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# Construction Biotechnology - a new area of biotechnological research and applications

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**Abstract** A new scientific and engineering discipline, Construction Biotechnology, is developing exponentially during the last decade. The major directions of this discipline are selection of microorganisms and development of the microbially-mediated construction processes and biotechnologies for the production of construction biomaterials. The products of construction biotechnologies are low cost, sustainable, and environmentally friendly microbial biocements and biogrouts for the construction ground improvement. The microbial polysaccharides are used as admixtures for cement. Microbially produced biodegradable bioplastics can be used for the temporarily constructions. The bioagents that are used in construction biotechnologies are either pure or enrichment cultures of microorganisms or activated indigenous microorganisms of soil. The applications of microorganisms in the construction processes are bioaggregation, biocementation, bioclogging, and biodesaturation

of soil. The biotechnologically produced construction materials and the microbially-mediated construction technologies have a lot of advantages in comparison with the conventional construction materials and processes. Proper practical implementations of construction biotechnologies could give significant economic and environmental benefits.

**Key words** Construction Biotechnology · Biocement · Biogrout · Biocoating · Bioplastics · Bioadmixtures

## **Introduction**

Medical, Pharmaceutical, Agricultural, and Environmental Biotechnologies are differentiated by their areas of applications. A new biotechnological discipline, Construction Biotechnology, arose for the last decade. Two major directions in Construction Biotechnology are the microbial production of the construction materials and the direct applications of microorganisms or their enzymes in the construction process. The aim of this review is to analyze the current trends and to show new potential directions for the further development of Construction Biotechnology.

## **Biotechnological admixtures**

Industrially produced microbial polysaccharides such as xanthan, welan, succinoglucan, curdlan, and chitosan are used in dry-mix mortars, wall plasters, self-leveling underlayers, and injection grouts to improve their viscosity, water retention, set retarding, and flowability (Plank 2004). The market share of microbial polysaccharides is expected to increase because of the technological advances and the growing trend to use naturally based or biodegradable

products as the building materials (Plank 2004; Ramesh et al. 2010). Major biotechnological admixtures are shown in Table 1.

#### **Insert Table 1**

Hypothetically, a lot of other biotechnological admixtures can be produced and used to improve properties of concrete and grouts (Table 2).

#### **Insert Table 2**

Several million tons of sewage sludge are produced annually as a waste in municipal wastewater treatment plants (MWWTPs). An addition of raw or dry sewage sludge to cement with mass ratio of 0.30 - 0.39 (mass of sludge dry solids/mass of the binder) is considered as an economic way to utilize the environmentally harmful sewage sludge that contains a lot of microbial pathogens, heavy metals, and persistent organics (Malliou et al. 2007). [There were made a lot of research showing that raw or dry sewage sludge of MWWTPs can be considered as a filler material for concrete and bituminous mixes, which could be applied for the landfill construction \(Aziz and Koe 1990; Cheilas et al. 2007; Fytili and Zabaniotou 2008; Katsioti et al. 2008; Lin et al. 2012; Rodríguez et al. 2010; Song et al. 2013; Valls and Vazquez 2001; Valls et al. 2004; Yagüe et al. 2005; Yang et al. 2013\).](#)

However, for better setting, plasticity, and lower shrinkage of cement pastes, the more appropriate approach could be usage of biopolymers such as linear and branched polysaccharides, globules of ribosomes, globular proteins, and linear chains of DNA that were extracted and separated from sewage sludge. The use of extracted biopolymers could be better because the whole sewage sludge is toxic and pathogenic material. Our experiments with an addition of pure linear or branched polysaccharides (xanthan and amylopectin), globular protein (albumin), and linear biopolymer DNA to Portland cement showed that even addition of 0.1% of these hydrophilic biopolymers changed mechanical properties of concrete. These additions increased strength of concrete by 10 - 20% after 3 days of curing

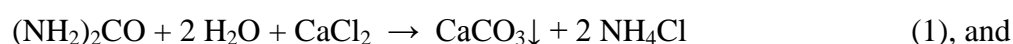
regardless different mixing methods or curing conditions. However, after 7 days of curing, the strength of concrete without biopolymers became higher by 10 - 30% than that of the samples with biopolymers. So, it is possible to expect that biopolymers extracted from sewage sludge can perform the same functions as polysaccharide admixtures and can be used as the set retarder, plasticizer, thickener, emulsifier, hydration, and shrinkage controller.

