American Journal of Applied Scientific Research
2017; 3(6): 80-86
http://www.sciencepublishinggroup.com/j/ajasr
doi: 10.11648/j.ajasr.20170306.12
ISSN: 2471-9722 (Print); ISSN: 2471-9730 (Online)

Review Article

Factors Affecting the Self-Healing Efficiency of Cracked Concrete Structures

Meseret Getnet Meharie[1, 2, *], James Wambua Kaluli[1], Zachary Abiero-Gariy[1], Nandyala Darga Kumar[3]

[1]Department of Civil Engineering, Pan African University Institute for Basic Sciences, Technology and Innovation, Nairobi, Kenya
[2]Department of Construction Technology and Management, Adama Science and Technology University, Adama, Ethiopia
[3]Department of Civil Engineering, Fiji National University (FNU), Samabula, Suva, Fiji Islands

Email address:
mesget86@gmail.com (M. G. Meharie), wambuak@gmail.com (J. W. Kaluli), zagariy@yahoo.co.uk (Z. Abiero-Gariy), ndargakumar@yahoo.com (N. D. Kumar)
[*]Corresponding author

To cite this article:
Meseret Getnet Meharie, James Wambua Kaluli, Zachary Abiero-Gariy, Nandyala Darga Kumar. Factors Affecting the Self-Healing Efficiency of Cracked Concrete Structures. *American Journal of Applied Scientific Research.* Vol. 3, No. 6, 2017, pp. 80-86.
doi: 10.11648/j.ajasr.20170306.12

Received: July 5, 2017; **Accepted**: July 18, 2017; **Published**: November 28, 2017

Abstract: Self-healing concrete is the ability of concrete to repair its cracks autogenously or autonomously. Since some years ago, several studies have been conducted towards the improvement of self-healing efficiency of cracked concrete structures through various methods for the betterment of its application. However, there is a need to prepare a thorough review report on the factors that affect self-healing efficiency of concrete. This paper focusses a review on several factors that affect the self-repairing efficiency of self-healing smart concrete from the extant recent literature. Based on the review carried out, it can be concluded that formation of $CaCO_3$ or Ca $(OH)_2$ in natural process, the dosage of capsule and type of healing agent in chemical process, and the type of bacteria and precipitation of $CaCO_3$ in biological process of self-healing are the most vivid factors. It can also be summarised as better self-healing efficiency is achieved during early age of concrete, with narrower cracks, higher concentration of Ca^{2+} ions, optimum thickness of capsule shell and dosage of capsule.

Keywords: Crack, Smart Concrete, Self-Healing Concrete, Natural Self-Healing Process, Chemical Self-Healing Process, Biological Self-Healing Process, Mineral Admixtures

1. Introduction

Concrete is the second most consumed construction material in the world next to water. Many of the infrastructures across the world are built with cementious materials mainly concrete. The widely use of these cementitious materials are because of their cost-effectiveness and availability. However, because of the degeneration of concrete materials, complex interaction between concrete materials and their service environment, absence of advanced design and condition assessment tools, and timely maintenance, many concrete structures are in a state of absolute disrepair [3]. Concrete is strong in compression but weak in tension, it cracks under sustained loading and due to aggressive environmental agents and reduce service life of concrete structures [9; 17]. Cracks may occur when concrete is in a plastic state or after it has completely hardened. Cracking is inevitable in reinforced concrete structures. Temperature changes, structural issues and freeze thaw can produce cracks which can ultimately lead to major problems for concrete structures and reduce the life of them. Moreover, cracks inevitably exist in inevitable in reinforced concrete structures. Temperature changes, structural issues and freeze thaw can produce cracks which can ultimately lead to major problems for concrete structures and reduce the life of them. Moreover, cracks inevitably exist in concrete due to thermal effect, chemical shrinkage, dry shrinkage, early-age autogenous shrinkage, freeze-thaw effect, the relatively low tensile strength, and a combination of these factors [3]. Crack formations result in decrease of durability, permeability and strength of the concrete structures.

This degradation of concrete leads to ingress of deterious substances into concrete, results in deterioration of structures. Because of increase in the permeability of the concrete the water can easily pass through the concrete and comes in the contact with the reinforcement of the concrete structure and after some time corrosion starts and finally the strength of concrete will decrease [19]. Thus, it is very essential to control the crack propagation and to heal the cracks as fast as possible.

