Living Materials: How Microbes are Becoming the Building Blocks of The Future

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Personal Motivation for Topic Choice

I drew inspiration for this topic from the The Unnatural History Museum of Singapore, which I visited in October 2025. The exhibition was held as part of Singapore Design Week, to highlight the role that design has played in our nation-building journey.[1] The exhibition featured various innovative and thought-provoking displays, including building materials made with bacteria and fungi, such as Eco-Cement and mycelium structures. Eco-Cement is a biocement developed by scientists at Nanyang Technological University, that is created from industrial carbide sludge, urea, and bacteria.[2] On the other hand, a local mycological design studio, Bewilder, has explored the use of fungi by cultivating mycelium materials for structural and design applications.[3]

I was fascinated and amazed by the novel and unique applications of microbiology to fields like civil engineering and environmental sustainability. As a Pharmacy student, my exposure to microbes has largely been framed within the context of disease, infection, and antimicrobial therapy. Microorganisms are often portrayed as pathogens that cause harm to human health and should be eliminated. However, the museum opened my eyes to the value and power of microbes, which can be harnessed to benefit us and tackle real-world challenges. Microbial living materials offer sustainable alternatives to traditional construction materials, which contribute to carbon emissions and global warming. This is germane to Singapore which is a highly urbanised city. Exploring this topic allows me to broaden my perspectives beyond pharmacy and appreciate the interdisciplinary potential of microbiology in shaping a more sustainable future.

The Need for Sustainable Construction

The buildings and construction sector is the largest source of greenhouse gas emissions, contributing to 37% of global emissions in 2023.[4] This is mainly driven by the production and use of materials such as cement, steel, and aluminum, which accounted for more than half of the construction industry's carbon emissions in 2022.[5] These traditional building materials are carbon-intensive and emit tremendous amounts of carbon dioxide (CO_2) throughout their lifecycle, during extraction, manufacturing, transport, construction, refurbishment, and disposal.[6] This is known as embodied carbon and leaves a significant carbon footprint. Cement manufacturing alone produced a whopping 1.6 billion metric tonnes of CO_2 globally in 2022, which translated to approximately 8% of the world's total CO_2 emissions.[7]

As urbanisation increases and cities develop, the demand for infrastructure will grow. The built environment will continue to expand, which will release more greenhouse gases and exacerbate global warming. The global construction industry's carbon footprint is projected to more than double by 2050.[5] Continued use of conventional construction materials will impede us from achieving the goals of the Paris Agreement to limit global temperature rises to below 2 °C, preferably 1.5 °C, above pre-industrial levels. Hence, it is imperative that we switch to greener, sustainable alternatives such as biobased materials, to reduce carbon emissions and protect our planet.

Besides their adverse effects on the environment, traditional building materials also present issues such as durability, in particular concrete, which is one of the most commonly used

materials.[8] Concrete is brittle, has low tensile strength, and shrinks when it hardens and dries. This makes it susceptible to crack formation, which can weaken its integrity and allow harmful substances like chloride ions to penetrate, leading to reinforcement corrosion and reduced lifespan. The cracks in concrete are often fixed with plastic-modified materials such as epoxy resin, which is not environmentally-friendly. Furthermore, high costs are incurred to inspect, maintain and renovate the damaged concrete. This reinforces the need for sustainable solutions such as microbial self-healing concrete.

The Solution: Microbial Building Materials

Microbial materials have emerged as a promising solution that can overcome the challenges associated with traditional construction materials and pave the way for a sustainable future in construction. By leveraging microbes and their biological processes, we can produce and enhance construction materials. A key mechanism is microbially-induced calcite precipitation (MICP), whereby urease-producing bacteria hydrolyse urea to generate carbonate ions, which subsequently react with soluble calcium ions to form calcium carbonate, which is the mineral found in limestone, marble and chalk.[9,10,11] When this reaction occurs in soil or sand, the calcium carbonate precipitate helps to bind the soil particles together or fill the pores between them, improving the strength and reducing the permeability of soil. This forms biocement, which is a renewable cementitious product that can be used to replace cement for soil improvement. Using the same mixture but in lower dosages produces biogrout, which can help to reduce porosity and water permeability.[12]

An example of biocement is Eco-Cement, an invention by Nanyang Technological University, that utilises waste materials – industrial carbide sludge, a byproduct from the production of acetylene gas, and urea, a waste product that is excreted in urine.[10,11] Bacteria is added to the mix to activate MICP, forming a strong and sturdy block. The sand treated with biocement achieved an unconfined compression strength of up to 1.7 megapascals, which is superior to that of the same soil treated using an equivalent amount of cement, and the permeability decreased by two orders of magnitude. Moreover, biocement is produced at room temperature, unlike cement manufacturing which involves burning raw materials at extremely high temperatures exceeding 1000 °C to form clinkers, the binding agent for cement. This process generates significant carbon dioxide, hence biocement is a greener alternative that uses less energy and does not contribute to carbon emissions. In addition, since biocementation produces calcium carbonate, the same mineral found in limestones, this reduces the need to mine limestones, which damages the environment too and limestone is a finite resource.

Biocement shows great potential for use in soil improvement projects such as strengthening the ground, reducing water seepage for use in construction or excavation, and controlling beach erosion along coastlines.[10] Eco-Cement has been tested at East Coast Park and Sisters' Islands and proved comparable to traditional cement mixes. Beyond beaches, it has even been used to restore historical monuments such as a Buddha hand from the Dazu Rock Carvings, a UNESCO World Heritage Site in China.[2] Currently, it is being explored for water seepage prevention and artificial reef scaffolds.

