International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-7, Issue-6C2, April 2019

Effect of Bacteria on Performance of Concrete/Mortar: A Review

Ankita Sikder, Purnachandra Saha

Abstract: Bacterial concrete is a special type of concrete where due to microbial activity mineral precipitation take place which results in self-healing and cracks repairing of concrete. Mineral precipitation due to microbial activity is a process named as Biomineralization in which calcium carbonate precipitation is formed due to microbiologically induced calcite precipitation (MICP) process. This process is natural and eco-friendly. The objective of this study is to discuss the performance of concrete/mortar with respect to self-healing, mechanical properties, and durability properties. The study shows that when bacteria used in cement treatment or during concrete production or mortar curing due to MICP process compressive and split tensile strength increase and both water absorption and porosity reduced and also a reduction in chloride permeability was observed which makes concrete more durable. So it can be concluded that bacterial concrete can be use in construction for self-healing, crack repairing and improving durability.

Index Terms: Bacterial Concrete, Biomineralization, MICP, Self-healing, Mechanical Properties, Durability.

I. INTRODUCTION

Concrete is the second most broadly utilized material in the Earth after water. It is the single construction material utilized most generally all through the world. Portland cement concrete is the most generally utilized construction material, with a yearly generation of around 10 km3/year and the major part of which being used in the construction of the reinforced concrete structures [1]. Concrete is a composite material which is composed of coarse and fine aggregates bonded together with cement paste. The main constituent of concrete cement has a high environmental impact on global warming because the amount of CO2 emitted from cement industry is about 10% of total worlds CO2 emission [2]. In the year 2013 worldwide more or less 4.08 billion metric tons of cement was produced and in 2014 it increases to 4.2 billion metric tons of cement [3]. According to the compound annual growth rate of the cement industry, it is estimated that the cement industry will grow more than 9% by 2020 [4].

However, concrete is used as a most wildly consumed construction material due to its easy availability, low cost, good compressive strength etc.; has some drawback also. The main drawback of concrete is it has low tensile strength due to which micro-cracks occur when the structure is subjected to sustained loading and when exposed to an aggressive environment the life of the structure become degrading. In the current scenario, everyone is concerned about the degradation of concrete and major cost involvement in maintenance and repair of concrete structures. To reduce the cost, attention is given upon the processes of concrete degradation and to the method to retardation or even to get over of concrete degradation [5]. The traditional repairing methods consist of complex technology, excessive cost and have few adverse consequences on the environment, which cannot fulfill the demand of modern perception for concrete materials. The method of using biology development to repair small cracks and pores was first suggested [6] in year 1995 to got a new solution for the problem. Research in the field of concrete materials suggests that it is feasible to create a smart, cement-based material that has the capability of self-healing by investing the metabolic activity of microorganisms to provide biomineralization [7, 8]. Biomineralization is a biochemical process which includes a chain of biochemical reactions by microorganisms where calcium carbonate precipitation is one of the remedial products. MICP is the process behind it. Using various methods, bacteria can be included into cement-based materials like during cement treatment or during concrete production or during curing or after curing in the form of a spray. After incorporating bacteria the process of biomineralization occurs inside or outside of the microbial cell and result in a formation of biominerals (such as $CaCO_3$) which can block the cracks up-to certain extent and reduce the permeability of concrete. This new type of concrete is known as Bacterial concrete. The objective of this study is to discuss the potential of concrete/mortar with respect to self-healing, mechanical and durability properties.

II. BACTERIAL CONCRETE

A. Self-healing study

Self-healing is an important criterion for healing micro-cracks or small cracks of concrete and increase structures strength, durability etc. Under certain circumstance, micro-cracks and small cracks in concrete can be healed. For self-healing presence of liquid water is an important criterion because in case of specimens stored at 95%RH no self-healing ascertained [9]. The primary self-healing can be based on physical, chemical or mechanical processes. However, it was reported that calcium carbonate precipitation has the most evidential factor which can influence the self-healing of concrete [9, 10, 11, 12]. It was observed that for self-healing not only sufficient amount of healing compound required but also a minimum number of bacterial spores are required and also need to ensure that in the healing process sufficient amount of cells take part [13]. Crack or self-healing capacity of concrete decreased with increasing crack width and age of

Revised Manuscript Received on April 09, 2019.

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cracking [14]. Cracks occur due to excessive loading can be healed by bacterial treatment of concrete [15]. Hydro-gel encapsulated spores have shown improved self-healing efficiency [16, 17]. Silica-gel protected bacteria have shown better self-healing efficiency than non protected pure bacteria [18]. Incorporation of super plasticizer in bacterial concrete has shown the ability to improve self-healing efficiency of cells [19].

