Journal of ENVIRONMENTAL Treatment Techniques

J. Environ. Treat. Tech.
ISSN 2309-1185

Journal web link: http://www.jett.dormaj.com

Identification of Gaps to Conduct a Study on Biological Self-healing Concrete

Amirreza Talaiekhozan[1,2], Mohamad Ali Fulazzaky[1], Ali Keyvanfar[3], Ramin Andalib[3], Muhd Zaimi Abd Majid[3], Mohanadoss Ponraj[1], Rosli Bin Mohamad Zin[3], Chew Tin Lee[4], Arezou Shafaghat[3], Mohd Warid Hussin Ir[3]

[1]Institute of Environmental and Water Resources Management, Water Research Alliance, Universiti Teknologi Malaysia, UTM Skudai, 81310 Johor Bahru, Malaysia.
[2]Department of Civil and Environmental Engineering, Jami Institute of Technology, Fooladshahr, Iran.
[3]Construction Research Alliance, Faculty of Civil engineering, Universiti Teknologi Malaysia, UTM Skudai, 81310 Johor Bahru, Malaysia
[4]Bioprocess Engineering Department, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.

Received: 15/07/2013 Accepted: 10/10/2013 Published: 14/10/2013

Abstract

Biological self-healing concrete is a new idea to have concrete structures with more durability. Although, several papers have been published on biological self-healing concrete, a suitable instruction to conduct this type of studies is not reported. Aim of this paper is collecting comprehensive information about conducting a study on self-healing concretes based on previous studies. This paper present many new ideas that have not been completely study. Some idea such as application of fungi, thermopiles bacteria, mix culture of microorganisms or using of aerobic or anaerobic bacteria to design biological self-healing concrete are suggested in this paper. Ideas of this paper can help researchers to find a suitable and novel subject in biological self-healing area to conduct a strong research.

Keywords: Self-healing concrete, bio-concrete, cement

1. Introduction

Self-healing concrete is defined as the ability of concrete to repair its small cracks autonomously [1]. Idea of self-healing concrete is inspired from natural phenomenon at organisms such as trees or animals. Damaged skin of trees and animals can be repaired autonomously [2]. Remediating cracks in concrete structure is necessary because cracks not only influence the service durability, but also harmful for the structure safety [3].

Recently developing of self-healing concrete technology has been becomes an important objective of researches in biotechnology and civil engineering area [4-10]. Although, during of 1980 decade few articles can be found on self-healing concrete, serious studies on this area has been established since the late 1990's. Among all self-healing designing methods, biological methods are youngest one.

Several processes have been suggested for self-healing concrete design. Self-healing processes are classified into natural and man-made processes. Among of proposed natural processes, formation of calcium carbonate and calcium hydroxide are the most important reason to heal concrete naturally [11-18]. Although, concrete has naturally ability of healing itself, only small cracks can be naturally healed [19].

Chemical and biological processes (as man-made processes) are useable to design self-healing concrete. Many articles have been published about chemical and biological self-healing concrete development. However, number of articles on biological methods to design self-healing concrete is not considerable. Gollapudi et al. introduced biological self-healing concrete as an environmentally friendly process at the mid-1990s [20]. Especial strains of bacteria that are able to precipitate especial chemicals such as polymorphic iron-aluminum-silicate ($(Fe_5AI_3)(SiAl)O_{10}(OH)_5$) and calcium carbonate ($CaCO_3$) are used to design a biological self-healing concrete. Precipitation of these especial chemicals on the concrete using microorganisms can reduce permeability towards gas and capillary water uptake. Calcium carbonate precipitation is found worldwide especially at oceans [21, 22].

Nowadays, study on biological self-healing concrete is an interesting area for researchers. Several parameters should be considered to have a successful and comprehensive study. Due to lack of knowledge and a comprehensive resource to present gaps about biological self-healing concrete, many similar studies are published. Although, these studies present useful information about self-healing concrete, they could not present a comprehensive taxonomy and gaps to conduct a new study at this area. The aim of this study is presentation of several gaps to conduct a study in self-healing concrete.

Corresponding author: Muhd Zaimi Abd Majid, Construction Research Alliance, Faculty of Civil engineering, Universiti Teknologi Malaysia, UTM Skudai, 81310 Johor Bahru, Malaysia, e-mail: mzaimi@utm.my.