Microorganisms that can carry out MICP are typically halotolerant bacteria with constitutive or inducible urease activity, including *Sporosarcina pasteurii*, various species from the *Bacillus* genus (*B. cereus, B. megaterium, B. sphaericus, B. pseudofirmus, B. subtilis, B.*

alkalinitrilicus, B. licheniformis, B. lentus), and *Staphylococcus* species. Besides ureolytic microbes, alternative metabolic pathways can also achieve MICP, such as the carbon-concentrating mechanism of cyanobacteria.[13] Researchers have engineered living building materials (LBMs) using a photosynthetic cyanobacterium *Synechococcus* sp. PCC 7002 (*Synechococcus*) to biomineralise a sand-hydrogel scaffold. The biomineralised material demonstrated increased fracture toughness and achieved mechanical properties comparable to conventional cement materials. A significant advantage of cyanobacteria is that they utilise CO_2 and sunlight to grow, thus their use in LBMs will be a valuable substitute for carbon-intensive traditional building materials. Furthermore, the exponential growth of bacteria can be leveraged to regenerate many living bricks rapidly from just a single starting brick, demonstrating the potential for self-replicating construction materials.

Besides bacteria, another unexpected unsung hero can produce sustainable building materials – fungi. Mycelium, the underground root network of fungi, can be cultivated on organic waste such as sawdust, bamboo, coffee grounds, or leaves, where it grows and binds these loose particles together into a cohesive mass.[14] The mycelium-based mass will then be moulded and shaped into blocks to form bricks, which can be used for construction. As a result, mycelium materials can be produced using low-cost, renewable resources including agricultural waste and food waste, while simultaneously upcycling waste into functional building components. This can help to reduce and repurpose waste, offering immense benefits for the environment. Moreover, mycelium is organic and biodegradable, thus it can be composted at the end of its lifecycle, unlike conventional construction materials that contribute to landfill accumulation. Other favourable properties that mycelium possesses include lightweight, ability to absorb sound, and mechanical strength, thanks to the biopolymers it contains, such as chitin and cellulose.

Fungi can also be harnessed to promote self-healing of concrete.[8] Similar to bacteria, fungi is capable of MICP, whereby it produces calcium carbonate precipitates through biomineralization or organomineralization, which can then be used to fill up cracks which develop in concrete. Fungal strains that show promise as self-healing agents include *Trichoderma reesei*, *Aspergillus nidulans* and *Fusarium oxysporum*. Fungi has been found to contribute to the development of the rimstone dams of travertine in the Huanglong park area in Sichuan, China, through encouraging calcite crystal formation.[15]

Challenges and Limitations

Notwithstanding their promising potential, microbial building materials face several challenges that need to be addressed in order to facilitate wider adoption. One of the primary barriers is cost and scalability.[16] While laboratory studies have demonstrated the feasibility of microbial processes, translating them to large-scale construction projects remains difficult. The production, cultivation, and maintenance of microbial systems can be complex and often require specific conditions, which can increase operational costs. For example, the bacterium *Sporosarcina pasteurii* is commonly used for MICP but it is cultivated almost exclusively in complex media, which only results in low or moderate bacterial growth.[17] Researchers have found ways to improve the cultivation of *S. pasteurii* through determining its nutritional requirements and optimal conditions for growth, resulting in higher yield. This increases the cost-effectiveness and makes MICP economically more feasible for application in the construction industry. Furthermore, the vast environmental benefits of microbial materials offer cost savings and the use of waste materials can mitigate some of the costs.

Microbial building materials may also pose safety concerns. As a Pharmacy student, this is especially pertinent and it is crucial that we ensure the safety of microbial materials so as to prevent harm to people exposed to the microbes and protect their health. Microbes, including bacteria and fungi, can produce allergens that may cause allergic reactions like skin rashes and asthma.[18] Some microbes even produce toxins, which are harmful compounds that can cause serious health problems if inhaled or ingested. Fungal spores can also cause adverse health effects like respiratory issues. Although rare in microbial building materials, opportunistic pathogens can cause infections, especially in immunocompromised individuals such as the elderly and people who are undergoing chemotherapy.

Hence, there should be a thorough screening process for the microbial candidates to ensure that the microbes selected are non-pathogenic to prevent transmission of diseases to humans. After implementation, safety assessments should be carried out to evaluate the safety of the microbial materials. For example, tests to detect any toxins or harmful by-products released by the microbes into the air, microbial contamination, or the growth of any new microbes. Observational studies could be conducted to assess the short-term and long-term impact of the microbial materials on the health of the building occupants. Besides rigorous testing, it is also important to develop regulations to guide the safe and effective use of microbes in the construction industry.

Conclusion

In conclusion, building materials made with microbes represent a novel and interdisciplinary approach to tackle the environmental and structural challenges of the construction industry. By harnessing biological processes such as MICP, microbial materials offer a sustainable alternative to conventional construction materials, with a myriad of benefits including reduced carbon emissions, improved material performance, and the utilisation of waste resources. However, significant challenges remain, with regards to scalability, cost, and safety. Despite these limitations, ongoing research and development will continue to advance construction biotechnology and microbial materials have strong potential to transform the construction industry towards a more sustainable and resilient future.

Reflection

Through writing this essay, I have gained new insights into the capabilities and applications of microbes, and a newfound appreciation for microbes. Exploring microbial construction materials has expanded my perspectives on the role and value of microbes beyond their traditional association with disease in pharmacy. I am deeply amazed by how microbes can be harnessed to create living building materials, which present a sustainable solution to the woes of the construction industry, and can benefit the environment greatly. This topic has highlighted the importance of interdisciplinary collaboration, as expertise from different fields, such as microbiology, engineering and materials science, are needed to complement each other and develop innovative solutions. Overall, this experience has reinforced the potential of microbes as powerful tools to address real-world challenges.

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