rapidly growing field of study, living materials for the built environment serve a variety of goals, including lowering carbon footprints, maximizing resource utilization, creating novel features, and boosting carbon sequestration. The circularity of the building sector can be further improved by using waste materials in their creation. Living building materials (LBMs) are materials that include microorganisms and exhibit biological characteristics. They are a synthesis of design, material science, chemistry, and bioengineering [1].

Bioengineered building materials have several benefits including the elimination of the problems faced by the construction industry. The future of biotechnology and material science lies in bioengineered materials that can grow, heal themselves, and generate energy. These materials also provide a new paradigm for architecture [1]. Innovation in these domains may not yet be widely used for commercial purposes, but it has the potential to significantly alter how people view the built environment. Nowadays, there has been a lot of research and development in the field of biomaterials which can be used and implemented in construction.

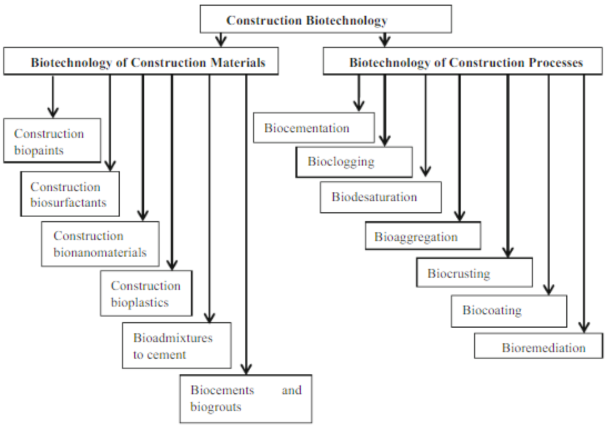
II. BIOTECHNOLOGY IN CONSTRUCTION

In the past ten years, a new biotechnological field called construction biotechnology has evolved. Construction Biotechnology is a new subject that aims to generate environmentally friendly building materials such as bio bricks, bio cement and bio concrete. The biotechnological manufacturing of construction biomaterials is a sustainable process because leftover renewable agricultural and biotechnological biomass is

Manuscript received on 17 October 2024 | Revised Manuscript received on 28 October 2024 | Manuscript Accepted on 15 November 2024 | Manuscript published on 30 November 2024.
*Correspondence Author(s)
Stuti Goyal*, Student, Department of Architecture, School of Planning and Architecture, Vijayawada (Andhra Pradesh), India. Email ID: stuti.goyal9@gmail.com, ORCID ID: 0000-0001-6035-1978

used as organic raw materials and components of composite bio cement [2].

Researchers have provided numerous innovative environment-friendly alternatives for the construction industry in the last few years. The microbial generation of building materials and the direct use of microorganisms or their enzymes in the construction process are two significant areas of construction biotechnology [2].



[Fig.1: Directions of Construction Biotechnology, Source:] [2]

III. BIOMATERIALS

Biomaterials can be synthesized in the laboratory or extracted from nature using a variety of chemical methods that include metallic components, polymers, ceramics, or composite materials. There is a definite trend toward adopting biodegradable materials and biopolymers in the building sector [3]. Using biodegradable plastics reduces the amount of land required for disposal. There is a significant trend in the construction industry toward the use of biodegradable materials and biopolymers [3].

Biomaterials enable us to capture and apply natural traits to deliver specific performance characteristics. Biomaterials have the potential to bring the following benefits to building materials:

- Capture and storage of carbon removed from the atmosphere by recent photosynthesis
- End-of-life biodegradability
- Linear coefficients of thermal expansion that are close to zero (Controlled decay inside an anaerobic digester would generate both organic fertilizer and bio-methane to supply energy)
- The ability of water phase shifts in cells to manage temperature and humidity in confined environments.
- Excellent vapor diffusivity and 'Fickian' vapor dispersion
- Typically, high specific heat capacity
- Low thermal diffusivity
- High performance-to-weight ratios