Smart concretes and structures are intelligent systems that have properties different from normal concrete, such as self-sensing and self-healing properties, or have the ability to react upon an external stimulus, such as stress and temperature. Now a days smart concrete becomes a promising engineering material to develop intelligent infrastructure through material composition design, special processing, introduction of other functional components, and modifying the microstructure so that improving serviceability, safety, reliability, and durability of the concrete structures can be provoked [3]. There are several types of smart concrete and structures such as self-sensing, self-healing, self-adjusting, self-heating, self-cleaning, electromagnetic (EM) shielding/absorbing, energy harvesting, light-transmitting, and aircraft arresting properties. Among these types, self-healing smart concrete is the one which is a pretty quick acting to overcome the aforementioned scenario so as to extend the service life of the concrete structures. Therefore, smart cementitious materials with self-healing property, which have the built-in capability to repair structural damage autonomously or with the minimal help of an external stimulus, are very promising in the field of application [15].

Since two decades ago, several studies have been conducted toward the improvement of self-healing efficiency of cracked concrete structures through natural, chemical and biological methods for the betterment of its application. It can be realized that ensuring the effectiveness of self-healing of cracks in concrete is still the interest of many researchers. Apart from this it is very essential to identify the different factors that affect the effectiveness of self-healing process and closely look at how they do affect the self-healing efficiency. Therefore, the purpose of this paper is to closely look at the aforementioned factors that affect the self-repairing efficiency of self-healing smart concrete. Accordingly, several factors from the extant literature has been thoroughly addressed and discussed.

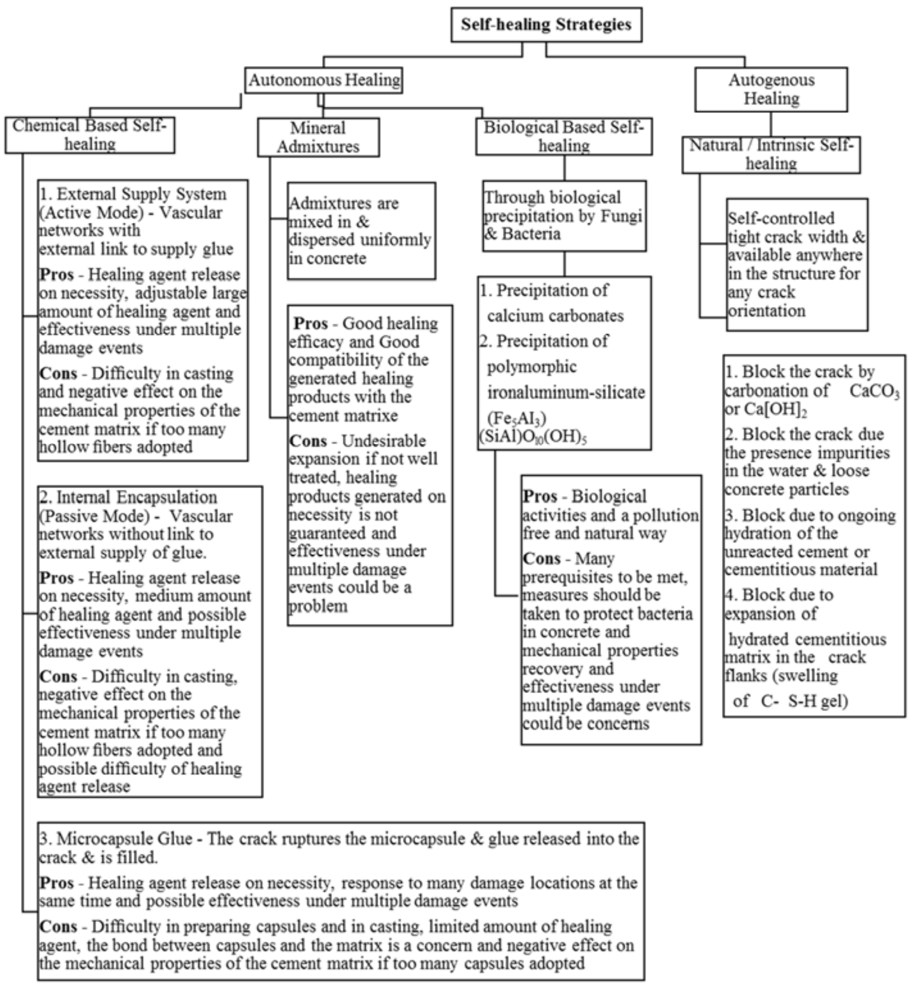


Figure 1. *Classifications of Self-healing Processes in Concrete.*

2. Self-Healing Smart Concrete

The idea of self-healing of cracks in concrete is inspired from the natural phenomenon by trees, animals or human body when they get wounded. In the human body, small wounds are easily treated by the body itself, requiring no further care. For bigger wounds to be healed, the body may need outside assistance. Likewise concrete is like a living body, in that it can self-heal its own small wounds (cracks) as an intrinsic characteristic. However, cracks do not heal easily in conventional concrete due to its rather brittle nature. It calls into question the effectiveness of self-healing in conventional concrete materials with no control over crack formation [2; 18].

