

Development and Performance of Bacterial Self-healing Concrete - A Review

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Self-healing concrete is a type of concrete that able to autogenously fill up cracks without any intervention from external sources. Various methods of producing a self-healing concrete are available in the previous researches but using bacterial as self-healing agent enables the concrete to be environmentally friendly. This paper reviews the elements that are important in developing a bacterial self-healing concrete. The elements include type of bacteria and the criteria needed in selecting a bacteria as source of healing agent. Most of the researches used *Bacillus* genus but quite a few have produced bacterial self-healing concrete from non-axenic bacteria. There are also various bacteria and nutrients concentration being incorporated inside self-healing concrete which resulted in wide range of performance. Most of the researches indicates that addition of bacteria with or without nutrients affect mechanical properties of concrete negatively. However some of the studies indicates the opposite result on mechanical strength. Hence, the influence of bacterial and nutrient addition on concrete strength would also depends on the method of incorporating them. Permeability of concrete could also be improved by the addition of self-healing bacteria. The permeability has been measured in term of chloride migration, gas permeability and carbonation which indicates enhancement compared to plain cement mortar.

1. Introduction

Application of concrete as construction material are becoming wider. Variety of structure is built using concrete material due to its abundance availability and high workability. Concrete also produces a strong material especially in term of compressive strength. This broad application of concrete in various structure elements require periodically inspection and maintenance. Concrete possess brittleness that would likely experience cracking due to creep, shrinkage or overstressed. Maintenance work should be carried out on these defects to avoid further damage to the whole structure. Cracks in concrete will allow penetration of detrimental substance that may cause carbonation in concrete or corrosion to the embedded steel reinforcement. The permeability of substances would also lessen the aesthetic value of structure. The maintenance work that need to be carried out could be complicated should the cracking occurred at area with limited access like bridge spanning over broad river or live traffic. The financial cost of repairing such structure would be expensive. The work is also very hazardous to the maintenance worker and people in the vicinity. Concrete with ability to fill the gap due to crack autogenously would solve this maintenance issue. The cost can be reduced especially in term of periodical inspection work. Concrete that can fill the crack autogenously is considered as self-healing concrete. Self-healing concrete has been produced previously by producing concrete with excessive portion cement in the overall mixture. The excess portion of cement would be un-hydrated and will perform chemical reaction with water that penetrate the hardened concrete through cracks to produce new cementitious bonding. Besides that, chemical substances have also been used as self-healing agent in the concrete. One of the



chemical product is sodium silicate solution which form C-S-H gel by reacting calcium hydroxide inside the concrete [1]. However, the healing agent is chemically synthesized and not environmentally friendly. Recent researches provide alternative solution to chemically synthesized healing agent with bacterial as healing agent. Bacteria of genus *Bacillus* could precipitate calcium carbonate (CaCO_3) to seal the cracks from inside the concrete. Bacterial self-healing agent was able to reseal crack of 0.3mm in 20 days [2]. The use of bacteria as self-healing agent has started since Jonkers et al (2010) incorporated the bacteria during mixing of concrete rather than using it as repair material such as in Ramachandran et al.(2001) [3] [4]. The study indicates the ability of this bacteria to survive high alkalinity of concrete environment.

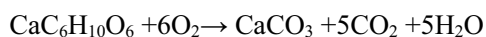
2. Self-healing Concrete and Factors Affecting the Healing Ability

