An overview of techniques based on biomimetics for sustainable development of concrete

V. Ramesh Kumar, B. Bhuvaneshwari, S. Maheswaran, G. S. Palani, K. Ravisankar and Nagesh R. Iyer*

Biomimetics is a field of science that studies biological processes for effectively using them in the development of innovative engineering materials and systems. It is a new field of emergence in materials science and engineering in which lessons learned from biology form the basis for evolution of novel technological materials. Biomimetics is finding application in diverse areas ranging from micro/nano electronics to civil/structural engineering. This article presents a critical review of the literature on biomimetics in civil engineering and its application for the development of sustainable materials in the construction industry. It includes various methodologies such as biodeposition, which has influenced material evolution, and biomineralization, which is a complex phenomenon by which organisms form minerals seen in various geothermal systems. The article deals with the initial usage of Bacillus pasteurii for filling up the pores for crack remediation and research work on it by changing the nutrient source and strain improvement of the same towards increasing the strength of concrete. The article also discusses a new type of thermophilic anaerobic microorganism belonging to Shewanella species, which when added to concrete, has shown to increase the strength of the concrete. This is due to growth of filler material within the pores of the cement–sand matrix. Thus, there is ample scope for development of biomimetics-based sustainable construction materials.

Keywords: Biodeposition, biomimetics, biomineralization, concrete, microorganisms.

BIOMIMETIC approaches have considerable potential in the development of new high-performance materials with low environmental impact. Biomimetics can be regarded as – abstracting processes from nature, identifying the business opportunity for these processes and applying them. Biomimetics is not about copying nature, but about learning from it. At present most industrial interest in biomimetics is found in the aerospace, textiles, computing, artificial intelligence and sensor sectors, with a limited track record in construction (mainly in materials and design). Few examples are: (i) Self-cleaning paints (e.g. Lotusan[1]) are based on the lotus effect, the unique ability of a lotus leaf surface to avoid wetting. This is mainly due to the presence of microscale protuberances covered with waxy nanocrystals on the surface. Both the protuberances and the wax crystals make the surface of lotus super-hydrophobic in nature, which means water droplets easily roll over the leaf surface taking contaminants and dust particles with them. This phenomenon is popularly known as the 'self-cleaning effect'. The self-cleaning property is highly important for water plants. This natural phenomenon occurring in lotus leaf led to the finding of a new self-cleaning paint. (ii) Honeycomb structures[2]. Honeycomb structures (e.g. the Eden Project biomes, and lightweight stone veneer cladding products) are interesting architectural approaches (e.g. branching tree-like roof supports at Stuttgart Airport), and tensairity beams[3] and structures (developed by the Swiss Company Airlight Ltd in close cooperation with prospective concepts; http://www.empa.ch/plugin/template/empa; last accessed on 22 March 2010) are based on a combination of cylindrical membranes filled with compressed air and supporting struts and cables. These are systems of rigid pneumatic beams inspired by the way in which the opposing compressive and tensile forces balance each other. These have found applications in deployable structures[4], bridges, canopies and roof structures for commercial buildings. The static response of such beams under bending loads has been numerically and experimentally studied by Luchsinger and Crettol[4]. Current areas where

The authors are in the CSIR-Structural Engineering Research Centre, CSIR Campus, Taramani, Chennai 600 113, India.
*For correspondence. (e-mail: ramesh@sercm.org)

biomimetics is being considered globally include energy and resource efficiency, added functionality in materials and structures, robotics, lightweight structures, and architecture and design of cost-effective structural systems.

