Splitting Tensile Strength Analysis of High-Strength Concrete Using Ureolytic Bacteria from Local Landfill as Microbial Self-Healing

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Abstract. High-strength concrete is a brittle material due to its low tensile strength. Splitting tensile strength of concrete can be used to determine the concrete tensile capacity. High-strength concrete has high bearing capacity and good durability during its service life but excessive loads and extreme environmental influences can reduce its strength, thus, early maintenance is needed. Efforts that can be made are applying self-healing concrete using ureolytic bacteria obtained from local landfill Gampong Jawa, Banda Aceh, namely Bacillus sp. Splitting tensile strength test of concrete was carried out using cylindrical specimen with diameter 15 cm and height 30 cm. Bacillus sp. bacteria can produce calcium carbonate ($CaCO_3$) as concrete crack-healing with the help of precursors, i.e., urea and Ca^{2+} ion along with nutrient broth as their nutrients. To ensure better bacterial viability, the bacteria along with their precursors and nutrients were encapsulated with diatomaceous earth and then coated with cement paste. Variations used are the concentration of bacteria along with their precursors and nutrients, i.e., 1.27%, 1.53%, and 1.79% from cement weight. To activate the $CaCO_3$ formation by bacteria, the specimens were cracked first with a load of approximately 40% of its splitting tensile strength after being soaked in water for 7 days, then soaked again in water for 28 days for crack-healing before being tested. Splitting tensile strength analysis showed that the higher the concentration of Bacillus sp. bacteria, the greater the difference of splitting tensile strength between initial cracking load and after self-healing treatment, which indicates better crack-healing efficacy.

1 Introduction

High-strength concrete made using a lot of cement augmented with additives and admixtures having a low water to cement ratio. The main advantages offered by high-strength concretes are high bearing capacity and serviceability as well as high compactibility and durability.

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Thus, it is suitable to be used as construction material for various advanced and modern infrastructures that require large load bearing capacity and high resistance to extreme and corrosive environments, such as high-rise buildings, long bridges, toll roads, large dams, deep foundations, retaining wall and offshore buildings [1]. Nevertheless, high-strength concrete is more brittle than normal-strength concrete, because the strength of cement paste and interface between aggregates and cement paste are greatly increased near the aggregate strength, resulting in a low tensile strength. In addition, high-strength concrete is susceptible to the formation of microcracking at early-age due to the use of large amounts of cement and cementitious additives, which cause high hydration heat and large shrinkage [2].

The tensile strength is needed to plan the thickness of concrete slab and to calculate the cracking load and cracking moment of the concrete, as well as to determine the level of ductility. The vulnerability to early-age cracking means that high-strength concrete must be treated from the beginning. If these microcracking are allowed to arise, they will propagate progressively due to the service loads imposed to the structure. If left until a high level of damage occurs it will require expensive structural repair and strengthening costs.

One smart solution to overcome this is by using bacteria that are included in the concrete mixture and will remain in the concrete structure after the concrete hardens. Bacteria can function as a catalyst for self-healing concrete by producing $CaCO_3$ to close concrete cracks. One of the bacteria that can be used is ureolytic bacteria. Ureolytic bacteria produce the urease enzyme which is able to hydrolyze urea to form calcium carbonate ($CaCO_3$) with the help of calcium ions. Urea and Ca^{2+} ions are precursors, then, to ensure the viability of bacteria, nutrition is provided, namely nutrient broth. Bacteria along with their precursors and nutrition can be mixed directly into the concrete mix, but to ensure better viability during casting and after being in harsh concrete environment, bacteria can be embedded in the encapsulation medium.

The process of calcium carbonate formation is called Microbial-Induced Carbonate Precipitation, MICP [3]. Urea $CO(NH_2)_2$ which is found in the environment, in the soil or which is given as precursor to ureolytic bacteria will be hydrolyzed through urease enzyme produced by bacteria in the existence of water vapor and oxygen to become carbamic acid or aminocarboxylic acid (NH_2COOH) and ammonia (NH_3), as shown in Equation (1). In the presence of moisture (water vapor and oxygen) carbamic acid will be decomposed into ammonia and carbonic acid (H_2CO_3) as in Equation (2). The amount of ammonia produced increases, which will lead to the increase of the pH of ureolysis activity. Further, carbonic acid will be converted into two negatively charged carbonate ions (CO_3) in the cell wall of ureolytic bacteria (Equation 3), and ammonia will be decomposed into positively charged ammonium cations (Equation 4). In addition to urea, to produce $CaCO_3$ precipitation in the hydrolysis process of ureolytic bacteria, dissolved Ca^{2+} ions must be added which can be obtained from the $CaCl_2$ solution. In the final phase $CaCO_3$ is formed according to the reaction in Equation (5).