Self-healing concrete, also called self-repairing concrete, is mostly defined as the ability of concrete to repair its cracks autogenously or autonomously [2; 3]. There are several similar words in the area of self-healing concrete technology naming self-healing, self-repair, autonomous healing, automatic healing, auto-treatment, self-treatment, bio-concrete, bio-inspired, biological concrete, calcite bio-mineralization, and calcite precipitation [2]. So far several techniques have been evolved and tested to find the efficient way of self-healing of cracks. [1] Classified self-healing concrete into two categories: autogenous self-healing concrete and autonomous self-healing concrete. In the study of [17], self-healing methods were categorized into three main approaches such as Intrinsic, biological based and chemical based self-healing. [2; 15] also reviewed the natural, chemical and biological processes of self-healing concrete technologies with thorough discussion. All in all, the classification of self-healing concrete methods are explained as shown in the figure 1 below.

3. Factors Affecting the Efficiency of Self-Healing Process

3.1. Size of the Crack

Generally, natural or autogenous healing is mostly effective for very narrow cracks [4; 17]. As stated in [2], natural self-healing can be useful for cracks with widths up to 0.1–0.2 mm. [12] Reported that the natural healing process can heal the crack width of 5 – 300 μm. As far as size of the crack is concerned with respect to microbial or biological, [18] Realized that the crack was more and more difficult to be repaired with the increase of average crack width and they investigated that the repair ability of microbial repair agent was limited for specimens with crack width up to 0.8 mm. [5] also investigated the self-healing potential of cracks in cement-based materials incorporating the bacteria with respect to width of cracks between 0.1 and 1.0 mm. The result indicated that the bacteria showed excellent repairing ability to small cracks. Cracks below 0.4 mm was almost completely closed. It was concluded that cracks width influenced self-healing effectiveness significantly. Likewise, [4] were also found that bacterial based self-healing approach can heal up to 0.46 mm wide cracks of bacterial specimens after 100 days of curing. Smaller crack width requires less self - healing products to fill the crack and it will be easier to grow from both surfaces of the crack to get connected [22]. In general, it can be generalized that the narrower the cracks the more likely to be completely healed [12].

3.2. Age of Concrete & Its Crack

Further hydration of an-hydrate cementations components is mainly due to the natural self-healing properties in concrete and only applies to very young concrete. Whereas, the formation of calcium carbonate most likely causes self-healing at later ages [2; 3; 12].

Concrete cracking may occur in any time of its service life. [5] Investigated the self-healing potential of early age cracks in cement-based materials incorporating the bacteria which can produce carbonic anhydrase. They prepared cement-based materials specimens which were pre-cracked at the age of 7, 14, 28, 60 days to study the repair ability influenced by cracking time. The experimental results indicated that the bacteria showed excellent repairing ability to small cracks formed at early age of 7 days and self-healing agent had lost the repair effect at later age of beyond 60 days. Finally, they comprehended that the repair effect reduced with the increasing of cracking age. Moreover, the survival numbers of bacteria in matrix reduced with the increasing of cracking age because of the high alkaline environment in cement-based materials. When the amount of active bacteria reduced to quite small, $CaCO_3$ precipitation couldn't be induced. [14] Identified that the crack healing ratio of specimens dropped significantly along with the extension of cracking age. Wang et al said the healing performance does not stay constant. The healing efficiency decreases with the age of sample [27].

3.3. Temperature, Pressure & Healing Time

The healing performance will improve with higher temperature, higher pressure and longer healing time [27].

3.4. Presence of Water & Air

Free water is pretty important for crack healing process. It is possible to say that all of the studies conducted so far stated that the presence of water is essential to facilitate healing of the cracks [22]. The healing process is only effective when water is available, thus makes it difficult to control [3; 12]. Han et al stated that continued hydration of un-hydrated cement particles is faster in water and water also promotes the dissolution of calcium hydroxide from the concrete matrix near the crack surface for the formation of calcium carbonate healing products. Another study confirmed that the amount of available water and the time to available in cracks are quite vital for sufficient healing [11]. [18] Also generalized that cracks heal themselves with the help of ongoing hydration reactions of anhydrous cementitious materials resulting in further calcium-silicate-hydrate gels and calcium carbonate precipitation mechanisms and with the need of air and water as well.