### **Biotechnological cements and grouts**

Biocement or biogrout is usually a dry matter or solution of one or several inorganic soluble salts and biomass of microorganism(s) or their enzyme(s), which are necessary to initiate transformation and precipitation of inorganic components. Several types of the biocementing/biogrouting materials and processes are described briefly below.

#### *First type of calcium-based biocementation/biogrouting*

The most popular type of biocementation and biogrouting is based on microbially-induced calcium carbonate precipitation, usually abbreviated as MICP or MICCP. It is a sequence of the following steps: 1) adhesion of cells of urease-producing bacteria (UPB) on the soil particle or rock surface; 2) creation a microgradient of carbonate/bicarbonate concentration, and the increase of the pH in the site of cell attachment due to hydrolysis of urea by urease (Eq.1):



3) formation of calcite, vaterite, or aragonite crystals attached to the soil particle/rock surface.

The formation of the microgradient of alkaline pH and increased carbonate concentration around bacterial cell due to hydrolysis of urea follows with crystallization of calcium carbonate (Ferris et al. 1996, Gollapudi et al. 1995, Ivanov and Chu 2008; Sarayu et al. 2014). Chemical precipitation of  $\text{CaCO}_3$  from the calcium salt solution did not create the strength in the treated sample of sand (Stabnikov et al. 2012).

The major drawbacks of the conventional MICCP are high pH about 8.5 - 9.2 and formation of ammonium. Ammonium is harmful for aquatic environment, and high pH increases the risk of corrosion (Pacheco-Torgal and Labrincha 2013a). Ammonium is also dissociating at pH above 8.2 to toxic ammonia gas that is releasing to atmosphere. Therefore, safer types of biogeochemical reactions have to be developed and used for biocementation and biogrouting (Ivanov and Chu 2008) as shown below.

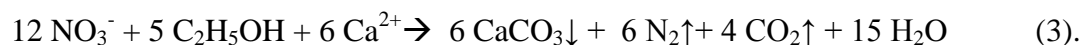
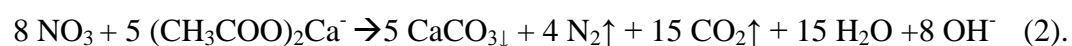
Microorganisms that are performing first type of calcium-based biocementation/biogrouting are halotolerant bacteria with constitutive or inducible urease activity, which can quickly decrease if bacteria produce also proteases (Chu et al. 2014a).

mainly the Gram-positive species of *Sporosarcina pasteurii* (former *Bacillus pasteurii*) and physiologically similar species of the genus *Bacillus*: *B. cereus* (Castanier et al. 2000); *B. megaterium* (Bang et al. 2001; Dhami et al. 2014), *B. sphaericus* (De Muynck et al. 2011; Hammes et al. 2003; 2008a,b; Wang et al. 2012), *B. pseudofirmus* (Jonkers et al. 2010), *B. subtilis* (Reddy et al. 2010), *B. alkalinitrilicus* (Wiktor and Jonkers 2011), *B. licheniformis* (Vahabo et al. 2014), *B. lentus* (Sarda et al. 2009), *Bacillus sp.* (Hammes et al. 2003; Lisdiyanti et al. 2011; Stabnikov et al. 2011; 2013), or halotolerant species from genus *Staphylococcus* (Christians et al. 1991; Jin et al. 1994; 2004; Stabnikov et al. 2013). It could be expected that the extreme halophiles *Haloarcula aidinensis*, *H. hispanica*, *H. japonica*, and *H. marismortui* that show maximum urease activity at 18 - 23% NaCl (Mizuki et al. 2004) could be also used.

