Strength Improvement Studies on Self-Healing Characteristics of Bacterial Concrete (Review Paper)

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***ABSTRACT*-The application of concrete is rapidly increasing worldwide and therefore the development of sustainable concrete is urgently needed for environmental reasons. As present, about 7% of the total atmospheric carbon-dioxide (CO_2) emission is due to cement production and its mechanisms that would contribute to a longer service life of concrete structures and it makes the material not only more durable but also sustainable. Cracks are common failures in concrete. Cracks may develop due to addition of excess of water during mixing of concrete, or may be due to shrinkage or creep. In this paper, the following notable points regarding development of a two component self-healing system, characterization studies done with different bacterial species, variation in compressive strength of concrete upon bacterial cell concentrations, physical properties of self-healing concrete, potential of bacteria to act as a self-healing agent etc., are observed and identified from the other research works. A specific group of alkali-resistant spore forming bacteria preferably of genus Bacillus are selected and added to concrete or mortar paste for development of self-healing capacity in structures.**

***Keywords* :Crack remediation, Characterization Studies, Compressive strength, Spore formation**

1. INTRODUCTION

Concrete is a strong and relatively cheap construction material and is therefore presently the most used construction material worldwide. Though concrete has a massive production, it exerts a negative effect on the environment. It is estimated that cement production alone contributes to about 7% of global anthropogenic CO_2 emissions [2]. In the construction sector, concrete is considered as one of the most important building materials around the world. Advancement in concrete technology is in its strength improvement and its enhancement in durability, using pollution-free and natural methods. This needs to be taken care of at the design stage itself [3]. Autogenous crack-healing capacity of concrete has been recognized in several recent studies. Mainly microcracks with widths typically in the range of 0.05 to 0.1 mm have been observed to become completely sealed particularly under repetitive dry/wet cycles. The mechanism of this autogenous healing is chiefly due to secondary hydration of non- or partially reacted cement particles present in the concrete matrix [1]. The development of a self-healing mechanism in concrete that is based on a potentially cheaper and more sustainable material then cement could thus be beneficial for both economy and environment. The main goal of the present research therefore was to develop a type of sustainable self-healing concrete using a sustainable self-healing agent. It was reported that the effect of bio-deposition improves the durability of cement mortar/concrete specimens.

It was also observed that deposition of $CaCO_3$ crystals decreased the water absorption of the sample depending on the inherent porosity of the specimen leading to a decrease in the carbonation rate by about 25–30% [3]. Another aspect of concrete is its liability to cracking, a phenomenon that hampers the material's structural integrity and durability. The effects of durability problems reflect so much on the money spent for maintenance and repair of concrete structures [2]. Cracking of concrete is a common phenomenon. Without immediate and proper treatments, cracks in concrete structures tend to expand further and eventually require costly repair. Though it is possible to reduce the extent of cracking by available modern technology, crack remediation is still being under research. Commercial crack sealing techniques includes use of epoxy resins, epoxy mortar and other synthetic mixtures.

Use of bacteria in concrete remediation is an unorthodox concept in current concrete research. It is however, a new approach to an old idea that a microbial mineral deposit constantly occurs in natural environment. The long term goal is to understand the significance of micro-organisms in concrete structures [8]. Therefore, bacterially induced calcium carbonate precipitation has been proposed as an alternative and environmental friendly crack repair technique [9]. Durability problems such as crack formation are typically tackled by manual inspection and repair, i.e. by impregnation of cracks with cement or epoxy-based or other synthetic fillers. An integrated healing agent will save manual inspection and repair and moreover increases the structure's durability. Addition of such an agent to the concrete mixture would save money and environment [2].

2. CONSIDERATIONS

In order to consider practical application several characteristics have to be determined. Viability and functionality of incorporated bacteria is enhanced until several months after concrete casting. For practice long-term self-healing capacity is needed, ideally for the duration of the service life of the concrete structure. Also multiple healing events should be possible. Cost efficiency is also important. Concrete is a relatively cheap construction material, and adding a self-healing material to the concrete mixture has to be economically feasible. Also efficiency of the healing agent is an important factor.

3. METHODOLOGY

The methodology for producing a self-healing concrete involves the following steps.

i. Selection and cultivation of bacteria.
ii. Preparation of test specimens.
iii. Characterization studies
   - X-ray diffraction
   - Scanning Electron Microscopy (SEM)
   - Thermo-Gravimetric Analysis (TGA)
   - Compressive Strength and Tensile Strength Testing
   - Ultrasonic Pulse Velocity

3.1 Selection of Bacterial Species

Spore forming alkali-resistant bacteria can be isolated from its source. Bacterial strains such as *Bacillus pasteurii, Escherichia coli, Bacillus sphaericus, Bacillus subtilis, Bacillus cereus* etc., are commonly used for research works. Initially these bacteria are obtained from the source and first cultured in a solid media and then transferred to nutrient broth (liquid media) which is sterile and kept shaking in an incubator.

