# Chapter 14
# Production of Bacteria for Structural Concrete

**Varenyam Achal**

**Abstract** This chapter reviews a novel, green and economical concrete based on microbially induced calcium carbonate precipitation (MICP). Microbial or bacterial concrete is product of MICP, produced by ureolytic bacteria, requires much less energy to produce. Such bacteria are abundant in nature in almost every environment and can be reproduced at fast rate at low cost. Calcium carbonate precipitated during the process of MICP might help building materials and structures by improving compressive strength and impermeability, and ultimately their durability. Harnessing this novel process of biogeochemistry may bring in enormous economical benefits to construction industries and will open a new door to the research in the arena of geotechnical and structural engineering. This chapter critically reviews the production and mechanism of MICP. Further, a thorough understanding of the research in the area of microbial-based cementitious materials, which lead to improving the durability of building materials and structures, has been discussed.

## 14.1 Introduction

Everything comes with a price, an old saying; however, true even when we talk about our modern civilization. Thanks (in one way) to cement, which builds modern civilization, however at the cost of massive pollution to the health and environment. On the other hand, the cement production is energy consuming and environmentally unfriendly process as contributes about 7 % of global anthropogenic $CO_2$ emissions (Worrell et al. 2001). It is true that we cannot replace cement completely with other building material; however, there is high scope to reduce

V. Achal (✉)
Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration,
East China Normal University, Shanghai, China
e-mail: varenyam@re.ecnu.edu.cn

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this substance in construction to lower the environmental hazard caused by cement. Again question rises, what about the quality of such structure? We need to find a novel way to do this without compromising the quality of building structures. Finding such a sustainable material means, we could reduce the environmental impact of cement.

Concrete is the most widely used building material and most of the building structures are made up of it. However, natural processes including earthquake or weathering or land subsidence and human activities play enough roles to degrade or reduce the durability of concrete structures. Durability of concrete is the ability of a concrete to resist deterioration, particularly deterioration due to weather exposure, chemical exposure or surface abrasion (Reddy et al. 2012).

Though ignored for centuries with respect to their role in construction industry, bacteria have enormous potential in carbonate formation leading to increment in compressive strength, a key parameter while designing buildings structures. Moreover, bacteria are omnipresent, especially in soil, regardless of normal to harsh environmental conditions. It can be used perfectly in construction as live building materials, rather than inert one, as it can precipitate carbonate when required, even once construction is over. Together with building components, nutrient solutions; bacteria in cementitious materials will form "concrete ecosystem." Concrete ecosystem (perhaps a term coined first time here) looks simpler as will contain only microbes as living component in conjunction with cement, sand, aggregates and some other building materials; however, the ecosystem process under it is highly complex due to harsh environment. It provides favorable condition for Microbially induced Calcium Carbonate Precipitation (MICP).

The importance of MICP has been reported in several applications including remediation of heavy metals (Achal et al. 2011a, 2012a), soil strengthening/improvement (Whiffin et al. 2007), restoration of calcareous stone materials (Tiano 1995; Castanier et al. 1999; Stocks-Fisher et al. 1999; Rodriguez-Navarro et al. 2003), wastewater treatment (Hammes et al. 2003), sand consolidation (Achal et al. 2009a), strengthening of concrete (Ramchandran et al. 2001), and durability of building materials (Achal et al. 2010a). The present chapter outlines, based on the reports from researchers worldwide, the mechanism driving MICP, concrete construction using bacteria (thus known as *microbial concrete*, a term coined by Achal et al. (2011b)) and how microbial concrete is effective to enhance the durability of building structures.