IV. BIOMATERIALS USING MICP

Microbially induced calcium carbonate precipitation (MICP) is a bio-geochemical process that results in the precipitation of calcium carbonate within the soil matrix. MICP is caused by metabolic interactions between various microbial populations and organic and/or inorganic chemicals in the environment, according to Mortensen and colleagues [4]. MICP has recently attracted a lot of interest due to its potential in construction and geotechnical applications. This technology has been employed in sand bio cementation, soil consolidation, self-healing concrete or mortar manufacturing, and heavy metal ion removal from water. MICP products frequently exhibit increased strength, durability, and self-healing capabilities. The MICP approach can also improve sustainability, particularly in the building sector, where a large amount of the materials utilized are not sustainable. MICP cannot arise without the presence of bacteria. Bacteria stimulate the conversion of appropriate chemicals into carbonate ions, alter the microenvironment to favor calcium carbonate precipitation, and function as calcium carbonate crystal precipitation sites [5]. Calcium carbonate precipitation is aided by a combination of biological and chemical processes such as 'pH, temperature, substrate medium, and microorganism bioavailability [6].

In this study, the most widely used building materials globally i.e. concrete, cement and bricks [7] are being taken to be reviewed for their bio alternatives namely bio-concrete, bio-cement and bio-bricks.

A. Bio-Concrete

The term "bio-concrete" refers to concrete that has had bacteria added to it that can precipitate calcium carbonate (MICP). This type of concrete helps to close fractures that form in the concrete and is known for having a self-healing quality.[8] In both natural and experimental settings, bacteria from a range of natural environments have been seen precipitating calcium carbonate. Numerous bacterial species and abiotic factors (such as salinity and medium composition) seem to play different roles in the formation of calcium carbonate precipitation in various settings [9]. The enzyme urease, which is nickel-dependent and present in bacteria, fungi, and plants, breaks down urea into ammonia and carbon dioxide to increase the pH of the environment. The primary circumstance that encourages calcite precipitation is an alkaline pH. Calcium ions bind to the bacterial cell wall due to the negative charge or potential of the cell surface. If high quantities of calcium ions are available adjacent to the bacterium and carbonate ions are present at a super saturation level, calcium carbonate crystals will form on the bacterial cell wall [10].

Microbial concrete is created from calcite precipitated by beneficial microorganisms. It is named after ureolytic bacteria, which are utilized in this process. When microbial urease hydrolyzes urea, ammonia and carbon dioxide are released into the environment. This increase in pH leads to the accumulation of insoluble calcium carbonate [11].

MICP, which is powered by urea hydrolysis, denitrification, and dissimilatory sulphate reduction, has been discovered to aid in the manufacturing of bio concrete while also increasing its mechanical and durability properties [12].

i. Comparison Between Bio Concrete and Traditional Concrete

The development of microbial self-healing concrete, often referred to as

Retrieval Number: 100.1/ijies.B93930112223
DOI: 10.35940/ijies.B9393.11111124
Journal Website: www.ijies.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

bioconcrete, presents a significant advancement over traditional concrete in terms of durability and sustainability. Traditional concrete is highly susceptible to cracking due to various factors, including drying shrinkage and thermal stress, which can lead to costly repairs and reduced lifespan.

In contrast, research indicates that bioconcrete, which utilizes bacteria to produce calcium carbonate and seal cracks, not only enhances the material's structural integrity but also demonstrates superior performance metrics. For instance, studies have shown that the compressive strength of bioconcrete exceeds that of conventional concrete by 15% in split tensile strength tests and by 30% in flexural strength assessments. Moreover, bioconcrete exhibits a remarkable ability to withstand larger strains, maintaining structural stability even after crack formation. This contrasts sharply with traditional concrete, which typically fails under similar conditions. While challenges remain in the widespread adoption of bioconcrete, the evidence suggests that its integration into sustainable construction practices could significantly mitigate the drawbacks associated with traditional concrete, thereby contributing to more resilient infrastructure [13].

ii. Advantages Bio-Concrete

The cement contains bacteria or other elements that produce new calcium to fill cracks, reducing water infiltration into the structure. This process enhances structural integrity for many additional years, allowing for self-repair of fractures without the need for external assistance. Compared to normal concrete, there is a significant increase in both compressive and flexural strength.

iii. Disadvantages of Bio-Concrete

It is not suitable for applications that require higher compressive strength, such as tall buildings. Self-healing concrete costs twice as much as regular concrete. However, when used in the construction of bridges, tunnels, and highways, bioconcrete has the potential to save billions of dollars in annual maintenance costs. Jonkers is currently working to reduce the material's cost for large-scale applications. A cubic meter of bioconcrete currently costs approximately 200 Euros ($239 USD). Jonkers believes that his innovative method of encapsulating bacteria and calcium lactate could reduce the cost of bioconcrete by up to 50%, making it only slightly more expensive than regular concrete.

