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Properties of Bacterial-based Self-healing Concrete- A review

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Abstract: The phenomenon formation of micro-cracks in concrete is common, this leads to costly maintenance. Concrete needs to be repaired. This causes degradation of concrete leads to ingress of deterious substances into concrete, results in deterioration of structures. To overcome these situations self-healing techniques are adopted. By the addition of urease producing bacteria along with calcium source results in calcite precipitation in concrete. Bio-mineralization techniques give favorable results in sealing the micro-cracks in concrete. The freshly formed micro-cracks can be sealed up by continuous hydration process in concrete. The ureolytic bacteria i.e., bacillus pasteurii which can produce urea is added along with the healing agent to seal the freshly formed micro-cracks by $CaCo_3$ precipitation. For the improvement of pore structure in concrete the bacterial concentrations were optimized for better results. Increase of durability, compressive strength and reduction of permeability in concrete is attained. Ability to heal and seal the cracks in concrete was observed. Maintaining pH under favorable conditions, permeability of concrete, crack healing capacity of concrete was observed.
Keywords: Self-healing, Micro-cracks, Ca Co_3 precipitation, Bacteria, Hydration, Bacillus pasteurii.

1.0introduction

Rapid growth and development in the infrastructure can be seen over the past hundred years in the construction activities. In this development concrete plays an important role in the development of the infrastructure in the day-to-day life. Among all the building materials concrete is the artificially made building material which is got special characteristics. Concrete is the most widely used building material in the construction activities due to its durability and high compressive strength. The capability of concrete in resisting the chemical attacks, weathering action and abrasion by maintaining their engineering properties desired can be seen. Over last decade self-healing approach have been adopted in showing promising results in the concrete structures. The durability of the properties refers to trouble-free performance [11]. The ingress of moisture and other harmful chemicals into the concrete may result in the decrement of strength and life [5]. The durability of the concrete is decreased due to the ingress if sulphates and chlorides into the concrete. This may leads to the corrosion in the reinforcement. To overcome these problems self-healing approaches may be adopted. Autogenous self-healing techniques are adopted by embedding bacteria and healing agent to precipitate Ca Co_3 on the freshly formed micro-cracks. The precipitation of calcite by continuous hydration of cement helps in production of calcium carbonate precipitation with the help of urease producing bacteria.

The influence of ureolytic bacteria i.e., bacillus pasteurii on concrete helps in calcite formation by continuous hydration of cement in concrete [20]. The bio-mineralization of the concrete can be done for the improvement of crack healing capacity of the concrete by bio-cementation, bio-deposition and bio-deposition techniques. The microbiologically induced calcium carbonate precipitation (MICP) which comes under the category of bio-mineralization [8]. The addition of bacteria by poly-urethane immobilization and spore formation techniques helps in bonding and crack healing aspects in the concrete [16]. The microbial carbonate precipitation can be obtained by ureolytic activity and the bio-mineralization of the bacteria. The bacteria used are capable of precipitating calcite by producing urea with the help of calcium source [19]. The bacteria are added at the time of mixing process of concrete along with calcium sources, nitrogen and phosphorous ingredients. These agents can remain dormant in concrete for up to 200 years [8].The usage of capsules or vascular systems to introduce bacteria into the concrete makes the concrete sound by the presence of bacteria throughout the concrete matrix [17] .By the addition of effective pozzolonic materials which are extremely fine and having high silica content helps in improving the life span of the structure. Industrial bi-products such as silica fume and fly ash can be used for the replacement of cement in concrete for the decrement of porosity in concrete. Silica fume which is porous, extreme fine and has a high bonding strength which makes concrete dense and helps in reduction of permeability in concrete [21,11] .

Recently, the self-healing approaches have been showing promising results in remediating the cracks in the earlier stages of formation of cracks. On the other hand precipitation of calcite in the concrete specimens by hydro-gel encapsulation, capsules and vascular systems seems to be good at self-healing in the construction activities and researches. Different calcium sources may be adopted for the precipitation of calcite by the continuous hydration of the un hydrated cement particles in the concrete. Thus, the replacement of cement by natural/recycled products may decrease the cement content in concrete, which helps in reduction of Co_2 emission in the manufacturing process of cement.