2. Conduction a Study on Self-healing Concretes

To conduct each study on self-healing concretes seven steps presented at figure 1 can be considered. Following more details about these steps are presented.

2.1 Selection of microorganisms type

Microorganisms can grow in every parts of Earth, such as soil, water and oil reservoir, acidic hot springs, industrial wastewater and etc. Usage of microorganisms to design self-healing concrete has been suggested by several researchers [23, 24]. Microorganisms divide into four important categories: bacteria, fungi, yeasts, and viruses that they have various shape and size. Among of these microorganisms' types, bacteria are frequently used by researches to design self-healing concrete. Some strains of bacteria that are able to precipitate especial chemicals are frequently used to design a biological self-healing concrete. Based on few studies both of bacteria and fungi are applicable to design self-healing concretes. However, our information about using of fungi at this area is negligible. Using of fungi on self-healing concretes is more complicate and expensive than bacteria and it is why few reports are published at this area.

Although using of biological methods is an environmental friendly, pollution free and natural way to design self-healing concretes, these methods have some disadvantages such as many prerequisites to be met, measures should be taken to protect bacteria in concrete, and mechanical properties recovery and effectiveness under multiple damage events could be concerns [12]. Unfortunately, effect of microorganisms on concrete strength is also not completely clear and it yet needs to be verified [23].

2.2 Selection of bioprocess reaction

Recognized bioprocesses for design self-healing concrete are divided into two major category containing (a) calcium carbonate precipitation and (b) polymorphic iron-aluminum-silicate precipitation. Microbial calcium carbonate can be precipitated as a by-product during urea hydrolysis, photosynthesis, and sulfate reduction [25]. As a microbial sealant, calcium carbonate exhibited its positive potential in selectively consolidating simulated fractures and surface fissures in granites and in the consolidation of sand. Besides this, a durability study on concrete beams treated with bacteria, exposed to alkaline, sulfate and freeze-thaw environments were also performed. Results of this experiment elaborated that, concentration of bacteria has a great effect on concrete durability and it is increased with rising in the bacteria concentration. Calcium carbonate can be found at three nucleation (same chemical formula, different structure) with names calcite, aragonite and vaterite. The most stable form of calcium carbonate is calcite. Aragonite is another form of calcium carbonate and it is a metastable. It can be canverted into calcite over time. Vaterite is also othre form of calcium carbonate that is rarely found in nature [26]. pH and temprature have a grate impact on the vaterite morphology. Onder different renge of pH, three vaterite crystal types with names Spherulite, hexagonal-plate, and lettuce are formed. Spherulite, hexagonal-plate, and lettuce can be formed at $pH < 9.3$, pH 9.6, and pH 8.5, respectivly [27].

The primary role of bacteria in precipitation of calcium carbonate is attributed to their ability to increase pH of environment through different bacterial metabolisms [28]. Apparently, biological calcium carbonate precipitation using ureolytic bacteria is the most popular way to design self-healing concrete. These bacteria are able to product urease enzyme. This enzyme has impact on precipitation of calcium carbonate. The chemical process appears as follows:

$$CO(NH_2)_2 + H_2O \xrightarrow{Urease\ enzyme} NH_2COOH + NH_3$$

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3$$

$$H_2CO_3 + H_2O \leftrightarrow HCO_3^- + H^+$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^-$$

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

Bacteria cell wall has negative charge and for this reason cell wall is able to draw positively charged calcium ions, which deposit on their cell wall surface. The Ca^{2+} ions then react with the CO_3^{2-} ions leading to the precipitation of calcium carbonate at the cell surface. This precipitation serves as the nucleation site.

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

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

Percipitation of calcium caronate by *Proteus mirabilis* and *Proteus vulgaris* can be seen in Fig. 2 to 4. These pictures were taken by 40x zoom [36]. Silica accumulator bacteria have been found in several laboratury experiments [29]. A complex iron-aluminum-silicate was found on surface of isolated bacteria cells from a lake contaminated with metal sediment [30]. The experiments showed that chemical formolation of this polymorphic iron-aluminum-silicate is $(Fe_5AI_3)(SiAl)O_{10}(OH)_5$. The Leuconostoc mesenteroides plays an important role in precipitating silica at acidic pH. This bacterium utilizes carbohydrates to produce lactic acid creating an acidic environment, in which the solubility of colloidal silica becomes reduced resulting in precipitation. Unfortunately, acidic pH is not good for durability of concrete then this method is not popular. Ratio of silicate and calcium carbonate is very important in concrete but using of silicate precipitation to design a biological self-healing concrete can change this ratio.