3.2 Measurement of Bacterial Cells

Concentration of bacterial cells is measured by Haemocytometer and optical density could be found by spectrophotometer analysis before adding bacteria to cement composites. Gram staining method was used to determine the morphology of the bacterial strains and the bacterial cultures are tested for urealytic activity and also calcium carbonate precipitation [9]. Before addition to cement cement mixture for test specimen preparation, bacteria should be cleaned from culture residues by repeated centrifugation and resuspension of obtained cell pellet in a clean tap water. Ureolytic bacteria such as B. sphaericus could precipitate $CaCO_3$ by conversion of urea into ammonium and carbonate. Strains of *B. subtilis* were used in the formation of calcium silicate gel by means of adsorbing silicate using chemically modified *B. subtilis* (CMBS). It is found that there is 28% improvement in compressive strength of CMBS incorporated concrete compared to control concrete with optimum concentration [3]. The matrix of fresh concrete is highly alkaline particularly due to the formation of portlandite (calcium hydroxide) which is after calcium-silica-hydrate quantitatively the most important hydration product of ordinary Portland cement (OPC).

Matrix capillary water of young concrete is typically characterized by pH values between 11 and 13. Bacteria added to the concrete mixture thus do not only have to resist mechanical stresses due to mixing but should also be able to withstand a high alkalinity for prolonged periods. Most promising bacterial agents for incorporation in the concrete matrix therefore appear to be alkaliphilic (alkali-resistant) spore-forming bacteria. As the concrete matrix is toxic due to ingress oxygen (diffusion through matrix capillaries) incorporated bacteria also need to be oxygen tolerant.

Such aerobic alkaliphilic spore-forming bacteria occur within the genus *Bacillus*, and several representatives of these were therefore selected to test their applicability as healing agent in concrete [2]. The starting point of the research is to find bacteria capable of surviving in an extreme alkaline environment. Cement and water have a pH value of up to 13 when mixed together, usually a hostile environment for life most organisms die in an environment with a pH value of 10 or above. The search concentrated on microbes that thrive in alkaline environments which can be found in natural environments. Samples of endolithic bacteria (bacteria that can live inside stones) will be collected along with bacteria found in sediments in the lakes. Strains of the bacteria genus *Bacillus* will be found to thrive in this high-alkaline environment. Different types of bacteria which can survive in such a high Ph environment is mentioned in Fig 2.1. It is found that the only group of bacteria that will be able to survive is the ones that produced spores comparable to plant seeds. Such spores have extremely thick cell walls that enable them to remain intact for up to 200 years while waiting for a better environment to germinate. They would become activated when the concrete starts to crack, food is available, and water seeps into the structure. This process lowers the pH of the highly alkaline concrete to values in the range (pH 10 to 11.5) where the bacterial spores become activated [9].

APPILCATIONS	TYPES OF BACTERIA
As crack healer	B. pasteurii
	Deleya halophila
	Halomonas eurihalina
	Myxococcus xanthus
	B. megaterium
For surface treatment	B. sphaericus
As water purifier	B. subtilis
	B. sphaericus
	Thiobacillus

Fig. 1 Different types of bacteria and their applications

3.3 Preparation of Test Specimens

Bacterial concrete casted by using ordinary Portland cement mixed with bacterial concentration 10^6 cells/ml of water. Conventional concrete samples are also casted in parallel. The specimens are cured under tap water at room temperature and tested at 7, and 28 days [9].

3.4 Characterization Studies

The formation of calcite by means of bio-mineralization can be analysed by using various characterization techniques or methods. These techniques are specialized or involve all modes of microbial analysis like imaging, diffraction and spectroscopy, including light, X-rays, neutron or electron as primary radiation. To conduct the above studies, samples should be collected from the tested mortar or concrete specimens in the form of powders or broken pieces [3].

X-ray diffraction: This test is performed to indicate the presence of calcite. Higher the peak values obtained, higher is the presence of calcite. Hence it can be said that microbially precipitated calcite improves the performance of cement composites.

Scanning Electron Microscopy (SEM): The deposition of calcite inside the micro cracks of concrete by bacteria is analyzed under SEM. The increase in compressive strength of concrete can be examined by doing SEM analysis. To determine whether the increase in compressive strength of the specimens with bacteria and sand in their cracks could be attributed to the microbial calcite precipitation, the crack samples with the highest strength values are examined under SEM [8].

Compressive Strength and Tensile Strength: Compressive strength of cement paste, mortar and concrete with bacteria is performed using automatic compression testing machine. Split tensile strength concrete with bacteria is performed.

Ultrasonic Pulse Velocity: The time taken for the pulse to pass through the concrete is measured by electronic measuring circuits [9].