2.1 Type of Bacteria Used as Self-healing Agent

Most of the studies by Wang Jianyun employs *Bacillus sphaericus* LMG 22557 as the bacteria of self-healing agent while Jonkers et al (2010) used *Bacillus pseudofirmus* DSM 8715 and *B. cohnii* DSM 6307 in the study [3] [5] [6] [7]. Another strain of *Bacillus* used is *Bacillus Megaterium* which also prove viable as healing agent in concrete [8] [9]. Based on these studies, bacteria from genus *Bacillus* has been used widely and proving the ability to survive high alkalinity of concrete medium. These studies also show the capability of type *Bacillus* bacteria to precipitate CaCO_3 after being activated by water. However most of the researches used laboratory produced of isolated bacterial strain. Reliance on laboratory supplied bacterial strain would increase the cost of producing self-healing concrete. Another study used non-axenic bacteria that were grown using sub-stream of vegetable plant as nutrient source [10]. The study shows that even a non-axenic bacteria can perform as self-healing agent with less cost compared to laboratory obtained bacteria. The bacteria were able to seal crack of 0.45mm width in 28 days. This is comparable to bacteria of genus *Bacillus* that sealed crack of 0.3mm in 20 days [2].

2.2 Bacteria Concentration

The performance of sealing not only depends on the type bacteria but also the amount bacteria and nutrient added to the concrete. The amount of bacteria spore incorporated into the concrete may increase the rate of crack-sealing but nutrients are needed to produce CaCO_3 after spore being activated by water. The amount of nutrients will limit the amount of CaCO_3 as in the following reaction [3]:



In a research by Wang et al. (2014), the amount of spores incorporated in 1m^3 concrete mixture is within 2% of hydrogels where each hydrogel contain 10^9 spores/ml [6]. This mixture resulted in 80-90% healing of 0.3mm crack width and 30-50% healing of 0.3-0.7mm crack width in 28 days. The hydrogel that serves as healing agent also contain nutrient and urea to assist in precipitating CaCO_3 . A study that used *Bacillus Megaterium* as the bacterial healing adopted 10^5 cells/ml solution in the concrete mix composition [9]. From the mixture, about 186×10^5 cell/ m^3 was used in the concrete composition. Another study used almost the same concentration of 10^8 spores/L and resulted almost the same healing percentage as Wang et al (2014) [12]. The study shows that the bacteria solution of 10^8 spores/L which impregnated into Light Weight Aggregate (LWA) recovered 69% of water tightness within 28 days. The width of crack healed was not measured but it was comparable to 0.3-0.7mm crack width as recorded by Wang et al (2014). The amount of spores impregnated is equal to 5% of cement in the total concrete mixture. Study by Da Silva et al (2015) found that addition of bacteria self-healing agent caused reduction in compressive strength of concrete [10]. Addition of 0.5-1.0% of self-healing agent of Cyclic EnRiched Ureolytic Powder (CERUP) caused the least reduction of compressive strength. Addition of 3-5% of CERUP reduced the compressive strength of 28 days concrete by 35-52%. In conclusion, amount of self-healing agent should be limited to 1-2% of cement content in concrete mixture to reduce negative impact on concrete mechanical strength. The amount of spores incorporated in concrete mixture of 10^8 spores/L could also produce the same healing effect as higher concentration of spores in mixing solution. This may be due to the ability of bacteria to reproduce once being activated from spores.

2.3 Nutrient Types and Concentration

Type of nutrient accompanying bacteria also affect the outcome. A study that used calcium lactate of 0.5% of cement weight in the concrete mixture indicates the viability of calcium lactate as deposition agent compared to urea [3]. Hydrolysis of urea could produce massive amount of nitrogen and increase the probability of corrosion on steel reinforcement [3]. The result of the study proved the mineralization of 20-80 μ m sized particle on the cracked concrete surface. A research of using bio-reagents containing urea and calcium nitrate also shows the viability of mineralization process in bacterial self-healing concrete [6]. The amount of urea and calcium nitrate used in the study is 0.9g and 1.2g respectively. The amount of urea and calcium nitrate used in concrete mixture of this study is higher compared to Jonkers et al (2010) which is about 1.2% of cement content. The result was higher crack filling efficiency compared to sample with no nutrient as the maximum crack width sealed was 0.5mm. Ramin A et al (2016) used bacterial broth medium culture which contain 80g/l of calcium lactate and 20g/l of urea. The amount is lower compared to Tziviloglou E et al (2016) which used 200g/l of calcium lactate in the bacterial mixing solution. The effect of nutrient such as calcium lactate, calcium nitrate and urea is to form Calcium Carbonate due to bacterial metabolic conversion [3]. Most of the researches show white particles precipitation on crack surface and this is aligned with the ability of carbonate precipitating bacteria. This is further proved by a study that immersed cracked mortar in calcium lactate and calcium gluconate solution [12]. The result indicates that calcium lactate and calcium gluconate increased the self-healing kinetic of mortar by increasing the availability of calcium and carbonate ion in the cracks.