## 14.2 Microbially Induced Carbonate Precipitation

Microbially induced calcite precipitation is resultant of complex biochemical reaction often governed by an enzyme urease (urea amidohydrolase; EC 3.5.1.5) produced by microbes. This reaction/precipitation requires urea as substrate while calcium source as chief agent for calcite production. During microbial urease activity, 1 mol of urea is hydrolyzed intracellularly to 1 mol of ammonia and

1 mol of carbamate (Eq. 14.1), which spontaneously hydrolyses to form an additional 1 mol of ammonia and carbonic acid (Eq. 14.2) (Burne and Chen 2000). These products subsequently equilibrate in water to form bicarbonate and 2 mol of ammonium and hydroxide ions (Eqs. 14.3 and 14.4) that give rise to an increase in pH and ultimately shift the bicarbonate equilibrium, resulting in the formation of carbonate ions (Eq. 14.5). High pH condition favors the formation of $CO_3^{2-}$ from $HCO_3^-$ (Knoll 2003). Finally, the carbonate concentration will increase, inducing an increase in supersaturation level leading to $CaCO_3$ precipitation around the cell in the presence of soluble calcium ions (Eqs. 14.6 and 14.7).

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3 \tag{14.1}$$

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3 \tag{14.2}$$

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \tag{14.3}$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^- \tag{14.4}$$

$$HCO_3^- + H^+ + 2NH_4^+ + 2OH^- \leftrightarrow CO_3^{2-} + 2NH_4^+ + 2H_2O \tag{14.5}$$

$$Ca^{2+} + Cell \rightarrow Cell - Ca^{2+} \tag{14.6}$$

$$Cell - Ca^{2+} + CO_3^{2-} \rightarrow Cell - CaCO_3^- \tag{14.7}$$

Based on the above equations, it may be said that calcium carbonate precipitation is a biochemical process governed mainly by five key factors: (1) the urease, (2) the calcium concentration, (3) the concentration of dissolved inorganic carbon (DIC), (4) the pH, and (5) the availability of nucleation sites. The availability of nucleation site is very important for continuous and stable calcium carbonate formation. It is isolated from the environment by a delimiting geometry by limiting the diffusion in and out of the system (Sarayu et al. 2014). The ion movement is enabled by active pumping with organelles or passive diffusion to enable the microorganisms to use a great variety of anatomical arrangements (Perry 2003), as shown in Fig. 14.1. The production of $CO_3^{2-}$ from bicarbonate ($HCO_3^-$) in water is strongly pH dependent, an increase in $CO_3^{2-}$ concentration occurs under alkaline conditions that lead to deprotonation of the functional groups like carboxyl, hydroxyl, and phosphate of the bacterial cell wall and creates a strong electrostatic affinity to attract cations and enables the accumulation of calcium ions on the surface of the cell wall. On the other hand, the calcium ions in the solution are attracted to the bacterial cell wall due to the negative charge of the later. Upon addition of urea to the bacteria, dissolved inorganic carbon and ammonium are released in the microenvironment of the bacteria. In the presence of calcium ions, this can result in a local supersaturation and hence heterogeneous precipitation of calcium carbonate occurs on the bacterial cell wall (Reddy et al. 2012).

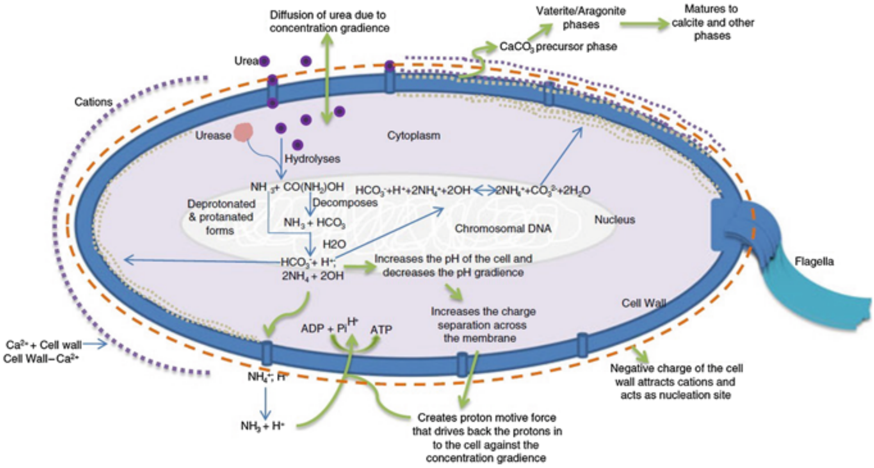


**Fig. 14.1** Pathway of biomineral secretion and precipitation in a bacterial cell (Reprinted with permission from Sarayu et al. 2014)

The concrete ecosystem, rich in calcium source, provides favorable condition for MICP as calcium carbonate precipitation readily occurs in alkaline environments abundant of the calcium ($Ca^{+2)}$ and carbonate ($CO_3^{2-}$) ions (Stocks-Fischer et al. 1999; Ramachandran et al. 2001; Qian et al. 2010a).