B. Biocement

Biocement is a material that utilizes native soil bacteria to bind soil particles through a process known as microbially induced calcite precipitation (MICP). By employing microorganisms, it creates a robust and renewable construction material with minimal environmental impact. MICP biocement is provided as a dry powder that must be mixed with water. This method, known as biocementation, results in a material that can serve as a sustainable alternative to traditional cement in construction projects. The process of using bacteria to facilitate calcium carbonate precipitation involves several chemical reactions, including urea hydrolysis. Due to its efficiency in terms of cost and time, this technique has become one of the most commonly used methods for producing biocement.

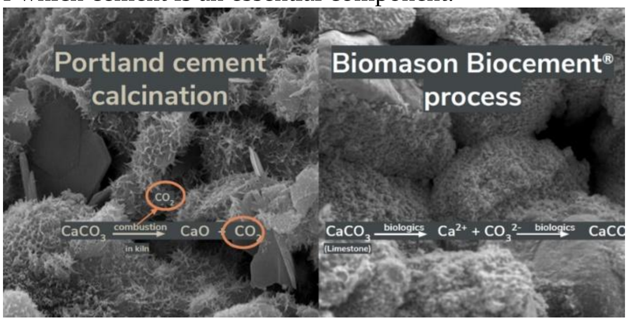
Biomason uses natural microorganisms to create bio-cement at room temperature while releasing no carbon dioxide. Its novel bio-cement approach mimics nature's use of carbon as a building material, producing cement in a biological, circular system rather than the 200-year-old, environmentally harmful Portland cement (OPC) manufacturing method. Biomason manufactures cement in an altogether new way, addressing the root cause of emissions [14].

By 2030, bio-cement will have eliminated 25% of the worldwide carbon emissions from the concrete industry. Biomason bio-cement is used in projects all over the world, and bioLITH® precast tile products are available for purchase. "Since the introduction of Portland cement in 1824, it has remained the major element used in concrete, and hence the most prevalent internationally," said Michael Marks, founding general partner at Celesta Capital. Biomason has employed microorganisms to create sustainable, structural biocement® at room temperature, rethinking regular cement and providing a more environmentally responsible option [14].

Biomason biocement's chemical method mixes aggregate (limestone), microorganisms, and nutritional feedstock. The feedstock activates the bacteria, allowing them to perform what they do naturally: replicate and produce calcium carbonate crystals. With the addition of nutrients, the calcium carbonate crystalline structure begins to join as a network, resulting in calcite polymorph, or cement replacement [14].

i. Comparison Between Bio Cement and Traditional Cement

OPC production contributes more than 8% of world carbon emissions, which is four times that of the aircraft sector. After water, the world's second most utilized substance is concrete, of which cement is an essential component.



[Image 1: Comparison Between Chemical Process of Portland Cement and Biocement, Source:] [14]

ii. Advantages of Bio- Cement

MICP biocement has various potential applications, including crack treatment, concrete corrosion mitigation, and biogrout (a soil improvement approach) manufacturing. The process can be described simply as "brewing beer with sand", and completely replaces the kiln and calcinator with a bioreactor, reducing the CO2 emissions compared to OPC by about 75%. Bio-cement synthesis is more energy efficient because it requires temperatures in the 30 to 40 °C range, whereas conventional cement production requires temperatures above 900 °C. Because industrial wastes such as Lactose Mother Liquor (LML) and Corn Steep Liquor (CSL) can also be used as raw materials for bacteria,

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

bio-cement production may be more cost-effective.