3. Method to Produce a Self-healing Concrete

There are studies that embedded the bacteria with or without nutrient into concrete directly. One of the way is by replacing fresh water portion in concrete mixture with bacterial solution [8] [9]. This method used bacterial cell rather than spore which further simplify the embedding process. However, use of an active bacterial cell state rather than dormant state of spore may cause early conversion of calcium source during mixing of concrete. This may reduce the healing ability of bacteria concrete due to depleted calcium source once the concrete has hardened. Krishnapriya et al (2015) reported bacteria concrete precipitated white particles at 70 days of specimen and full crack healing was achieved at 81 days of concrete age despite using active bacteria cell in the concrete. An advantage of embedding live bacteria is that the microstructure of concrete can be improved due to ongoing precipitation by the bacteria [4]. This is indicated by increase in compressive strength at 28-days compared to 7-days of age. An almost similar to this method is investigated by Jonkers et al (2010) but by using bacteria spore incorporated into the mortar specimen. The study indicates that most of the spores were crushed in concrete after 28 days of age [3]. This was due to hydration process in concrete that reduced the pore volume and led to crushing of embedded spores. This reduced the mineral-forming capacity of bacterial cements. Therefore, a protective vehicle is necessary to protect the spores inside concrete.

One of the method is to impregnate light weight aggregate (LWA) with spores along with calcium source and nutrient. LWA which is porous will serves as vehicle to transport bacteria self-healing agent into concrete and protect it from crushing. LWA of expanded clay particle has been investigated and resulted in continuous healing activity from 28 to 56 days [11]. However, the replacement of sand with expanded clay particles resulted in lower concrete compressive strength by 40%. Another type of aggregate used in a study is diatomaceous earth which has pore sizes ranging from 0.1-0.5 μ m [5]. The study indicates profound healing capacity which represented by capillary water absorption at crack. Concrete with bacillus-infused diatomaceous earth reduced absorption by 50% compared to concrete with the bacterial aggregate. Other research by Chen et al (2016) using ceramsite also reported reduction in permeability [13]. This method utilized the porous network of LWA and use simple procedure.

Another method is to change the bacteria and calcium source from solution to powder form. This method did not use any protective vehicle for bacteria hence it is similar to direct method. Da Silva et al (2015) produced CERUP by air drying and filtration followed by grinding to produce particle size below 500 μ m (Figure 1) [10]. Wang et al (2014) dried the bacteria spore and nutrient by freeze drying method [6]. The spore and nutrient were encapsulated into hydrogel and then injected between glasses before being freeze grinded and freeze drying to form powder. Hydrogel serves as water retainer to assist in bacteria metabolic conversion of calcium source. This allow self-healing to occur with minimal water availability. A realistic condition of concrete would not have abundance of water unless it is a submerged structure. The study indicates of 40-90% healing ratios with maximum healed width of 0.5mm even under realistic wet-dry cycle [6]. The cycle consists of 1 hour of sample immersion in

water and 11h of dry condition. The amount of water introduced to sample is lower by 22 hours compared to study by Tziviloglou et al (2016) yet achieving a comparable result. However, the addition of hydrogel in the concrete resulted in delay hardening of concrete. This has caused sample to be demoulded only after 48hours in mould. Hydrogel may have interrupted the formation of C-S-H gel which caused retardation in concrete setting. Coating of self-healing agent that contains hydrogel, spores and nutrient may prevent the retardation effect.