## 14.3 Why MICP and Microbial Concrete?

Natural processes, such as weathering, faults, land subsidence, earthquakes, and human activities create fractures and fissures in concrete structures or monuments. These fractures and fissures are detrimental since they can reduce the service life of the structure (Achal et al. 2011b). Such processes often weaken strength, induce porosity and also give an unattractive appearance, and cracks lead to easy passage for aggressive environment to reach the reinforcement and initiate corrosion. There are synthetic agents (epoxy, hydroxyl-epoxy) or latex binding agents (such as acrylic, polyvinyl acetate, butadiene styrene) or silanes or organic–inorganic products available in the market to protect or repair damaged concrete structures; however, suffer from being expensive, and problems associated with different thermal expansion, degradation with age and the need for constant maintenance. Appearance of cracks and fissures is an inevitable phenomenon during the aging process of concrete structures when exposed to weather changes. Such cracking leads to easy passage for aggressive environment to reach the reinforcement and initiate corrosion. Moreover, sometimes repair is carried out in the areas where it is not possible to shut down the plant or it is hazardous for human beings. Hence, in such situations, a way should be found out to self healing materials that seal the cracks automatically. Recently, a novel technique has been reported that utilizes microorganisms in remediation of cracks and fissures in natural and man-made structures by precipitation of calcium carbonate.

On the other hand, the cement industry has for some time been seeking procedures that would effectively reduce the high energy requirements and environmental costs of cement manufacture (Rong and Qian 2012). The answer very much depends up on "microbial concrete" that is based on MICP process consists of three materials, namely, alkalophilic microbes, substrate solution and calcium ion solution. The great promise of MICP-based microbial concrete has been demonstrated to enhance the durability of building materials, consolidation of sand columns, and repair of limestone monuments and concrete (Gollapudi et al. 1995; Tiano et al. 1999a; Ramachandran et al. 2001; De Muynck et al. 2008; Qian et al. 2009; Achal et al. 2011b; Rong et al. 2012). Microbial concrete can improve the strength and durability of structures, which are considered to be the requirements for concrete or any other building materials. A major goal of using microbial concrete is to ensure the quality parameters or durability of building structures.

## 14.4 Quality Parameters for Concrete Structures

The quality of any building material depends on three major parameters, (i) strength, (ii) permeability, and (iii) corrosion. For an efficient microbial concrete it should produce more compressive strength, less permeability and should not affect corrosion of any reinforcement (Reddy et al. 2012). When MICP came in practice, the first building material to test was sand where the process of MICP was well established. Sand is the common material used to make most of the building materials and structures, thus research to confine a novel methodology with sand is warranted.

### *14.4.1 Biosandstone*

The process of MICP was proposed as a novel method for cementing loose sands to produce structural materials, termed as biosandstone (Fig. 14.2). It consists only of alkalophilic urease producing bacteria, substrate solution (urea), calcium source and sand. A typical set-up for the sand consolidation experiment to develop biosandstone was simplified in Reddy et al. (2012), where sand (either mixed with bacterial culture or later injected directly in the column) was plugged through a plastic column and the cementation fluid (consists of nutrient media with urea and calcium source) was injected or dropped at specific rate in the column in gravity free flow direction.

