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Properties of fly ash concrete containing tropical soil bacteria

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Abstract. The autonomous crack healing process using microbiologically induced calcium carbonate precipitation (MICP) is a sustainable alternative to overcome propagation of micro-cracks and restore the durability of concrete. This paper presents the potential use of tropical soil bacteria as a self-healing agent for fly ash concrete. A solution of 10^7 cells/mL *Lysinibacillus sphaericus* (*L. sphaericus*), was selected to be the self-healing agent by replacing partially the amount of water. Concrete cube specimens with 30% fly ash, were cured under two conditions, which are water and air curing. The potential effects of the self-healing agent was evaluated in terms of the ultrasonic pulse velocity (UPV), initial surface absorption test (ISAT) and compressive strength. The initial results show an improvement of UPV and between 12% and 54% improvement on the compressive strength for the bacterial concrete compared to the control specimen. It was probably due to the presence of the microbial calcium carbonate that fills the concrete pores through the inclusion of bacteria in the concrete. However, based on the ISAT value, the direct addition of bacterial solution increased the concrete's permeability. Thus, further investigation is suggested to assess the self-healing effect towards permeability and compressive strength of bacterial concrete.

1. Introduction

1.1 Concrete Structure

For the past few decades, concrete has becoming one of the most preferable and widely used materials in construction industry due to the availability of raw materials and its flexibility to suit any design and usage of a building or structure. Concrete is used to construct mid-rise, high-rise building and other infrastructures such as bridges and tunnels. Concrete normally designed to be able to maintain its strength and durability throughout the service life of the structure. However, the conventional and basic mix design may be limited only to certain environment and type of building or structure. Hence, numerous research using blended cement has been done to improve the properties of concrete such as workability, strength, durability and provide resistance to chemical substances. Pozzolanic materials such as fly ash, slag or silica fume were introduced in the concrete mix to achieve certain desired concrete properties.



Concrete is a hard, strong and durable construction material. Deterioration of concrete will decrease its durability and strength. One of the causes of concrete's deterioration is cracks. Furthermore, the formation of cracks and voids in concrete can lead to the corrosion of steel reinforcement through further ingress of moisture and other substances. Proper maintenance and repair is essential to prevent concrete's deterioration and maintain its serviceability.

In Malaysia, awareness on repair and maintenance works became more significant as the allocation for repair and maintenance works increased from RM 296 million during the Eighth Malaysian Plan to RM 1,079 million in the Ninth Malaysian Plan. The existing condition of the building, the age of the building, complaint related to the performance of the building, request from the client, financial aspects and safety and health requirements should be considered in decision making of maintenance cost [1]. It shows that maintenance of building was not only costly but also time consuming.

1.2 Self-healing Bio-concrete

Crack remedy using synthetic emulsion such as latex, requires higher cost and not environmental friendly. In recent years, researchers has developed a new green technique to seal crack in concrete by employing bacteria that can produce or precipitate mineral biologically [2]. The basic concept of this biotechnologies approach is mimicking the healing process of bone fractures in human body by mineral that was produced by cells in the bone [3]. Figure 1 shows an example of natural self-healing concrete. The white mineral compound that fill the cracks suggested that in this area, there are microbial activities that can heal the crack.

Microbiologically induced calcium carbonate precipitation (MICP) is the most widely used bio mineralization method in civil engineering industry to enhance the durability of concrete and assist concrete to regain its performance after the defect occurs. MICP can also use to improve the sand properties, repair limestone monuments and prevent leakage in concrete [4]. The most favorable mechanism of MICP is the degradation of urea by ureolytic bacteria or known as ureolysis because it is less complicated and easier to manage [5].



Figure 1. Natural self-healing concrete.

1.3 Self-healing Agents

There are two self-healing agents that will be used to produce self-healing bio-concrete, which are bacteria and precursor or organic compound. The bacteria used as a self-healing agents must be nonpathogenic, able to remain viable for long time period in dormant state and have the ability to precipitate carbonate in the environment with high temperature and pH values. By replacing parts of Ordinary Portland Cement (OPC) with fly ash, the pH of concrete can be reduced through secondary hydration [6]. Therefore, the tendency of bacteria to survive in blended cement is much higher than plain OPC.

Most of the bacteria can be found from soil, sand, water, coral, plants or limestone [7]. Based on previous study, alkaliphilic spore-forming bacteria genus *Bacillus* was the most suitable bacteria that can be used as self-healing agent in concrete [8].

The other component of self-healing concrete is the precursor or organic compound. The function of this compound is to participate through the chemical reaction to produce calcium carbonate. A researcher has used amino acid and calcium lactate as organic mineral precursor in their research. From their study, it can be concluded that acid amino hardly affected the compressive strength of concrete. Meanwhile the calcium lactate has enhanced the compressive strength value [9]. Other researchers have also used yeast extract, peptone and calcium acetate precursor compound [10].