The bioreactor costs vastly less than the kiln infrastructure reducing CAPEX costs and lowering OPEX costs, as it includes less mechanical equipment while converting the factory into a lower-risk category reducing insurance premiums. It also allows the cement production facilities to be closer to cities, closer to where the raw materials are generated and saves on transportation emissions and costs. This adds up to double-digit gross margin improvement for cement manufacturers, an enormous cost-savings in an industry where margins are typically razor thin [14]. Bio-cement manufacturing is more efficient. Furthermore, studies on bio-cement have revealed that it has equivalent shear strength, durability, and lower water absorption capacity and permeability to traditional cement.

iii. Disadvantages of Bio-Cement

The method of production is complex compared to ordinary cement and resultantly conventional cement is still cheaper than bio-cement. There are very less companies who are manufacturing bio-cement around the world which makes it not easily available. Although Bio-Cement has shown to be a highly promising substitute, its economic potential has yet to be fulfilled. Getting ecological material from labs to fields necessitates an interdisciplinary approach and extensive study by professionals from many backgrounds. To allow for microbial activity, the process of bio-cementation requires regulated temperatures, pH levels, concentrations and diffusion rates of nutrients and metabolites, and so on, making it more difficult than traditional approaches. Economic solutions for utilizing high-grade nutrients in the process must also be investigated to lower total operating expenses.

C. Bio-Bricks

Bio bricks as the name suggests are an alternative building material that is sustainable and engineered using ingredients from the biological systems. Bricks are the building blocks for any construction project and are used to build in enormous quantities all over the world for constructing permanent structures. Every year, more than 1.3 trillion bricks are produced worldwide, with much of them being handcrafted in coal-fired ovens. Carbon dioxide emissions from brick baking are significant.

Current brick production methods vary greatly, but most include high-energy procedures of compression under high pressures and/or baking at the high temperatures. The most frequent method of brick production is high-temperature fire of clay. Sand-lime bricks, which are created using water, sand, and lime mixed, compacted together at a pressure of 20 MPa, and then autoclaved for up to 9 hours at temperatures of up to 190 C, are an alternative to red clay bricks [15]. The bricks are cured at room temperature and have strengths ranging from 2.7 to 5 MPa. 2009 [16] Adobe, rammed earth, and compressed earth bricks are other techniques of producing earth-based construction materials [17][18]. Researchers have conducted several trials with various biologically derived materials to create sustainable alternatives to clay bricks. Under 50% treatment saturation, bio-cementation using microbially induced calcite precipitation (MICP) was employed in one study to produce sandstone-like bricks known as "bio-bricks." The compressive strength of the bio-bricks produced under partially saturated circumstances was 9 MPa, which was twice the value obtained under fully saturated conditions. Various mechanical qualities were also investigated, including water absorption (approximately 10%), salt attack (mass loss of around 0.5 g), and fire resistance. The results revealed that the bio-bricks generated are appropriate for use as a building material, with the added benefit of being a greener alternative to standard burnt clay or cement bricks [19]. Ginger Krieg Dosier used sand, calcium chloride, and urine to make a bacteria-grown brick. Rather than being fired in a kiln, the bricks are created at room temperature using MICP. The completed brick has the look of sandstone but is as sturdy as clay-fired brick or even marble, according to Metropolis Mag. Common bacteria and urea, a substantial component of human urine, are among the constituents.

Sand, which is abundant in nature, is utilized as the base for these bricks. Then, employing bacteria that provide an environment for the crystallization process, a nitrogen supply, a calcium source, and water, a "liquid cement" is created. "The ions are drawn to the bacterial cell walls, forming a calcium carbonate coating that allows particles to stay together," Dosier explains. The solution is poured over the sand in a mould and applied frequently over the course of five days until a solid substance forms. Bacteria eventually dies due to a lack of food and water. To save water, the irrigation system is a closed loop that uses recycled water for the following batch. "We can develop bricks that light in the dark, absorb pollutants, and change colour when wet," Dosier explains.

According to research, the amount of calcium carbonate produced is proportional to the number of treatments; the greater the number of treatments, the greater the compressive strength [20]. When the influent calcium concentration was gradually increased, the compressive strength increased. The greatest compressive strength obtained was 2.7 MPa, which was higher than compressive strengths obtained by bio-columns generated from synthetic urine (0.9 MPa) [21] and higher than MICP experiments performed by Al Qabany and Soga 2013 (0.35 - 1.3 MPa) [22] and S. G. Choi (0.88 – 1.1 MPa) [23]. The strength was larger than the normal strength of 40% limestone bricks measuring 0.75 MPa, but it was less than the strength of conventional face and non-facial bricks measuring 9 to 12.5 MPa and 3 to 10.5 MPa, respectively. The wide variety of compressive strengths seen in different investigations might be attributed to changes in bacteria colony sizes, liquid flow patterns, and sand surface area [23].

