Journal of Civil Engineering Research 2015, 5(3): 53-58
DOI: 10.5923/j.jce.20150503.01

A Review Paper on Self Healing Concrete

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Abstract Crack formation is very common phenomenon in concrete structure which allows the water and different type of chemical into the concrete through the cracks and decreases their durability, strength and which also affect the reinforcement when it comes in contact with water, CO_2 and other chemicals. For repairing the cracks developed in the concrete, it requires regular maintenance and special type of treatment which will be very expansive. So, to overcome from this problem autonomous self-healing mechanism is introduced in the concrete which helps to repair the cracks by producing calcium carbonate crystals which block the micro cracks and pores in the concrete. The selection of the bacteria was according to their survival in the alkaline environment such as B. pasteurii, Bacillus subtilis and B. spharicus which are mainly used for the experiments by different researchers for their study. The condition of growth is different for different types of bacteria. For the growth, bacteria were put in a medium containing different chemical at a particular temperature and for a particular time period. Bactria improves the structural properties such as tensile strength, water permeability, durability and compressive strength of the normal concrete which was found by the performing different type of experiment on too many specimens had varying sizes used by different researchers for their study of bacterial concrete in comparison with the conventional concrete and from the experiment it was also found that use of light weight aggregate along with bacteria helps in self healing property of concrete. For gaining the best result a mathematical model was also introduced to study the stress-strain behavior of bacteria which was used to improve the strength of concrete.

Keywords Bacteria, Bacillus pasteurii, Concrete, Bacillus sphaericus

1. Introduction

Concrete is very good material to resist the compressive load to a limit but if the load applied on the concrete is more than their limit of resisting load, it causes the strength reduction of concrete by producing the cracks in the concrete and the treatment of the cracks in very expensive. Some of the property like durability, permeability ad strength of the concrete structure is also decreases. Due to increase in the permeability of the concrete the water easily pass through the concrete and come in the contact with the reinforcement of the concrete structure and after some time corrosion start due to this strength of the concrete structure will decreases so it will be necessary to repair the cracks [1]. By introduce the bacteria in concrete it producing calcium carbonate crystals which block the micro cracks and pores in the concrete [2]. In concrete micro cracks are always avoided but to some extent they are responsible to their failure in strength.

The selection of the bacteria is depend on the survive capability of bacteria in the alkaline environment. Most of the microorganisms die in an environment with pH value of 10 or above [3].

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Published online at http://journal.sapub.org/jce

Strains of the bacteria genus Bacillus will be found to succeed in high alkaline environment. The bacteria survive in the high alkaline environment that formed spores comparable to the plant seeds. The spores are of very thick wall and they activated when concrete start cracking and water transude into the structure. The pH of the highly alkaline concrete lowers to the values in the range 10 to 11.5 where the bacterial spores become activated. There many bacteria other then Bacillus which are survive in the alkaline environment shown in Table 1 [4].

Table 1. Bacteria other then Bacillus which are survive in the alkaline environment

S.No.	Application	Types of Bacteria
1.	As a crack healer	B. pasteurii
		Deleya Halophila
		Halomonasrurihalina
		Myxococcus Xanthus
		B. megaterium
2.	For surface treatment	B. sphaericus
3.	B. spharicus	Bacilllussubitilis
		B. sphaericus
		Thiobacillus

Different types of bacteria used by different researchers for the study of bacteria such as Jonker et al. [5] used *Bacilllus cohnii* bacteria to precipitate $CaCo_3$, Santhosh et al. [6], Day et al. [7], Bang et al. [8] used *Bacillus pasteurii* while *Bacillus lintus* used by Dick et al. [9].