Background for use of biomimetics in concrete

Biomimicry innovation methods can help us to create products and processes that are sustainable, perform well, save energy, reduce materials cost, and redefine and eliminate waste and subsequent environmental degradation. Biomimetic approaches have provided an inspiration for evolving new techniques/processes to many engineering problems. A fundamental biological principle is that of minimizing the use of materials in non-critical areas, which can reduce weight and cost. In the present scenario in a country like India, where infrastructure development is one of the deciding factors for economical and social development, the production process, use of resources and means of efficient disposal of waste should be looked up critically. Concrete is considered as one of the most important building materials around the world. It is a mixture of inert mineral aggregates, e.g. sand, gravel, crushed stones and cement. Cement consumption and production is closely related to construction activity, and therefore to the general economic activity. Cement is one of the materials with the highest production around the world. Due to the importance of cement as a construction material, and the geographic abundance of the main raw material, i.e. limestone, cement is produced virtually in all countries. The widespread production is also due to the relative low price and high density of cement that limit ground transportation because of the relatively high costs. Cement production is a highly energy-intensive process. Energy consumption by the cement industry is estimated at about 2% of the global primary energy consumption, or almost 5% of the total global industrial energy consumption[5]. Due to the dominant use of carbon-intensive fuel, e.g. coal, in clinker-making, the cement industry is also a major emitter of CO_2. Besides energy consumption, the clinker-making process also emits CO_2 due to the calcining process. By increasing the strength of the concrete by using microorganisms will result in structural member of reduced dimensions and will also help to produce relatively leaner concrete mix. Hence there is considerable reduction in the usage of cement. This will lead to reduction of CO_2 emission and result in a green environment. The amount of CO_2 produced by different countries in the world is given in Table 1. It can be observed that the developing countries produce more CO_2 emissions compared to the developed countries. The average world intensity of carbon emissions during cement production is 0.81 kg CO_2/kg cement. Although China is the largest emitter of CO_2, the most carbon-intensive cement region in terms of carbon emissions per kg of cement produced is India (0.93 kg CO_2/kg), followed by North America (0.89 kg CO_2/kg), and China (0.88 kg CO_2/kg)[6].

The emissions of CO_2 can be reduced by:

- improvement of the energy efficiency of the process;
- shifting to a more energy-efficient process (e.g. from (semi) wet to (semi) dry process);
- replacing high-carbon fuels by low-carbon fuels;
- applying lower clinker/cement ratio (increasing the ratio of additives/cement): blended cements;
- application of alternative cements (mineral polymers);
- removal of CO_2 from the flue gases;
- improving the strength of concrete by less energy-consuming materials, thereby reducing the amount of cement being used.

Biomimetics-based construction materials can be thought of as less energy-consuming materials to improve the

Table 1. Global carbon emission from cement production during 1994 (from Marland *et al.*[5])

Country/region	Cement production (Tg)	Primary intensity (MJ/kg)	Primary energy (PJ)	Process carbon emission (Tg CO_2)	Carbon emission energy use (Tg CO_2)	Total carbon emission (Tg CO_2)
China	423	5.0	2117	175	197	372
Europe	182	4.1	749	73	56	129
OECD Pacific	151	3.5	533	65	47	105
Rest of Asia	124	4.9	613	56	179	105
Middle East	111	5.1	563	51	44	95
North America	88	5.4	480	39	40	78
EE/FSU	101	5.5	558	42	38	80
Latin America	97	4.7	462	41	30	71
India	62	5.0	309	28	30	60
Africa	41	4.9	201	18	15	33
World total	1381	4.8	6585	587	830	1126

1 Tg, 1 million tonnes = 10^9 kg; 1 Tg CO_2 = 0.27 Tg C = 0.27 million tonnes carbon, 1 PJ = 1 petajoule (1 PJ = 10^{15} J).
OECD, Organization for Economic Cooperation and Development; EE/FSU, Eastern Europe/Former Soviet Union.