The cementation fluid also contains nutrients that are necessary for the bacterial growth and metabolism to perform MICP and can be transported through


**Fig. 14.2** Biosandstone (Reprinted with permission from Achal et al. 2011a)

sandstone cores (Jenneman et al. 1984). The bacterial sand consolidation was resulted into porosity reduction from sand, as reported by Kantzas et al. (1992) when they found up to 50 and 90 % reduction in porosity and permeability, respectively in sand consolidated by *Bacillus pasteurii*. Such reduction might be due to high deposition of calcite in column, as Achal et al. (2009a) found 40 % calcite deposition in the sand column consolidated by a mutant of Sporosarcina pasteurii. The sand column of size 32.10 and 18.40 mm showed good amount of compressive strength, measured up to 2 MPa (Mega Pascal) when $CaCl_2$ was used as calcium source for biosandstone (Qian et al. 2010b). The microbial induced precipitated substance in bio-sandstone was checked using X-ray diffraction (XRD) and energy dispersion spectroscopy (EDS), and calcite as main microbial induced substance was seen in biosandstone (Fig. 14.3).

The positive results of MICP on biosandstone lead researchers to think beyond this building material i.e., sand. Researchers started focus on more complex building material such as cement and concrete, and studied effect of MICP on the improvement of strength, permeability and other durability parameters.

### *14.4.2 Microbial Concrete and Compressive Strength*

Compressive strength is the first and foremost prerequisite to judge building materials or structures, expressed as the ultimate compression load per cross sectional area, usually in psi, Pa or $Kg/cm^2$. It is required to determine whether the concrete mixture used in construction meets the requirements of the specified strength in the job specification or not. There are several researches on mortars, where microbial concrete was used to enhance its compressive strength. Mortar or cement mortar refers to a workable paste to use during construction, consisting of cement, sand and water, while the term concrete consists of similar constituents in addition to aggregates.

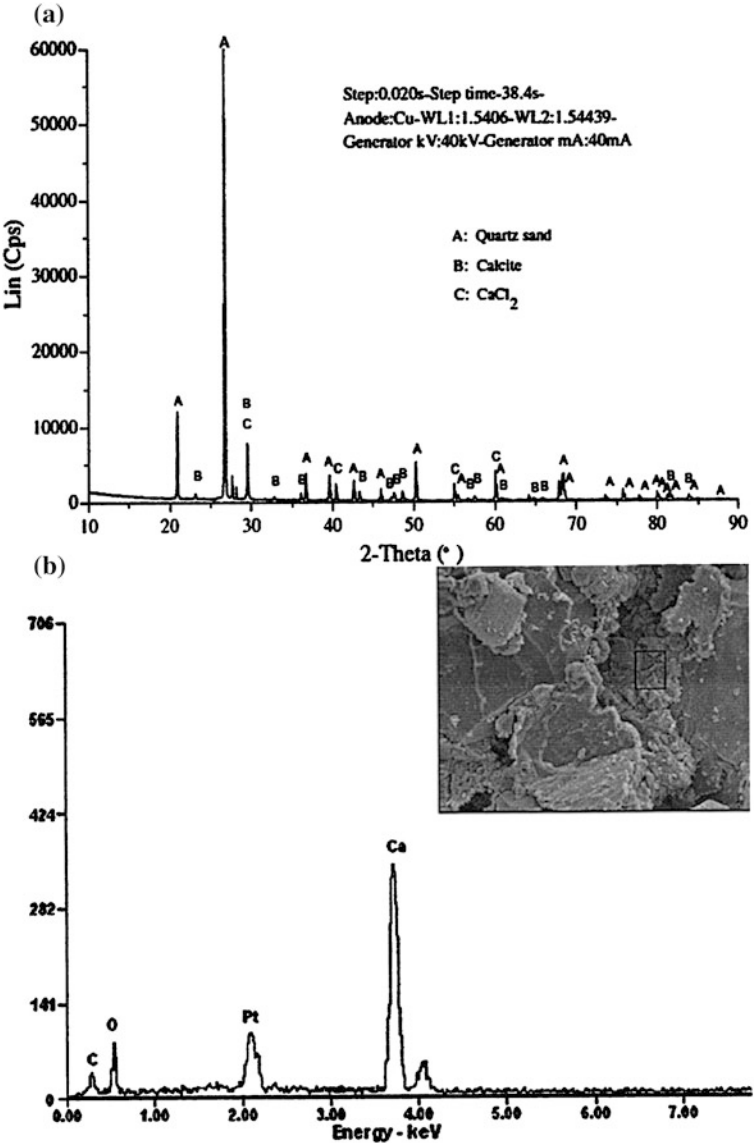


**Fig. 14.3** **a** X-ray diffraction, and **b** Energy dispersion spectroscopy of mineral phases microbial induced precipitated biosandstones (Reprinted with permission from Rong et al. 2012)