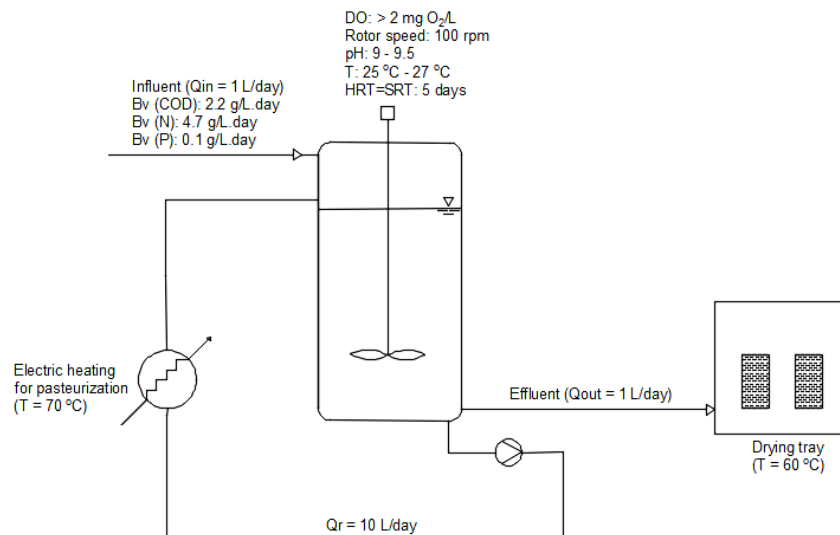


Figure 1. Schematic diagram showing the process of producing CERUP at 5L scale [10].

4. Properties of Self-healing Concrete

4.1 Compressive Strength of Bacterial Self-healing Concrete

Incorporation of self-healing agent in concrete will affect its microstructure and this is implicated on its mechanical strength. Concrete is classified based on its compressive strength which served as design parameter for structural application. Previous studies employs various type of concrete consist of cement mortar, concrete with aggregate which was based on Design of Experiment (DOE) and this had resulted in wide range of compressive strength. Figure 2 shows the results of compressive strength based on nine different researches. Most of the results are within normal strength concrete which is between 10 – 40MPa. The highest value was recorded by Ramachandran et al (2001) which is more than 60MPa at 28 days of age [4]. The study embedded the bacteria by directly mixing the solution containing bacteria with cement and sand. However, the bacterial solution used was phosphate rather than water which improves the strength of concrete. The ratio of phosphate solution to cement is 0.49 which is the normal ratio of water-to-cement used for concrete. This is comparable to Krishnapriya et al (2015) that used potable water with 0.55 water-to-cement ratio. The study recorded a 28-days compressive strength of 38.3MPa. The value is lower compared to Ramachandran et al (2001) even though the ratio of aggregate-to-binder was higher by 58%. The low result of compressive strength may be due to the quality of microstructure produced. Phosphate solution improve the strength of binder compared with potable water and the use of fine aggregate increased the compactness of concrete microstructure. The aggregate used by Krishnapriya et al (2015) comprised mix of coarse and fine aggregate while Ramachandran et al (2001) contained only sand [8]. Andalib et al (2016) also used the same method as Krishnapriya et al (2015) and the compressive strength is congruent with the latter [9].

Another method that also used direct mixing of bacterial self-healing agent is Jonkers et al (2010). The study produced bacterial self-healing concrete with 49MPa of compressive strength at 28-days of age [3]. However, the water-to-cement ratio is the lowest compared to previously mentioned studies which is 0.4. The concrete composed of only cement, water and bacterial self-healing agent. This indicates that the strength is contributed by binding material only which is cement. Reduction in water-to-cement ratio will improve the binding material by reducing the pore volume. This lead to increase in compressive strength of concrete. However, reduction of pores in concrete microstructure may reduce the ability to autogenous healing in bacterial concrete. Direct mixing of bacteria into concrete positioned the healing agent inside the pore of concrete. As concrete ageing, the pore is reduced that result crushing