Another successful project has been the development of bio-bricks from agricultural waste products by researchers. Their creation serves two purposes: waste management and the production of environmentally friendly, long-lasting construction materials. This material is placed in moulds and pounded with a wooden block to create a compact brick. After allowing the moulds to cure for a day or two, the sides are removed and the brick is left to dry for fifteen to twenty days. It takes roughly a month for these bio-bricks to attain their working strength after air drying [24].

Many researchers have done experimentation for engineering the bio bricks with ingredients like

Retrieval Number: 100.1/ijies.B93930112223
DOI: 10.35940/ijies.B9393.11111124
Journal Website: www.ijies.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

agricultural waste, sand, husk, bacteria, natural fibers etc. in different proportions.

The testing for water absorption and compressive strength are done for the respective bricks for comparison with the conventional bricks. Despite the fact that many of the qualities favored the bricks. According to a study done in the United States, the water absorption of bio-bricks ranged from 10.16% to 17.89%, which is equivalent to typical red bricks [25]. The researchers added natural fiber to the materials in this study, which increased the compression strength of the bio-bricks by 50-70% [26].

i. Advantages of Bio-Bricks

These bricks can replace traditional bricks providing the benefits to the environment by massive reduction in carbon emission and not harming the environment negatively unlike the traditional bricks. These bricks give high insulation to heat and sound and aid in the maintenance of building humidity, making these dwellings suited for a hot-humid environment like India [27][28]. The bricks are cured at room temperature and can contribute to waste management.

ii. Disadvantages of Bio-Bricks

Although these bio-bricks are not as strong as burnt clay bricks and cannot be used to build load-bearing structures on their own, they can be used in low-cost housing in conjunction with a wooden or metal structural framework. The disadvantage is that microbial-induced calcite precipitation generates a large quantity of ammonia. Microbes degrade ammonia into nitrates, which contaminate groundwater. To address this issue, Dosier intends to create a mechanism that will trap pollutants and recycle them back into the brick-production cycle. Also, there is still a requirement to further work upon the economical factor and compressive strength of the bricks to commercialize as par to the traditional bricks.

V. DISCUSSION

All three alternative materials discussed in this paper have been tested by various researchers over the course of the last decade. It has been found that the ingredient, the type of microorganisms, the treatment and the process of making or engineering the materials define their characteristics and properties such as compressive strength, flexural strength, water absorption capacity etc. It's also worth noting that the presence of microorganisms does not endanger human health because they can only survive in the alkaline conditions of concrete. All these materials have been experimented in the past and still under experimentation involving different treatments to get the desired properties of the material. In other words, this field of technology has an ability to modify the same material for different properties and requirements, for example for temporary and permanent structures. The major advantage of these materials is that they contribute to the eco-friendly environmental construction practices by reducing the energy consumption and carbon emissions to a large extent in the manufacturing process and providing an option for biodegradability. Bio concrete and bio-cement have self-healing applications where bacteria with the help of oxygen in the environment closes the crack and prevents the steel to corrode due to ingress of water. It might be beneficial in the preservation or restoration of constructions made of porous materials. Moisture, chemicals, pollutants, and other contaminants can have a negative influence on the strength and look of buildings, monuments, and other fragile things. The process's effectiveness may be affected by a variety of environmental circumstances, including weather and pH levels. The advantages and disadvantages of the materials are discussed further.

VI. CONCLUSION

In the construction industry, biomaterials can be proven to resolve numerous issues faced while using conventional materials. The major benefit of all the new engineered materials is that they are energy efficient and are capable of reducing carbon emissions to a large extent. Many companies are also accelerating their technology platforms to enable broader applications in various biologically engineered construction materials. For example, Bio mason has been working on a technology that will enable the concrete value chain, including ready mix technology, which would have up to 95% reduction in CO2 compared to OPC and would truly revolutionize cement production as we know it. Although many materials are still in the experimental stage and those which are available to use are not economical, there is a future scope of further research and experimentation.

VII. ACKNOWLEDGMENT

I would like to thank Assistant Professor Dr. Nagaraju Kaja for his encouragement during the preparation of this review paper, which was completed as part of my Master's program at the School of Planning and Architecture. I also appreciate the support of my peers and faculty members.

DECLARATION STATEMENT

I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed solely.