Perhaps, the improvement of the compressive strength of Portland cement mortar cubes based on MICP was initiated by Ramachandran et al. (2001). They experimented on two different bacteria, namely, *Bacillus pasteurii* (later renamed as *Sporosarcina pasteurii*) and *Pseudomonas aeruginosa* and mixed bacterial cells in form of pellets to mortars. The mortars were cured in solution containing urea and calcium chloride for 7 days. When tested for compressive strength, it was recorded about 65 MPa in the presence of *S. pasteurii*, which was relatively higher than control mortars (55 MPa). As *P. aeruginosa* is not reported to induce calcite precipitation, it couldn't improve the compressive strength of mortars.

Other than bacteria of genus *Bacillus*, *Shewanella* sp. was used to enhance the compressive strength of mortars by 17 and 25 % at 7 and 28 days, respectively; however, they cured mortar specimens in air (Ghosh et al. 2005). Just like *P. aeruginosa*, there was no increment in the compressive strength with *Escherichia coli* (non-urease producing bacterium). Later, while mixing spores of *Bacillus pseudofi rmus* and *Bacillus cohnii,* an increment of 10 % mortar compressive strength was recorded (Jonkers and Schlangen 2007).

One of problems associated, while studying compressive strength, with microbial concrete is cost factor used in growing bacterial cells or curing in nutrient media. To overcome this, Achal et al. (2009b) replaced the commercially available nutrients with some industrial by products such as lactose mother liquor (LML) and corn steep liquor (CSL). An improvement of 17 % in the compressive strength of mortar cubes was noticed with *S. pasteurii* grown and cured with LML medium compared to control (23.2 MPa) at the end of 28 days. Later, Achal et al. (2010a) reported 35 % improvement in the compressive strength of mortar at 28 days with *S. pasteurii* prepared mortar cubes with CSL-urea medium. The similar experiment resulted into 36 % improvement in the compressive strength, when CSL was replaced with commercial nutrient medium (Achal et al. 2011b). The effect of different media on the compressive strength of cement mortar using *S. pasteurii* has been summarized in Fig. 14.4. Their experiments were of great potential with respect to economization of microbial concrete preparation.

The overall trend of an increase in the compressive strength was very much dependent on calcium carbonate precipitation induced by bacterial cells and the behavior of bacterial cells within the cement mortar matrix. As cement mortar remains still porous during the initial curing period, though bacterial cells get good nourishment; but growth might not be proper due to the completely new environment for bacteria, especially high cement pH (Achal et al. 2011b). As the curing period proceed, bacterial cells started growing and start precipitating calcium carbonate within mortar matrix. The bacterial growth and curing period led to plugging of pores in the matrix and the flow of the nutrients and oxygen to the bacterial cells stops that causes the cells either died or turned into endospores and acts as an organic fiber that may enhance the compressive strength of the mortar cubes (Ramachandran et al. 2001).

Further, to confirm MICP process in the improvement of compressive strength, researchers analyzed mortar specimens with techniques such as X-ray diffraction (XRD) and visualized with scanning electron microscope (SEM).