of bacteria self-healing agent. This is indicated by reduce in production of large-sized precipitation in bacterial concrete of 28-days compared to 7-days of age. This is in line with the fast decrease in 0.8-1 μ m pore diameter in concrete of 28-days. The number of viable bacteria cells in concrete has also reduced by almost 75% by 22-days of age and no cell was detected at 135-days of age. The issue of bacteria durability in concrete was also observed by another study that recorded decrease in overall trend of concrete compressive strength at 28-days of age compared to 7-days [4]. The study argued that pores were clogged with precipitation hence blocking the flow of oxygen and nutrient to the bacteria. This led to stagnant or reduction of compressive strength due to reduce production of precipitation by viable bacteria.

Incorporation of bacterial healing agent in concrete by powder form resulted in compressive strength of about 51MPa [10]. Mix composition of the concrete specimen is almost the same with Krishnapriya et al (2015) with water-to-cement ratio of 0.5 and the aggregate-to-binder ratio of 3.0. However, the different method of incorporating bacteria resulted in higher compressive strength of concrete.

Another method of producing bacterial self-healing concrete resulted in lower compressive strength which is 27MPa at 28-days of concrete age [11]. This method used LWA as protective vehicle for bacteria and 0.5 of water-to-cement ratio. Although the water-to-cement ratio is close to previously mentioned studies, the reduction in compressive strength is due to incorporation of LWA. About 40% reduction of compressive strength based on comparison with reference specimen that used fine sand as aggregate. Further impregnation of bacteria into LWA only affected the early strength as the 28-days compressive strength was similar with empty LWA.

Addition of partial cement replacement or recycled material were also investigated along with bacterial self-healing concrete. Chahal et al (2016) recorded 38.2MPa of compressive strength with 10% silica fume addition and 10^5 cells/ml of *S. Pasteurii* bacteria. The compressive strength had increment even after 28 days as recorded at 91-days to be 44MPa [14]. This was due to bacteria activity inside concrete that precipitated CaCO_3 which resulted in strength increment overtime. Another study that incorporated fly ash along with *Bacillus Megaterium* resulted in 27.6MPa which is 19% increment compared with concrete with fly ash and bacteria [15]. Use of rice husk ash (RHA) with bacteria in concrete recorded about 40MPa of compressive strength [16]. RHA was replacing cement content in mixture by 10% with water-to-cement ratio of 0.5. This is comparable to Bang et al (2011), Achal et al (2011) and Andalib et al (2016) [16] [17] [9]. This study used mixture of crushed stone and sand as the aggregate which is almost the same composition of all the researches mentioned [16].

In conclusion, the inclusion of bacterial self-healing agent in concrete mixtures alter the microstructure of concrete and reflected in its compressive strength. Bacterial self-healing agent is also compatible to be mixed with partial cement replacement additive. Adoption of inferior material such as LWA to transport bacteria inside the concrete will give negative impact on the compressive strength. However, protecting the bacteria from crushing is important to ensure the autogenous healing ability of concrete. Hence, certain reduction should be expected in incorporation of bacterial self-healing agent. Therefore, application of ultra-high performance concrete (UHPC) with bacterial self-healing agent may produce a self-healing concrete with practical strength and autogenous healing ability that does not degrade overtime. However, the previous researches indicate the ability of bacterial self-healing concrete to achieve compressive strength of more than 60MPa.