4. BIO-MINERAL PRECURSOR COMPOUNDS AND SAMPLE PREPARATION

Three different organic compounds, peptone, calcium lactate and calcium glutamate, which could be used by both bacterial strains as energy and carbon sources for grows, are tested for their potential applicability as bio-mineral precursor compound in concrete. To investigate bio-mineral producing potential of applied healing agents, test specimen comprising one healing agent component, both healing agent components or no healing agents are prepared. Concentration of healing agents in cement stone specimen was identical to specimen used for compressive strength testing. After 10 days incubation at room temperature, specimen fragments were rinsed with demineralized water and without any further preparation directly studied for mineral formation at crack surfaces by environmental scanning electron microscopy [1]. The combination of suitable bacteria and calcium lactate as mineral precursor compound calcium lactate indeed resulted in production of calcium carbonate precipitates in concrete cracks.

5. EFFECT OF HEALING AGENT ADDITIONS ON SPECIMEN STRENGTH

As incorporation of healing agents to concrete may have unwanted negative effects on material properties, development of compressive strength of control specimen without additions as well as specimen with bacteria or organic compound additions was investigated. Incorporation of a high number of bacteria appears to have a mildly negative effect on compressive strength development as bacterial test specimen appeared almost 10% weaker then control specimen. Effect of organic compound incorporation on development of strength appeared however strongly dependent on compound identity.

6. BACTERIAL SPORE FORMATION

Addition of manganese to the growth medium stimulated the formation of bacterial spores substantially. Light microscopic analysis of growing cultures. Spores could be easily visualized by ESEM analysis due to their thick cell walls and their diameter appeared to be typically in the size range of 0.8–1 μm.

7. RESULTS AND DISCUSSIONS

One major problem associated with crack formation is that the process results in a drastic increase in material permeability increasing the risk of matrix and embedded reinforcement degradation by ingress water and other aggressive chemicals. Active bacterially mediated mineral precipitation could result in crack-plugging and concomitant decrease in material permeability. As bacteria function as catalyst, a suitable mineral precursor compound needs additionally to be incorporated in the material matrix to provide a truly autonomous repair mechanism. However, the maximal allowable amount of mineral precursor compound introduced to the concrete mixture is likely limited as larger quantities may negatively affect other concrete properties such as setting time and (final) strength [2]. Self-healing concrete should be able to heal or seal, by filler material formation, freshly formed cracks to inhibit ingress of water and other chemicals which could cause preliminary degradation of the material matrix or embedded reinforcement. In this study we investigated the bio-mineral production capacity of cement stone specimen in which bacteria were incorporated as healing agent. The integrated bacteria applied in this study are affiliated to alkali-resistant spore-forming species of the genus *Bacillus*. Particularly acid-producing bacteria such as sulphur or ammonium-oxidizing strains are likely harmful as their metabolic waste products etch and dissolve the concrete matrix. For this reason anti-microbial chemical agents are sometimes purposely added to concrete mixtures to inhibit bacterial activity. Substantially less mineral production was observed when both healing components, bacteria and calcium lactate, were incorporated.

A reason for this phenomenon may be that calcium lactate added to the cement paste mixture may have become completely integrated in the material matrix and thus not accessible for bacterial conversion later on [1]. In conclusion we can state that alkali-resistant spore-forming bacteria related to the genus Bacillus represent promising candidates for application as self-healing agent in concrete and probably other cement-based materials. It is found that cement stone incorporated bacterial spores are able to convert concomitantly incorporated calcium lactate to calcium carbonate-based minerals upon activation by crack ingress water [2]. Although concrete with a high self-healing (crack healing) potential is wanted, the addition of healing agents such as bacteria and/or (organic) chemical compounds to the paste may result in unwanted decrease of strength properties.

8. CONCLUSIONS FROM LITERATURE STUDY

1. Concrete incorporated bacteria can produce copius amounts of minerals which can potentially seal freshly formed cracks.
2. From the compressive strength studies in mortar and concrete cubes incorporated with B. cereus and B. pasteurii shows 29% increase in compressive strength.
3. In the case of wild strain, it is observed that strength increases up to 38% for optimal concentration of cells.
4. The presence of chloride ions in Portland cement produces a negative impact on the compressive strength on Portland cement mortar.
5. At lower concentrations, the presence of B. pasteurii increases the compressive strength of Portland cement mortar cubes.
6. An increase of microbial biomass, as dead forms in particular, reduces the strength of cement mortar cubes.
7. Increase of overall strength of mortar when mixed with micro-organisms resulted from the presence of adequate amount of organic substance in the matrix due to the microbial biomass, but not from the presence of calcite induced by microbial growth.
8. Results obtained from SEM examination confirm that calcite precipitated during microbial growth is the main substance that increases the compressive strength of cracked mortar cubes.
9. Microbiological remediation is more efficient in shallow cracks than in deeper cracks, primarily because the micro-organisms grow more actively in the presence of oxygen.
10. Increase in compressive strength is mainly due to the consolidation of the pores inside the cement mortar with microbiologically induced calcite precipitation.
11. When the bacterial cell concentration is increased more than optimum level, the strength gain is about 40% in case of paste and about 28.2% in mortar for B. sphaericus and Sporosarcina pasteurii species respectively, compared to that of conventional mix.

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