Both healing agents can be added directly to concrete mix or by encapsulation of light weight aggregate [11]. However, the amount of the self-healing agents should be limited as larger quantities may give negative effect to other concrete properties such as setting time and final compressive strength [12]. Figure 2 shows the basic components of self-healing bio-concrete.

Most of previous study, only focusing on the effect of incorporating bacteria as self-healing concrete using OPC. Hence, the purpose of this study is to identify the potential use of tropical soil bacteria as a self-healing agent for concrete using blended cement especially fly ash.

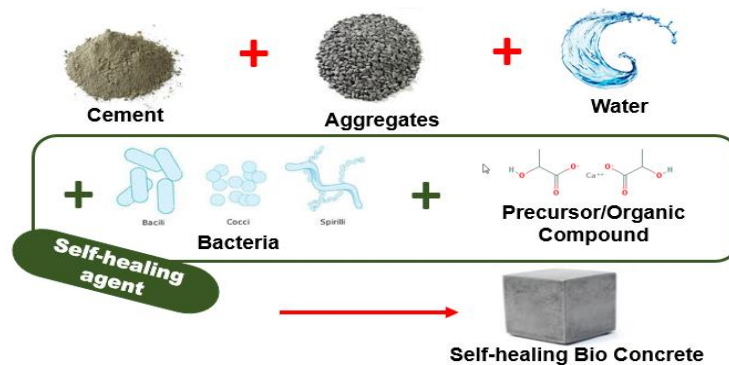


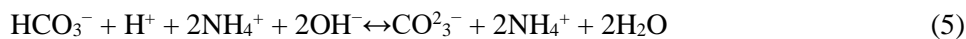
Figure 2. Components of self-healing bio-concrete.

1.4 Mechanism of MICP

Ureolysis involved three phases to form calcium carbonate. It includes the degradation of urea by the bacteria, formation of carbonate ions and precipitation of calcium carbonate. Once moisture present, the reaction will be started. Urea is hydrolyzed to ammonia and carbamic acid (1). Then, the carbamic acid will spontaneously hydrolyzed to another mole of ammonia and carbonic acid (2). Both the ammonia and carbonic acid further equilibrated in water and form bicarbonate, ammonium and hydroxide ions (3)(4) [13, 14, 15].



The formation of hydroxide ions during the degradation of urea, will increase the pH, shift the bicarbonate equilibrium and form carbonate ions (5) [13, 14, 15].



The cell wall of the bacteria is negatively charged, so it will draw cations, including calcium ion to deposit on their cell surface. The calcium ions then react with the carbonate ions and precipitate calcium carbonate at the cell surface that will seal and block the cracks (6)(7) [13, 14, 15].



2. Materials and Methods

2.1 Preparation of Bacterial Solution

The self-healing agent used in this study was *Lysinibacillus sphaericus* (L. sphaericus). Based on the previous study, L. sphaericus has the ability to precipitate more carbonate compared to other ureolytic bacteria that was isolated from tropical soil in Universiti Teknologi Malaysia [16]. A solution of L. sphaericus (10^7 cells/mL) was inoculated into growth medium (urea 20 g/L, yeast extract 5 g/L, peptone 5 g/L and NaCl 10 g/L) for 24 hours at 37 °C with 150 rpm to obtain a one-day stock culture. At this stage, carbonate ions, CO_3^{2-} was formed through ureolysis. Then, the bacterial solution will be mixed with the mineral precursor, which is calcium chloride (CaCl_2). The function of the mineral precursor is to provide calcium ions, Ca^{2+} . Figure 3 shows the components of bacterial solution that was used in this study.

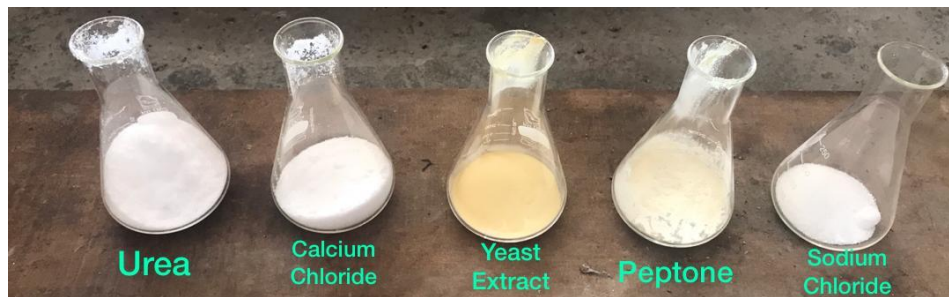


Figure 3. Components of bacterial solution.