In some cases, when soil is rich with indigenous microorganisms having needed biogeochemical function, for example urease activity, soil biotreatment can be performed only by indigenous microorganisms, without preparation and supply of microbial inoculum (Burbank et al. 2011; 2012 a, b). However, if microorganisms are indigenous it does not mean that they are safe for humans, animals, and plants. There may be pathogenic or opportunistic alkalophilic and halophilic bacteria with urease activity (Stabnikov et al. 2013). Therefore, selection and use of safe pure bacterial culture or may be even crude enzyme composition for soil biotreatment could be a safer and more reliable biotechnological option then using of enrichment culture or indigenous bacteria.

#### *Second type of calcium-based biocementation/biogrouting*

Precipitation of calcium carbonate is going due to increase pH and the production of carbonate by heterotrophic bacteria during anoxic oxidation of organics, for example due to bioreduction of nitrate by denitrifying bacteria using acetate (Eq. 2) or ethanol (Eq. 3):



There are known several reports on denitrification and even simultaneous biocementation of sand using calcium salt under denitrification process (DeJong et al. 2006; Eseller-Bayat et al. 2012; Hamdan et al. 2011; Montoya et al. 2012; Rebata-Landa and Santamarina 2012; Weil et al. 2011; Yegian et al. 2007). However, our experiments on an application of denitrifying bacteria *Paracoccus denitrificans* DSM 413 for bioclogging of sand showed that an addition of  $\text{Ca}^{2+}$  ions to the final concentration 0.1M stopped bioreduction of  $\text{NO}_3^-$  ions. It

was no N<sub>2</sub> gas production, the pH did not change and was at the level of 6.8 - 7.2, and finally there were no bioclogging and biocementation of sand after this treatment. Hypothetically, an absence of simultaneous biocementation and denitrification when Ca<sup>2+</sup> ions were added to the medium for denitrification was due to the strong precipitation of phosphate or sulfate by calcium ions, and as a result these essential nutrients for growth and denitrifying activity will be not available for bacteria.

Meanwhile, the sequential denitrification and then biocementation were successful in our experiments. This sequential treatment of sand decreased its hydraulic conductivity from  $4 \times 10^{-5}$  to the levels below  $1 \times 10^{-8}$  m/s. Biocementation after bioproduction of N<sub>2</sub> gas increased the stability of the microbubbles of nitrogen gas in the sand pores due to biocementation in the channels between the sand grains (Chu et al. 2015, not published data). Therefore, the sequential denitrification and biocementation process could be used for the bioclogging and biocementation of the porous soil and the fractured rocks in the tunnel construction, mitigation of soil liquefaction, construction of hydro-insulating walls and other works that are needed to make porous soil or fractured rocks almost impermeable for water.

### *Third type of calcium-based biocementation/biogrout*

Calcium phosphate precipitation from calcium phytate (the main storage of phosphorus in the plant seeds) using phytase activity of microorganisms (Roeselers and van Loosdrecht 2010) produced a mixture of the crystal forms such as monetite (CaHPO<sub>4</sub>), whitlockite [Ca<sub>9</sub>(Mg,Fe<sup>2+</sup>)(PO<sub>4</sub>)<sub>6</sub>HPO<sub>4</sub>], and hydroxyapatite [Ca<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>OH] with the Ca-to-P molar ratio 1.55. The problem of this type of biocementation is a low solubility of calcium phytate (in the described study its concentration was 5.6 mM), so big volumes of the calcium phytate solution must be pumped through soil. However, notwithstanding the results of the numerous



biomedical studies on the biomimetic formation of hydroxyapatite as a major component of a bone, the biotechnology of hydroxyapatite as a cementing geotechnical material is still unknown. Biotechnological “bones of earth” have to be developed yet.

#### *Fourth type of calcium-based biocementation/biogrout*

Important biocementation biotechnology could be a precipitation of calcite using removal of CO<sub>2</sub> from the solution of calcium bicarbonate (Ehrlich 1999). This process requires an addition of urea to increase the pH and produce carbonate ions (Eq. 4).

urease



However, it can be performed at almost neutral pH, so no toxic ammonia gas (NH<sub>3</sub>) will be released to atmosphere because almost all nitrogen will be in the form of water-soluble ammonium ions (NH<sub>4</sub><sup>+</sup>) at a pH below 8. Meanwhile, at a pH about 9, which is a typical pH for the first type of calcium-based biocementation/biogrout, almost 50% of nitrogen will be in the form of gaseous NH<sub>3</sub>.

