The Practical Use of Biocement as Self-healing Agent and in Construction Requires a Socio-Ecological Approach

Varenyam Achal

Abstract The migration of increasing population towards urban area demands high number of infrastructures that brings additional load on the environment due to cement usage. It is noteworthy that cement is not a sustainable material and causes 5–7% of global CO_2 emission. In addition, many infrastructures suffer from strength and durability problems because of natural or anthropogenic activities during their service life. Nature, on other hand, guides the society and scientific community for sustainable construction through ecologically defined prototypes, such as ant hills, coral reefs or mineralized structures of biological organisms that ultimately inspires for biologically produced (bio) cement. Biocement is the product of biomineralization that can be used as particle replacement to conventional cement or an additive in construction to reduce the dichotomy due to CO_2 emission or non-sustainable nature associated with cement. It is important to bring science or scientific research of biocement to the practice by considering factors preventing its implementation for human or environmental welfare, otherwise this science will remain stick to textbooks or journals. At the same time science and technology provided only limited success in biocement practice, thus holistic approach considering social and ecological aspects is highly required. Thus, socio-ecological model is presented in this article for highlighting as well as overcoming barriers and challenges in biocement related research preventing the use of same in practice and fulfilling theory to practice gap.

Keywords Nature · Biocement · Environment · Infrastructure · Sustainable construction

V. Achal (✉)
Department of Environmental Engineering, Guangdong Technion—Israel Institute of Technology, Shantou 515063, China
e-mail: varenyam.achal@gtiit.edu.cn; varenyam@technion.ac.il

Technion—Israel Institute of Technology, 3200 Haifa, Israel

V. Achal and C. S. Chin (eds.), *Building Materials for Sustainable and Ecological Environment*, https://doi.org/10.1007/978-981-16-1706-5_1

1 Background

Concrete is the most used man-made material on the earth despite of its adverse impact on the environment coming from its precursor, ordinary Portland cement (OPC). In addition, cementitious materials are prone to many natural and anthropogenic activities resulting in reduced compressive strength and durability of such structures, and crack formation. Thus, altogether there are three issues associated with cement/concrete, (i) crack formation as building structures are liable to it with duration of time, (ii) reduced strength and durability due to natural causes such as earthquake or anthropogenic activity, and (iii) carbon dioxide (CO_2) emission, as 5–7% of the global CO_2 emission is due to production of cement that is more than 3 billion tonnes per year recently and more than 4.5 billion tonnes in 2016 (https://cembureau.eu/cement-101/key-facts-figures/). Thus, construction involving only OPC cannot be sustainable from environmental aspect.

Considering such problems associated with cementitious materials, Mother nature provides environment-friendly solutions through microbially induced calcium carbonate precipitation (MICCP), a type of biomineralization. Calcium carbonates are the most widely distributed biomineral in nature, can be found exclusively in mollusk shells, corals reefs, exoskeletons of many marine organisms and others. Because of its cementing nature, calcium carbonate present in biological organisms serve as biocement that brings strength, self-healing properties and stability into those organisms. The biocementation property can be mimicked in the environment with the help of microbes, which can be used together with cementitious materials in order to mitigate problems associated with cement.

2 What is Biocement?

There are many microbes (including both bacteria and fungi), which can mediate the formation of calcium carbonate; a type of cementing material, in microbially induced carbonate precipitation (MICP) process. Thus produced cement of biological origin is referred as 'biocement'. This process is well-established from hypothesis (from examples of nature) to theory (Achal et al. 2016). In brief, microbes of ureolytic nature hydrolyze urea (as substrate in reaction or process) to produce bicarbonate ions by producing an enzyme urease, and in the presence of free calcium ions, the calcium carbonate gets precipitate (Castanier et al. 2000). The precipitation of calcium carbonate or biocement ultimately improves both compressive strength and the durability by reducing permeability of water and aggressive ions to cementitious materials and structures. In case of crack formation in cementitious materials, biocement utilizes calcium found in the proximal environment and combines with carbon from carbon dioxide in the air.