2.2 Preparation of Concrete Specimens

Concrete specimens with normal grade (30 N/mm^2) was prepared according to the Department of Environment's Design Method (DoE method). The cube specimens with the dimensions of 100 x 100 x 100 mm were produced. The control samples were prepared using 70% OPC with the addition of 30% fly ash. The cube specimens were cured under two conditions; in air and water. For the bacterial concrete, parts of the water were replaced with a bacterial solution. The bacterial solution was directly incorporated in the concrete during the mixing process. The potential of the self-healing agent was evaluated in terms of the ultrasonic pulse velocity (UPV), initial surface absorption test (ISAT) and compressive strength. Both UPV and ISAT tests were conducted according to BS 1881-201: 1986 [17]. Meanwhile the compressive strength of concrete specimens was determined based on BS EN 12390-3:2009 [18]. Table 1 shows the mix proportion of the concrete sample.

Table 1. Mix proportion of concrete specimens

Concrete type	Mix proportion						
	OPC (kg/m ³)	Fly ash (kg/m ³)	Water (L)	Bacterial solution (L)	Mineral precursor (g/L)	Fine agg. (kg/m ³)	Coarse agg. (kg/m ³)
Control	330	140	250	-	-	900	735
Bacterial concrete	330	140	241.6	8.4	5	900	735

3. Result and discussion

3.1 Ultrasonic Pulse Velocity (UPV)

UPV test is one of the non-destructive tests to determine homogeneity and any presence of voids or other internal imperfections in concrete specimens. Therefore, the results of UPV is used as an indicator of cracks healing in concrete specimens. Table 2 shows the result of UPV for this study. As can be seen in this table, there was an increase of UPV for concrete specimens under both water and air curing conditions. These results suggested that the void within the concrete specimens might be filled by the calcium carbonate that was precipitated through the ureolysis process. Previous study reported that the inclusion of bacteria in the concrete has a positive effect on the durability and improved the UPV. The self-healing agent used have the ability to penetrate, precipitate and fill the pores with microbial calcium carbonate in the concrete [19, 20, 21].

Table 2. Result of UPV in the concrete specimens

Concrete type	UPV (m/s)
Water curing	
Control	4,400
Bacterial concrete	4,540
Air curing	
Control	3,800
Bacterial concrete	3,920

3.2 Initial Surface Absorption Test (ISAT)

Figure 4, Figure 5 and Figure 6 show the ISAT value for the 3 days, 7 days and 28 days concrete specimens, respectively. These figures show that ISAT value gradually decreased with time. It can be observed that the overall ISAT value for the 28 days concrete specimens was lower than the 7 days and 3 days concrete specimens due to less void or crack. From the graphs, it shows that water cured concrete specimens has lower ISAT value than air cured concrete specimens.

The absorption value of self-healing bio concrete was higher than the control specimens. It might be caused by the method of incorporating bacteria in the concrete specimens. As mentioned before, the bacterial solution was used by replacing parts of the water in the concrete mix. Consequently, it may affect the water cement ratio of the concrete specimens and increase the ISAT values for the self-healing bio concrete.

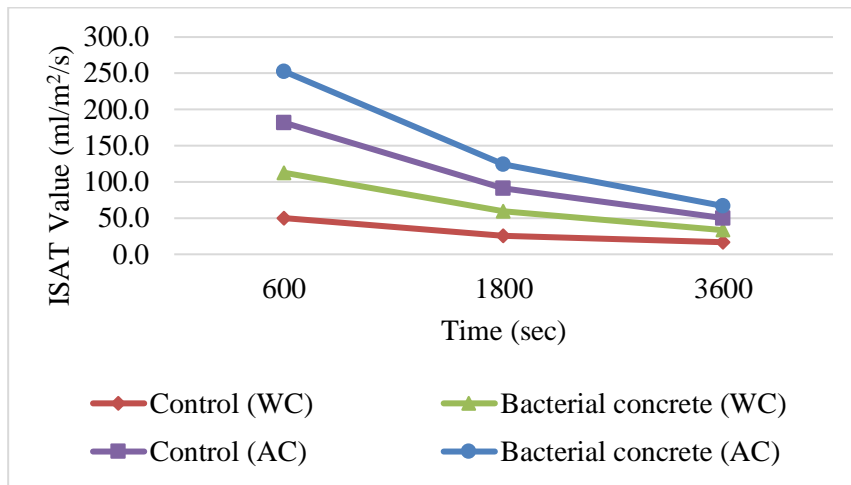


Figure 4. ISAT values for 3 days concrete specimens.