Another advantage of this calcium bicarbonate based biocementation/biogrout is that only 0.5 mole of urea will be spent for the precipitation of 1 mole of calcium (Eq. 4). This is extremely important for large scale geotechnical applications because the cost of urea in conventional biocementation (in the first type of calcium-based biocementation/biogrout) exceeds 50% of the total costs.

#### *Iron-based biogrout*

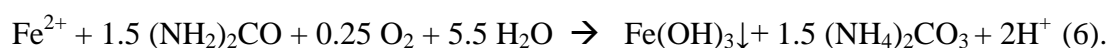
Precipitation of iron minerals can be used for the soil biogrouting (Ivanov and Chu, 2008; Ivanov et al. 2012; Weaver et al. 2011). However, dissolved ferric and ferrous salts are stable at acid pH. Chelates of iron can be stable at neutral pH but are expensive for large-scale geotechnical applications. Cellulose-containing wastes and iron ore can be used for the production of relatively cheap dissolved ferrous salts and chelates by anaerobic cellulose-fermenting and iron-reducing bacteria (Ivanov et al. 2015). Iron-based bioclogging could be suitable biotechnology for geotechnical applications if to combine three bioprocesses shown below:

- 1) acidogenic fermentation of cellulose-containing agricultural or food processing residuals with the production of acetic, propionic and butyric acids;
- 2) bioreduction of iron ore using products of acidogenic fermentation or other cheap electron donors (Ivanov et al. 2009; Guo et al. 2010):



- 3) biooxidation and bioprecipitation of ferrous chelates (Ivanov et al. 2012; 2015):

urease



Urease-producing bacteria and urea have to be used to maintain the pH above the neutral value because oxidation of ferrous ions and hydrolysis of ferric ions is accompanied with acidification of solution. The advantages of using iron ore are: 1) that it is cheap commodity, 2) there is no ammonia release to atmosphere, and 3) the clogging compound ferric hydroxide is more ductile and stable at a low pH. A solution containing  $\text{Fe}^{2+}$  that is produced by iron-reducing bacteria from iron ore can be used not only for the soil bioclogging but also for

simultaneous soil and water remediation because of a high adsorption capacity of ferrous and ferric (hydr)oxides for heavy and radioactive metals, and halogenated and oxygenated xenobiotics (Ivanov et al. 2015).

#### *Biogrout for mitigation of soil liquefaction*

Microbial bioreduction of nitrate by organics (see Eqs. 2 and 3) in water-saturated sandy soil produces a big quantity of nitrogen gas partially desaturating this soil and thus mitigating earthquake soil liquefaction (Hamdan et al. 2011; He et al. 2013; Eseller-Bayat et al. 2012; Montoya et al. 2012; Rebata-Landa and Santamarina 2012; Weil et al. 2011; Yegian et al. 2007). The major advantages of the biogas production *in situ* are as follows: 1) the distribution of the gas bubbles in soil is uniform because a biogrout is a liquid with the same viscosity as water and can be distributed evenly in porous soil; 2) nitrogen gas is inert and has low solubility in water (Chu et al. 2013; 2014b; Landa and Santamarina 2012).

#### **Construction bioplastics**

There is a clear trend in the construction industry for using of the biodegradable materials and biopolymers (Plank 2004; Ramesh et al. 2010). The use of biodegradable plastics in construction reduces the land for disposal of construction wastes after demolition and diminishes the cost of construction works because the biodegradable plastic foams, sheets, liners, and fences can be left in soil without their excavation and disposal. The bioplastics are producing from the renewable sources (Ikada and Tsuji 2000) so their use increases environmental and economic sustainability of the construction industry (Edwards 2015).