REFERENCES

1. R. Davey, "What to Know About Bioengineered Construction Materials." Mar. 2022., AZoBuild. Retrieved on October 28, 2022 from https://www.azobuild.com/article.aspx?ArticleID=8514.
2. V. Ivanov, "Stabnikov V. and Ivanov V. (2016) Biotechnological production of biopolymers and admixtures for eco-efficient construction materials. In: Biopolymers and Biotech Admixtures for Ecoefficient Construction Materials (F. Pacheco Torgal, Volodymyr Ivanov, J. A," 2016. Researchgate.net. [accessed

2022 Oct 28]. https://www.researchgate.net/publication/317184477 https://doi.org/10.1016/B978-0-08-100214-8.00003-8

3. J. Plank, "Applications of biopolymers and other biotechnological products in building materials.," Appl. Microbiol. Biotechnol., vol. 66, no. 1, pp. 1–9, Nov. 2004, https://doi.org/10.1007/s00253-004-1714-3
4. B. M. Mortensen, M. J. Haber, J. T. Dejong, L. F. Caslake, and D. C. Nelson, "Effects of environmental factors on microbial induced calcium carbonate precipitation," J. Appl. Microbiol., vol. 111, no. 2, pp. 338–349, Aug. 2011, https://doi.org/10.1111/j.1365-2672.2011.05065.x
5. S. C. Chuo et al., "Insights into the Current Trends in the Utilization of Bacteria for Microbially Induced Calcium Carbonate Precipitation.," Mater. (Basel, Switzerland), vol. 13, no. 21, Nov. 2020, https://doi.org/10.3390/ma13214993
6. A. Rajasekar, S. Wilkinson, and C. K. S. Moy, "MICP as a potential sustainable technique to treat or entrap contaminants in the natural environment: A review," Environ. Sci. Ecotechnology, vol. 6, p. 100096, 2021, https://doi.org/10.1016/j.ese.2021.100096
7. B. Huang et al., "A Life Cycle Thinking Framework to Mitigate the Environmental Impact of Building Materials," One Earth, vol. 3, 2020, https://doi.org/10.1016/j.oneear.2020.10.010
8. H. M. Jonkers, "Bacteria-based self-healing concrete," 2011. HERON. 2011 [accessed 2024 Oct 28];56. https://heronjournal.nl/56-12/1.pdf
9. N. K. Dhami, M. S. Reddy, and A. Mukherjee, "Improvement in strength properties of ash bricks by bacterial calcite," Ecol. Eng., vol. 39, pp. 31–35, 2012. https://doi.org/10.1016/j.ecoleng.2011.11.011
10. S. Stocks-Fischer, J. K. Galinat, and S. S. Bang, "Microbiological precipitation of CaCO3," Soil Biol. Biochem., vol. 31, no. 11, pp. 1563–1571, 1999, https://doi.org/10.1016/S0038-0717(99)00082-6
11. S. S. P. Reddy and P. P. Aparna, "Performance of Standard Grade Bacterial (Bacillus Subtilis) Concrete," 2010. Researchgate.net. [accessed 2024 Oct 28]. https://www.researchgate.net/publication/267799642
12. M. J. Castro-Alonso, L. E. Montañez-Hernandez, M. A. Sanchez-Muñoz, M. R. Macias Franco, R. Narayanasamy, and N. Balagurusamy, "Microbially induced calcium carbonate precipitation (MICP) and its potential in bioconcrete: Microbiological and molecular concepts," Frontiers in Materials, vol. 6. Frontiers Media S.A., p. 126, May 29, 2019. https://doi.org/10.3389/fmats.2019.00126
13. Udhaya, S. & Devi, Vandhana & Jeyaseelan, Philips & R L, Lija. Experimental study on bio-concrete for sustainable construction. Materials Today: Proceedings, 2023, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2023.03.676
14. Horvath R. Revolutionizing cement with biotechnology. Biomason. 2021 Aug 23 [accessed 2022 Oct 28]. https://biomason.com/
15. Y. Fang, Y. Gu, Q. Kang, Q. Wen, and P. Dai, "Utilization of copper tailing for autoclaved sand–lime brick," Constr. Build. Mater., vol. 25, no. 2, pp. 867–872, 2011, https://doi.org/10.1016/j.conbuildmat.2010.06.100
16. J. Oti, J. Kinuthia, and J. Bai, "Unfired clay bricks: From laboratory to industrial production," Proc. Inst. Civ. Eng. Eng. Sustain., vol. 162, pp. 229–237, 2009, https://doi.org/10.1680/ensu.2009.162.4.229
