A REVIEW ON APPLICABILITY OF BACTERIA IN SELF-HEALING SELF-CURING CONCRETE

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Abstract - *Concrete is the most widely used material in construction industry. However the main disadvantage of concrete is its low tensile strength which results in crack formation. The presence and propagation of cracks will seriously affect the life of concrete structure. Hence it is essential to arrest these cracks. A solution to this problem is Self-Healing Concrete (SHC). There are many studies concerned with the production of self-healing concrete. Encapsulated bacteria are the main healing agents used for this purpose. The properties of hardened concrete mainly depends on extend of hydration in cement matrix. Proper hydration is achieved by proper curing methods. The process of curing is difficult in regions experiencing water inadequacy and inaccessibility. Self-curing techniques can be used to overcome this problem. The current review is to study the applicability of bacteria as self- healing agent in self-curing concrete.*

***Key Words*: Concrete, Cracks, Curing, Healing, Bacteria**

1. INTRODUCTION

Concrete, due to its availability of raw materials, affordability, durability and compressive strength is the most widely used construction material. However a lot of concrete structures undergo degradation and deterioration overtime. The causes include formation of cracks, permeability as well as improper curing. The cracks formed will create a passage for the ingress of water, acidic fluids or gases into the concrete which causes reaction with reinforcement and results in corrosion. Improper curing techniques will lead to lack of proper hydration. In both cases, the strength and durability are compromised. Proper inspection is inevitable for ensuring the quality of concrete. But this will be difficult for large scale infrastructure due to high capital and also in case of inaccessible areas. Hence the application of self-healing and self-curing techniques in concrete is of great importance. Concrete will be able to detect and heal the damage without any manual intervention. The problem of incomplete hydration by inadequate curing will also be solved. Bacteria incorporation will enhance the process of healing by means of inducing calcium carbonate precipitation. Type of bacteria should be selected in accordance with environment which it is used. There are many factors which affect the viability of bacteria in concrete such as dense mix, temperature, Ph etc. There are several methods used to protect bacterial spores from adverse conditions in concrete such as encapsulation, incorporation of bacterial solution in hydrogels, coating of solution immersed light weight aggregates etc. By incorporating self-healing efficiency in self-curing concrete, the cost for maintenance and repair of concrete can be considerably reduced.

2. SELF-CURING CONCRETE

Gopala Krishna Sastry et al. (2017) studied self-curing concrete with different self-curing agents. The study focused on the impact of self- curing agents such as Poly Ethylene Glycol (PEG), Poly Vinyl Alcohol (PVA) and Super Absorbent Polymer (SAP) on the concrete mix of M25 grade. Strength properties of various concrete mixes using self-curing agents (PEG 400, PEG 600, PVA and SAP) were discussed in the study. When the percentages of self-curing agents in concrete were increased, its workability also increased. The optimum value of compressive strength was obtained when 1.5% of PEG 400 was used. Hence PEG was superior in enhancing the property of concrete compared to PVA and SAP.

Sivakumar et al. (2017) conducted research on the effect of polyethylene glycol as internal curing agent in concrete. The PEG 600 was varied at percentages of 0.5, 1 and 1.5 in M30 grade concrete. They found that addition of PEG increased the compressive strength and split tensile strength of concrete. When higher amount of PEG were used, it resulted in higher and earlier heat production rate due to hydration. Also the effectiveness of internal curing by means of PEG applied to concrete was the highest when 0.5% of PEG was added to the concrete.

Babitha Rani et al. (2017) conducted studies on self-curing concrete with addition of PEG 400 and its effect on compressive strength by varying the percentage of PEG by weight of cement from 0% to 1.5%. Concrete grade of M20 was used in the study. It was found that PEG 400 could help in self-curing by giving strength on par with conventional curing. It was also found that 1% of PEG 4000 by weight of cement was optimum for M20 grade concretes for achieving maximum strength without compromising workability.

Basil M Joseph (2016) conducted study on properties of self-curing concrete using PEG. The mechanical characteristics of M25 grade concrete was observed by varying the percentages of PEG from 0% to 1.5% by weight of cement. The aim also included to obtain the optimum percentage of PEG in concrete. Strength tests were conducted for both 7 and 28 days. The optimum dosage of PEG400 for maximum strengths (compressive, tensile and modulus of rupture) was found to be 1%. As percentage of PEG400 was increased, slump as well as compaction factor also got increased. Also the strength of self-curing concrete was higher compared to that of conventional concrete.