3 What Are Potential Benefits of Biocement?

Construction industry is integral part of human civilization in recent era owing to increased population and demand for infrastructures. As this industry is highly dependent up on cement that is not a sustainable material, pursuit of the sustainable construction is of utmost importance. Sustainable construction is a holistic process aiming to sustain harmony between the nature and constructed environment by creating settlements. Efforts are high on biomimetic approach from nature by taking examples from various biological organisms, which are principally at same level as building materials with potential to be used for sustainable construction.

Biocement is one of novel material that can partially replace cement during construction and at the same time enhances durability and strength of structures. It ultimately lowers environmental load by cutting amount of cement usage and lead to sustainable construction. Thus, biocement strives to achieve the dual ambition of producing new knowledge and improving socio-ecological practice with sustainability approach. In brief, major potential benefits of biocement include:

- Biocement can partially replace conventional cement without compromising engineering properties of resulting building structures.
- It has potential to lower CO_2 emission by reducing cement usage in construction.
- The addition of biocement in construction improves mechanical and impermeable properties of resulting building structures.
- Biocement is prominent in inhibiting corrosion in reinforced structures.
- It has also shown its potential in enhancing mechanical and impermeable properties of building structures in the presence of secondary cementitious materials.
- Biocement has healing as well as self-healing property leading to filling the cracks automatically in building structures.
- It is environment friendly material compared to materials of chemical origin for crack healing purposes.
- Biocement is also beneficial in ground improvement by enhancing engineering properties of soil with potential to decrease soil liquefaction.

Recently, the potential of biocement took it to beyond practice for its application by research group of Henk Jonkers from Delft University of Technology. In his words:

> We (Prof. Jonkers and his research group) are indeed applying and commercializing biocement in the form of bacterial-based self-healing concrete and repair mortar in the Netherlands. Commercialization is done by the Delft University of Technology spinoff Basilisk (Basiliskconcrete.com). Typical applications of self-healing concrete are in form of wastewater treatment tanks and water reservoirs which need to be watertight and repair mortar for waterproofing of leaky basement walls and for structural repair of damaged concrete constructions. Main application field is currently waterproofing of constructions while ongoing research investigates if durability of constructions such as delay of reinforcement corrosion and decrease of sensitivity to frost damage can also be achieved.

On other side, Nele de Belie from Ghent University, Belgium who doesn't require introduction in the area of biocement has already completed a demo project and bringing biocement close to the market. The self-healing agent, MUC+ consisted of a mixture of MUC (mixed ureolytic culture derived from microbial biomass) and anaerobic granular bacteria was applied to make roof plate on the construction site and installed on the pit after fabrication around Kennedy tunnel and the Liefkenshoek tunnel in Antwerp, Belgium. Visual inspection showed crack-free surface of roof after 6 months of casting (De Belie et al. 2018). They are upscaling the self-healing agents by partners of the EC project HEALCON. Such projects show how the use of biocement can improve the socio-ecological practice of sustainable construction. However, at the same time challenges in making biocement successful in construction industry cannot be ignored. The communication presented in this article also highlights those challenges to ravel exact situation of practice related to biocement.

4 Limited Usage of Biocement in Construction Practice and Associated Barriers

The research on biocement is going on for more than last 15 years. Despite of benefits associated with biocement, there is still limited use of this material. Considering importance of biocement in cement and concrete industry, most research so far has established it at laboratory scale; however, actual situation on practice of biocement at various levels is unknown to many. Despite some of reports on the use of biocement at large scale, it is too early to speculate success of biocement.

There are many barriers and challenges that impede biocement use in practice for sustainable construction with cementitious materials. In brief:

- Theory-practice gap for biocementation—The process of bocementation inspired from various biomimetics approach is easy to understand and convertible from hypothesis to theory; however, there is gap in bringing this theoretical concept to practice for sustainable construction due to microbial inefficiency, economic consideration, and unacceptability of bio-based materials by civil or construction engineers among others. Moreover, microbes require optimal environment to grow to carryout metabolic activities. As biocement precipitation is enzyme-based process, microbes lack optimum conditions (mainly pH, temperature, nutrients, and substrate concentration) in cementitious environment to produce sufficient amount of enzyme that ultimately affects biocement production.
- Environmental condition for biocementation—Cementitious materials provide inhospitable environment and harsh conditions for microbes to produce biocement whether due to high alkalinity of cement or limited oxygen supply; thus, not necessarily accelerate biological activity (Lee and Park 2018).
- Economic feasibility—The success of any product depends very much on its production cost. The biocementation process requires nutrients to grow microbes and provide substrates in order to produce biocement, and it could be as high as