[26] Described that the presence of water is the most critical environmental factor in engaging Engineering Cementitious Composites (ECC) healing in terms of cementicious matrix as a means of preventing crack propagation. [14] Also confirmed that water curing is the best way for bacteria-based self-healing concrete.

3.5. Dosage, Size & Dispersion of Capsules

Chemical healing process is the artificial healing by injecting chemical compounds into the crack for healing. The self-healing by encapsulation which is a part of chemical self-healing mechanism, has the potential to deliver higher quality self-healing, in terms of the wider range of crack width that can be healed and faster response to cracking in the matrix [17]. [15] Summarized the comparison between different self-healing strategies. They stated the possible effectiveness of self-healing under multiple damage events through encapsulation even though it results in negative effect on the mechanical properties of the cement matrix if too many hollow fibres or capsules adopted.

Capsules are provided to the concrete mix to upswing the self-healing capacity of the cracked concrete. In doing so, adding the right dosage of capsule and is proper distribution inside the concrete mix is very important. One of the most challenging things during the design of the concrete mix is the right dosage of self-healing capsules. Addition of higher dosage than required would result a negative effect on the initial strength of the concrete. On the other extreme, adding a smaller dosage than required decease the probability of a crack passing through a capsule and opening [24].

Capsule based self-healing materials sequester a healing agent inside discrete capsules. When the capsules are ruptured for example by damage, the self-healing mechanism is triggered through the release and reaction of the healing agent in the region of damage [12].

A mathematical model of the bacterial self-healing of a crack in concrete is developed and implemented for the two-dimensional case. The model allows to consider the combinations of parameters (crack width, capsule size, etc.) in order to analyse the efficiency of self-healing concrete [21]. [7] Investigated the effects of capsules on self-healing efficiency. In their study the probability of a crack hitting capsules with a certain diameter was calculated by Monte Carlo simulations. Finally, they determined the self-healing efficiency as the function of the dosage of capsules in the account of effects of the size of capsules. [9] Also studied the relationship between self-healing efficiency and the dosage of capsules with different size. They realized that the self-healing efficiency increases with the increase of capsules. Their study has shown that the self-healing efficiency is the highest when the capsules size is 6.5 mm and increases by 15% when the dosage of capsules is 3%.

Finally, it was concluded that the increase of positive effect (the capacity of inducing self-healing) of capsules is larger than that of negative effects (decreasing mechanical properties) when the dosage of capsules increases. The following figure 2 shows the relationship between dosage of capsules and self-healing efficiency.

[17] Described that shell thickness and microcapsule size (diameter) are the two main design parameters in the preparation of microcapsules for effective self-healing process. If microcapsule walls are too thin then it would fail during the manufacturing process such as concrete mixing, pouring, and setting. On the other extreme, if capsule shells are too thick it will not allow breaking or fracturing of the shell as the crack penetrates through the microcapsule's plane [24].

[27] Also stated that the capacity of healing agents depends on the amount of capsules dispersed inside the matrix. They realized that the more locally dispersed capsules, the more healing agents will be available and local healing will be more effective. All in all, to secure a successful healing process and overcome the negative effect on initial strength the capsule shell should be thin and rough, and the size should be suitably large to provide sufficient healing agents.

Moreover, capsules can be distributed only in the areas where cracking is more likely to occur and prepare of a desirable shell thickness for good self-healing efficiency [24; 27].

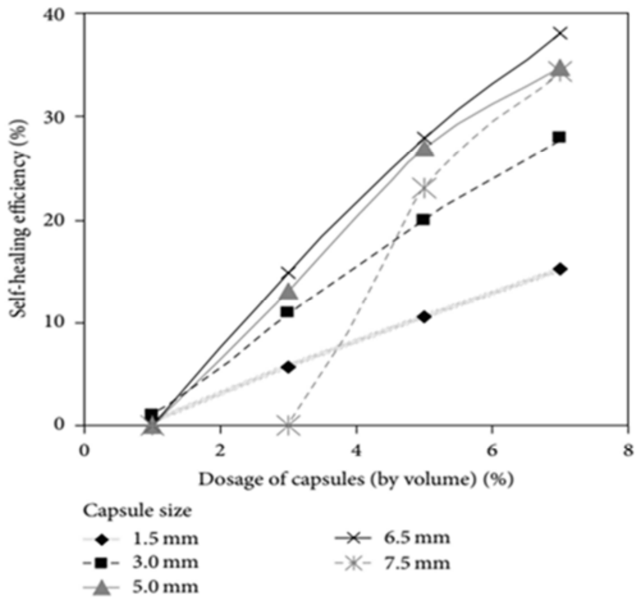


Figure 2. *The self-healing efficiency with different amount of capsules Source: Huang & Ye [9].*