### *Composites and co-polymers with polyhydroxyalkanoates (PHAs)*

PHAs are accumulated to the content of 80% of dry biomass as the granules inside cells of many bacterial species, for example the representatives of the bacterial genera *Acinetobacter*, *Alcaligenes*, *Alcanivorax*, *Azotobacter*, *Bacillus*, *Burkholderia*, *Delftia*, *Klebsiella*, *Marinobacter*, *Pseudomonas*, *Ralstonia*, and *Rhizobium*. Accumulated PHAs can be extracted from bacterial biomass and used in practice as bioplastic with melting temperature 160 - 180°C, tensile strength 24 - 40 MPa, and elongation at break 3 - 142 %. These properties are comparable with the properties of petroleum-based thermoplastics (Braunegg et al.1998; Castilho et al. 2009; DeMarco 2005; Khanna and Srivastava 2005; Lenz and Marchessault 2005; Lowell and Rohwedder 1974; Steinbuchel et al.2003; Sudesh et al. 2000; Sudesh and Abe 2010; Volova 2004).

The crude bioplastic, produced without expensive extraction of PHAs, could be used for the construction applications. A major advantage of PHAs for the construction applications is biodegradability of the bioplastic to carbon dioxide and water for 1.5 years in soil and 6.5 years in seawater (Castilho et al. 2009; Mergaert et al. 1992; Reddy et al. 2003). The biodegradation rate of the crude bioplastic should be even higher because 20 - 50% of its content are fast degrading proteins, RNA and DNA.

The applications of PHAs bioplastic from the bacterial biomass could be the production and use of the biodegradable construction materials, which can diminish the land area required for their landfilling because they degrade very quickly in soil or in the landfill. For example, the biodegradable bioplastic foam can be used for insulation of the walls and partitions in the temporarily constructions. The bioplastics can be used also as the sealants and insulants replacing petrochemical plastics in the construction industry (Willke and Vorlop 2004). Other examples of potential application of the crude nanocomposite from

bacterial biomass containing PHAs are the silt and dust fences that can be landfilled for the fast biodegradation or even left in the construction ground for degradation. There could be a big market for the biodegradable bioplastic foam as a construction material that does not require incineration after demolition.

To reduce a cost of this bioplastic it must be produced from the cheap raw materials using batch or continuous non-aseptic cultivation of mixed bacterial culture (Beun et al. 2006; Ivanov et al. 2015; Loosdrecht et al. 2007; 2008; Yu 2006) and even without extraction of bioplastic from the bacterial biomass. The raw materials can be organic fraction of municipal solid wastes, liquid wastes of municipal wastewater treatment plants, food-processing wastes, agricultural wastes such as unbaled straw, corn-cobs, -stalks and -leaves (corn stover), silage effluent, horticulture residuals, farm yard manure, coconut-husks, -frond and -shell, coffee-husk and -hull, cotton (stalks), nut shells, rice-hull, -husk and -straw, and sugar cane bagasse. Globally, 140 billion metric tons of biomass is generated every year from agriculture, which is an equivalent to approximately 50 billion tons of oil (UNEP 2009). So, biomass-containing wastes have attractive potentials for large-scale bioplastic production for the construction industry.

#### *Composites and co-polymers with polylactic acid (PLA)*

Approximately the same criteria of applicability exist for PLA (Ebnesajjad 2012). However, PLA is a pure biotechnological/chemical product so it is the more expensive material than crude PHAs and polypropylene (PP) or polyvinylchloride (PVC) but cheaper than pure PHAs. Price for PLA in 2009 was about 1.9 Euro/kg, while prices for pure PHAs were 2.4 - 4.0 Euro/kg, and for PP and PVC they were 1.0 - 1.1 Euro/kg (Sin et al. 2012). Therefore,

PLA can be used for the production of the more expensive or more environmentally friendly materials than petrochemical plastics or crude PHAs.