strength of concrete which will have low environmental impact and help reduce the carbon footprint of the cement industry. The general ideas of biomimetics which can be used for concrete are biodeposition and biomineralization, which are the natural biological processes of certain species of microorganisms such as bacteria. Though concrete is quite strong mechanically, it suffers from several drawbacks such as low tensile strength, permeability to liquids and gases, the consequence of which are corrosion of reinforcement, susceptibility to chemical attack and low durability. Modifications have been proposed from time to time to overcome these drawbacks, but most of them are not easy and/or good enough[7]. For instance, cracking of concrete is a common phenomenon. Without immediate and proper treatment, cracks in concrete structures tend to grow further and eventually require costly repair. Reducing the extent of cracking in concrete has been the subject of research for many years[7–10]. There are a large number of products available commercially for repairing concrete: structural epoxy, resins, epoxy mortar and other synthetic mixtures. Currently, these types of synthetic filler agents are extensively used in concrete crack repair. Because cracks in concrete structures continue over time, the remedy should be applied repeatedly as and when the crack limit is exceeded. Moreover, several of these products are organic coatings consisting of volatile organic compounds. The air-polluting effect of these compounds during manufacturing and coating has led to the development of new formulations such as inorganic coating materials. Due to the above limitations, the use of biomimetics as an alternative for improvement of strength and durability was studied. The idea is to use microorganisms for biodeposition[11] of available minerals inside the concrete. Like biodeposition and its applications in concrete structures, another emerging research concept used in the construction industry is biomineralization. It is a widespread, complex phenomenon by which organisms form minerals, occurring in various geothermal systems. It is defined as a biologically induced precipitation in which an organism creates a local microenvironment that allows optimal extracellular chemical precipitation of mineral phases. Bacteria are very small, but have the largest surface-to-volume ratio of any lifeform. Therefore, they provide a larger contact area that can interact with the surrounding environments[12]. The unique properties and functions of biomineralization have inspired innovative high-performance composites for construction applications, as well as other new materials. Use of microorganisms within mortar/concrete leading to the process of biomineralization is now a potential field of research in concrete technology, and an inherent cement-based biomaterial was developed to remediate the cracks and fissures in concrete structures[13]. *Bacillus* species are able to precipitate on their cell constituents and in their micro-environment by conversion of urea into ammonia and CO_2. The bacterial degradation of urea locally increases pH and promotes microbial deposition of CO_2 as calcium carbonate ($CaCO_3$) in a calcium-rich environment[14,15]. The $CaCO_3$ so produced can be useful both as a binding agent and a pore-filling medium to improve the strength. The binding property can be useful for improving the adhesive property between the concrete matrix, thereby increasing the strength of concrete, whereas the pore-filling effect is useful in the reduction of capillary pores, hence both the strength and durability of concrete is increased.

Review of the literature

Alvarado[16] found that bacteria, namely *Sporosarcina pasteurii* present in the natural soil deposits precipitate a mineral called calcite which acts as a binding agent to convert sand to sandstone. This naturally occurring biological process can be mimicked in the cement/concrete structures for both improving the binding property and also for the reduction of capillary pores. Based on the above idea, the process of microorganism in a concrete can be thought of a biomimetic technique for improvement of both strength and durability.

Biomimetics for durability aspects of concrete

Willem De Muynck *et al.*[17] also confirmed that the biodeposition treatment resulted in an increased resistance of mortar specimens towards carbonation, chloride penetration, and freezing–thawing. In their study employing cementitious materials, the biodeposition treatment might be regarded as a coating system, as the carbonate precipitation was mainly a surface phenomenon due to limited penetration of the bacteria in the porous matrix.

Ramakrishan *et al.*[18] used *B. pasteurii*, a common soil bacterium for remediating cracks and fissures in concrete utilizing microbiologically induced calcite ($CaCO^+$) precipitation. As a microbial sealant, $CaCO_3$ exhibited its positive potential in selectively consolidating simulated fractures and surface fissures in granites and in the consolidation of sand. The objectives of the investigation were to study the effect of different concentrations and efficiency of bacteria when suspended in different media (water, phosphate buffer and urea–$CaCl_2$) on the durability of concrete. It was concluded[18] that the presence of bacteria in different media increased the resistance of concrete towards alkali, sulphate, freeze–thaw attack and drying shrinkage. Phosphate buffer proved to be an effective medium for bacteria compared to the other two media (water and urea–$CaCl_2$). Concrete made with bacteria suspended in water did not perform well as expected, because bacteria cannot survive in water. The durability of bacterial concrete was found to increase with increase in the concentration of bacteria.

Bang *et al.*[19] reported high compressive strength of concrete cubes, whose cracks were retrofitted by calcite