3.6. Healing Agent and Its Viscosity

Several researches have been carrying out by using different healing agents to boost the self-healing efficiency when the crack occurs in concrete or mortar since few years ago. The viscosity of the healing agent is the very important parameter. The viscosity should not be too high to properly flow out of the capsules and to fill the crack. On the other hand, if the viscosity is too low, the agent could leak out of the crack or it could disappear due to absorption by the surrounding matrix [12].

The healing efficiency obtained with microcapsule and fibre encapsulation of the healing agent is relatively low since the amount of healing agent released might be insufficient to fill the damaged area, with cracks that can be up to 200 mm [20]. [1] Experimentally investigated self-healing cement-based materials incorporating extruded cementitious hollow tubes. They were used sodium silicate and potassium silicate as healing agents in terms of their ability to diffuse through cracks and of their ability to restore the initial mechanical properties of mortars. The result of this experiment has shown that best performance was displayed when using cementitious hollow tube containing sodium silicate.

In addition, [6] experimentally proved that crack sealing can be enhanced by the application of superabsorbent polymers. When cracking occurs, superabsorbent polymers are exposed to the humid environment and swell. This swelling reaction seals the crack from intruding potentially harmful substances. In an environment with a relative humidity of more than 60%, samples with 1 m% of superabsorbent polymers showed healing gives the best results and the superior self-sealing capacity.

3.7. Concrete Materials Composition

[13] Identified some factors that affect the self-repairing capacity. They generally realized that the characteristics of concrete beam materials affect the self-repairing capability. They also experimentally investigated the stiffness of concrete beam with different materials such as the stiffness of beam made from pouring both clays and silicones and both epoxy cements and mortars. Finally, it was concluded that the characteristics of material have certain level of effect on it. The self-repairing capacity of concrete beam is low with flexible materials, and in order to achieve full crack recovery the current intensity must be large enough. They presented the crack recovery with these materials in figure as shown below.

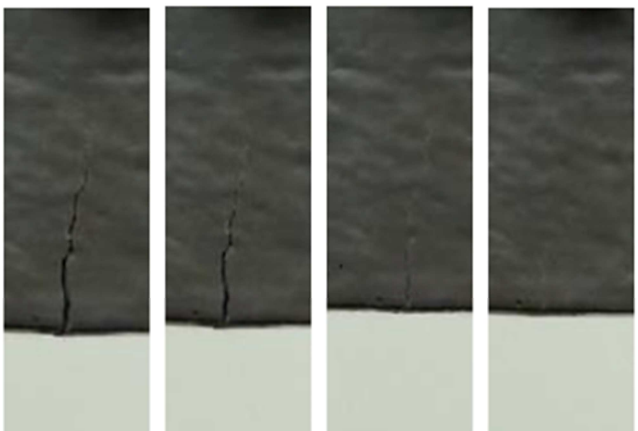
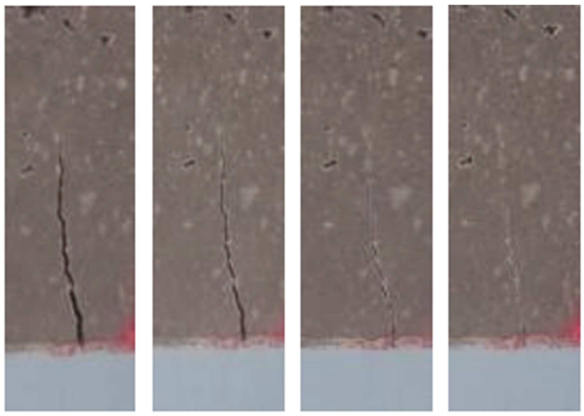


Figure 3. *Crack closure of concrete beam made from pouring epoxy cements and mortars.*



Source: Sun et al [13]

Figure 4. *Crack closure of concrete beam made from pouring both clays and silicones.*

Various types of fiber reinforced cementitious composites (FRCCs) were experimentally studied by Nishiwaki et al, to evaluate their self-healing capabilities regarding their water-tightness and mechanical properties. Tensile loading test was used to induce cracks in the FRCC specimens. In this study the specimens were immersed in static water for self-healing. It was determined that the FRCCs containing synthetic fiber and cracks of width within a certain range (<0.1 mm) exhibited good self-healing capabilities regarding their water-tightness using water permeability and reloading tests [25].

