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A Review Paper on Self-Healing Concrete

Nishant Dahake[1], Vivek Lakshane[2], Avanti Koche[3], Rutuja Nanotkar[4] and Nupur Kale[5]

[1]*Yashwantrao Chavhan Collage of Engg., Nagpur*
[2]*Anjuman Collage of Engg., Nagpur*
[3]*Government Collage of Engg.,Nagpur*
[4]*KDK College of Engg., Nagpur*
[5]*KDK College of Engg., Nagpur*

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. sphaericus which are mainly used for the experiments by different researchers for their study. Bacteria 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. It is expected that further development of this new type of self-healing concrete will result in a more durable and moreover sustainable concrete which will be particularly suited for applications in wet environments where reinforcement corrosion tends to impede durability of traditional concrete constructions.*
Keywords: *Bacteria, Bacillus pasteurii, Concrete, Bacillus sphaericus*

I. Introduction:

Crack formation in concrete is a phenomenon that can hardly be complete avoided due to for example shrinkage reactions of setting concrete and tensile stresses occurring in set structures. While larger cracks can potentially hamper a structures' integrity and therefore require repair actions, smaller cracks typically with a crack width smaller than

0.2 mm are generally considered unproblematic (Neville A.M, 1996). Although such micro cracks do not affect strength properties of structures they do on the other hand contribute to material porosity and permeability. In several studies indications have been found that concrete structures have a certain capacity for autonomous healing of such micro cracks (Neville A.M, 2002) & (Li V.C. et al, 2007). By introduce the bacteria in concrete it producing calcium carbonate crystals which block the micro cracks and pores in the concrete. In concrete micro cracks are always avoided but to some extent they are responsible to their failure in strength (Gollapudi et al, 1995).

II. Bacteria based self-healing concrete:

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 (Edvardsen C, 1999). 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 than Bacillus which are survive in the alkaline environment shown in Table 1 (Reinhardt H.W. and joss M., 2003).

Table1. Bacteria other than 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

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)). (J. Dick et al., 2006)

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

$NH_2COOH + H_2O \longleftrightarrow NH_3 + H_2CO_3 \longrightarrow$ (2) $H_2CO_3\ HCO_3^- + H^-$ (3)
$2NH_3 + 2H_2 \longleftrightarrow 2NH_4^- + 2OH^-$ (4) $\longleftrightarrow HCO_3^- + H^+ + 2NH_4^+ + 2OH^- \longrightarrow CO_3^{2-} + 2NH_4^+ + 2H_2O$ (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) and Eqs. (7)) (Reinhardt H.W. et al., 2003).
$Ca^{2+} + Cell \longrightarrow Cell\text{-}\ Ca^{2+} \longrightarrow$ (6) $Cell\text{-}\ Ca^{2+} + CO_3^{2-}\ Cell\text{-}\ CaCO_3\downarrow$ (7)

III. Methods:

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 [C. C. Gavimath et al.], 5 to 10µm [Aldea, C.-M et al. 2000 and Edvardsen, C 1996], 100µm [Jacobsen, S et al. 1995], 200µm [Wiktor, V. et al. 2011], 205µm [Wiktor, V. et al. 2011] and 300µm [Şahmaran, M et al. 2008].

Condition of Microorganism and Its Growth:

zsterilized. 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 [Srinivasa Reddy V1 et al.]. B. sphaericus LMG 225 57 (BCCM, Gent) was used for the study [J. Dick, W. et al. 2006 and F. Hammes et al. 2003]. 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 [Kim Van Tittelboom a et al. 2008, Bacillus sphaericus 2006, Environmental protection agency 1998]. 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 [Kim Van Tittelboom a, et al. 2008].

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 [Johnna K. Galinata et al.].

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/mm2 with a standard deviation of 2.19 N/mm2 [Kim Van Tittelboom a, et al. 2008]. 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 105 cells/liter, 106 cells/liter and 107 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 [Peruzzi R, et al.].

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 [m dhaarani and k prakash].

Ureolytic Mixed Culture:

This culture was obtained by the active biomass in a semi-continuous reactor. It was filled with 1 litre activated sludge collect from an aerobic wastewater treatment plant which was then sediment in Imhoff comes, tap water replaced the 0.3 litre 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 [Kim Van Tittelboom a Nele De Belie et al. 2009].

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 [De Muynck, W., et al. 2010] this change will affect its compressive strength. Capacity to heal cracks was substantially improved for concrete containing in LWA encapsulated healing agent [Jonkers, H. and m dhaarani and k prakash].

IV. Tests:

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 X 108 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/mm2 [Willem De Muynck et al. 2009]. It is observed that bacterial concrete shows the better tensile strength as compare to the conventional tensile strength as shown in table 2 [Peruzzi R, Poli T, et al. 2003].

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

Sr. No.	No. of Days	Split tensile strength of conventional concrete cylinders, N/mm2	Split tensile strength B. sphaericus concrete cubes, N/mm2	B. sphaericus concrete cubes, N/mm2 % 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

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 [Willem De Muynck et al. 2009].

Table3. The different type of treatment according to the mechanism and composition.

Group	Subgroup	Composition of conventional technique/nutrient solution
Biodeposition 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

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 [Kei-ichiimamoto et al.]. 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 [Willem De Muynck et al. 2009].

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 [Willy Verstraeteb. 2009].

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 h0tillhfin 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=atln (h0/ hf) At

Where k coefficient of water permeability (m/s); a is the cross-section area of the glass tube (m2); A is the cross-section area of the cylinder (m2); T is the thickness of the cylinder (m); t is the time of water falling from h0 to hf (s); h0 and hf 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 [Nele De Belie a et al. (14 July 2011)].

Compressive Strength:

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

Sr. 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 subtilisJC3 as compare to the conventional concrete [Srinivasa Reddy V et al.]. 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 [J Cult Herit 2003].

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= - Doxygen * dC (z) / dZ Where Doxygen is the diffusion coefficient of O2 in water, and C(Z) is the concentration of O2 at depth Z [Virginie Wiktor and Henk M. Jonke]

V. Stress Strain Behaviour:

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 [SasikalaCh et al.].

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
0.0007	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

VI. Conclusion:

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 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. 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 [SasikalaCh et al.]. According to De Muynck et al. [ACI Mater. J. 1999] 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. [De Muynck, W. 2010] quantified the cracks healing capacity of the concrete containing LWA (light weight aggregate)

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