The bioplastics are most often used as fibre reinforced polymer composites consisting of reinforcing fibres embedded in a bioplastic matrix. Synthetic fibers are widely used to reinforce plaster or concrete (Balaguru et al. 1994; Suchomel and Marsche 2013; Zeiml et al. 2006) because natural plant fibers have variable and changeable mechanical properties (Suchomel and Marsche 2013). PLA can be used for the manufacturing of: 1) composite biodegradable fibers for reinforcement of the construction materials (Bajpai et al. 2013; Huda et al. 2006; Faludi et al. 2013; John and Thomas 2008; Pilla 2011; Saba et al. 2015); 2) biocomposite sheets for construction and packaging containing PLA, cellulose or starch (Pilla 2011); 3) biodegradable resin composition for construction molds (Tokiwa and Tsuchiya 2003); and 4) for the production of environmentally friendly flooring material resin, which can be recycled or rapidly decomposed upon the discarding (Ko et al. 2014). PLA can be used for the manufacturing of bionanocomposites by the blending of PLA with 1- 5% of the functional nanoparticles increasing the thermal and electrical conductivity of bioplastic, its wettability, and decreasing surface roughness in comparison with conventional PLA (Maizatunisa et al. 2013; Ray et al. 2012).

## **Participation of microorganisms in the construction processes**

### *Construction microbial biotechnologies of biotreatment in situ*

The microbial treatment can be performed *in situ* as: bioaggregation of soil particles and biocrusting of soil surface to control water and wind erosion of soil and soil dust emission (Bang et al. 2011; Stabnikov et al. 2011; 2013b); biocoating of solid surface to protect it from

corrosion and decay or to enhance its colonization (Ivanov et al. 2015); [bioclogging of porous matrix to reduce its hydraulic conductivity \(Ivanov et al. 2012; Eryuruk et al. 2015\)](#); biocementation of porous matrix to increase its strength (Achal et al. 2010; 2011; Chu et al. 2012a; DeJong et al. 2010; 2013; De Muynck et al. 2008a, b; 2010; 2012; Dhami et al. 2012; Dosier 2011; Ghosh et al. 2005; 2006; 2009; Harkes et al. 2010; Ivanov 2010; Ivanov and Chu 2008; Li and Qu 2012; Mitchell and Santamarina 2005; Raut et al. 2014; Sarda et al. 2009; van Paassen et al. 2010; van der Ruyt and van der Zon 2009; Van Tittelboom et al. 2010; Whiffin et al. 2007); biodesaturation (biogas production *in situ*) to reduce liquefaction potential of water saturated soil (Chu et al. 2013b; He et al. 2013; Rebata-Landa and Santamarina 2012); bioencapsulation of clay particles to increase strength of soft clayey soil material (Ivanov et al. 2014); and bioremediation of polluted soil to immobilize pollutant in soil before construction (Fujita et al. 2004; Mitchell and Ferris 2005; Warren et al. 2001). The principles of these processes are shown in Fig. 1.

### **Insert Figure 1**

#### *Applications of biocements and biogrouts in construction and geotechnical engineering*

There are known the following applications of biocements and biogrouts: 1) to enhance stability of the slopes and dams (DeJong et al. 2013; van Paassen et al. 2010); 2) road construction and prevention of soil erosion (Ivanov and Chu 2008; Ivanov 2010; Mitchell and Santamarina 2005; Whiffin et al. 2007); 3) construction of the channels, aquaculture ponds, or reservoirs in sandy soil (Chu et al. 2013; Stabnikov et al. 2011); 4) sand immobilization and suppression of dust (Bang et al. 2011); 5) suppression of the dust-associated chemical and bacteriological pollutants (Stabnikov et al. 2013b); 6) production of bricks (Bernardi et al. 2014; Dhami et al. 2012; Dosier 2011; Raut et al. 2014; Sarda et al. 2009); 7) remediation