[18] Also studied the effectiveness of self-healing in Engineered Cementitious Composites (ECCs) with micron-size cracks. They stated that having cracks with widths at micro-meter levels allows them to add special attributes such as self-healing to ECC material. They have been proved that ECC material can recover by 85% depending on the test method utilized in the evaluation of self-healing rate. It can be realized that both ECC and FRCC exhibit good self-healing efficiency for micron-size cracks.

3.8. Expansive Agents & Mineral Admixtures

The use expansive agent and mineral admixtures are also results in good healing efficiency [15]. Applying mineral admixtures in concrete helped seal the cracks and reduce water leakage 15; 16]. [13] Proved the properties of shape memory materials alloy affect the self-repair ability. They embedded shape memory alloy (SMA) wires in concrete beam and found that the beam with SMA wires possesses good self-repair capability. Moreover, they realized that the beam crack slags will be stuck in the cracks and will hinder crack closure, which also has influence on crack closure. [10] Studied the changes in the physical properties and structure of the surface and internal sections of cracks during composite self-healing by cementitious composite materials and synthetic fibers. This study examined the effective dispersion of cracks in the cementitious composite materials reinforced with synthetic fiber, and demonstrated self-healing capacity of cracks is limited to 0.3 mm width.

The addition of different materials to concrete change the concrete matrix and can restrict the crack width. Some of the additives and their effects are explained in the table 1 below. The effect of adding minerals such as silica based materials, chemical expansive agents, swelling minerals and crystalline components was further experimented on mortar specimens with the load causing micro-cracks their average width of 0.05 mm. The test results showed that most of the crack were self-healed self-healing within the first 7 days. In another study, using mineral admixture cracks widths of 0.15 mm and 0.22 mm were completely healed within a period of 3 and 33 days respectively [16].

***Table 1.** Additives and Their Effects.*

Additives	Effect
Engineered cementitious composite (ECC)	- The use of fiber reinforced strain hardening engineered cementitious composite (ECC) can restrict the crack width and thus promote autogenous healing. - Multiple cracks form in the ECC matrix and the maximum crack width remains below 60 µm.
Steel cord (SC)	- SC fibers showed minor crack closing efficiency as the steel started to corrode inside the crack
Poly vinyl alcohol (PVA) fibers	- Induced the highest healing efficiency through promotion of deposition of crystallization products, as hydroxyl groups, attached on the fiber structure, attracted calcium ions.
PVA fibers with embedded brittle tubes containing repair agent	- The fluid repair agent chemically reacted with silica particles in the concrete matrix to form crystals and results in high healing efficiency when cracks became larger than 200 µm.
Shape memory alloys (SMA)	- Crack widths do not not restricted at the moment cracks develop but at the time of unloading, cracks are closed due to the super elastic behavior of embedded SMA.

Source: Tittelboom and Belie [12]

3.9. Ca^{2+} Ions Concentration

Sufficient concentrations of carbonate ions or bicarbonate ions and free dissolved calcium ions, play an important role to exhibit healing mechanisms [23]. As far as optimal condition of self-healing is concerned, [10] confirmed that applying conditions of saturated $Ca(OH)_2$ solution plus CO_2 micro-bubbles, which supply the Ca^{2+} and CO_{3^-} necessary for self-healing, is effective in promoting self-healing performance. This is due to the generation of the self-healing substance and an increase in the quantity of precipitation available for crack reclamation. In the study of biological process of self-healing of cracks, [5] investigated the self-healing potential of early age cracks in cement-based materials incorporating the bacteria which can produce carbonic anhydrase. They also addressed that the transportation of CO2 and Ca^{2+} controlled the self-healing process. The computer simulation analyses revealed that self-healing process and mechanism of microbiologically precipitation induced by bacteria and the depth of precipitated $CaCO_3$ could be predicted base on valid Ca^{2+}. The depth of precipitated $CaCO_3$ declined with the increasing of crack width, which coincided with the self-healing efficiency under different cracks width. A certain amount of $CaCO_3$ precipitated on the surface of cracks, finally closed the crack surface, and obstructed the self-healing in depth of crack. [8] Also experimentally investigated the effect of Ca^{2+} ions on self-healing. They added $Ca(OH)_2$ into water as a healing agent so as to explore and compare the self-healing behaviour of cracks with saturated $Ca(OH)_2$ solution with that with distilled water. It was found that self-healing progresses faster in saturated $Ca(OH)_2$ solution than that in water. This reveals that the higher concentration of Ca^{2+} ions can improve the self-healing efficiency.