2.3 Selection of microorganisms resource

Microorganisms that are useable to design self-healing concrete can be found at three different ways contain adaptation, isolation and using commercial microorganisms.

2.3.1 Adaptation of microorganisms

Adaptation of microorganisms to precipitate of calcium carbonate is a novel method that some studies are conducting on it. Unfortunately, only little information has been reported about this complex method to precipitate calcium carbonate. As you can see at previous parts, some effective factors on the biological calcite precipitation rate are (1) the concentration of dissolved inorganic carbon contains, (2) the pH, (3) the calcium ions (Ca^{2+}) concentration, and (4) the presence of nucleation sites. By rearranging these effective factors, scientists try to adapt microorganisms for precipitation of calcium carbonate. This method yet need to be verified.

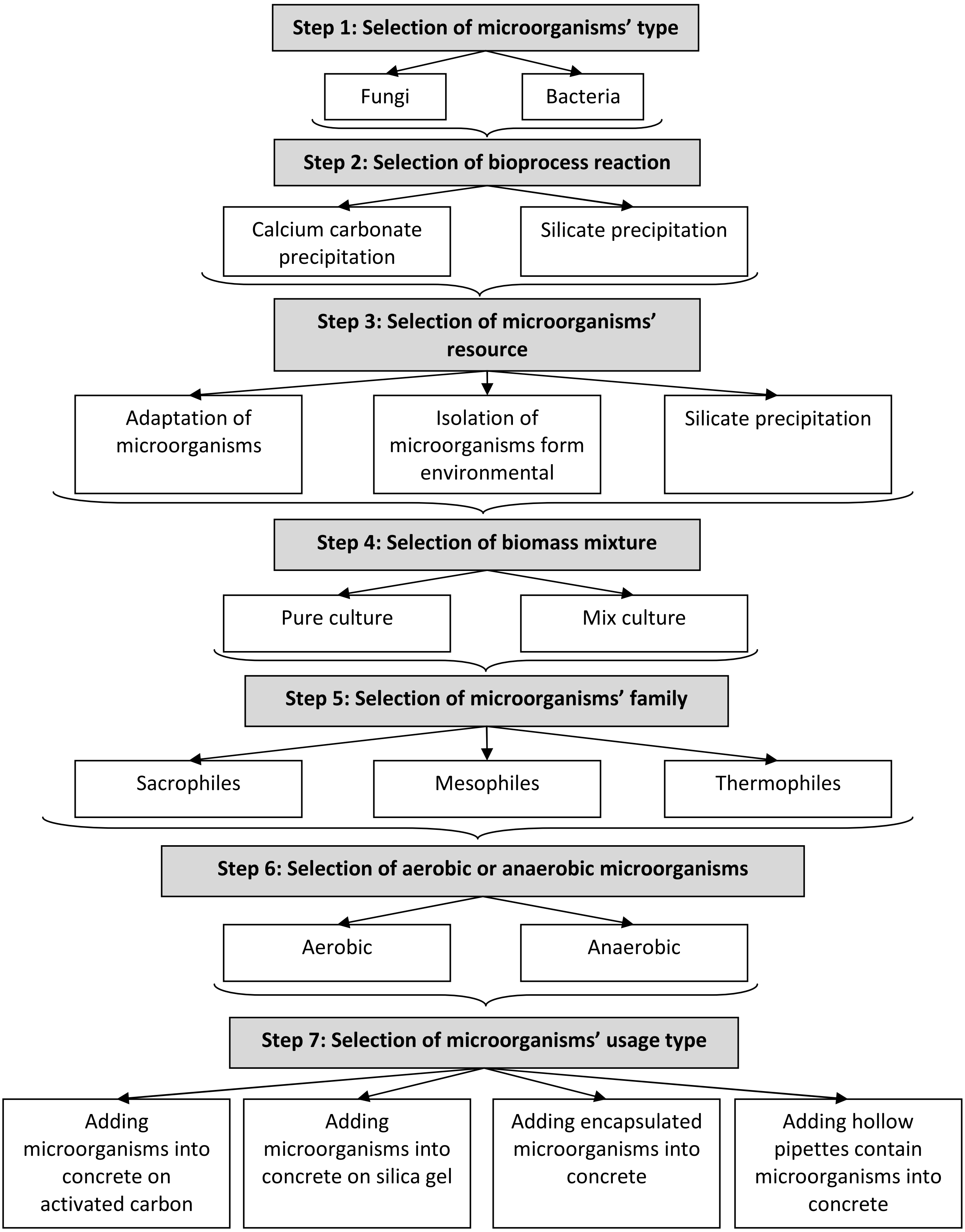

Figure 1: Different steps to conduct a study on biological self-healing concrete

Figure 2: Microbial persipitation of calcium carbonate around of a concrete crack

Figure 3: Microbial persipitation of calcium carbonate around of a concrete crack

Figure 4: Microbial persipitation of calcium carbonate around of a concrete crack

2.3.2 Isolation of microorganisms

Microorganism isolation is another way to find suitable microorganisms. Fortunately, Microorganisms can be found at all part of Earth. Some places have an appropriate condition to grow suitable microorganisms to design self-healing concrete such as alkaline lake or polluted lake with metal ions. Some isolation methods can be used to isolate microorganisms from environment. Isolation methods are not often complicated and expensive. A clear procedure can be also found for this method. Several researchers could isolate very suitable microorganisms to precipitate calcium carbonate or silicate [27].

2.3.3 Application of commercial microorganisms

The last way for finding a suitable microorganisms to application in self-healing researches is using commercial microorganisms or isolated microorganisms at previous studies. It is a cheap and reliable way to prepare suitable microorganism for self-healing concrete design. A list of identified microorganisms during previous studies can be found in Table 1.

2.4 Selection of biomass mixture