Various bacteria have capability to precipitate calcium carbonate. Bacillus Sphaericus generate urease which induces the hydrolysis of ureainto Carbonate and ammonium. After that from environment the negatively charged cell wall of the bacteria draw cat ions to sediment on their cell surface, including Ca^{2+}.The Ca^{2+}-ions later on react with the $CO^{2-}{}_3$ ions, which lead to the $CaCO_3$ precipitation at the cell surface [18]. Chemical equations take place here for self-healing of concrete are:

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3 \quad (1)$$

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

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \quad (3)$$

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

$$HCO_3^- + H^+ + 2NH_4^+ + 2OH^- \leftrightarrow CO^{2-}{}_3 + 2NH_4^+ + 2H_2O \quad (5)$$

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

$$Cell\text{-}Ca^{2+} + CO^{2-}{}_3 \rightarrow Cell\text{-}CaCO_3\downarrow \quad (7)$$

Table I represents the Characteristics of most commonly used bacteria used by different authors.

Table I: Characteristics of most commonly used bacteria used by different authors.

Most Comomty used bacteria [reference]	Characteristics
Sporosarcina pasteurii or Bacillus Pasteurii [8, 11, 15, 19, 24, 25, 27, 30, 33, 36, 37, 39, 41, 44]	Most commonly used microorganism in cement-based materials. It is alkaliphilic and endospore-forming, a bacterium. Its endospore helps it in endure an extreme environment. It has strong urease activity. It can produce $CaCO_3$ through biomineralization which helps in strength gain, reduce sorptivity, water absorption, water, and chloride permeability and increase resistance against freeze-thaw. It is also known as biological construction material which is ecologically sound.
Bacillus subtilis [12, 20, 35]	It has the ability to form tough protective spores when subjected to unfavorable conditions which allow it to tolerate extreme environmental conditions and high mechanical pressure. It can produce $CaCO_3$ through biomineralization which helps in strength gain.
Bacillus sphaericus [5, 16, 18, 25, 41, 45]	It is a ureolytic, alkali-tolerant spore-forming strain with high urease activity. It shows a pessimistic zeta-potential and a constant formation of heavy $CaCO_3$ crystals which helps in strength gain, reduce water absorption, water permeability and increase resistance against freeze-thaw.
Bacillus Cohnii [4, 21, 30, 38]	It is a non-ureolytic, alkaliphilic spore-forming bacteria which can survive up to 70°C. It also helps in strength gain and reduce sorptivity.
Bacillus halodurans [22, 30, 31]	It has ability to tolerant alkali-tolerant. It can increase strength and reduce water absorptionand porosity as well as chloride permeability.

III. MECHANICAL PROPERTIES

A. Compressive Strength study

The most effective properties of hardened concrete are compressive strength, by which the strength and durability of concrete are affected. Properties of hardening concrete depend on several factors like cement to sand ratio, water to cement ratio, curing age and other different properties of concrete [20, 21]. When Portland cement partially replaced 10% by bacteria treated cement kiln dust (CKD) concrete matrix achieved a higher compressive strength compared with control concrete might be because of the inappropriate alkalinity that expands the disintegration of silicate and for this arrangement of calcium silicate hydrate likewise increments and in the event of above substitution rate quality declines might be because of lower concrete substance and decreased or delay in the hydration of bond When cement replacement 10% by fly-ash then concrete strength increased using different types of bacteria also [24, 25]. When silica fume added to cement as a cement replacement (10%) then also strength increased may be due to deposition of the $CaCO_3$ in the pores resulting in a reduction in pores subsequently [26, 27]. In case of cement replacement by 10% RHA also shown increased in concrete strength due to very fine texture of RHA and activated silica content that reacted with hydration production of cement and produces secondary CSH-gel [28]. Therefore, an addition of bacteria can increase compressive strength while added in cement replacement and during concrete production or during curing or after curing in the form of spray [29]. But in some cases, no significant change found between bacterial and control concrete [30]. On the other hand, in some cases decreased in compressive strength also observed. It was observed that by replacing sand with lightweight aggregate result in a decrease in compressive strength where the presence of healing agent has no effect on it [11]. It was found that when cement replaced by cement baghouse filter dust (CBFD) compressive strength decreased because it is not cementations in nature so cement content reduced but when bacteria added to it, strength improved slightly due to calcite precipitation although this is lower than 0% CBFD bacterial concrete the strength gain where above the prescribed standard concrete [31].

Some study showed that substrate solution and its concentration and molarities have an evidential influence on the strength of the concrete [2, 20, 32, 33, 34]. It was found that (dead and alive cells of bacteria has no affirmative effect on the compressive strength while) the cell wall of bacteria influence in increased compressive strength [35]. In some cases, it was observed that bacterial cubes cured in calcium added water may be to influence the bacterial activities [3, 4, 7, 36]. Fig. 1 shows the compressive strength of Control and bacteria treated concrete without and with10% cement replacement.