of cracks in concrete and rocks and increase of durability of concrete structures (Achal et al. 2010; Ghosh et al. 2005; Li and Qu 2012; Ramachandran et al. 2001, Santosh et al. 2001; Van Tittelboom et al. 2010); 8) the reduction of hydraulic conductivity of landfill clay liners (Eryuruk et al. 2015); 9) concrete durability improvement (Pacheco-Torgal and Labrincha 2013a,b); 10) self-remediation of concrete (De Muynck et al. 2008; Ghosh et al. 2006; Jonkers 2007; Jonkers et al. 2010; Siddique and Chahal 2011; Wang et al. 2012; Wiktor and Jonkers 2011; Wu et al. 2012) modification of a mortar (Ghosh et al. 2009; Vempada et al. 2011); 12) consolidation of a porous stone (Jimenez-Lopez et al. 2008); 13) bioremediation of weathered-building stone surfaces (Achal et al. 2011; Fernandes 2006; Webster and May 2006); 14) reduction of the fractured rock permeability (Cuthbert et al. 2013); 15) construction of ponds and channels (Chu et al. 2013; Stabnikov et al. 2012); 16) sealing of porous soil with biopolymers (Bergdale et al. 2012); 17) partial desaturation of sand due to nitrate bioreduction of organics following with nitrogen gas production *in situ*, which is the effective process for the mitigation of earthquake - soil liquefaction (Chu et al. 2011; 2013; Eseller-Bayat et al. 2012; Hamdan et al. 2011; He et al. 2013; Montoya et al. 2012; Rebata-Landa and Santamarina 2012; Seagren and Aydilek 2010; Weil et al. 2011; Yegian et al. 2007); 18) encapsulation of marine clay to produce solid filler (Ivanov et al. 2015).

Depending on the application and treatment regime, it is possible to produce the biocemented crust on the soil surface, the biocemented layer of the defined thickness, or biocemented monolith (Fig.2).

### **Insert Figure 2**

Usually, from 3 to 5 new potential applications of biocements and biogrouts are described in the literature every year. For example, new applications are the sealing of the tunnels and fractured rock before the tunnels construction (Chu et al. 2015, not published), the sealing of the storage of the nuclear power wastes and landfills, and coating of the



concrete surface for its protection. So, Construction Biotechnology is a fast developing discipline but the major problem of this development is the transfer from laboratory data to the innovative field tests and then the investments to the large-scale geotechnical and industrial applications.

Biocemented materials are brittle but this problem could be probably solved using composite strengthening through combination of mineral and organic nano- and micro-particles by biomimetic approach (Sarikaya, 1994; Mayer and Sarikaya, 2002; Pacheco-Torgal and Labrincha, 2013b) with the 3D-composite structure of hierarchically arranged nano- and micrometric units (Imai et al., 2010) or just with the layers of inorganic and organic materials. Like cement with an addition of nanomaterials (Pacheco-Torgal and Jalali, 2011), applications of composite inorganic brittle minerals and elastic micro- or nano-materials (Yao et al., 2011; Mayer and Sarikaya, 2002) can also be useful to increase ductility of biocement.

The common problems of the Construction Biotechnology processes are biosafety, environmental safety and occupational safety. There must be developed processes with an application of the safe bacterial strains and without release of toxic ammonia to occupational zone.

#### *Bioremediation of the construction sites using biocementation*

One way of soil bioremediation is fixation of pollutants in soil (Kavamura and Esposito (2010). Biocementation can co-precipitate toxic radionuclides  $^{90}\text{Sr}$ ,  $^{60}\text{Co}$ , heavy metals such as Cd (Fujita et al. 2004; Mitchell and Ferris 2005), and capture 95% of Sr added to soil (Warren et al. 2001). After biotreatment of the sand surface in the dosage  $15.6 \text{ g Ca/m}^2$ , the release of the sand dust and its artificial pollutants to atmosphere significantly decreased in comparison with control. The decreases of the dust pollutants release were as follows:

99.8%, 92.7 %, 94.4 %, and 99.8% for dust, phenanthrene, lead nitrate, and bacterial cells of *Bacillus megaterium*, respectively. This immobilization of dust and dust pollutants was due to bioaggregation of the fine sand particles from 29  $\mu\text{m}$  in control to 181  $\mu\text{m}$  (Stabnikov et al. 2013b). So, in case of a radiation dispersal device attack (Cordesman 2002; Parra et al. 2009) the bioaggregation of soil surface can protect the environment from the dispersion of the radioactive pollutants.

## **Conclusions**

Construction Biotechnology as a new research and engineering discipline includes two parts: microbial production of construction materials and microbially-mediated construction processes (Fig. 3).