17. D. Silveira, H. Varum, A. Costa, T. Martins, H. Pereira, and J. Almeida, "Mechanical properties of adobe bricks in ancient constructions," Constr. Build. Mater., vol. 28, no. 1, pp. 36–44, 2012, https://doi.org/10.1016/j.conbuildmat.2011.08.046
18. F. Pacheco-Torgal and S. Jalali, "Earth construction: Lessons from the past for future eco-efficient construction," Constr. Build. Mater. - CONSTR BUILD MATER, vol. 29, 2012, https://doi.org/10.1016/j.conbuildmat.2011.10.054
19. L. Cheng, T. Kobayashi, and M. A. Shahin, "Microbially induced calcite precipitation for production of 'bio-bricks' treated at partial saturation condition," Constr. Build. Mater., vol. 231, p. 117095, 2020, https://doi.org/10.1016/j.conbuildmat.2019.117095
20. S. E. Lambert and D. G. Randall, "Manufacturing bio-bricks using microbial induced calcium carbonate precipitation and human urine," Water Res., vol. 160, pp. 158–166, 2019, https://doi.org/10.1016/j.watres.2019.05.069
21. J. Henze and D. G. Randall, "Microbial induced calcium carbonate precipitation at elevated pH values (>11) using Sporosarcina pasteurii," J. Environ. Chem. Eng., vol. 6, no. 4, pp. 5008–5013, 2018, https://doi.org/10.1016/j.jece.2018.07.046
22. A. Al Qabany and K. Soga, "Effect of chemical treatment used in MICP on engineering properties of cemented soils," Géotechnique, vol. 63, pp. 331–339, 2013, https://doi.org/10.1680/geot.SIP13.P.022
23. S. G. Choi, J. Chu, R. C. Brown, K. Wang, and Z. Wen, "Correction to 'Sustainable Biocement Production via Microbially Induced Calcium Carbonate Precipitation: Use of Limestone and Acetic Acid Derived from Pyrolysis of Lignocellulosic Biomass,'" ACS Sustain. Chem. Eng., vol. 5, no. 8, p. 7449, Aug. 2017, https://doi.org/10.1021/acssuschemeng.7b02137
24. P. Rautray, A. Roy, D. Mathew, and B. Eisenbart, "Bio-Brick - Development of Sustainable and Cost Effective Building Material," Proc. Des. Soc. Int. Conf. Eng. Des., vol. 1, pp. 3171–3180, 2019, https://doi.org/10.1017/dsi.2019.324
25. Y. Li, K. Wen, L. Li, W. Huang, C. Bu, and F. Amini, "Experimental investigation on compression resistance of bio-bricks," Constr. Build. Mater., vol. 265, p. 120751, 2020, https://doi.org/10.1016/j.conbuildmat.2020.120751
26. J. Umanadh, "Researchers develop bio-bricks from agricultural waste | Deccan Herald." https://www.deccanherald.com/science-and-environment/researchers-develop-bio-bricks-from-agricultural-waste-769036.html (accessed Nov. 02, 2022).
27. Jegatheeswaran, D., & Narmatha, V. (2020). Mechanical and Microstructural Characteristics of Self-Healing Bacterial Concrete. In International Journal of Innovative Technology and Exploring Engineering (Vol. 9, Issue 6, pp. 1856–1860). https://doi.org/10.35940/ijitee.f4396.049620
28. Nurulhuda, A., Izman, & Ngadiman, N. H. A. (2019). Fabrication PEGDA/ANFs Biomaterial as 3D Tissue Engineering Scaffold by DLP 3D Printing Tecshnology. In International Journal of Engineering and Advanced Technology (Vol. 8, Issue 6, pp. 751–758). https://doi.org/10.35940/ijeat.f7989.088619

AUTHOR PROFILE

Stuti Goyal, is an architect and project manager with over five years of experience in the construction industry. She holds a Master's degree in Building Engineering and Management from the prestigious School of Planning and Architecture. Stuti is passionate about sustainability and actively explores innovative technologies in construction that promote eco-friendly practices. Through her research, Stuti aims to bridge the gap between traditional practices and modern sustainable solutions, paving the way for a more resilient future in architecture and construction.