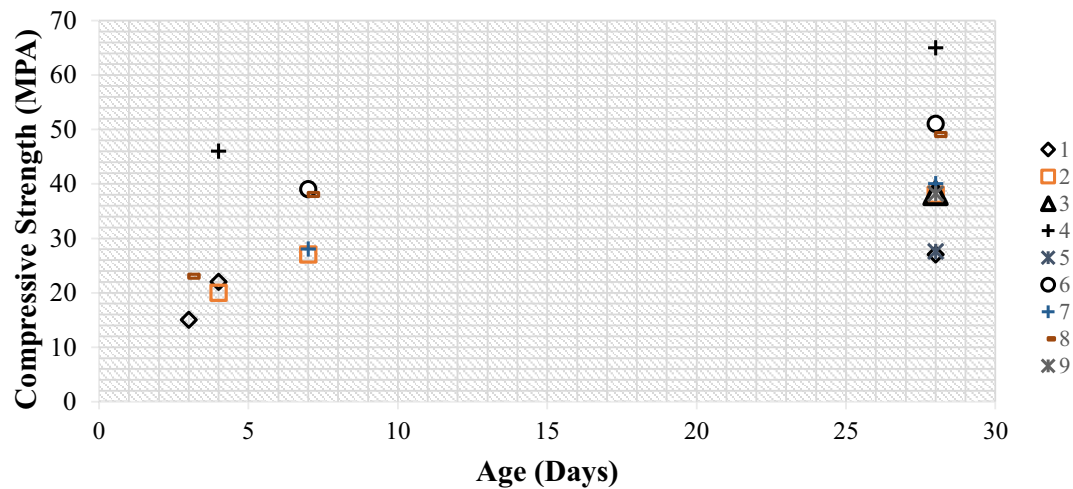


Figure 2. (1) Tziviloglou et al (2016) [11], (2) Andalib et al (2016) [9], (3) Krishnapriya et al (2015) [8], (4) Ramachandran et al (2001) [4], (5) Achal et al (2011) [17], (6) Da Silva et al (2015) [10], (7) Raffat et al (2016) [15] (8) Jonkers et al (2010) [3], (9) Chahal et al (2012) [14]

4.2 Crack Remediation

Performance of autogenous healing is done by visually measuring the width of crack healed or measuring the decrease in permeation rate of cracked concrete. Cracks were created at 28 days of age and then were cured in full water immersion or wet-dry cycle. Wet-dry cycle consist of alternating exposure of cracked area to water which closely simulate the actual condition of concrete structure as compared to full water immersion. Figure 3 shows comparison of three different studies regarding the performance of bacterial concrete in crack healing. Overall, bacterial self-healing concrete recorded 0.45-0.54mm of healed width. Da Silva et al (2016) recorded maximum width of 0.45mm healed under full water immersion [10]. Highest width healed was recorded using LWA containing *Bacillus Subtilis* in concrete [18]. The maximum width healed is about 0.53mm. Under lower duration of immersion, bacterial concrete managed to heal maximum crack width at 0.5mm [6]. However the scarcity of water exposure caused the percentage of healing after 28 days of cycle to be in the range of 40-90%. Longer cycle may increase the percentage. Tziviloglou et al (2016) used longer immersion of specimen by 11 hours compared to Wang et al (2014) but also did not achieved 100% crack healing [11] [6]. However, after 56 days of wet-dry cycle, the sample achieved close to 100% of healing in term of water tightness.

his indicates that exposure of water to crack area influence the healing efficiency of bacterial concrete.

his is shown by researches that managed to fully healed visible cracks by maximizing the exposure of water to specimen. Krishnapriya et al (2015) reported fully healed of visible cracks in bacterial concrete by 81 days of fully immersion [8].

Crack healing performance has also been quantify by reduction of water permeation overtime. Combination of ceramsite, brewer yeast and *Bacillus Mucilaginous* in concrete able to reduce water permeability coefficient from $7.9-8.3 \times 10^{-5} \text{m/s}$ to $0.8 \times 10^{-7} \text{m/s}$ after 49 days of healing period [13]. The reduction is almost 100% and in agreement with Tziviloglou et al (2016) that achieved 96% of water tightness recovery at 56 days [13] [11]. Even though both researches adopted different method in measuring the permeability, the results indicate the ability of bacterial concrete to autogenously heal crack. A study by Wang et al (2014) reported water permeability of bacterial concrete decreased by 68% which is from $10^{-5}-10^{-4} \text{m/s}$ to $10^{-6}-10^{-7} \text{m/s}$ which is in line result reported by Chen et al (2016) [6] [13]. This result was achieved after 28 days of healing and under 1 hour of water immersion every 12 hour cycle. This is contributed by water entraining substance of hydrogel in the self-healing agent component.