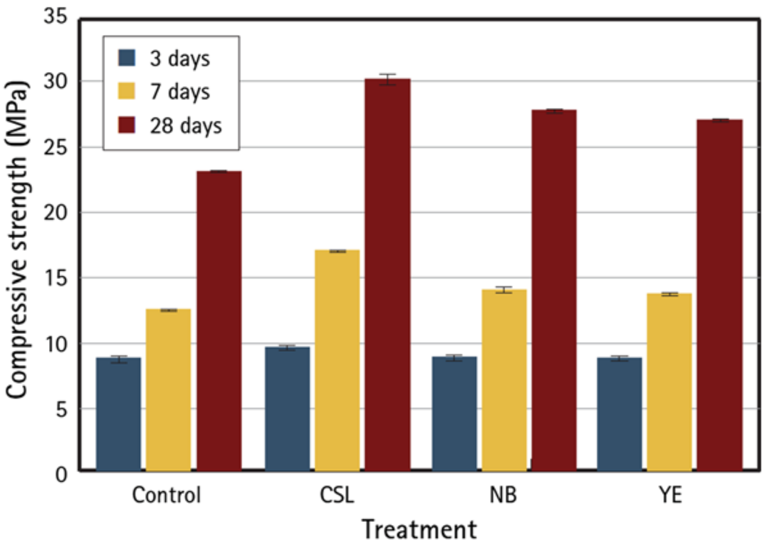


**Fig. 14.4** Effect of *S. pasteurii* on the compressive strength of cement mortar cubes grown in different media at 3, 7 and 28 days (Reprinted with permission from Achal et al. 2010a)

### *14.4.3 Microbial Concrete and Permeability*

Permeability is an important factor on which concrete durability depends, known to be property that governs the rate of flow of fluid into porous mortar or concrete. Such property controls the ingress of moisture, gas or harmful substances to the concrete structures. Any adverse condition affecting building materials or structures targets permeation properties easily. Some of commercially available substances, which can be used to make such surface impermeable, are not successfully used due to disadvantages such as, an incompatibility of the protective layer and the underlying layer due to differences in their thermal expansion coefficient or disintegration of the protective layer over time and a need for constant maintenance (Reddy et al. 2012).

The ability of MICP to improve impermeability on building material surface was first observed by Tiano et al. (1992) when they successfully used organic matrix macromolecules extracted from *Mytilus californianus* shells to induce the precipitation of calcium carbonate within the pores of the stone. The calcite precipitation resulted in a slight decrease in porosity and water absorption by capillarity (Tiano 1995), which was reduced about 60 % from the limestone (Tiano et al. 1999b). Further, Le Metayer-Levrel et al. (1999) confirmed bacterial carbonatogenesis/biocalcification on the stone surface resulted into permeability reduction without affecting its aesthetic appearance, with conclusion that biological mortars or cement could be used to affix small pieces broken from statues and to fill small cavities on limestone surfaces. Later Dick et al. (2006) reported calcite induced by *Bacillus* sp. was effective in reducing the water absorption rate of limestone. Such researches provided way to choose other building materials. An increase in the resistance of concrete toward alkali, sulfate, freeze thaw attack and drying shrinkage was observed with calcite precipitating bacteria (Ramakrishnan et al. 1998). While studying the durable effect of *Bacillus sphaericus* on mortars, De Muynck et al. (2008) found a significant decrease of the water uptake compared to untreated specimens (a reduction of 45, 43, and 24 % with increasing w/c) and 19 % decrease of the chloride migration coefficient. Later, they (De Muynck et al. 2008) concluded that the carbonate precipitation was mainly a surface phenomenon due to the limited penetration of the bacteria in the porous matrix, resulted in a decrease of water absorption and gas permeability from mortars.

*Bacillus* sp. CT-5, isolated from commercially available cement, was used to prepare mortars and a sorptivity test was performed on it (Achal et al. 2011b). Over a period of 168 h, the mortars with bacterial cells absorbed nearly six times less water than the control cubes. The presence of bacteria resulted in a significant decrease of the water uptake compared to untreated mortars. The deposition of a layer of calcium carbonate crystals on the surface resulted in a decrease of the sorptivity.