2.0 The properties of bacterial based self healing concrete

2.1 Self-healing Approach

Self-healing approaches are promising techniques for the remediation of micro-cracks in concrete. The autogenous self-healing techniques show better results in healing of micro cracks on the surface of the concrete. The formation of perveous layer on the existing layer of concrete shows precipitation of Calcite [20]. As concrete is a high alkaline building material the bacteria is added should be alkali-resistant to withstand in high-alkali environment [13].The experiments showed cracks can be healed up to 0.46 mm wide cracks of bacterial specimens after 100 days of curing [1]. The CSH gel is increased by treatment of bacteria in concrete specimens to precipitate calcite [21] which affects the healing capacity by bacterial concentration. The presence of silicate substances in concrete matrix makes porous and reduce ingress of water into concrete [11]. Calcium carbonate can be formed on the surface of the concrete by reacting with CO_2 present in the calcium hydroxide by following reactions

$$CO_2 + Ca\,(OH)_2 \rightarrow Ca\,CO_3 + H_2O \quad (1)$$

$$Ca\,(C_3H_5O_2)_2 + 7\,O_2 \rightarrow CaCO_3 + 5\,CO_2 + 5\,H_2O \quad (2)$$

The $Ca(OH)_2$ is a soluble mineral will be dissolved in water, ingress into the crack and will be out at the time of leaching. This process is more efficient because of active metabolic conversions of calcium nutrients and bacteria present in the concrete [13]. Several studies investigated that the bio-mineralization in cement materials shows possibility to show self-healing characteristics in concrete. The influence of urea producing bacterial cells shows precipitation of Ca CO_3in urea extract medium (UYE medium). The compressive strength that was similar or higher than the neat mortar was observed [17]. The increment in compressive strength was observed up to 15 % and the decrease in porosity at 28 days was observed [24]. The efficiency of the concrete may be defined as performing permeability tests on low pressure environments. Visual examination of the crack filling may be adopted to check the better performance of crack filling improvement.

2.2Microbiologically Induced $CaCO_3$ Precipitation (MICP)

Microbiologically induce $CaCO_3$ precipitation helps to bind the particles such as sand, gravel in the concrete to form a composite material in sealing or healing the micro-cracks in concrete. The involvement of microorganisms in $CaCO_3$ precipitation leads to development of bio-based environment in the concrete as a durable building materials. Bacillus subtilis is robust ureolytic bacteria which is aerobic, spore forming bacterium uses urea as energy producing source and generates carbonate by increasing the pH environment

[13]. By converting urea into ammonium and carbonate Bacillus subtilis JC3 can able to precipitate $CaCO_3$ in high alkaline environment. The mechanism of involvement of in $CaCO_3$ precipitation is of three types: i. spontaneous mechanism, by photosynthesis microorganism; ii. Through nitrogen cycle; iii. Through sulfur cycle [13]. The bacterium which is capable of producing urea helps in precipitating calcium carbonate on the surface of the cracked specimen with the help of calcium source. The $CaCO_3$ can be formed due to the CO_2 in the $Ca(OH)_2$ present in the concrete as stated in Eq:1,Eq:2. The two self-healing agents i.e., bacterial spores and calcium based nutrients were introduced into the concrete at the time of mixing process; the agents which were mixed will not be active at the time of mixing. The agents will be activated only when the cracks appear the ingress of water starts activating the healing agents. This mechanism may be defined as Microbiologically Induced Calcium Carbonate Precipitation (MICP). This precipitation happens due to hydration of non-hydrated cement particles in the concrete matrix with the contact of ingress of water into the cracks. The $CaCO_3$ precipitation can be controlled by pH, calcium concentration, and carbonate concentration and nucleation sites presence. This formation of precipitated calcium carbonate can be viewed under Scanning Electronic Microscope (SEM). The process may result in bio-based crack sealing technique in concrete.

2.3 Role of Bacteria

Various selected types of bacteria were used as construction materials genus Bacillus was used for the precipitation of calcite on the surface of the concrete. The nutrients for the bacteria which are able to precipitate calcite are calcium sources, phosphorous and nitrogen sources. These bacterial components remain dormant in concrete, when the seepage of water take place into the formed cracks helps in reacting with the nutrient to precipitate calcite i.e., Ca CO_3 [8]. Various types of bacteria used in concrete are shown in fig.1 which is able to precipitate Ca CO_3 on the surface of the concrete cracks.