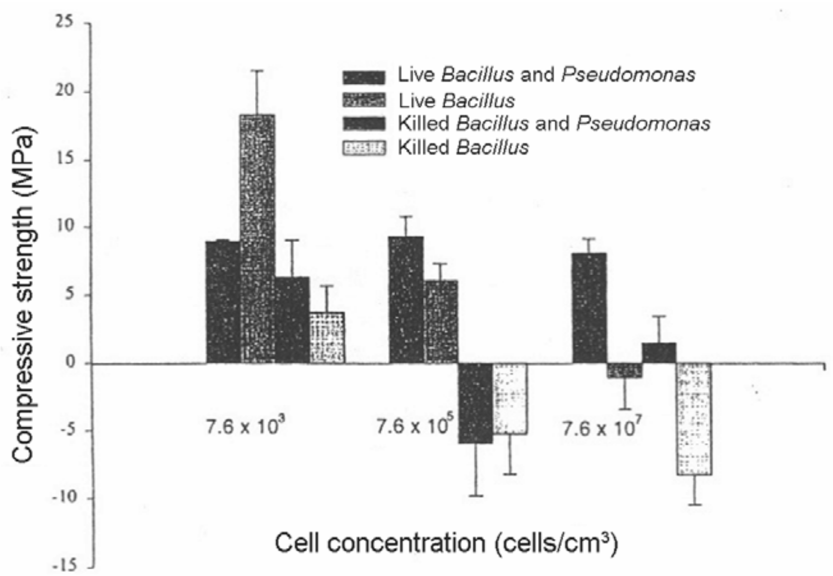

Figure 1. Increase in strength of cement with respect to bacterial concentration[14].

precipitation, induced by polyurethane-immobilized *B. pasteurii* cells, and inferred that the calcite might remain as a form of precipitation, not as a bonding material. Stocks-Fischer *et al.*[20] also found and suggested the potential use of the microbial calcite precipitation process in remediation of the surface and sub-surface of porous media like concrete. Various studies[13,18,21] have shown that pioneering results of innovative techniques based on microbial mineral precipitation have led to the use of bacteria in concrete. Ramachandran *et al.*[13] used the endospore-forming soil microorganism, *B. pasteurii*, for calcite precipitation by producing urease enzyme and studied the two types of the specimen, one with microorganism and the other with microbial mixtures. The study showed that there was increase in the compressive strength of the cement mortar cubes containing low concentration of *B. pasteurii*. However, the strength of the cubes decreased as the cell concentration (Figure 1) and curing time increased, indicating that pore space is created by the dead biomass of microorganism.

Cracks filled with bacteria and sand demonstrated a slight increase in compressive strength and stiffness values when compared with those without cells. It was concluded[13] that *B. pasteurii* was effective in crack remediation and can be used for strength enhancement.

Biomimetics for strength aspects of concrete

Another study[22] was carried out using the bacterium *S. pasteurii* with lactose mother liquor (LML) as an alternative nutrient source. The compressive strength of the mortar cubes increased as shown in Figure 2. It was found that LML can be used as an alternative medium for precipitation of calcite in place of the more expensive medium such as yeast.

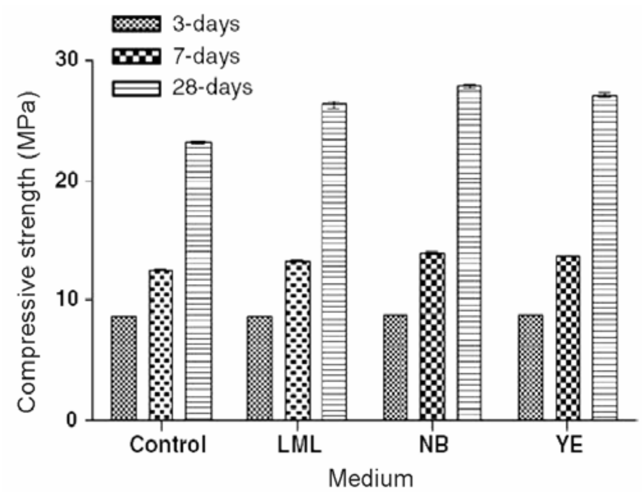

Figure 2. Compressive strength achieved using different growth media[22]. LML, Lactose mother liquor; NB, Nutrient broth; YE, Yeast urea.

Studies were also carried out to increase the production of calcite and to enable the survivability of the bacteria in a high-pH environment[22]. Anchal *et al.*[23] were successful in developing phenotypic mutants of *S. pasteurii* (namely, MTCC 1761). These bacteria were developed by UV radiation to test their ability for enhanced urease activity, which is a chemical process by which the microorganism consumes and breaks down urea to form ammonia and eventually calcite. The mutant named Bp M-3 was found to be more efficient in improved urease activity compared to the other mutants and the wild-type strain. This study suggested that calcite production due to biomineralization process is highly effective and provides a useful strategy as a sealing agent for filling pores or cracks in structural components. The improved strain of *S. pasteurii* by mutagenesis was also proven to survive at very high pH values. The enhanced urease activity of Bp M-3 was compared with other mutant strains and wild strain as shown in Figure 3.