Microorganisms can be applied at concrete in to form of pure and mix. In near all studies researchers have used pure microorganisms for their research. Only few researchers used mix culture of microorganisms to design self-healing concrete. Therefore, using different mix cultures of microorganisms can be a suitable research area to conduct a new research on self-healing concrete.

2.5 Selection of microorganisms family

The type of bacterial culture and medium composition had a profound impact on calcium carbonate crystal morphology [31]. Three microorganisms' families contain psychrophiles, mesophiles and thermopiles can be used to design biological self-healing concretes. Obligate psychrophiles are those organisms having a growth temperature optimum of 15°C (59° F) or lower. They cannot grow above 20°C (68°F) [32]. A mesophile is an organism that grows best in moderate temperature, neither too hot nor too cold, typically between 20 and 45 °C (68 and 113 °F). A thermophile is an organism — a type of extremophile — that thrives at relatively high temperatures, between 45 and 122 °C (113 and 252 °F). Mesophiles and thermophiles have been used in previous studies but psycrophiles never. Microorganism activities rate in psycrophiles are lower than other types, it can be why psycrophiles do not used at previous studies. Gosh and Mandal (2006) performed a study to design self-healing concrete using thermophilic bacteria. They used Esherichia coli as a thermophilic bacterium. The culture of Esherichia coli was conducted on 65° C. Live bacteria were directly added to fresh concrete with different concentration range (between 0 and 10^5 cell/ml of water used). Results of tests showed that, overall compressive strength concrete containing live cells was increased in comparison with control specimens [35].

2.6 Selection of aerobic or anaerobic microorganisms

Oxygen is very limited into concrete. For this reason using microorganisms such as Pseudomonas aeruginosa that is anaerobic, can be useful for self-healing concrete design. Some studies using anaerobic and aerobic microorganisms have been found. However, the focus of these studies was not on oxygen limitation into concrete. Although, we know both anaerobic and aerobic microorganisms are usable for self-healing concrete design, mechanisms of these processes have not yet fully understood.

