Earth-Science Reviews 148 (2015) 1–17

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Biomineralization for sustainable construction – A review of processes and applications

Varenyam Achal [a,*], Abhijit Mukherjee [a,b], Deepika Kumari [c], Qiuzhuo Zhang [a]

[a] School of Ecological and Environmental Sciences, East China Normal University, Shanghai 200241, China
[b] Department of Civil Engineering, Curtin University, Bentley, WA 6102, Australia
[c] Xinjiang Key Laboratory of Environmental Pollution and Bioremediation, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China

ARTICLE INFO

Article history:
Received 6 January 2015
Accepted 11 May 2015
Available online 20 May 2015

Keywords:
Biomineralization
Sustainable construction
Biocement
Calcium carbonate
Urease
Building materials

ABSTRACT

Modern civilization is facing the dichotomy of rapid development of infrastructure that makes concrete as most traded material on the earth other than water. However, the production of cement, key ingredient of concrete, releases roughly a tonne of CO_2 into the environment with each tonne of cement production. The environmental concerns and sustainability issues associated with cement and concrete necessitate alternative and better approach in the construction. Nature, on the other hand, has a plethora of examples of sustainable habitats such as coral reefs, silk webs and ant hills. Recent advances in biotechnology have great potential of emulating nature's way of building in modern days infrastructures at a scale that would sustain increasing population. Further, many of the biological materials of nature, be it ceramics or polymeric composites formed in the process of biomineralization, provides basis for sustainable construction. This paper elaborates nature's way of construction based on biomineralization and discusses the progress of different biological pathways for sustainable construction. Main milestones achieved have been identified and the effect of biological intervention on the properties of structural materials has been highlighted. Variety of applications of biomineralization based technology in the construction has been reported. The paper briefly documents the future directions of the technology.

Contents

1. Introduction . . . 2
2. Nature's ways of construction . . . 2
3. Alternate pathways for biocementation . . . 4
   3.1. Biologically controlled mineralization . . . 4
   3.2. Biologically induced mineralization . . . 4
      3.2.1. Photosynthetic microorganisms . . . 4
      3.2.2. Sulphate reducing bacteria . . . 4
      3.2.3. Bacteria involving nitrogen cycle in mineralization . . . 4
   3.3. Microbially induced calcium-carbonate precipitation (MICP) . . . 5
   3.4. Biocement . . . 6
4. Challenges . . . 7
   4.1. Cost of the technology . . . 7
   4.2. Increasing yield . . . 7
   4.3. Alkaline conditions . . . 7
   4.4. Perceived harmful effects – chlorides . . . 8
5. Structural properties . . . 9
   5.1. Strength . . . 9
   5.2. Water permeability . . . 9
   5.3. Chloride ion permeability . . . 10
   5.4. Reinforcement corrosion . . . 10
6. Applications . . . 11

* Corresponding author.
E-mail address: varenyam@re.ecnu.edu.cn (V. Achal).

http://dx.doi.org/10.1016/j.earscirev.2015.05.008
0012-8252/

6.1. As a binder . . . 11
6.2. As a cement admixture . . . 11
6.3. As a barrier layer . . . 12
6.4. As a repair system . . . 12
7. Economy analysis of biocementation . . . 13
8. Future directions . . . 14
8.1. Archiving of microbial varieties . . . 14
8.2. Local adaptation . . . 14
8.3. Life cycle assessment . . . 14
8.4. Expanding application domains . . . 14
9. Concluding remarks . . . 14
Acknowledgements . . . 15
References . . . 15

1. Introduction

Development of modern infrastructure such as roads, bridges and buildings has proven to bring in economic prosperity. The emerging economies are now emulating the developed ones in rapidly building their infrastructure, resulting in the consumption of construction materials such as cement, brick and steel is at their record highs and it is predicted to grow for the next fifty years (Schneider et al., 2011). As a result, the construction industry accounts for half of global resource usage, up to 40 percent energy consumption and up to 20 percent of the emission of greenhouse gasses. Experts have expressed serious doubts about the sustainability of the present construction technologies. Development of an alternative method of construction that does not hinder the progress of infrastructure and at the same time does not cross the boundaries of sustainability would be a great step to avert the crisis. Nature has been building its habitats for millions of years in a sustainable way. It is worthwhile to examine the natural ways of building habitats and to what extent they can be emulated in engineering construction.