Different microorganisms have been used[20,23] to increase the compressive strength of cement mortar and for remediation of cracks in concrete. It was shown[21,24] that the addition of specific microorganisms to cement–sand mortar or concrete deposits inorganic substances inside the pores of the matrices, which can be used as a filling material to remediate cracks within the structures. Also, bacterially induced $CaCO_3$ precipitation was proposed[20,23] as an alternative and environment-friendly crack repair technique. Gollapudi *et al.*[25] were the first to introduce this novel technique in fixing crack by employing environment-friendly biological processes[26,27]. It was also noted that the addition of an anaerobic hot-spring bacterium (closely related to the *Shewanella* species) to mortar/concrete could increase the compressive strength by about 25–30% with respect to the control mortar[21,27]. Ghosh *et al.*[27] found that the filler material within the pores of the cement–sand mortar increased the compressive strength of the mortar by about 25%, as shown in Table 2, with the addition of anaerobic microorganism of about 10^5 cells/ml of water concentration after 28 days of curing[21]. However, they did not find any improvement in the cement mortar using another bacterial microorganism, namely *Escherichia coli*.

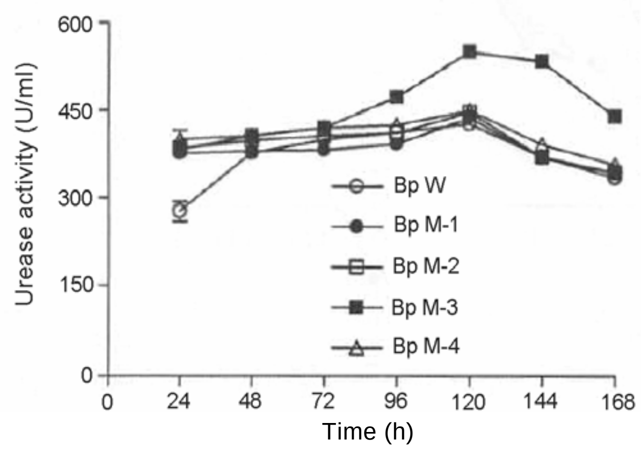

Figure 3. Comparison of urease activity for different strains[23].

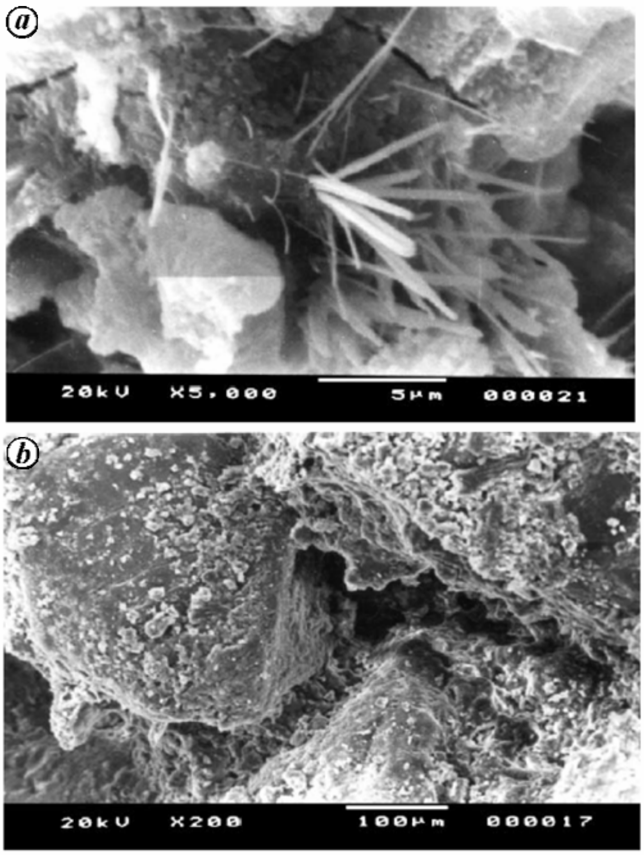

Figure 4. Comparison of SEM photomicrographs of mortar[21]. (***a***) With microorganism and (***b***) without microorganism.

The growth of anaerobic bacterium inside the concrete was observed with help of scanning electron microscopy (Figure 4). The biologically induced cement-based material exhibited better durability and crack repairing performance compared to normal concrete materials[26].