Mousa Magda I et al. (2014) analyzed the physical properties of self-curing concrete incorporated with self-curing agents such as pre-soaked lightweight aggregate (Leca) or polyethylene-glycol, and the addition of silica fume on the properties was studied. The concrete with polyethylene-glycol as self-curing agent, showed better properties than concrete with saturated Leca. 2% PEG or 15% Leca was obtained as the optimum dosage. Results of the study demonstrated that a significant improvement took place in the physical properties for self-curing concrete with poly-ethylene glycol as self-curing agent.

Mohanraj et al. (2014) studied self-curing concrete incorporated with polyethylene glycol. The compressive strength of self-cured concrete was higher than that of concrete cured by full curing and sprinkler curing. The split tensile strength of self-cured cylinder specimen was higher than that of the conventionally cured specimen. Self-cured concrete was found to have less water absorption values compared with concrete cured by other methods. Self-cured concrete is thus found to be less porous.

Vedhasakthi K (2014) studied the workability and strength characteristics of normal strength and high strength concrete casted with the self-curing agents and compared with the corresponding conventionally cured concrete. For the normal strength self-curing concrete of grades M20, M30 and M40, IS method of mix design was adopted. Mix proportions of high strength self-curing concrete of grades M60, M70 and M80 were obtained based on the guidelines given in modified ACI 211. Super plasticizer dosage was varied with grade of concrete. Trial dosages of 0.8%, 1% and 1.2% of the weight of cement were used for M60, M70 and M80 grades of concrete respectively. The strength of the concrete increased significantly with the increase of self-curing agent Ie concrete with 0.3% of PEG gave more strength than that with 0.25%.

Jagannadha Kumar et al. (2012) investigated about the strength characteristics of self-curing concrete. Study involved the use of shrinkage reducing admixture polyethylene glycol (PEG 400) in concrete which is beneficial for self-curing and better hydration and hence strength. In the study, the effect of admixture (PEG 400) on compressive strength, split tensile strength and modulus of rupture by varying the percentage of PEG by weight of cement from 0% to 2% were studied both for M20 and M40 mixes. It was found that PEG 400 could help in self-curing by giving strength on par with conventional curing. It was also found that 1% of PEG 400 by weight of cement was optimum for M20, while 0.5 % was optimum for M40 grade concretes for achieving maximum strength without compromising workability.

Ananthi et al. (2017) experimentally investigated the properties of self-curing concrete. The chemical agent PEG was used with different percentage; 1%, 2% and 3% to the weight of cement. Super plasticizer named glenium was used to improve the workability of concrete. The property such as compressive strength and split tensile strength of concrete was examined with normal curing and self-curing at 7 days and 28 days for M40 mixes. From the result obtained, it was observed that the optimum dosage of PEG 400 for maximum strength was found to be 2% for M40 grade. An average increase in the compressive strength of 12% was found when self-curing concrete of PEG 400 was used in curing than the conventional curing of concrete. Self-curing concrete had 1.5% higher tensile strength than conventional concrete.

Udaya Banu et al. (2018) studied about self-curing concrete using PEG-400 in PPC. PEG-400 was added in the ratios 0.5%, 1%, 1.5% and 2% to the weight of cement. It was found that the optimum dosage of PEG 400 for maximum strength was 1.5% for M20 grade concrete. The strength and durability properties of internally cured concrete with PEG 400 gave better result compared with external cured concrete and the cost requirement was also low for internal curing when compared with external curing.

Sri Rama Chand Madduru et al (2016) experimented on the effect of self-curing chemicals in self-compacting mortars. Two self-compacting mortars 1:1 with w/c = 0.34 and 1:3 with w/c = 0.5 were investigated with two self-curing agents (Polyethylene Glycol 400 and 200). A comparison was made considering three curing conditions namely wet curing, self-curing and no curing. Different dosages, i.e. 0%, 0.1%, 0.5% and 1.0% mass of PEGs were attempted with the above two curing agents. Mini-slump flow and V funnel tests were done to confirm flow properties required as per the specifications. Water retention, compressive strength, sorptivity and acid durability tests were carried out on SCM specimens. The loss of moisture content in self-compacting mortars was minimized due to the use of PEG as self-curing agent. Self-cured self-compacting mortar specimens attained compressive strength values nearly equal to wet cured specimens. The study had confirmed that from the strength and durability point of view the optimum dosages of PEG 200 and PEG 400 were 0.5% & 1.0%.