60% of the total operating costs. Commercially available nutrients in the process are often expensive, while some research involved industrial by-products for the purpose of making the process economic; these are still confined to laboratory or small scale only as reported in Achal et al. (2009). This is one of prime challenge preventing biocement practice research at large-scale or field studies.
- Markets−The success of biocement research depends on the collaboration between microbiologists and civil engineers. However, microbes are often misunderstood as pathogenic from civil or construction engineers that halts success of such research and in uncertainty there is always risk bringing biocement into markets. As biocement production is expensive due to commercial nutrients usage, there could be price factor also compared to other available solutions in market. Public opinion on the disapproval of bio-based materials in building structure could also be of concern in preventing biocement in markets.

5 Socio-Ecological Model in Biocement Research

Technological and economical aspects are not necessarily main reasons behind problems associated biocement practice; however, broader approach is required to make success in biocement research. There are previous efforts to overcome above said barriers but not enough to make biocement usage in practice. With limited success, more holistic approach is required in fruitful research. Only science and technology are not enough and there is need to consider social and ecological aspects in biocement research, therefore I propose socio-ecological model (SEM) in this article. The SEM can play a major role identifying and overcoming those barriers in biocement related research (Fig. 1). The SEM assesses individual, interpersonal, community, and policy (McLeroy et al. 1988); however, it has never been used before in biocement related research. Individual in this model represents biocement related research or researcher; it is also confined to available knowledge starting from inspiration from nature to mimicking it at laboratory scale. To improve biocement practice from individual level, researchers should focus on 'knowledge gap' through existing literatures that can correlate factors leading to barrier related to theory and practice gap.

Interpersonal level represents co-operation and collaboration between different researchers working in biocement-related fields. Such collaborative teams will be able to rectify barriers by clear and direct communication through deep insights into each other's works. Community level in SEM of biocement research denotes markets. As there is involvement of community from civil engineering and microbiology fields in biocement, to ensure success in commercial markets, it would be very important to understand product at scientific level from both communities. Also, there could be negative perception from buyers (public) on how tiny invisible microbes can improve strength or durability of building structures, why it should be used or what if those microbes spread disease? Policy in SEM for biocement research depicts funding agency in addition to societal view. Funding agency could be at international, collaborative international, national or provincial level. It can play a big role in taking

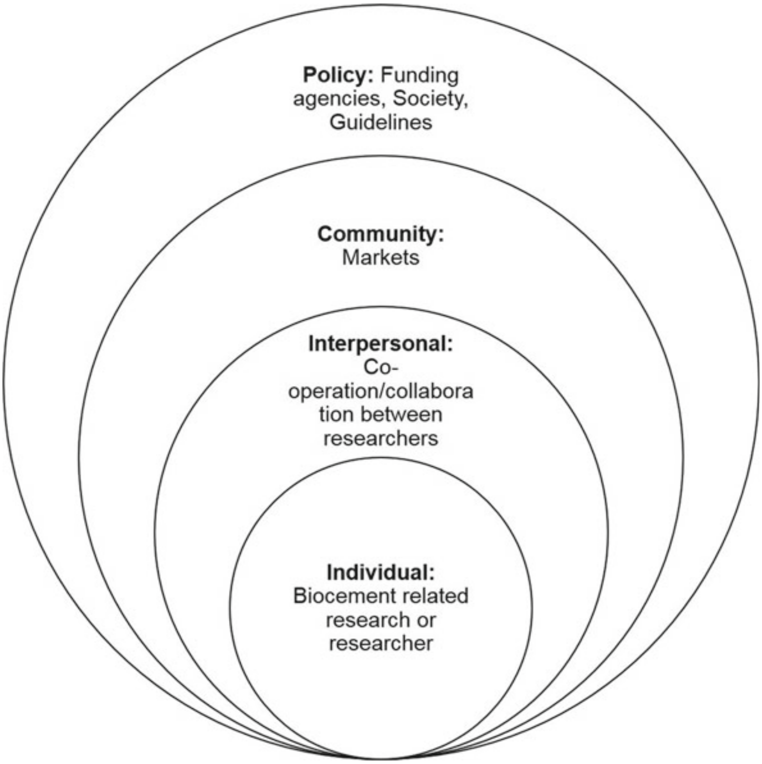

Fig. 1 Representation of Socio-Ecological Model in biocement research to identify and overcome barriers and challenges for theory to practice gap