2.7 Method of microorganism usage

Adding microorganisms to biological self-healing concrete can be carried out in different methods contain (a) adding microorganisms directly to fresh concrete, (b) adding spore of microorganisms, (c) adding microorganisms after immobilization onto silica gel or activated carbon, (d) adding encapsulated microorganisms, or (e) using of microvascular networks to distribute of microorganisms throughout of concrete structure [12, 14, 34].

Table 1: List of microorganisms applicable for developing self-healing concrete based on the respective self-healing mechanisms

Self-healing mechanisms	Name of microorganisms	References
Ureolytic process	Sporosarcina Pasteurii (or Bacillus Pasteurii)	[41, 37, 38]
	Bacillus megaterium	[42, 39, 40]
	Halomonas euryhaline	
	Myxococcusxanthus	
	Deleya halophila	[43]
	Bacillus sphaericus	[44]
	Bacillus lentus,	[45]
	Slime-producing bacteria	[46]
	Acinobacter sp	[26]
	Escherichia coli	[35, 47, 48]
	Pseudomonas aeruginosa	[49]
	Shewanella sp	[50]
	B. Cohnii	[51]
	B. pseudofirmus	[51]
	Bacillus amyloliquefaciens	[32]
	Bacillus alkalinitrilicus	[52]
Silica process	Leuconostoc mesenteroides	[20]

Some researchers have been carried out by adding microorganisms directly into fresh concrete. It is cheapest way to conduct a research on biological self-healing concrete [33]. pH of fresh concrete is between 10 to 13. The temperature of fresh concrete can be also near 70 degree centigrade. After drying of concrete, there is not enough water. Therefore, suitable bacteria have to have a high resistance against high pH, temperature, and serious limitation of water. Usually mesophilic microorganisms cannot have a normal growing in this condition.

Dislike of bacteria, spore of bacteria is very resistance against inappropriate condition and some bacterial spores can live more than 60 years. Then in some studies instead of direct using of microorganisms in fresh concrete, spores were used. To avoid microorganisms from inappropriate condition, encapsulated microorganisms can be used. Encapsulation of microorganisms is an expensive and complex way. Using of vascular or microvascular networks to distribute of a liquid contain microorganisms throughout of concrete are other ideas to avoid microorganisms from inappropriate condition. However, these methods are extremely complex and they do not have constructability using present technology.

The use of immobilized microorganisms onto silica gel or activated carbon is a suitable way from aspect of cost. However, effect of using these materials on the strengthening of concrete is not completely clear.

Acknowledgements

This work was financially supported by University Teknologi Malaysia (UTM) contract research grant (Vote number: 4S042), Research Management Center, Construction Research Alliance (CRA), International Doctoral Fellowship (IDF), and Research and Innovation Center (TNCPI).

Reference

1- Ghosh S.K. (Ed.), Self-Healing Materials: Fundamentals, Design Strategies, and Applications, Wiley WCH, GmbH, 2009.
2- van Breugel K. Is There a market for self-healing cement-based materials. In: Proceedings of the first international conference on self-healing materials, Noordwijk aan zee, the Netherlands; April 2007.
3- Zhong W, Yao W, Influence of damage degree on Self-healing of Concrete. Construction and Building Materials, 2008;22: 1137-1142.
4- Balazs A.C., Modeling self-healing materials, Mater. Today 10 (2007) 18–23.
5- van der Zwaag S. (Ed.), Self Healing Materials–an Alternative Approach to 20 Centuries of Materials Science, Springer, Dordrecht, The Netherlands, 2007.
6- Wool R.P., Self-healing, Materials: a review, Soft Matter 4 (2008) 400–418.
7- Nosonovsky M., Bhushan B., Multiscale Dissipative Mechanisms and Hierarchical Surfaces: Friction, Superhydrophobicity, and Biomimetics, Springer-Verlag, Heidelberg, Germany, 2008.
8- Nosonovsky M., Bhushan B., Thermodynamics of surface degradation, self-organization, and self-healing for biomimetic surfaces, Phil. Trans. R. Soc. A. 367 (2009) 1607–1627.
9- Koch K., Bhushan B., Ensikat H.J., Barthlott W., Self-healing of voids in the wax coating on plant surfaces, Phil. Trans. R. Soc. A 367 (2009).
10- Nosonovsky M., Amano R., Lucci J.M., Rohatgi P.K., Physical chemistry of selforganization and self-healing in metals, Phys. Chem.Chem. Phys. 11 (2009) 9530– 9536.
11- Edvardsen C. Water permeability and autogenous healing of cracks in concrete. ACI Mater J 1999;96:448–54.
12- Schlangen E. Fracture mechanics. CT5146 Lecture Notes. In: Hua X. Selfhealing of Engineered Cementitious Composites (ECC) in concrete repair system. Master thesis, Delft University of Technology; 2010.