Further studies were carried out to study $CaCO_3$ precipitation for its ability to improve the compressive strength of mortar[28]. New bacterial genera that are capable of improving the compressive strength of mortar were discovered. Based on these studies four microorganisms, namely *Sporosarcina soli*, *Bacillus massiliensis*, *Arthrobacter crystallopoietes* and *Lysinibacillus fusiformis* were isolated and studied for their calcite precipitation. Crystal aggregates of $CaCO_3$ were identified in the bacterial colonies. It was concluded from 7-day strength that both *S. soli* and *L. fusiformis* showed improved compressive strength relative to control, but *B. massiliensis* and *A. crystallopoietes* did not show any improvement in strength. From 28-day strength it was concluded that *A. crystallopoietes* showed the greatest improvement in strength.

Studies were carried out to identify the key factors in the optimal biological $CaCO_3$ precipitation on limestone, which is an important ingredient for cement[11]. The biological key factors had to be used for quick screening, contrary to the slow chemical–physical structural analysis. Another fascinating area of biology that has intrigued materials scientists is nature's ability to create a remarkable variety of intricate inorganic structures. The growing interdisciplinary research at international level is aimed at understanding the biological systems in accomplishing the synthesis of inorganic materials under mild ambient conditions. The interface between biology and materials chemistry can be advantageously used in the fabrication of advanced hybrid material structures. Some of the examples of biomineralization (fabrication of inorganic materials by organisms) include magnetite[29] and

Table 2. Improvement in strength of mortar for different cell concentrations[21]

	Average mortar compressive strength (MPa)							
	3 days		7 days		14 days		28 days	
Cell concentration/ ml of water	Strength ± SD	Percentage increase relative to control	Strength ± SD	Percentage increase relative to control	Strength ± SD	Percentage increase relative to control	Strength ± SD	Percentage increase relative to control
Nil	8.67 ± 0.28	–	12.60 ± 0.47	–	16.00 ± 0.81	–	23.13 ± 0.23	–
10	8.68 ± 0.44	0	12.74 ± 0.89	1.11	16.21 ± 0.22	1.31	24.21 ± 0.43	4.66
10^2	8.76 ± 0.47	1.04	12.87 ± 0.46	2.14	16.44 ± 0.38	2.75	25.00 ± 0.88	8.08
10^3	8.80 ± 0.69	1.49	12.98 ± 0.81	3.01	16.87 ± 0.64	5.43	25.40 ± 0.84	9.81
10^4	8.89 ± 0.87	2.53	13.40 ± 0.53	6.34	17.10 ± 0.37	6.87	25.44 ± 0.97	9.98
10^5	9.34 ± 0.81	7.73	14.70 ± 0.74	16.67	19.50 ± 0.42	21.87	28.98 ± 0.86	25.29
10^6	9.20 ± 0.28	6.11	13.80 ± 0.58	9.52	17.50 ± 0.81	9.38	26.52 ± 0.27	14.65
10^7	8.86 ± 1.01	2.19	13.00 ± 0.23	3.17	17.00 ± 0.45	6.25	25.69 ± 0.74	11.06

silver[30] nanoparticles synthesized by bacteria; cadium sulphide nanoparticles[31] synthesized by yeast cells; the silica frustules[32] of diatoms and the silica spicules[33,34] of the sponge *Euplectella*.

The fundamental process in microorganisms for transforming minerals involves proteins and/or other biological macromolecules that control the nucleation and growth of the inorganic structure. The process of biomineralization and assembly of the inorganic components into hierarchical, sophisticated structures has led to the development of a variety of approaches that mimic the recognition and nucleation capabilities found in biomolecules for inorganic materials synthesis. The implication of biomineralization on the development of materials either at the nano- or micro-scale has stimulated significant progress in understanding the underlying biochemical processes.

Summary and concluding remarks

Thus, it is evident that the minerals produced by the process of biomineralization, which is a normal biological process in certain types of micro-organism can be used both as a binder and pore filler in the process of improving the strength of concrete. The study also has shown that more such types of organism can be identified and efficiently used in the process of strength and durability improvement. There is scope and need for examining biological processes that have influenced materials science on biodeposition and biomineralization treatment such as microbial precipitation towards evolving a new methodology/technology for production of new sustainable construction materials with improved structural strength and durability. Using the new materials developed, it is possible to construct structures, which will be 'green' and 'sustainable', requiring optimum resources and energy.

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