3. SELF-HEALING CONCRETE

Wang et al. (2014) conducted experiments on self-healing concrete by use of microencapsulated bacterial spores. Microcapsules which were resistant to high Ph and humidity were used as bacterial carriers. Microcapsules were able to behavior ductile while mixing and brittle when hardening. Hence the microcapsules were able to break on crack formation. The breakage was verified by Scanning Electron Microscope. Healing capacity was identified by crack healing ratio and water permeability. The results indicated that the healing ratio in the specimen with bacteria was higher than those without bacteria. Maximum crack width healed in the specimen of bacteria series was 970 μm, about four times than that of non-bacterial series. The overall water permeability in bacteria series was about 10 times lower than non-bacteria series.

Kim Van Tittelboom et al. (2010) conducted research on the use of bacteria to repair cracks in concrete. The bacteria used in the research were Bacillus sphaericus and enzyme was urease which catalyzes the hydrolysis of urea into ammonium and carbonate. The crack healing potential of bacteria and traditional repair techniques were compared in the research by means of water permeability tests, ultrasound transmission measurements and visual examination. Thermogravimetric analysis showed that bacteria were able to precipitate CaCO3 crystals inside the cracks. It was seen that pure bacteria cultures were not able to bridge the cracks. However, when bacteria were protected in silica gel, cracks were filled completely. Silica gel was used to protect the bacteria against the high pH in concrete. Protection of the bacteria by means of this gel matrix seemed to be effective as CaCO3 crystals were precipitated inside the matrix which was not the case if only bacteria were used, without immobilization in the silica gel.

Nele De Belie et al. (2008) investigated bacterial carbonate precipitation as an alternative surface treatment for concrete. He studied the effects of bacterial CaCO3 precipitation on parameters affecting the durability of concrete and mortar. Pure and mixed cultures of ureolytic bacteria were compared for their effectiveness in relation to conventional surface treatments. Bacterial deposition of a layer of calcite on the surface of the specimens resulted in a decrease of capillary water uptake and permeability towards gas. This bacterial treatment resulted in a limited change of the chromatic aspect of mortar and concrete surfaces. The type of bacterial culture and medium composition had a profound impact on CaCO3 crystal morphology. The use of pure cultures resulted in a more pronounced decrease in uptake of water, respectively less pronounced change in the chromatic aspect, compared to the use of mixed ureolytic cultures as a paste. The results obtained with cultures of the species Bacillus sphaericus were comparable to the ones obtained with conventional water repellents.

Jonkers et al. (2010) studied the application of bacteria as self-healing agent for the development of sustainable concrete. The potential of bacteria to act as self-healing agent in concrete, i.e. their ability to repair occurring cracks were analyzed. A specific group of alkali-resistant spore-forming bacteria related to the genus Bacillus was selected for this purpose. Bacterial spores directly added to the cement paste mixture remained viable for a period up to 4 months. A continuous decrease in pore size diameter during cement stone setting probably limited life span of spores as pore widths decreased below 1 m, the typical size of bacillus spores. However, as bacterial cement stone specimens appeared to produce substantially more crack-plugging minerals than control specimens, the potential application of bacterial spores as self-healing agent appeared promising.

Bang et al. (2001) experimented on calcite precipitation induced by polyurethane-immobilized bacillus pasteurii polyurethane (PU) foam was used to immobilize the whole cell of Bacillus pasteurii. The immobilized cells exhibited the rates of calcite precipitation and ammonia production as high as those of the free cells. Scanning electron micrographs identified the cells embedded in calcite crystals throughout PU matrices. Calcite in PU showed little effect on the elastic modulus and tensile strength of the polymer, but increased the compressive strengths of concrete cubes, whose cracks were remediated with PU-immobilized cells. Study on microbial remediation in concrete cracks had clearly identified that the use of a mixture of sand and microorganisms in concrete remediation increased the compressive strength.