13- Van der Zwaag S, editor. Self-healing materials: an alternative approach to 20 centuries of material science; 2007.
14- Yang YZ, Lepech MD, Yang EH, Li VC. Autogenous healing of engineered cementitious composites under wet–dry cycles. Cem Concr Res 2007;39:382–90.
15- Qian S, Zhou J, de Rooij MR, et al. Self-healing behavior of strain hardening cementitious composites incorporating local waste materials. Cem Concr Compos 2009;31:613–21.
16- Homma D, Mihashi H, Nishiwaki T. Self-healing capability of fibre reinforced cementitious composites. J Adv Concr Technol 2009;7(2):217–28.
17- Wua M, Johannesson B, Geiker M, A review: Self-healing in cementitious materials and engineered cementitious composite as a self-healing material, Construction and Building Materials 28 (2012) 571–583
18- Neville AM. Autogenous healing – a concrete miracle. Concr Int 2002; November: 76–82.
19- van der Zwaag S. (ed.) *Self healing materials – An alternative approach to 20 centuries of materials science*. Springer, The Netherlands; 2007; 161–194.
20- Gollapudi UK, Knutson CL, Bang SS, Islam MR. A new method for controlling leaching through permeable channels. Chemosphere 1995;30:695–705.
21- Leeder, MR, Sedimentology, George Allen and Unwin (Publishers) Ltd., London, 1982, 344 pp.
22- Ramachandran SK, Ramakrishnan V, Bang SS, Remediation of Concrete Using Micro-organisms. ACI. Materials, 2001;98: 3-9.
23- Jonkers HM, Thijssen A, Muyzer G, Copuroglu O, Schlangen E. Application of Bacteria As Self-Healing Agent for the Development of Sustainable Concrete. In: Proceedings of the 1st international conference on biogeocivil engineering, Delft, The Netherlands; June 23–25, 2008.
24- Tittelboom KV, Belie ND, Muynck WD, Verstraete W. Use of bacteria to repair cracks in concrete. Cem Concr Res 2010;40:157–66.
25- Knorre H, Krumbein W, Bacterial calcification. In: Riding RE, Awramik SM (Eds.), microbial Sediments. Springer-Verlag, Berlin, Germany, 2000;25-31.
26- Sanchez-Moral S, Canaveras JC, Laiz L, Saiz-Jimenez C, Bedoya J, Luque L, Biomediated precipitation of calcium carbonate metastable phases in hypogean environments: A short review, Geomicrobiology Journal, 2003;20(5), 491-500.
27- Kralj D, Brečević L, & Nielsen AE, Vaterite growth and dissolution in aqueous solution I. Kinetics of crystal growth. Journal of Crystal Growth, 1990;104(4), 793.
28- Douglas S, Beveridge TJ, Mineral formation by bacteria in natural Communities. FEMS. Microb. Ecol., 1998;26: 79-88.
29- Ferris FG, Fyfe WS, and Beveridge TJ, Metallic ion binding by Bacillus subtil is; implications for the fossilization of microorganisms, Geology, 1987;16, 149-152.
30- Gollapudi UK, Knutson CL, Bang SS, and IL M, A New Method For Controlling Leaching Through Permeable Channels, *Chemosphere*, 1995; 30(4): 695-705.
31- Berner RA, The role of magnesium in the crystal growth of calcite and aragonite from sea water, Geochim. Cosmochim. Acta., 1975;39: 489-504.
32- Lee N. Y., (2003) Calcite Production by Bacillus amyloliquefaciens CMB01, J. Microbiol., 41(4): 345-348.
33- Braissant O., Verrecchia E. P., Aragna M., (2002) Is the contribution of bacteria to terrestrial carbon budget greatly underestimated? Naturwissenschaften, 89(8): 366-370.
34- Narayanasamy R., Villegas-Flores N., Betancourt-Silva F., Betancourt-Hernandez J., Balagurusamy N., (2010) Application of bacteria in repairing the concrete cracks—A review, Concrete under Severe Conditions, 1237-1244.