IV. RESULTS & Findings

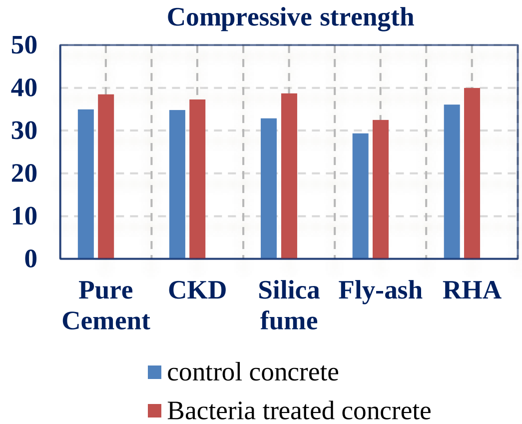

Fig. 1: The compressive strength of Control and bacteria treated concrete without and with10% cement replacement.

A. Split Tensile Strength study

The most popular indirect method used to find tensile strength of concrete is the split tensile strength test. Properties of hardening concrete depends on several factors like water to cement ratio, cement to sand ratio, curing age and other different properties of concrete [20, 21]. Concrete contains lower amount (10%) of CKD showed an increase in strength may be due to existence of it between cement and aggregates act like filler material but when bacteria treated CKD introduced to concrete in shown strength gain in later age may be due to the pozzolanic activity of bacteria treated CKD and slow hydration process [3]. It was observed that split tensile strength increase with the increase of $CaCO_3$ deposition [37]. Concrete containing 10% fly-ash as partial cement replacement shown increased split tensile strength due to use of fly-ash enriched by Bacteria [25].

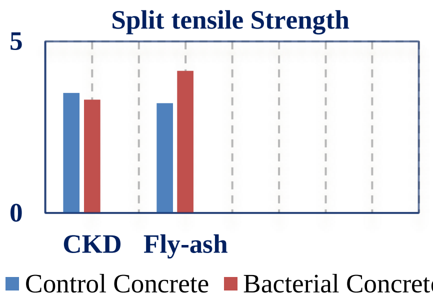

Fig. 2: The split tensile strength of control and bacteria treated concrete with 10% cement replacement.

Fig. 2 shows the split tensile strength of control and bacteria treated concrete with 10% cement replacement.

B. Flexural Strength study

Flexural Strength is one of the other properties of concrete that affects the structural performance of concrete. Properties of harden concrete depends on various factors such as water to cement ratio, cement to sand ratio, curing age and other different properties of concrete [20, 21]. In structural concrete of higher grade due to the maximum rate of $CaCO_3$ precipitation the maximum amount of strength development was acquired [2]. In some cases slightly improvement in flexural strength was observed due to the presence of biobased healing agents and their activity [21, 30]. It was observed that in absence of nutrients flexural strength slightly decreased and in presence of nutrients flexural strength increased than control concrete [38]. Concrete containing 10% fly-ash as partial cement replacement shown increased split tensile strength due to use of fly-ash enriched by Bacteria [25]. Fig. 3 shows Flexural strength of control and bacteria treated concrete without and with 10% cement replacement.

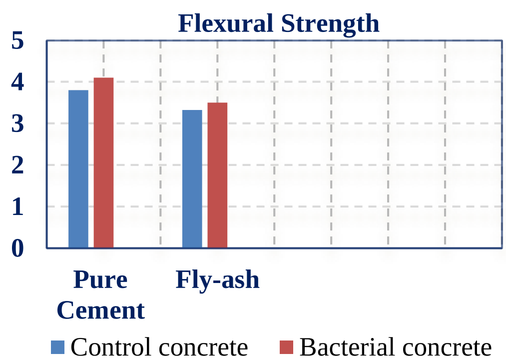

Fig. 3: Flexural strength of control and bacteria treated concrete without and with 10% cement replacement.

V. DURABILITY PROPERTIES

A. Sorptivity study

Sorptivity is a characteristic that characterizes the inclination of a porous material by capillary to soak up and transmit water. Sorptivity of cement mortar decreased with the incorporation of bacteria may be due to the existence of bacterial mineral precipitation in pores of cement mortar [4]. The sorptivity result shows initial self-healing but no significant change after the initial four-month [39]. Concrete containing 10% silica fume as cement replacement by mass shown reduction in sorptivity due to the pozzolanic reaction which leads to the formation of dense structure [26]. Concrete mixture comprises of bacterial cells showed lesser sorptivity values than control concrete mixtures prepared with or without CFBD [31].