First, 1 mol of urea is hydrolyzed intracellular to 1 mol of ammonia (Eq. (1)). Carbonate spontaneously hydrolyses to form additionally 1mol of ammonia and carbonic acid (Eq. (2)). These products subsequently form 1mol of bicarbonate and 2mol of ammonium and hydroxide ions (Eq. (3)) and (4)). The last 2 reactions give rise to a pH increase, which in turn shifts the bicarbonate equilibrium, resulting in the formation of carbonate ions (Eq. (5)). [9]

$$CO(NH_2)_2 + H_2O\ NH_2 \longrightarrow COOH + NH_3 \quad (1)$$

$$NH_2COOH + H_2O \longrightarrow NH_3 + H_2CO_3 \quad (2)$$

$$H_2CO_3 \longleftrightarrow HCO_3^-{+}H^- \quad (3)$$

$$2NH_3 + 2H_2O \longleftrightarrow 2NH_4^- + 2OH^- \quad (4)$$

$$HCO_3^- + H^+ + 2NH_4^+ + 2OH^- \longleftrightarrow CO_3^{2-} + 2NH_4^+ + 2H_2O \quad (5)$$

Since the cell wall of the bacteria is negatively charged, the bacteria draw cations from the environment, including Ca_2^+, to deposit on their cell surface. The Ca_2^+-ions subsequently react with the CO_3^{2-}-ions, leading to the precipitation of $CaCO_3$ at the cell surface that serves as a nucleation site (Eqs. (6) andEqs. (7)) [10].

$$Ca^{2+} + Cell \longrightarrow Cell\text{-}Ca^{2+} \quad (6)$$

$$Cell\text{-}Ca^{2+} + CO_3^{2-} \longrightarrow Cell\text{-}CaCO_3\downarrow \quad (7)$$

2. Material and Methods

2.1. Size of Cracks in Concrete

According to the analysis and study by different authors, that the cracks healed by autogenously healing was observed in various sizes such as0.05 mm to 0.87 mm [11], 5 to 10μm [12-13], 100μm [14], 200μm [15], 205μm [15] and 300μm [17].

2.2. Condition of Microorganism and Its Growth

Sookie S. Bang et al., was used *B. Pasteurii* ATCC 11859 for his study of bacterial concrete. Stock culture of *B. pasteurii* were maintained in ATCC 1832 medium containing 10 g trypcase, 5 g yeast extract 4.5 g tricine. 5 g of $(NH_4)_2SO_4$, 2 g glutamic acid and 10 g urea liter^{-1}, pH 8.6, which were filter-sterilized. For solid medium, a final concentration of 1.6% agar autoclaved separately was added later. Growth conditions of broth cultures for calcite precipitation in Urea-$CaCl_2$ medium. All cultures were grown at 30°C [18].

B. sphaericus LMG 225 57 (BCCM, Gent) was used for the study [19, 20]. A highly urease activity, incessant formation of the dense calcium carbonate crystal and a negative zeta-potential was shown by the type of strain. Human diseases are caused by *B. sphaericus*. From the laboratory test it was found that animal saw no measurable health effect that were exposed to large concentration of *B. sphaericus* by multiple routes of exposure. The human beings facing the problem like mild eye and skin irritation *B. sphaericus* come in contact [1, 21, 22].

Liquid culture media consisted of 3 g/L nutrient broth powder (Oxoid N.V., Drongen, Belgium), 2.12 g/L $NaHCO_3$ (VWR International, Leuven, Belgium) and 10 g/L urea (VWR International, Leuven, Belgium). Liquid media were sterilized by autoclaving for 20 min at 120°C. Cultures were incubated at 28°C on a shaker at 100 rpm for 48 h [1].

2.3. Effect of the pH on the Growth of the Bacteria

The bacterial growth is also depending upon the pH. Each microbial species have the different range of pH. The nutrient of different range of pH from 4 to 12 was prepared in test tube. Introducing the bacterial culture into it and growth was observed, the test was carried out by measuring the turbidity of the sample using Photo calorimeter and it was observed that the growth in pH range 7.5-9.0. *Bacillus pasteurii* had the growth in pH range of 7-9 and *Bacillus sphaericus* was 8-9 [23].