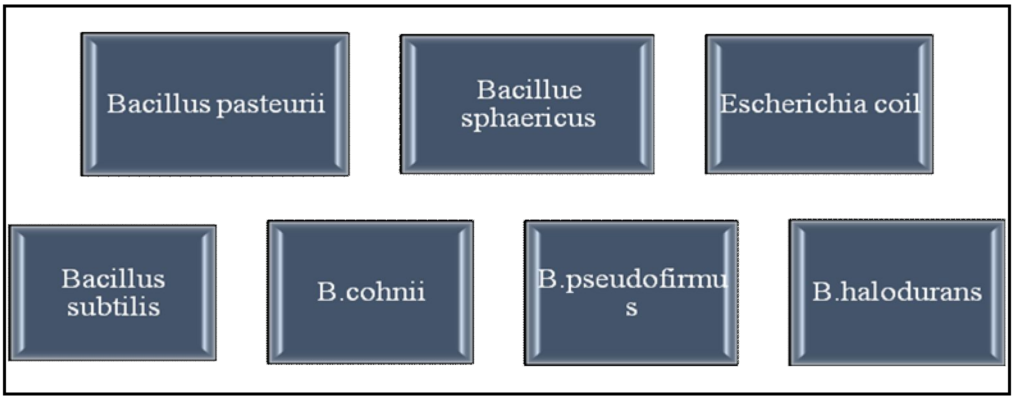


Fig.1 Types of bacteria used in concrete

The process of producing urease for the hydrolysis of urea CO $(NH_2)_2$ into carbonate (CO_3^{2-}) and ammonium (NH_4^+) can be as follows

$CO\ (NH_2)_2 + H_2O \rightarrow NH_2\ COOH + NH_3$ (3)
$NH_2\ COOH + H_2O \rightarrow NH_3 + H_2CO_3$ (4)
$H_2CO_3 \rightarrow HCO_3^- + H^+$ (5)
$2\ NH_3 + 2\ H_2O \rightarrow 2\ NH_4^+ + 2\ OH^-$ (6)
$H\ CO_3^- + H^+ + 2\ NH_4^+ + 2\ OH^- \rightarrow CO_3^{2-} + 2\ NH_4^- + 2\ H_2O$ (7)

1 mol. of urea is hydrolyzed intracellular to 1 mol. of carbonate and 1 mol. Of ammonia (Eq.3), carbonate hydrolyses to form 1 mol. Of ammonia and carbonic acid additionally (Eq.4), these components form 1 mol. of bicarbonate and 2 mol. Of ammonia and hydroxide ions (Eq.5, Eq.6).these reactions gives rise to pH increase resulting formation of carbonate ions (Eq.7), [19].

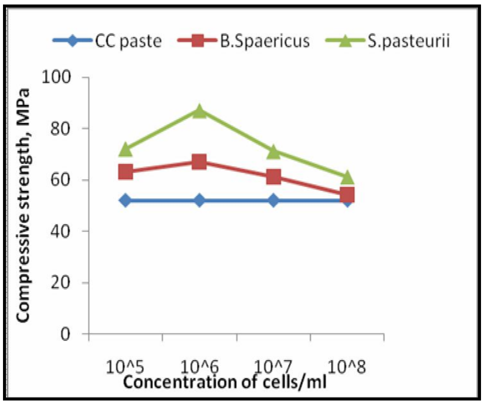
$Ca^{2+} + cell \rightarrow cell\text{-}\ Ca^{2+}$ (8)
$Cell\text{-}Ca^{2+}\ CO_3^{2-} \rightarrow cell\text{-}\ Ca\ CO_3 \downarrow$ (9)

In the above equations, the cell wall of bacteria is negatively charged; cations from the environment were drawn by bacteria. Including Ca^{2+} to deposit on cell surface. Subsequent reaction with CO_3^{2-} -ions can be seen by Ca^{2+} -ions leads to $CaCo_3$ precipitation at the cell surface (Eq.8, Eq.9) [25,8]. The bacterial cell walls present on the surface of the concrete can be visual by SEM analysis which shows the bacteria incorporated in the specimen for self-healing.