Achal et al. (2011c) performed the water impermeability test on the concrete cubes of dimension 150 mm (M20 grade), prepared with mutant *S. pasteurii* grown in commercially available nutrient broth (NB) and economic corn steep liquor (CSL) media with urea as substrate and calcium chloride as calcium source. The results indicated that the permeability of the concrete cubes prepared with bacterial cells was lower than that of the control irrespective of media used. The penetration at the sides of concrete was higher than that at the top due to better compaction and closing of pores at the top by calcite precipitated by bacterial cells. Further they reported that the resistance of concrete to chloride penetration increased with MICP. The permeability class type was recorded ''moderate'' for control concrete specimens, while the class changed to ''low'' type of concrete with bacterial cells as per ASTM C1202-05. For control samples, the average charge passed was 3,177 C, whereas for samples prepared with bacterial cells in NB and CSL media it was 1,019 and 1,185 C, respectively.

### *14.4.4 Microbial Concrete and Corrosion*

The corrosion of steel and reinforcing bar is a predominant factor causing widespread premature deterioration of concrete constructions worldwide (Raupach and Schiebl 2001). Corrosion and permeability goes together, higher the permeability, more would be corrosion and vice versa. The ingress of moisture, chloride ions, and carbon dioxide initiates corrosion through the concrete to the steel surface. Chloride-induced corrosion of reinforcing steel is one of the most pressing problems worldwide that the construction industry is facing today. The corrosion products of iron oxides/hydroxides expose the reinforcement to direct environmental attack that results in accelerated deterioration of the structure (Neville 1995). The solution to prevent corrosion of such structure can be achieved by sealing the paths of ingress to improve the life of the reinforced concrete (RC) structures.

As MICP promises to alleviate permeability and transport of pollutants inside concrete, it can be effective in reducing corrosion in RC by making protective layer or carbonate followed by calcite precipitation. However, there is scarce research on the role of MICP in corrosion prevention of RC structure. Such research was mainly reported by Achal et al. (2012b) where they performed detailed investigation leading to positive impact of MICP in the RC corrosion prevention.

To determine the effect of MICP, Achal et al. (2012b) prepared the RC specimens with bacterial cells (*Bacillus* sp. CT-5) and induced corrosion by applying a constant anodic potential of 40 V for 7 days. There was visible calcite precipitation on bacterially treated RC specimens. After 7 days of accelerated corrosion, numerous (at least seven) cracks with widths nearly 0.2 mm (0.008 in.) were observed on control specimens with one longitudinal localized crack of width 0.3 mm within 36 h, whereas in bacterially treated samples, a crack of that width appeared not before 168 h. The control specimens had significantly higher *Icorr* (60.83 mA/m$^2$ [39.25 mA/in.$^2$]) compared to MICP samples (14.78 mA/m$^2$ [9.53 mA/in.$^2$]) in nutrient and 20.03 mA/m$^2$ (12.92 mA/in.$^2$) in CSL media. An approximate four-fold reduction in *Icorr* by *Bacillus* sp. CT-5 suggests that the calcite precipitation has the effect of greatly reducing corrosion. Achal et al. (2012b) concluded that the formation of calcite might facilitate the protective passive film around the steel and act as a corrosion inhibitor by interrupting the transport process in such samples. Further, they also found that pullout strength was enhanced and mass loss of the reinforcing bar was reduced due to MICP.

Based on calcium carbonate induced by *B. pasteurii*, Qian et al. (2010a) showed improvement in the surface impermeability of cement mortars, resulted in resistance to the acid (pH > 1.5). They concluded MICP ability in the prevention of corrosion of building materials and structures. The results of various researchers on microbial concrete with their target materials have been summarized in Table 14.1.

## 14.5 Cost Analysis of Microbial Concrete?

As microbial concrete is novel product, which can be used to enhance the durability of building structures, many researchers or engineers doubt on its production cost. The costs of microbial concrete depend very much on the price of bacteria and nutrients. Further, the price of bacteria varies country to country; however, one standard bacterial strain, if bought from ATCC, costs US $500, and from MTCC, costs US $10, while CGMCC sells at US $200. De Muynck et al. (2010) reported the cost analysis of microbial concrete based on personal communication by an employee of the Belgian company FTB remmers 2008; http://www.ftbremmers.com/). The price of 1 kg lyophilized bacteria is about US $1,500 (1,100 €) and