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B. Water absorption study

Mortar cubes treated with bacteria showed drastically reduced water absorption compared to non treated specimens depending on the porosity of the mortar cubes. This is may be due to the surface deposition of $CaCO_3$ crystals, which physically hamper the movement of water [40]. The existence of bacteria remarkably decreases the rate of capillary water uptake in bacteria treated specimens due to the bacterial deposition [5, 9, 19, 26, 39]. Deposition of $CaCO_3$ on the cell walls of bacteria in both aggregate and concrete matrix results in reduced absorption of water. It prompted the specimen void to be reduced than the specimen in which bacteria deposition utilized up to reduce voids of aggregates [36]. Water absorption of bacteria treated concrete far lower than untreated concrete [41].

Water absorption decreased in case of cement replacement 10% by CKD may be due to the filler effect of it [3, 22]. When cement replacement 10% by fly-ash then water absorption decreased [24]. When silica fume added to cement as a cement replacement (10%) then also water absorption decreased may be due to deposition of the $CaCO_3$ in the pores resulting in a decrease in pores later [26,27]. In case of cement replacement by 10% RHA also showed decreased in water absorption due to reactive silica content and very fine texture of RHA that reacted with hydration production of cement and produce CSH-gel [28]. Fig. 4 shows Water absorption of control and bacteria treated concrete without and with 10% cement replacement.

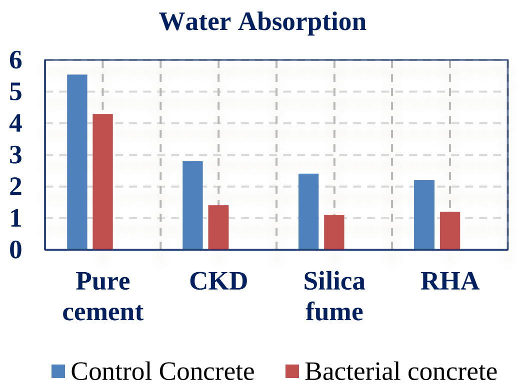

Fig. 4: Water absorption of control and bacteria treated concrete without and with 10% cement replacement.

C. Water Permeability study

Less permeable concrete means that concrete has less water absorption capacity. Deposition of $CaCO_3$ on the cell walls of bacteria in both aggregates and concrete matrix results in a reduction of permeability of urea-$CaCl_2$added water cured specimens. It caused the specimen voids to be smaller in comparison to the specimen in which deposition of bacteria utilized just to reduce voids of aggregates [36]. Use of bacteria in concrete leads to mineral precipitation that helps to fill micro cracks and pores which in turn reduce the permeability of concrete [1]. Permeability of bacterial concrete decreased due to the bacterial treatment [11, 14, 16, 18, 37, 42, 43].

Bacterial concrete made with partial cement replacement (by fly-ash/silica fume/RHA) shown a reduction in porosity and permeability compared to control concrete may be due to increases in fineness of cementing material and the deposition of the calcite in the pores resulting in a subsequent reduction in pores [24,26,27,28]. Therefore, an addition of bacteria can decrease the permeability of concrete while added during concrete production or during curing or after curing in the form of spray [29].

D. Chloride permeability study

Fiber reinforced mortar incorporated nutrients and bacteria exhibited better resistance against chloride penetration than normal mortar. This is may be due to the deposition of calcium carbonate layer on the surface and inside the pores of the mortar which concealed the pores and cracks [39, 40, 43]. The bacterial concrete specimen incorporate CBFD exhibited a moderate reduction in chloride permeability with increasing curing period of time [31]. When 10% cement partially replaced by silica fume chloride permeability reduced due to calcite deposition in concrete [26, 27]. In the case of 10% cement partial replacement with fly ash also chloride permeability reduced due to calcite deposition [24].

E. Freeze-thaw study

Bacteria treated concrete has shown better resistance than the control concrete against freeze-thaw environment may be due to the presence of calcium carbonate and microbial biomass regardless of the admixture [19,40,44]. The wet-dry environment is the best environment for crack healing than continues immersion in water may be because bacteria's workability reduces in water [9, 11, 13, 45].

VI. CONCLUSION

This study discussed the performance of concrete/mortar with respect to self-healing, mechanical properties, and durability properties. It is observed from this study that, compressive, split tensile and flexural strength of concrete/mortar increases and sorptivity, water absorption, water permeability, chloride permeability reduced up-to optimum concentration of bacteria. It has good resistance towards freeze-thaw and alkali, sulfate and chloride attack. All this happens due to the $CaCO_3$ precipitation of bacteria, which can fill small cracks and pores of concrete/mortar. It is an eco-friendly and far better process for self-healing of concrete and mortar than conventional technology. It can be concluded that bacterial concrete can play a major role in the modern construction industry as an eco-friendly, durable, self-healing construction material.

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