### **Insert Figure 3**

Microbial cements, grouts, polysaccharides and construction bioplastics can be made using industrial biotechnology processes. The microbial materials and processes can be used for the aggregation, clogging, cementation, desaturation, encapsulation of soil, and for the coating of the solid surfaces in the construction processes. The biotechnologically produced materials and construction biotechnologies have such advantages in comparison with the conventional construction materials and processes as environmental sustainability and safety, low cost materials and biotechnologies, controlled or low viscosity of admixtures and grouts, wide use of renewable resources, reuse of municipal, agricultural, and food processing wastes, use of calcium carbonate and iron ore mining waste, use of soft marine clay, no dust emissions, diversity of applications and methods of biotreatment. So, the practical implementations of the construction biotechnologies could give significant economic and environmental benefits.

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## Legends to Figures

**Figure 1.** The principles of soil biotreatment.

**Figure 2.** Spatial types of biocementation: (a) formation of the calcite crust on the sand surface, (b) formation of the biocemented layer of the defined thickness, (c) biocementation of monolith (bulk biocementation in 1m<sup>3</sup> of sand).

**Figure 3.** Directions of Construction Biotechnology.

**Table 1. Bio-based admixtures for concrete and grout** (based on Plank 2003; 2004; Mun 2007; Fytili and Zabaniotou 2008; Pacheco-Torgal and Jalali 2011a; Pei et al. 2013; and other sources)

Admixture	Biotechnological process	Function of admixture
Sodium gluconate	Biooxidation of glucose by bacteria <i>Gluconobacter oxydans</i> , filamentous fungi <i>Aspergillus niger</i> , or yeastlike	Set retarder; plasticizer; corrosion inhibitor used in concrete mix

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	fungi <i>Aureobasidium pullulans</i>	
Xanthan gum	Biosynthesis by bacteria <i>Xanthomonas campestris</i>	Thickener and set retarder for self-consolidated concrete
Welan gum	Biosynthesis by bacteria <i>Alcaligenes sp.</i>	Thickener, set retarder for self-consolidated concrete
Scleroglucan	Biosynthesis by fungi from genera <i>Sclerotium</i> , <i>Corticium</i> , <i>Sclerotinia</i> , <i>Stromatinia</i>	Thermostable thickener (no loss of viscosity at 90°C for 500 days)
Succinoglycan	Biosynthesis by bacteria <i>Alcaligenes sp.</i>	High shear-thinner with temperature-induced viscosity
Curdlan gum	Biosynthesis by bacteria from genera <i>Agrobacterium</i> or <i>Alcaligenes</i>	Thickener and set retarder for self-consolidated concrete
Polyaspartic acid	Chemical synthesis	Biodegradable dispersant, inhibitor of corrosion in concrete, air-entraining agent for concrete
Sodium alginate	Extraction from brown seaweeds	Stabilizer, thickener, and emulsifier
Carrageenan	Extract of plants or red seaweeds	Foam for protecting freshly poured concrete from premature drying during highway construction
Dextran	Biosynthesis by lactic acid bacteria	Admixture to Portland cement, self-leveling grouts, fresh or saltwater oil well cement slurries, and micro-fine cements improving flow resistance

Pullulan	Biosynthesis by yeastlike fungi <i>Aureobasidium pullulans</i>	Thickener and set retarder for self-consolidated concrete
Sewage sludge	Waste biomass of municipal wastewater treatment plants	Thickener and set retarder for self-consolidated concrete
Bacterial cell	Aerobic cultivation of bacteria	Microstructured filler for concrete walls

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**Table 2. Potentially applicable biotechnological admixtures for concrete and grouts**

Type of admixture	Function of admixture	Potential biotechnological products
Air-entraining admixture	Improve durability in freeze-thaw environments	Environmentally safe biosurfactants
Coloring admixture	Colored concrete	Colored iron compounds

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			produced by microbial reduction of iron ore
Foaming agents		Produce lightweight, foamed concrete with low density	Environmentally safe biosurfactants
Hydration admixtures	control	Suspend and reactivate cement hydration	Organic acids produced by fermentation
Shrinkage reducers		Reduce drying shrinkage	Biotechnologically produced bacterial and fungal osmoprotectors/water-retaining substances (polyols, oligosaccharides, peptides)