practice research by prioritizing biocement related research for its commercial use. Beside international, national or provincial level funding, construction or cement production industries can play major role by providing biocement research funding to researchers working on it. There is no guideline available on biocement that is required to show its importance for the advancement of research pertaining to fill theory-practice gap and to value it by society.

6 Conclusions and Future Prospective

Undoubtedly biocement has enormous potential for sustainable construction and it can fulfill the demand of millions of new infrastructures for growing population or urbanization. It is time for researchers to focus their work on advancement of biocement for its implementation and to fill the gap between current and future knowledge rather than performing routine experiments especially 'for practice' based on SEM presented in this article. It is important to understand SEM so that factors preventing implementation of biocement for actual practice won't be ignored. Furthermore, it is believed that scholars and practitioners from interdisciplinary research area involving microbiologists and engineers (of related branches in sustainable construction) can solve abovementioned barriers/challenges to the biocement use by finding economic nutrient substitute to commercially available nutrients, improving bacterial survivality in inhospitable concrete environment, public awareness about safety with bio-based materials in infrastructure, and large-scale or in situ applications in construction industry. Biocement arising from ecological research will provide great impact on social life with its effectiveness in terms of protecting the environment. The process of biocementation is indeed emerging technique for sustainable construction and it is important to know exact progress or real situation to bring related research *for practice* and even *beyond practice.*

The presented SEM model in this article is suitable for biocement practice as it provides great prospect keeping social and ecological aspects in research. At the same time, there is need to address following research questions:

– How to establish socio-ecological model practically in overcoming barriers in biocement practice research?
– What is the relationship between social and ecological issues in biocement production and usage?
– What are the ecological and economic costs and related benefits of biocement?
– What are characteristics of professional research co-operation in defining social and ecological aspects in overcoming barriers preventing biocement practice?
– What role can research co-operation or funding agency or society play in better facilitating the biocement practice by overcoming barriers?

Acknowledgement Author thanks Prof. Henk Jonkers and Prof. Nele de Belie for their inputs on the practical application of biocement.

References

Achal, V., Mukherjee, A., Basu, P. C., & Reddy, M. S. (2009). Lactose mother liquor as an alternative nutrient source for microbial concrete production by *Sporosarcina pasteurii*. *Journal of Industrial Microbiology and Biotechnology, 36,* 33–438.

Achal, V., Mukherjee, A., & Zhang, Q. (2016). Unearthing ecological wisdom from natural habitats and its ramifications on development of biocement and sustainable cities. *Landscape and Urban Planning, 155,* 61–68.

Castanier, S., le Metayer-Levrel, G., & Perthuisot, J. P. (2000). Bacterial roles in the precipitation of carbonate minerals. In R. E. Riding & S. M. Awramik (Eds.), *Microbial Sediments* (pp. 32–39). Heidelberg: Springer-Verlag.

De Belie, N., Van Mullem, T., Gruyaert, E., & Van den Heede, P. (2018). Self-healing concrete applied in a roof plate for an inspection pit in the oosterweel link: Healing efficiency and preliminary service life estimation, in *4th International Conference on Service Life Design for Infrastructures (SLD4)* (Delft, Netherlands), pp. 27–30.

Lee, Y. S., & Park, W. (2018). Current challenges and future directions for bacterial self-healing concrete. *Applied Microbiology and Biotechnology, 102,* 3059–3070.

McLeroy, K. R., Steckler, A., & Bibeau, D. (1988). The social ecology of health promotion interventions. *Health Education Quarterly, 15,* 351–377.