Jagannathan et al. (2018) analyzed the mechanical properties of bacterial concrete with two bacterial species. Bacillus sphaericus and bacillus pasteurii where selected for the study to enhance the strength and durability of concrete. When 10% of cement was replaced by fly ash enriched with bacillus sphaericus, higher strength was obtained than controlled concrete and concrete made with bacillus pasteurii. The compression test of concrete made with bacillus sphaericus gave 10.8% higher strength whereas the split tensile test gave 29.37% higher strength and in flexure 5.1% higher strength than controlled concrete. Concrete made with bacillus pasteurii gave less strength compared to bacillus sphaericus.

Sandip Mondal and Aparna (Dey) Ghosh (2018) investigated the optimal bacterial concentration for compressive strength enhancement of microbial concrete. Three different bacterial concentrations of Bacillus subtilis have been used in this study, namely 10^3 cells/ml, 10^5 cells/ml and 10^7 cells/ml of water. Results indicated that though the higher bacterial concentration of 10^7 cells/ml was more efficient for crack healing, the best performance in compressive strength enhancement was achieved with the bacterial concentration of 10^5 cells/ml. It was seen that for a given bacterial type and mortar mix, the different calcite precipitation patterns inside the mortar matrix at varying levels of bacterial concentrations constitute the reason for the existence of the optimal bacterial concentration for compressive strength enhancement. Higher cell concentrations lead to higher precipitation amount and rate and thus at higher cell concentration the crack healing and surface pore-healing are more efficient as compared to the lower cell concentration. The precipitation layer produced at the surface with higher cell concentration acted as a shield to the mortar which was able to protect the inner matrix of concrete from the penetration of water and harmful substances. They concluded that higher bacterial cell concentration would be more efficient where protection of concrete is more important than strength.

Rafat Siddique (2017) studied the effect of bacteria on strength, permeation characteristics and micro-structure of silica fume concrete. The cement was partially substituted with 5, 10 and 15% SF and with constant concentration of bacterial culture, 105 cfu/mL of water. Cement was substituted with silica fume in concrete by weight. At 28th day, nearly 10–12% increase in compressive strength was observed on incorporation of bacteria in SF concrete. The compressive strength of concrete increased from 32.9 to

36.5 MPa for SF, 34.8 to 38.4 MPa for SF5, 38.7 to 43.0 MPa for SF10 and 36.6 to 40.2 MPa for SF15 on addition of bacteria. Water absorption, porosity and capillary water rise reduced in the range of 42–48%, 52–56% and 54–78%, respectively, in bacterial concrete compared to corresponding nonbacterial samples at 28 days. Reduction in chloride permeability of bacterial concrete was observed and the total charge passed through bacterial concrete samples reduced by nearly 10% compared to nonbacterial concrete samples at 56 days of age. Calcite precipitation on addition bacteria and confirmed by SEM and XRD analysis is considered as the reason for improvement in properties of concrete. Economic study of bacterial SF concrete has also been carried out in the present work. The Benefit/Cost Ratio of bacterial SF concrete got reduced with the increase in SF quantity. Compared to control concrete, bacterial SF concrete containing 10% silica fume demonstrated highest benefit in improvement in its properties.

Jing Xu et al. (2018) experimentally studied self-healing of concrete cracks by use of bacteria containing low alkali cementitious material. A protective carrier for the bacteria by using calcium sulphoaluminate cement, which is a type of low alkali, fast hardening cementitious material with 20% silica fume was developed as a useful protective carrier for ureolysis-based bacterial self-healing system in concrete. Bacterial spores were successfully encapsulated into the carrier. Although the encapsulation resulted in a loss of viability, the bacterial activity could be preserved over a long period. By regulating the composition of the carrier material and the content of healing agents, the compatibility of the carrier with both the healing agents and the concrete matrix was optimized. The carrier, which acted as a support for the bacteria, was effective in preserving the bacterial activity over a long period of time. After embedding this bacteria-based self-healing system in concrete, cracks up to 417 lm with a crack closure near 100% was achieved in 28 days. The crack healing efficiency achieved by the combined use of low-alkali carrier and microbial $CaCO_3$ precipitation was evaluated by the quantitative image analysis, mechanical performance, and capillary water absorption tests. The regain ratio of compressive strength and water tightness increased 130% and 50% compared with the plain mortar.