3.10. Healing Mechanism

There are several natural processes that can block the cracks in concrete. Most of natural self-healing mechanisms can only partially fill the entrance of some cracks and cannot completely fill the cracks. Among the different natural self-healing mechanisms, formation of calcium carbonate and calcium hydroxide are the most effective methods to heal concrete naturally [2].

4. Conclusion and Recommendation

From the above review on factors that affect the self-repairing efficiency of self-healing smart concrete, some of the important conclusions are drawn. In general, it can be concluded that formation of $CaCO_3$ or $Ca(OH)_2$ in natural process, the dosage of capsule and type of healing agent in chemical process, and the type of bacteria and precipitation of $CaCO_3$ in biological process of self-healing are the most vivid factors in dealing with the self-healing capacity of cracked concrete structures. It can be summarized as the self-healing efficiency increases with the increase of capsules, narrower crack, early age of crack, optimum amount of water, thin shell of capsules and higher concentration of Ca^{2+} ions. In order to realize self-healing efficiency and reliability, it is very essential to take care in opting a healing agent and a suitable approach for a specific application. All in all, there is lack of work in standardization and/or common optimum point for practical application, insufficient study in relation to cause of crack and ensuring long term efficiency throughout the life of the structure. The information presented in this paper are supposed to be quite relevant for civil, biotechnologists and bioprocess engineers to insight more about the aforementioned critical factors for the betterment of real world practical application.

References

[1] Alessandra Formia, Sara Irico, Federica Bertola, Fulvio Canonico, Paola Antonaci, Nicola Maria Pugno and Jean-Marc Tulliani (2016): Experimental analysis of self-healing cement-based materials incorporating extruded cementitious hollow tubes. Journal of Intelligent Material Systems and Structures. Vol. 27 (19) 2633–2652. jim.sagepub.com

[2] Amirreza Talaiekhozani, Muhd. Zaimi Abd Majid, Mohamad Ali Fulazzaky and Chew Tin Lee (2014): A Review of Self-healing Concrete Research Development. Journal of Environmental Treatment Techniques, Volume 2, Issue 1, Pages: 1-11.

[3] Baoguo Han, Yunyang Wang, Sufen Dong, Liqing Zhang, Siqi Ding, Xun Yu and Jinping Ou (2015) Smart concretes and structures. A review. Journal of Intelligent Material Systems and Structures, Vol. 26 (11) 1303–1345.

[4] Chintalapudi Karthik, Rama Mohan Rao (2016): Properties of Bacterial-based Self-healing Concrete- A review. International Journal of ChemTech Research CODEN (USA): IJCRGG ISSN: 0974-4290 Vol. 9, No. 02 pp 182-188.

[5] Chunxiang Qian, Huaicheng Chen, Lifu Ren and Mian Luo (2015) Self-healing of early age cracks in cement-based materials by mineralization of carbonic anhydrase microorganism. Frontiers in Microbiology. Original Research. doi: 10.3389/fmicb.2015.01225.

[6] Didier Snoeck, Kim Van Tittelboom, Stijn Steuperaert, Peter Dubruel and Nele De Belie (2014) Self-healing cementitious materials by the combination of microfibres and superabsorbent polymers. Journal of Intelligent Material Systems and Structures 2014, Vol 25 (1) 13–24. DOI: 10.1177/1045389 X12438623.

[7] Haoliang Huang and Guang Ye (2013): The effects of capsules on self-healing efficiency in cementitious materials. 2nd International conference on Microstructural-related Durability of Cementitious Composites. ISBN: 978-2-35158-129-2.

[8] Haoliang Huang and Guang Ye (2015): Self-healing of cracks in cement paste affected by additional Ca^{2+} ions in the healing agent. Journal of Intelligent Material Systems and Structures. Vol. 26 (3) 309–320. jim.sagepub.com.

[9] Haoliang Huang and Guang Ye (2016) Numerical Studies of the Effects of Water Capsules on Self-Healing Efficiency and Mechanical Properties in Cementitious Materials. Hindawi Publishing Corporation Advances in Materials Science and Engineering. Article ID 8271214, 10 pages.