2.4 Mechanical properties

The main parameter that should be considered in the MICP process is the diffusion kinetics due to change of pore-structure. Though change in pore-structure gives better result in preventing ingress of harmful chemicals into concrete that may cause deterioration of structures. Compared to traditional concrete, the bio-cement incorporated concrete shows higher strength [19]. The urease producing alkaphilic bacterium, Bacillus pasteurii which is grown in nutrient media, added with healing agent of calcium source to the concrete mix shows relatively higher compressive strength when compared to traditional concrete.

The calcium silicate hydrate (CSH) gel in the concrete matrix is increased by selecting the specific amount of bacteria added to the concrete mix. A higher concentration of bacterial cells may cause disrupt in the concrete matrix due to excessive bacterial concentration. Thus, it reduces the compressive strength of concrete [21].



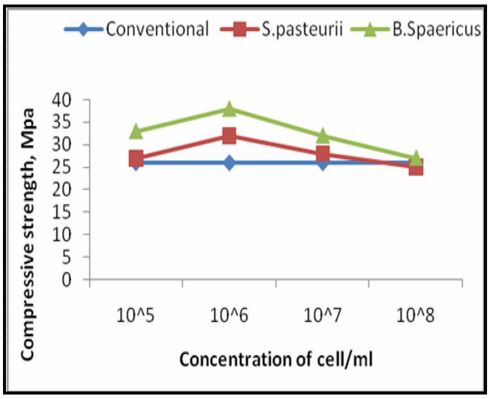


Fig. 2 Comp. strength of cement paste **Fig.3 Comp.Strength of cement mortar**

Experiments showed that the cell concentrations of 10^6 cells/ml of water in the cement paste and mortar specimens has higher compressive strength gain was up to 39.8% , 33.07% and 50% , 28.2% respectively [19]. Fig.2 and Fig.3 confirms the change in compressive strength is higher when the cell concentrations are 10^6 cells/ml of water in concrete matrix. The impact of the vegetative S.pasteurii cells in the concrete was investigated by adding different type of cells and they are attributed to the depletion of UYE nutrient medium and addition of end-products to the medium. The impact of UYE medium, killed cells and vegetative cells on compressive strength, hydration and composition can be seen in Fig.4 [17].

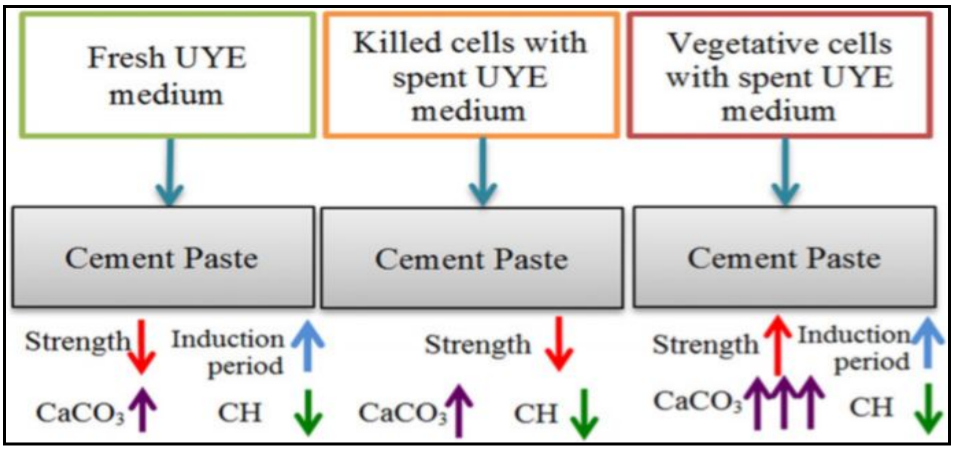


Fig.4 Impact of UYE medium, killed cells, vegetative cells on compressive strength

In the above research it has been shown that the increase in the compressive strength and $CaCO_3$ precipitation in the case of vegetative cells with spent UYE medium in cement paste as compared with respect to neat paste. The fresh UYE medium which is high in precipitating the calcite and a decrease in compressive strength was observed. The impact of killed vegetative cells with spent UYE medium also shows a decrease in compressive strength and rich in calcite precipitation.

The improvement in compressive strength was attained at a cell concentration of 10^6 cells/ml for all ages when an alkaliphilic aerobic microorganism bacillus subtilis JC3 was suspended into the concrete mix along with water. This study showed that 25% increase in compressive strength at 28 days was achieved. Due to involvement of growth filler material in the pores of the cement-sand matrix strength improvement can be observed by SEM and calcite precipitation can be seen in the mortar matrix [13].