2.4. Concrete Sample

Willem De Muynck et al. made a concrete specimen to study and for performing the test on the self-healing nature of concrete by using the ordinary Portland cement CEM 152.5 N, Sand, Aggregate and Water. The mould having the following dimension 150 mm X 150 mm X 150 mm, 150 mm X 150 mm X 600 mm and 160 mm X 160 mm X 70 mm were used. The specimens were placed in the room for 27 days at 20 – 25°C. After 28 days the compression test is done the prepared cube 150 mm X 150 mm X 150 mm and it is found that the mean compressive strength was 55.2 N/mm^2 with a standard deviation of 2.19 N/mm^2 [1].

Henk M. Jonkerset al. Preparing the specimen of the concrete having the following ingredient such as 53 grade cement, Fly ash, Fine and Coarse aggregate and microorganism of *Bacillus subtilus* is cultured and added to the water during the mixing of concrete in difference concentration like 10^5 cells/liter, 10^6 cells/liter and 10^7 cells/liter. Prepared M40 grade concrete cube of size 150 mm X 150 mm 150mm for measuring the mechanical properties a cylindrical specimen of 150 mm diameter and height of 300 mm were casted [24].

Srinivasa Reddy V et al. made a specimen to find the stress-Strain of the concrete sample were made of high strength grade of concrete such as M60. A cylindrical specimen were made of diameter 150mm and height 300mm. total 12 number of specimen were casted with bacterial concrete [25].

2.5. Ureolytic Mixed Culture

This culture was obtained by the active biomass in a semi-continuous reactor. It was filled with 1 liter activated sludge collect from an aerobic wastewater treatment plant which was then sediment in Imhoff comes, tap water replaced the 0.3 liter of supernatant, containing 2 g/lt nutrient broth powder, 10 g/lt SLM 1228 where 1 g/lt of SLM 1228 represent a chemical oxygen demand of 1135 mg/lt, 10 g/lt urea, a phosphorus concentration of 50 mg/lt and a Kjeldahl N concentration of 44 g/lt. the reactor continuously rotated and mix at 100 rpm and at 28°C this process gives the ecological advantages to the ureolytic bacteria and reproduce their growth [26].

2.6. Encapsulation Light Weight Aggregate

LWA is also used for improving the self healing property of the concrete. The ordinary aggregate of size 2-4mm which was replaced by the light weight aggregate of same size corresponding to a healing agent content of 15 kg m^{-3} concrete [27] this change will affect its compressive strength.

Capacity to heal cracks was substantially improved for concrete containing in LWA encapsulated healing agent [28, 29].

3. Test

3.1. Effect on the Strength Test

As amalgamation of healing agent to concrete may have unwanted negative effects on the mechanical properties. The consolidation of a high number of bacteria (5.8×10^8 cm^{-3} cement stone) shown to be negative effect on the compressive strength development as bacterial test specimen appeared almost weaker then control specimen. Tensile strength is the ability of a material to withstand a pulling (tensile) force. The tensile strength of the specimen was found to be 0.007 N/mm^2 [26]. It is observed that bacterial concrete shows the better tensile strength as compare to the conventional tensile strength as shown in table 2 [30].

Table 2. Comparison of compressive strength of conventional concrete and bacterial concrete

S.No.	No. of days	Split tensile strength of conventional concrete cylinders, N/mm^2	Split tensile strength *B. sphaericus* concrete cubes, N/mm^2	% increase in Strength
1.	3	3.78	4.30	13.75
2.	7	4.62	5.28	14.28
3.	28	4.85	5.74	18.35

3.2. Treatment Procedure

For the treatment procedure the specimen is immersed in the 0.3 and 0.6 L of a 1 day old stock culture of *B. sphaericus* prior to submerge in the nutrition solution for 24 days due to this ureolytic activity primarily result from bacteria inside the specimens. Selection of the treatment based on the commercial availability according to their different mechanisms in table 3 [26].