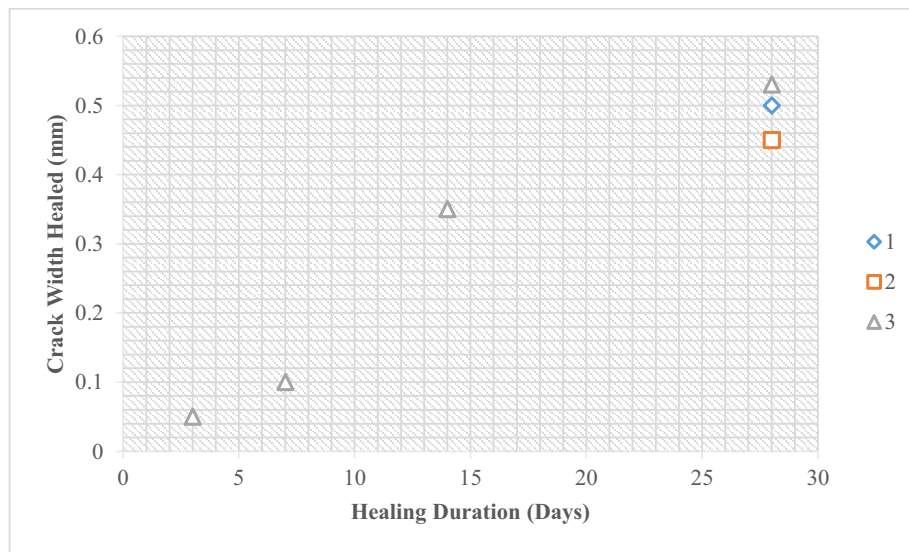


Figure 3. (1) Wang JY et al (2014), (2) Da Silva et al (2014), (3) Wasim et al (2016)

5. Future of bacterial self-healing high performance fibre reinforced concrete composite (HPFRCC)

Autogenous healing ability in concrete is a great advancement in concrete properties. The embedment of bacteria, calcium source and water entraining substance alter the matrix of concrete which affect its properties. Investigation using concrete with lower permeability and high strength is important to produce better bacterial self-healing concrete. High strength concrete mix would make up for loss in compressive strength due to incorporation of bacterial self-healing agent. This would produce concrete with practical strength and self-healing ability.

The precipitation process inside concrete due to bacterial activity need to be further studied. Researches that used urea along with calcium source in self-healing agent caused production of ammonia which will increase the risk of steel corrosion in reinforced concrete [3]. Carbonation resistance in bacterial concrete should also be studied especially after precipitation has occurred or on healed concrete. Calcium carbonate precipitation may also contributed by CaOH inside of concrete. CaOH which is the by-product of concrete hydration process serves as protection against carbonation in concrete. Using the CaOH to produce calcium carbonate will only lower the durability of concrete. Furthermore, durability of bacteria against detrimental substances also need to be investigated. Concrete is not only exposed to demineralized water but also to substances that contain chloride or sulphate. Ingression of this substances may reduce the self-healing ability of bacterial concrete. These parameters need to be explored before practical adoption can be done.

Conclusion

This paper highlight the production processes that have been investigated and the performance that have been measure on bacterial self-healing concrete. In conclusion, any type of bacteria with ability to metabolically convert calcium source into calcium carbonate can be used in producing autogenous healing concrete. It is important to provide protection to bacteria in concrete to sustain the self-healing ability throughout the life span of concrete. Bacterial concrete has lower strength compared to conventional concrete about the same composition. However, bacterial concrete able to fully repair visible crack autogenously compared to conventional concrete.

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