Many building materials use huge quantities of energy and produce high volumes of CO_2. Steel, brick and concrete are prime among them. However, in the last century use of concrete has surpassed all other building materials by a huge margin. Ordinary Portland Cement (OPC) is a vital construction material and also a strategic commodity (Vlasopoulos, 2010) with a market dominated by China, which is attributed to 57.3% of global consumption (CEMBUREAU, 2012). Despite the incremental improvements in process efficiency that have been adopted by the cement industry in recent years, OPC production is still responsible for around 6% of all anthropogenic global CO_2 emissions. In the current global setting, building construction and operation results in 50% of all CO_2 emissions worldwide. The push to reduce global CO_2 emissions is backed by governments, corporations and citizens who understand that the present rate of release of greenhouse gases into the atmosphere is a serious threat to future life and prosperity on the planet. Cement never appears to become a sustainable material (Gerilla et al., 2007).

Further, materials for infrastructure such as concrete, have been developed with a sole focus on strength believing that other functional requirements such as durability, thermal or hygral passivity would be automatically achieved. However, in reality, infrastructure materials have been found to degrade rather rapidly due to natural as well as anthropogenic causes. Often the situation is aggravated due to high CO_2 concentration in the atmosphere. The aggressive elements enter the concrete that has direct impact on the corrosion of reinforcements (Pacheco-Torgal and Labrincha, 2013). Corrosion leads to cracking and spalling of concrete that creates pathways for intrusion of deleterious materials. They affect other functional requirements such as hygral and thermal insulation. Synthetic agents such as epoxies and polyurethanes, water repellents such as silanes or siloxanes, and corrosion inhibitors such as cationic surfactants are often not compatible with their substrates and sometimes toxic.

On the other hand, Nature has been building habitats such as ant hills, coral reefs and spider webs in a sustainable manner for millions of years. The materials are synthesized at ambient conditions (thus requiring very little energy) and they are optimized to multifunctional requirements. For example, the spider's web needs to be resilient to be able to tangle the prey and stiff to maintain its shape. Thus, the silk of the web frame and drag lines is more than 1000 times stiffer than the catching spirals (Omenetto and Kaplan, 2010). Although the present technology cannot match the versatility of construction by nature, there are wonderful lessons to be learnt. Moreover, there are early indications of adaptability and scalability of some of the biological processes of nature in the construction industry (Achal et al., 2010a, 2011a; Achal and Mukherjee, 2015).

This paper provides a critical review on nature's ways of construction. As the discussion focuses on concrete, biocementation, its pathways and mechanisms, and its application in various building materials have been highlighted. A discussion on the economics of this novel biotechnology is provided. Challenges and future work on biocementation in construction are also outlined.

2. Nature's ways of construction

A large number of high-performance prototypes has been created by nature that humans can reverse engineer and in turn use as inspirations for creating synthetic products with similar superior performances (Ballarini and Buehler, 2013). There are inexhaustible sources of inspiration that come from nature, be it ceramic (tooth enamel, mollusk shell, spicules in sponges, diatoms), polymeric (arthropod exoskeleton, silk, plant cell walls), or fairly balanced composites (feathers, antlers, bones). Biological materials consist virtually of all composites utilizing basic components in different proportions and of a variety of structural architectures with high mechanical strength. Such materials are developed by nature by means of growth or biologically controlled self-assembly, adapting to the environmental conditions and using the most commonly found materials. These materials are composed of only about 10% of about 100 stable elements found in nature. They are notably light, restricted within the first two rows of the periodic table. The principal elements include hydrogen, carbon, oxygen, nitrogen, phosphorous, sulfur, silicon, and calcium. Common metals such as iron, copper and aluminium are either absent or found in minute quantities, e.g. iron oxide in radular teeth of chiton (Saunders et al., 2009). Most likely, reason for absence of metals is that the high temperatures necessary for processing of metallic elements are not amenable natural organisms (Chen et al., 2012).

Biological organisms produce composites containing both inorganic and organic components in complex structures, organized in terms of composition and structure, which provide properties for multifunctional performance. Table 1 specifies the major components responsible for mechanical strength in biological materials for natural habitats. Coral reefs and bone consists of calcium phosphate and collagen, respectively.