Table 3. The different type of treatment according to the mechanism and composition

Group	Subgroup	Composition of conventional technique/nutrient solution
Biodepositio n treatment	Ureolytic mixed cultures	1. Urea, NBP 2. Urea, calcium acetate 3. Urea, calcium chloride 4. Urea, NBP calcium acetate 5. Urea, NBP calcium chloride
	Bacillus sphaericus	1. Ureas, NBP 2. Urea, calcium acetate 3. Urea, calcium chloride 4. Urea NBP, calcium acetate 5. Ureas NBP, calcium chloride

3.3. Capillary Water Suction

Increase in water penetration resistance was determined by a sorptivity test, based on the RILEM 25 PEM (II-6) was carried out. Capillary water suction used to find out the absorption capacity of the bacterial concrete as compared to the conventional concrete. The value lower than 1 shows the relative decrease of water absorption and the value greater than 1 indicates the relative increase in water absorption. The result was expressed as the relative capillary absorption index as proposedby [31]. By performing the experiment on the various specimens it was found that the conventional concrete shows the lower value of relative capillary index. Willem De Muynck et al. also compare the pure culture and uerolytic mixed culture from his study it was found that the pure culture of *B. Sphaericus* had value of relative capillary index was lower as compare to the uerolytic mixed culture due to addition of the soluble calcium ions [26].

3.4. Gas Permeability

RILEM- CEMBUREAU method was used to find the Gas permeability using the principal as the Hagen- Poiseuille relationship for laminar flow of a compressible fluid through a porous body having small capillaries under steady state. Martin Sommer oxygen permeability experiment used measure the rate of flow of oxygen. It was found that the reduction of permeability in bacterial concrete as compare to the conventional concrete [26].

3.5. Water Permeability Test

For self-healing nature of concrete water permeability is also an important factor. After the splitting test the concrete specimen was broken completely. During the splitting test some fluid come out of the tube and emigrated into the cracks and then the specimen put in the curing room to wait till the solution become gel and the polyurethane foam formed after this cylinder were immersed into the water for 3 days. Take out cylinder after 3 days and dried it. The dry cylinder was fitted inside the PVC ring. During the water permeability test the vacuum saturation allows to establish a steady flow condition in a specimen which was first vacuumed in the vacuum chamber for 2-3 hours and then de-mineralized water was added into the chamber. The cylinder was kept immersed completely into the water for 24 hours due to the completely immersed specimen the vacuum stopped. Then cylinder was taken out and prepare for the water permeability test.

The whole setup kept watertight so that the specimen was in saturated state throughout the whole process of the measurement. The time for the decrease the water level from $h_0$till$h_f$in the glass tube was measured for 30 days of testing this water related with the water permeability of the cracked specimen. By the help of the Darcy's law, the coefficient of water permeability of the specimen can be calculated by the following equation:

$$K = \frac{at}{At} \ln(h_0 / h_f)$$

Where *k* coefficient of water permeability (m/s); *a* is the cross-section area of the glass tube (m^2); *A* is the cross-section area of the cylinder (m^2); *T* is the thickness of the cylinder (m); t is the time of water falling from h_0 to h_f (s); h_0 and h_f are the initial and final water levels (cm).

After performing the experiment it was found thatthe value of *k* range from 4 X 10^{-6} m/s to 7 X 10^{-6} m/s and the final k was 10^{-6} m/s which indicate that silica gel in the crack had limited capacity to decrease the water permeability. The initial crack width was 0.5 mm and decreased to 0.35 mm [32].