2.5 Crack healing ability and sealing of micro-cracks

The durability of the concrete can be enhanced by incorporating the bio-based self-healing techniques. The quantification of crack healing potential of a two component self-healing agent in expanded clay particles was investigated by Virginie wiktor et al [1]. When cracks are formed the bacterial spores and healing agent i.e., calcium lactate were released from clay particles by ingress of water. Results showed crack healing capacity was increased up to 0.46 mm wide cracks when compared to control specimens 0.18 mm wide cracks, after 100 days of submersion in water. It is shown that the self-healing agent shows increment of durability in concrete structures under wet conditions [1].The creation of cracks may be of two types [25], samples with standardized cracks and realistic cracks. In freshly formed concrete micro-cracks can be seen with naked eye, this may caused due to debris or segregation. These types of cracks may be called as standard cracks. The realistic cracks may be formed by wrapping fiber reinforced polymer [FRP] on concrete cylinders and they are coated with glass fibers [25] then allowed for tensile tests to create cracks in the concrete specimens. The other method which tensile tests were carried out up to first crack is formed in the specimens and then they are allowed for curing. The self-healing capacity of the specimens can be observed by SEM analysis and XRD technique. In this paper bio-mineralization in cement-based materials shows possibility to self-healing characteristics in concrete. He investigated that the impact of vegetative cells on hydration of cement in concrete matrix and compressive strength. The influence of urea producing bacterial cells shows precipitation of Ca Co_3 which helps in self healing. The compressive strength that was similar or higher than the neat mortar was observed. UYE medium helps in precipitation of $CaCo_3$ to seal the cracks in concrete.

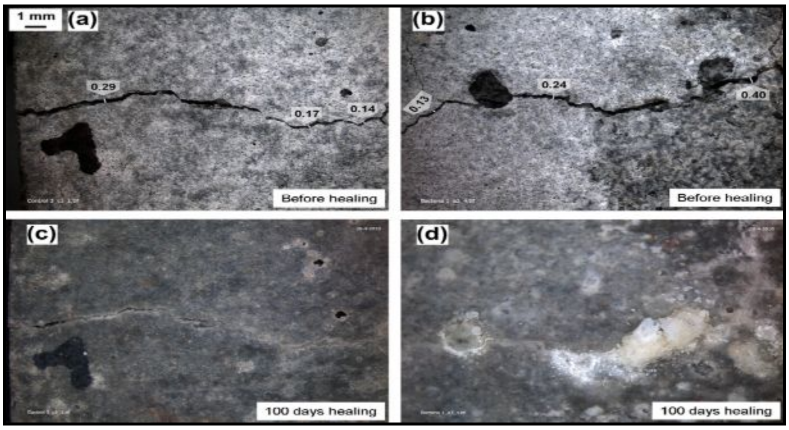


Fig.5 SEM images of crack-healing process in control specimensbefore healing (a), after 100 days healing (c), bio-chemical agent based specimen before healing (b), after 100 days healing (d).

3.0Conclusions

Based on the literature, the following conclusions were drawn.

Experiments have shown that the ability to heal the micro-cracks with the help of bacteria and healing agent was seen by SEM analysis and confirmed by XRD, that Ca Co_3 precipitation helps in sealing the micro-cracks. The amount of bacteria added in concrete affects the chloride penetration [11] results showed that high amount of bacteria added gives unsatisfied results.

The compressive strength observed for 91 days given satisfying results than compared to 28 day compressive strength observed for a bacterial concentration of 10^5 cells/ml. S.pasteurii formerly known as Bacillus pasteurii showed reduction in water absorption which increases the durability of concrete structures. The bacterial cells are potential admixtures in concrete helps in enhancing the mechanical performance of concrete

The SEM analysis and XRD analysis shows the capability of producing calcite by S.pasteurii in the cement composites.. Silica gel in concrete helps in protecting bacteria [25] in high pH environment. This resulted in increase in ability to fill the cracks confirmed by ultrasonic pulse velocity tests and SEM images. The biological treatment of the cement composites result in the crack sealing and decrease in water permeability and the advantages of incorporating bio-based cement composites primarily reduce the maintenance costs, repair costs and hence results in increase of durability of the structures.

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