35- Ghosh P., Mandal S., (2006) Development of bioconcrete material using an enrichment culture of novel thermophilic anaerobic bacteria, Indian Journal of Experimental Biology, 44:336-339.
36- Talaiekhozan A., Keyvanfar A., Andalib R., Samadi M., Shafaghat A., Kamyab H., Abd Majid M.Z., Mohamad Zin R., Fulazzaky M.A., Lee C.T., Warid Hussin M., Application of *Proteus mirabilis* and *Proteus vulgaris* Mixture to Design Self-Healing Concrete, impress in desalination and water treatment, 2013.
37- S. S. Bang, J. K. Galinat, V. Ramakrishnan, (2001) Calcite precipitation induced by polyurethane-immobilized Bacillus pasteurii, Enzyme and Microbial Technology 28: 404–409.
38- V. Ramikrishnan, R. K. Panchalan, S. S. Bang, (2005) Improvement of concrete durability by bacterial mineral precipitation, in Proc. ICF 11, Torino, Italy.
30- J. Dick, W. D. E. Windt, B. D. Graef, H. Saveyn, P. V. Meeran, N. Belie, W. Verstraete, (2006) Biodeposition of a calcium carbonate layer on degraded limestone by Bacillus species. Biodegradation, 17(4): 357-67.
40- M. A. Rivadeneyra, A. Ramos-Cormenzana, G. Delgado, R. Delgado, (1996) Process of carbonate precipitation by Deleyahalophila. Current Microbiology, 32(6): 308-313.
41- R. Siddique, N. K. Chahal, (2011) Effect of ureolytic bacteria on concrete properties, Construction and Building Materials 25: 3791–3801.
42- H. M. Jonkers, (2007) Self Healing Concrete: A Biological Approach, Self Healing Materials. An Alternative Approach to 20 Centuries of Materials Science, 195–204.
43- H. M. Jonkers, A. Thijssen, G. Muyzer, O. Copuroglu, E. Schlangen, (2008) Application of Bacteria As Self-Healing Agent for the Development of Sustainable Concrete. In: Proceedings of the 1st international conference on biogeocivil engineering, Delft, The Netherlands; June 23–25.
44- K. V. Tittelboom, N. D. Belie, W. D. Muynck, W. Verstraete, (2010) Use of bacteria to repair cracks in concrete. Cem Concr Res, 40: 157–66.
45- N. Chahal, A. Rajor, R. Siddique, (2011) Calcium carbonate precipitation by different bacterial strains, African Journal of Biotechnology, 10(42): 8359-8372.
46- S. M. Al-Thawadi, (2011) Ureolytic Bacteria and Calcium Carbonate Formation as a Mechanism of Strength Enhancement of Sand, Journal of Advanced Science and Engineering Research 1: 98-114.
47- K. L. Bachmeier, A. E. Williams, J. R. Warmington, S. S. Bang, (2002) Urease activity in microbiologically-induced calcite precipitation, Journal of Biotechnology 93: 171–181.
48- P. Ghosha, S. Mandala, B. D. Chattopadhyayb, S. Pal, (2005) Use of microorganism to improve the strength of cement mortar, Cement and Concrete Research, 35: 1980 – 1983.
49- C. Dry, (1990) Alteration of matrix permeability, pore and crack structure by the time release of internal chemicals. In: Proceedings of advance in cementitious materials. American Ceramic Society: Gaithersbury, Maryland, pp. 729– 68.

50- C. Nishiwaki, (1997) Fundamental study on development of intelligent concrete with self-healing capability. Master's thesis, Department of Architecture and Building Science, Graduate School of Engineering, Tohoku University.
51- M. J. Henk, T. Arjan, M. Gerard, C. Oguzhan, S. Erik, (2008) Application of bacteria as self-healing agent for the development of sustainable concrete, Ecological Engineering, 36(2): 230–235,
52- V. Wiktor, H. M. Jonkers, (2011) Quantification of crack-healing in novel bacteria-based self-healing concrete, Cement & Concrete Composites 33: 763–770.