Mian Luo al. (2015) investigated the factors affecting crack repairing capacity of bacteria-based self-healing concrete. The bacteria-based self-healing concrete was developed by adding the microbial self-healing agent which had the potential to improve self-healing capacity mainly by bacteria induced mineral precipitations. The precipitations formed at the cracks surface of the cement paste specimens were analyzed with Scanning Electron Microscope (SEM) equipped with an Energy Dispersive X-ray Spectrometer (EDS) and then examined by X-ray Diffraction (XRD). Moreover, the influence of crack width, curing ways and cracking age on the crack self-healing of cement paste with microbial self-healing agent was researched by the characterization methods of area repair rate and anti-seepage repair rate. The results showed that the microbial self-healing agent could be used to achieve the goal of concrete crack self-healing. The precipitations formed at the cracks surface were calcite, which appeared lamellar close packing morphology. However, the capacity of concrete crack self-healing depended on many factors. The crack was more and more difficult to be repaired with the increase of average crack width and the repair ability of microbial repair agent was limited for specimens with crack width up to 0.8 mm. Water curing was shown to be the best way for bacteria-based self-healing concrete. In addition, the crack healing ratio of specimens dropped significantly along with the extension of cracking age. When the cracking age was more than 60 days, the crack healing ratio was very small.

Chunxiang Qian et al (2016) studied the influence of bacteria-based self-healing agents on cementitious materials hydration kinetics and compressive strength. . The results showed that the rheology of cement mortar was significantly improved by the addition of bacteria-based self-healing agents. Incorporation of bacteria-based self-healing agents in cement greatly influenced the hydration kinetics. The self-healing agent containing calcium lactate could delay the hydration of cement resulting in final setting time to increase. However the self-healing agents containing calcium formate and nitrate accelerated the hydration resulting in initial and final setting time decrease. In addition, compressive strength test results showed that incorporation of calcium lactate in cement mortar resulted in early age compressive strength decrease, but the 28 day compressive strength increased compared to control. Incorporation of calcium formate in cement mortar enhanced compressive strength. Incorporation of calcium nitrate in cement mortar could result in unwanted compressive strength loss. Furthermore, mercury intrusion porosimetry test results indicated that the pore size distributions were different between cement paste samples with and without bacteria-based self-healing agents. The addition of bacteria-based self-healing agents increased the porosity between 100 and 1000 nm. The porosity between 100 and 1000 nm of the sample with calcium nitrate increased the most compared to the samples with calcium lactate and calcium formate. The incorporation of calcium formate increased the porosity between 100 and 1000 nm, but at the same time the small pores with a diameter under 10 nm increased. These results could be used to explain the compressive strength development.

4. CRITICAL REVIEW

Based on the review, it is evident that Polyethylene Glycol can be efficiently used for inducing self-curing in concrete. It has got superior property compared to Super Absorbent Polymers and Polyvinyl Alcohol. 1% of PEG 400 was found optimum for compressive strength and 0.5% of PEG 600 for effective internal curing. The slump was found increased with increased percentage of PEG. Split tensile strength was found higher than conventional concrete. Bacteria are able to induce the precipitation of calcium carbonate. Microencapsulated bacteria have higher healing ratio compared to those without bacteria. Pure culture of bacteria will give a decrease in uptake of water compared to mixed culture of bacteria. Concrete with Bascillus pasteurii gave less strength than Bascillus sphaericus. Comparing bacterial concentration, 10^7cells/ml was more efficient for crack healing. But compressive strength was higher for 10^5cells/ml. High bacterial concentration will increase the precipitation of calcium carbonate.

5. CONCLUSION

The concept of selective cementation of porous media by microbiologically-induced $CaCO_3$ has been introduced for remediation of damaged structural formations. Microbiologically-induced $CaCO_3$ precipitation results from a series of complex biochemical reactions of bacteria which results in self-healing of concrete. The bacteria to be used should be selected according to the environment into which it is applied. Higher percentages of bacteria would be more efficient where protection of concrete is more important than strength. There are many governing factors affecting efficiency of bacteria which includes temperature, high pH, humidity, dense mix etc. PEG was found better for incorporating self-curing in concrete. The continued hydration of concrete can be achieved and concrete having modified mechanical properties can be obtained by incorporating self-healing property in self-curing concrete. The combination of self-healing and self-curing properties in concrete will make it capable to detect and heal the damages without manual intervention.

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