3.6. Compressive Strength

Table 4. Comparison of compressive strength of conventional concrete and bacterial concrete

S.No.	No. of days	Compressive strength of conventional concrete cubes, N/mm²	Compressive strength of *B.sphaericus* concrete cubes, N/mm²	% increase in Strength
1.	3	19.24	25.16	30.76
2.	7	23.66	34.58	46.15
3.	28	34.52	45.72	32.21

Compressive strength of the concrete is the capacity of the structure to resist the load acting on them. By the adding of bacteria to the concrete it improves the compressive strength of concrete as compare to conventional concrete. The compressive strength of concrete was improved by 14.92% by adding *Bacillus subtilis*JC3 as compare to the conventional concrete [18]. It was found that *B. sphaericus* improved the compressive strength of concrete by 30.76% in 3 days, 46.15% in 7 days and 32.21% in 28 as compared to conventional concrete shown in table 4 [30].

3.7. Oxygen Consumption Measurement

Oxygen consumption measured when oxygen consumed by aerobic bacterial metallic conversion of calcium lattice. For the study the optical oxygen micro sensors were used for quantification of water submerged control and bio chemical healing agent containing mortar specimens and it can be calculated by calculating the change in oxygen concentration in the linear part of the gradient in the diffusive boundary layer using Fick's first law of diffusion.

$$J = - D_{oxygen} * dC(z) / dZ$$

Where D_{oxygen} is the diffusion coefficient of O_2 in water, and C(Z) is the concentration of O_2 at depth Z [33].

4. Stress-Strain Behavior of Concrete

The stress-strain behavior of concrete gives the value of toughness. The test were performed on the cylindrical specimen prepared in universal testing machine of 3000KN capacity and the following data was obtained as shown in table 5 [18].

Table 5. The Stress-Strain behavior of bacterial concrete of grade M60 as compare to controlled concrete

Controlled concrete		Bacterial concrete	
Strain	Stress, MPa	Strain	Stress MPa
0	0	0	0
0.0001	3.27	0.0001	2.83
0.0002	6.41	0.0001	5.66
0.0003	9.01	0.0002	8.49
0.0004	12.98	0.0003	11.32
0.0005	15.32	0.0003	14.15
0.0006	18.65	0.0004	16.99
0.0007	21.10	0.0004	19.82
0.0008	24.55	0.0005	23.20
0.0009	28.56	0.0006	25.70
0.0010	36.00	0.0007	31.00
0.0011	38.80	0.0008	34.60
0.0012	42.30	0.0010	40.00
0.0014	47.60	0.0011	46.70
0.0016	61.00	0.0012	54.90
0.0023	72.61	0.0014	61.00
0.0027	65.70	0.0015	82.40
0.0033	36.80	0.0023	94.21
0.0034	30.30	0.0033	51.00
0.0035	29.15	0.0035	36.08

5. Conclusions

Introducing the bacteria into the concrete makes it very beneficial it improves the property of the concrete which is more than the conventional concrete. Bacteria repair the cracks in concrete by producing the calcium carbonate crystal which block the cracks and repair it. Many researchers done their work on the self healing nature of concrete and they had found the following result that bacteria improves the property of conventional concrete such as increase in 13.75% strength increased in 3 days, 14.28% in 7 days and 18.35% in 28 days. The development of calcium carbonate crystal Decreases the water permeability by decreasing the width of cracks from 0.5 mm to 0.35 mm. Compressive strength was increases by 30.76% in 3 days, 46.15% in 7 days and 32.21% in 28 days and in mathematical modal it was found that the bacterial concrete shows the better value of stress and strain as compared to controlled concrete for the high strength grade of concrete [18]. According to De Muynck et al. [13] the regular inspection for the concrete will be less need due to use of self healing material used in the concrete. In a publication wiktor and jonkers et al. [27] quantified the cracks healing capacity of the concrete containing LWA (light weight aggregate) Encapsulation self – healing agent. They observe that the width of the cracks was less than 0.46 mm for bacteria- based specimens. From the capillary water suction test it was found that the bacterial concrete shows the lower values of relative capillary index as compare to the uerolytic mixed culture and from the gas permeability tests it was found that the permeability decreases in bacterial concrete as compare to the conventional concrete.

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