**Table 14.1** Overview of BioCement applications with respect to target, microorganism used and origin of country

| Target | Microorganism | Origin | References |
|---|---|---|---|
| Limestone protection | Biocalcin producing bacteria | France | Adolphe et al. (1990), Le Metayer-Levrel et al. (1999) |
| Monumental stone protection | *Mytilus californianus* | Italy | Tiano et al. (1992), Tiano (1995) |
| Monumental stone porosity | *Micrococcus* sp. | Italy | Tiano et al. (1999a) |
| | *Bacillus subtilis* | | |
| Biochemical properties of MICP | *B. pasteurii* | USA | Stocks-Fischer et al. (1999) |
| Concrete crack remediation | *B. pasteurii* | USA | Ramachandran et al. (2001) |
| Ornamental stone conservation | *Myxococcus xanthus* | Spain | Rodriguez-Navarro et al. (2003) |
| Concrete durability | *B. sphaericus* | Belgium | De Muynck et al. (2008) |
| Concrete crack repair | *B. sphaericus* | Belgium | Van Tittelboom et al. (2009) |
| Compressive strength of cement mortars | *Shewanella* sp. | India | Ghosh et al. (2005) |
| | *Bacillus* sp. CT-5 | | Achal et al. (2011b) |
| Greener media in BioCement | *S. pasteurii* | India | Achal et al. (2009b, 2010a) |
| Corrosion prevention | *Bacillus* sp. CT-5 | India | Achal et al. (2012b) |
| Bio-sandstone | Alkalophilic microbes, *Bacillus* spp. | China | Qian et al. (2010a), Rong et al. (2012), Rong and Qian (2012) |

2–3 g/m$^2$ is applied in concrete, which costs about US $4 (3 €)/m$^2$. The cost of nutrients is estimated to be about US $250 (180 €)/kg. Based on this analysis, the dosage for microbial concrete application will generally range between 0.04 and 0.08 kg/m$^2$, bringing the cost of nutrients to US $7–15 (5–10 €)/m$^2$ and the total product cost is estimated around US $31–39 (23–28 €)/m$^2$.

The additional cost during the preparation of biological mortar or microbial concrete will be that of bacteria and nutrient; however, the cost of nutrients can be reduced significantly by replacing standard or commercially available nutrients with such industrial by products, rich in carbohydrate/protein/energy sources. Achal et al. (2011c) successfully reduced the cost of microbial concrete production by replacing standard nutrient with corn steep liquor (CSL). Corn steep liquor can typically be available locally with a price of nearly US $2 (1.5 €)/L, which is very economic compared with standard nutrient medium and this brings the biodeposition cost to US $0.5–1.0 (0.3–0.7 €)/m$^2$. The performance of CSL was significantly better than standard laboratory nutrients in terms of microbial concrete production. Hence, CSL offers an economic advantage over the standard nutrient medium and the overall process cost reduces dramatically, and finding such other economic nutrient solution is of need.

## 14.6 Conclusions

The quality of building structures is very much dependent upon its strength and impermeability. However, many natural processes causes damage to such structures. In such a situation, it is very important to find novel additive to use during construction, which can improve the durability of structures as well, can be used in the remediation of damaged affects. Hence, a sustainable building material is need of time. Microbially induced calcium carbonate precipitation has great potential not only in the area of microbiology or environmental biotechnology, but also in civil and geotechnical engineering. The introduction of MICP-based microbial concrete offers a novel additive to cement-based materials with adequate impermeability, compressive strength, and reduced reinforced corrosion. The laboratory-based researches provide enough evidence for the successful use of microbial concrete; however, the real challenges are to use it in field studies and in construction of new structures. More research requires converting results achieved in the laboratory into practical applications. The microbial concrete can also be utilized in rehabilitation of heritage stone and lime mortar structures. This MICP-based process can also be carefully used in the remediation of structures that contain hazardous materials such as nuclear fill buildings. The production of bacteria for structural concrete will provide the basis for an alternative and high quality concrete sealant that is highly economic and environmentally safe, leading to the enhancement in the durability of building materials and structures.

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