[10] Heesup Choi, Masumi Inoue, Sukmin Kwon, Hyeonggil Choi, and Myungkwan Lim (2016) Effective crack control of concrete by self-healing of cementitious composites using synthetic fiber. Journal of Materials 2016, 9, 248; doi: 10.3390/ma9040248 www.mdpi.com/journal/materials.

[11] J. Y. Wang, H. Soens, W. Verstraete, N. De Belie (2014) Self-healing concrete by use of microencapsulated bacterial spores. Cement and Concrete Research 56 (2014) 139–152.

[12] Kim Van Tittelboom and Nele De Belie (2013) Self-Healing in Cementitious Materials—A Review. Journal of Materials 2013, 6, 2182-2217; doi: 10.3390/ma6062182.

[13] Li Sun, Dezhi Liang, Qianqian GAO, and Jianhong Zhou (2013) Analysis on Factors Affecting the Self-Repair Capability of SMA Wire Concrete Beam. Hindawi Publishing Corporation – Journal of Mathematical Problems in Engineering. Volume 2013, Article ID 138162, 6 pages, http://dx.doi.org/10.1155/2013/138162.

[14] Mian Luo, Chun-Xiang Quan and Rui-Yang Li (2015) Factors affecting crack repairing capacity of bacteria-based self-healing concrete. Article in Construction and Building Materials 87. DOI: 10.1016/j.conbuildmat.2015.03.117.

[15] Min Wu, Björn Johannesson, and Mette Geiker (2012) A review: Self-healing in cementitious materials and engineered cementitious composite as a self-healing material. Construction and Building Materials 28 (2012) 571–583.

[16] Mohamed Hussein Fawzy (2016) Effectiveness of Self-Healing in Repair of Strategic Concrete Structures "A Simplified Model". MSc Theses. The American University in Cairo School of Sciences and Engineering.

[17] Mukunda Madhab Borah and Nayanmoni Chetia (2016) A Review on Self-Healing Concrete. International Conference on Advanced Material Technologies (ICAMT)-2016.

[18] Mustafa Şahmaran, Gürkan Yildirim, Rezhin Noori, Erdogan Ozbay and Mohamed Lachemi (2015) Repeatability and Pervasiveness of Self-Healing in Engineered Cementitious Composites. ACI Materials Journal, 112 (4).

[19] Salmabanu Luhar, Suthar Gourav (2015) A Review Paper on Self-Healing Concrete. Journal of Civil Engineering Research 2015, 5 (3): 53-58.

[20] Sandra S Lucas, Max von Tapavicza, Annette M Schmidt, Ju ¨rgen Bertling and Anke Nellesen (2016) Study of quantification methods in selfhealing ceramics, polymers and concrete: A route towards standardization. Journal of Intelligent Material Systems and Structures. Vol. 27 (19) 2577–2598.

[21] Serguey V Zemskov, Henk M Jonkers and Fred J Vermolen (2014): A mathematical model for bacterial self-healing of cracks in concrete. Journal of Intelligent Material Systems and Structures. Vol 25 (1) 4–12. DOI: 10.1177/1045389 X12437887. jim.sagepub.com

[22] Sini Bhaskar (2016) Self-Healing Bacterial Cementitious Concrete Composites: Development and Performance Evaluation. PhD Dissertation. Department of Civil Engineering, Ryerson University. Toronto, Ontario, Canada.

[23] S. Van Der Zwaag, N. H. Van Dijk, H. M. Jonkers, S. D. Mookhoek 1 and W. G. Sloof (2009) Self-healing behaviour in man-made engineering materials: bioinspired but taking into account their intrinsic character. Philosophical Transactions of the Royal Society A (2009) 367, 1689–1704. doi: 10.1098/rsta.2009.0020.

[24] Svenja Kristin Reinke (2012) Polyurea/Polyurethane Microcapsules Based Self-healing Concrete. MSc Theses. University of Rhode Island.

[25] Tomoya Nishiwaki, Sukmin Kwon, Daisuke Homma, Makoto Yamada and Hirozo Mihashi (2014) Self-Healing Capability of Fiber-Reinforced Cementitious Composites for Recovery of Water-tightness and Mechanical Properties. Journal of Materials 2014, 7, 2141-2154; doi: 10.3390/ma7032141.

[26] Yingzi Yang, En-Hua Yang and Victor C. Li (2011) Autogenous healing of engineered cementitious composites at early age. Cement and Concrete Research 41 (2011) 176–183.

[27] Yongjing Wang, Duc Truong Pham and Chunqian Ji (2015) Self-healing composites: A review. Cogent Engineering (2015), 2: 1075686.