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Review

A review of microbial precipitation for sustainable construction

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HIGHLIGHTS

- Nature has solutions for the dichotomy of building while maintaining the environment.
- Microbial $CaCO_3$ can plug pores and bind grains to improve durability and strength.
- Energy consumption and emission of GHG from the microbial process is negligible.
- Economy, acceptance, recycling, CO_2 sequestration, self-healing are important issues.
- For life cycle analysis, data from industrial scale experiments are essential.

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ABSTRACT

Rapid urbanisation has accelerated consumption of concrete making it the most consumed artificial material. Present day concrete is one of the largest sources of anthropogenic greenhouse gas emission and is not sustainable. Microbial precipitation of $CaCO_3$ is a promising way of emulating nature's sustainable ways. This paper reviews current progress and potential of this technology. Prior research on the modes of application of the technology and consequent gains in strength and durability of construction materials has been summarised. Imperatives for a quantitative estimate of sustainability are identified. Progress necessary for industrial adoption of the technology has been discussed.

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1. Introduction

Infrastructure such as roads, bridges and buildings have been built at a rapid pace during the last hundred years and they have played a major role in the unprecedented economic prosperity of the world. Such constructions took place in the developed world during the middle of the last century and they are facing the challenge of maintenance and renewal. The emerging economies, on the other hand, are rapidly building their infrastructure now. As a result, consumption of building materials has grown at a very fast pace and would continue to grow in the foreseeable future [91]. Buildings are one of the largest consumers of natural resources, and they account for a significant portion of greenhouse gas emissions [26]. Among the materials of construction, cement concrete has gained the status of the most used artificially made material in the world. A world without concrete, and its dominant precursor, Ordinary Portland Cement (OPC), is hard to imagine [55]. Annually 3.5 billion tonnes of cement is produced worldwide with China alone consuming about 57.3% of it [24]. The cement industry faces challenges such as depleting raw materials and fuel reserves and growing environmental concerns. In the recent past, several advances have been made to address these concerns. Blending cement with recycled materials such as fly ash, blast furnace slag and silica fume is paramount among them. OPC production is still responsible for around 6% of global anthropogenic CO_2 emissions. In the current global setting, building construction and operation results in 50% of all CO_2 emissions worldwide. In order to become sustainable, construction industry must manage its environmental impact (both materials and energy use); social concerns (health and wellbeing) and economic liabilities (cost of construction) in an optimal fashion. Present building materials use huge quantities of energy and produce high volumes of CO_2 (Table 1). Thus, transformational change in building materials is imperative for ensuring sustainability.

Nature, on other hand, has been building materials in a sustainable way and of comparable properties for millions of years. They have a wide variety of forms such as ceramics (tooth enamel, mollusc shell, spicules in sponges, diatoms), polymers (arthropod exoskeleton, silk, plant cell walls), or balanced composites of both (feathers, antler, bone) [25]. Biological materials are virtually all composites with topologically designed material phases optimised for the intended function. For example, bones combine high modulus crystalline calcium phosphate deposited in a network of high toughness collagen fibrils resulting in material with tailored combination of toughness and stiffness. Moreover, through variation of the density of deposition graded mechanical properties are achieved. Thus, although bones and antlers of Elk deer are made of the same material combination, antlers achieve higher toughness through topological design [111]. In the recent years, due to the advent of precision equipment, great progress has been made in understanding the natural materials and compare them with manufactured ones [110]. It gives us an opportunity of simultaneously studying natural and manufactured materials for construction of habitats. In ant hills, for example, grains of sand are cemented together quite similar to the cement mortar. Like cement, coral reefs are made of a calcium compound (carbonate). Spiders generate two amazingly different silk protein fibres, Araneus MA silk (modulus 10 GPa) for web frame and draglines and Araneus viscid silk (modulus 0.003 GPa) [75]. Use of metals is negligible in natural materials; possibly due to non-availability of the luxury of fossil fuels. However, like in manufactured materials of construction, calcium compounds in the form of phosphates, carbonates and sulphates is abundant in nature. The major difference is that nature consumes negligible amount of energy for the production of those compounds. Thus, emulating natural construction has tremendous potential for developing sustainable construction materials.

Table 1
Embodied energy and emission of building materials.

Material	Energy (MJ/kg)	Carbon (kg CO_2/kg)	Density (kg/m^3)
Aggregate	0.083	0.0048	2240
Concrete (1:1.5:3 eg in situ floor slabs, structure)	1.11	0.159	2400
Concrete (eg in situ floor slabs) with 25% PFA RC40	0.97	0.132	–
Concrete (eg in situ floor slabs) with 50% GGBS RC40	0.88	0.101	–
Bricks (common)	3.0	0.24	1700
Concrete block (medium density 10 N/mm^2)	0.67	0.073	1450
Aerated block	3.50	0.30	750
Limestone block	0.85	–	2180
Cement mortar (1:3)	1.33	0.208	–
Steel (general – average recycled content)	20.10	1.37	7800
Steel (section – average recycled content)	21.50	1.42	7800

(Source: http://www.greenspec.co.uk/embodied-energy.php).

Recently, biomineralisation has been successfully achieved in construction materials [83,31]. The technology seems promising in structural [104,4] and geotechnical [37] applications. With success in the laboratory, field applications are beginning to emerge. The hydraulically fractured Fayette Sandstone formation 341 m (1118 feet) below the ground surface in the Gorgas #1 well at the Southern Company Gorgas Power Plant in Walker County, Alabama has been remediated with MICP [29]. In heritage preservation, MICP has been performed on the Angera Cathedral, Chiesa di Santa Maria di Angera in Italy [77]. Biomineralisation of 100m^3 of sand for ground improvement has been demonstrated [103]. Wiktor and Jonkers [113] recently reported significant sealing of cracks with MICP in a parking garage.

This paper examines the potential of biomineralisation as a sustainable construction material. Its application in geotechnical engineering has been recently reviewed [38]. The focus of this paper is its application in improving various building materials in terms of their strength, permeability and durability. An attempt has been made to identify the gaps for estimating the life cycle and sustainability of these materials.

2. Biomineralisation

Mineralisation is often used in civil engineering, which reflects producing minerals, chiefly carbonate products. In biomineralisation living organisms participate in the process of mineralisation. Living organisms produce minerals, more specifically, an inorganic mineral phase, with a biopolymer [25]. Biomineralisation is of two types; (i) biologically controlled mineralisation (BCM), and (ii)

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