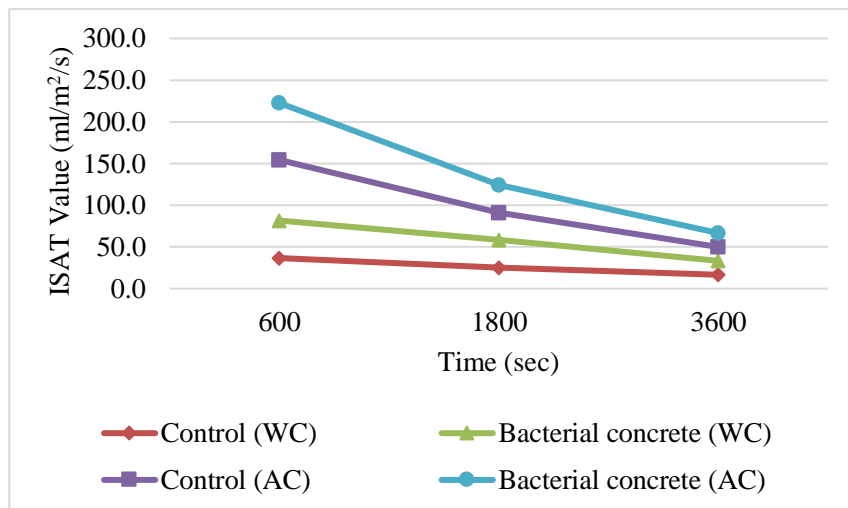


Figure 5. ISAT values for 7 days concrete specimens.

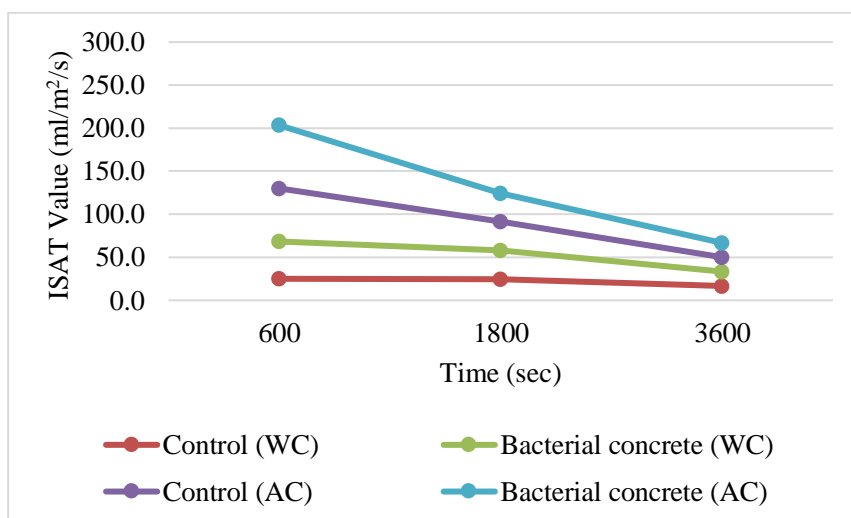


Figure 6. ISAT values for 7 days concrete specimens.

3.3 Compressive Strength of Concrete Specimens

The main purpose of incorporating bacteria was to enhance the durability of the concrete. However, it must be ensured that the concrete can maintain its strength to sustain the load. According to a research conducted, by incorporating bacteria may increase the compressive strength of concrete by 15 to 60% after 7 days [22, 23]. However, it was depending on the type and amount of bacterial solution used. Different strain of bacteria may affect either the compressive strength, durability or both of them [24]. Thus, the effect of ureolysis using *L. sphaericus* towards compressive strength of concrete specimens was carried out.

Table 3 presents the compressive strength of the concrete specimens. It clearly shows that the compressive strength of the concrete specimens was increased with the presence of the bacteria. For the water cured concrete specimens, the compressive strength for 3 days specimens was increased by 12%, 29% strength increment for the 7 days specimens and 12% strength increment for the 28 days specimens. Meanwhile, for the air cured concrete specimens, the compressive strength increase about 26%, 54% and 7% for 3, 7 and 28 days concrete specimens, respectively. The increase of the compressive strength indicated positive effect of incorporating bacteria in the concrete specimens.

Table 3. Compressive strength of concrete specimens

Concrete type	Compressive strength (N/mm ²)		
	3 days	7 days	28 days
Water curing			
Control	17.17	20.36	28.65
Bacterial concrete	19.15	26.33	32.23
Air curing			
Control	13.71	16.29	27.36
Bacterial concrete	17.26	25.13	29.30

4. Conclusions

The study investigated the influence of bacteria as a self-healing agent in concrete specimens with fly ash. It has been assumed that *L. sphaericus* has the capability to precipitate calcium carbonate. Based on the investigation, it can be concluded that the byproduct of the ureolysis process has the potential to heal cracks and increase the compressive strength of concrete. The effectiveness of the self-healing agent may be influenced by the curing condition as concrete specimens that was water cured has better performance than air cured specimens. The optimum quantity of the self-healing agent and method of incorporating in the mix play important role too in order to maximize the self-healing effect especially for reducing initial permeability.

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