Through the ureolytic hydrolysis reaction, 1 mole of urea is hydrolyzed by the urease enzyme into 1 mole of ammonia and carbamic acid, and carbamate will be hydrolyzed spontaneously to yield 1 mole of ammonia and carbonic acid. Then, carbonic acid is converted into bicarbonate.

$$CO(NH_2)_2 + H_2O \xrightarrow{urease} NH_2COOH + NH_3 \quad (1)$$

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

$$H_2CO_3 \rightarrow 2H^+ + 2CO_3^{2-} \quad (3)$$

$$NH_3 + H_2O \rightarrow NH^{4+} + OH^- \quad (4)$$

$$Ca^{2+} + 2CO_3^{2-} \rightarrow CaCO_3 \quad (5)$$

Currently, research using ureolytic bacteria as concrete crack-healing has been relatively widely studied. However, utilization of ureolitic bacteria originating from local landfills to heal cracks in high-strength concrete is still rarely studied. Thus, this research aims to determine the effectiveness and efficacy of ureolytic bacteria obtained from landfill Gampong Jawa, Banda Aceh City, namely Bacillus sp., as crack healing for high-strength concrete. Based on research conducted by [4] from soil originating from the Gampong Jawa landfill, three dominant types of urolytic bacteria were obtained, namely Bacillus (7 isolates), Staphylococcus (1isolat), and Solibacillus (2 isolates). Using local bacteria has many added values, namely being able to prevent environmental pollution, acclimatize to local conditions, as well as the technology applied could be locally adapted.

2 Methods

2.1 Materials

In this research, the main parameter used was the bacterial concentration along with precursors, i.e., urea and Ca^{2+} ions obtained from dissolved $CaCl_2$, and nutrition in form of Nutrient Broth. Bacterial concentration was varied to 1.27%, 1.53%, and 1.79% from the cement weight. Concentration of 1.27% consists of bacteria 0.50%, urea 0.44%, $CaCl_2$ 0.22%, and nutrient broth 0.11%. Then, concentration of 1.53% comprises bacteria 0.60%, urea 0.53%, $CaCl_2$ 0.27%, as well as nutrient broth 0.13%. Furthermore, concentration of 1.79% consists of bacteria 0.70%, urea 0.62%; $CaCl_2$ 0.31%, and nutrient broth 0.16%, all from the cement weight.

Bacteria used were Bacillus sp. originating from Gampong Jawa Landfill Banda Aceh City, which can yield calcium carbonate (calcite) precipitation in amount of 0.14435 ± 0.007725 g [4]. Based on results of bacterial concentrations calculation using the McFarland 0.5 standard test, the concentration of Bacillus sp. was 1.5 x 10^8 CFU/mL (CFU = Colony Forming Units).

Bacteria bacillus sp. together with precursors dan nutrient were encapsulated into diatomaceous earth which were mixed into the concrete mixture as a substitution for 20% of fine aggregates. The purpose of encapsulation was so that the bacteria have good resistance during casting as well as after being in harsh concrete environment, but the encapsulation pellets will break if cracks appear in the concrete.

High-strength concrete was made with Portland cement of 550 kg/m^3, split having a maximum diameter of 12 mm as coarse aggregates, natural river sand with a maximum diameter of 2.36 mm as fine aggregates, silica fume of 8% by cement weight as additive and Viscocrete-10 superplasticizer of 1.5% by cement weight. The w/c- ratio used was 0.30. Mix design of concrete was calculated by trial and error with a volume ratio. The volume weight of high-strength concrete was taken into account to be 2550 kg/m^3, in them the volume weight of aggregate taken as 70%. The ratio between fine aggregates to coarse aggregates was taken 40%.

2.2 Testing of Concrete Splitting Tensile Strength

The high-strength concrete splitting tensile strength tests were conducted on cylinders possessing diameter of 150 mm and height of 300 mm according to ASTM C 496 – 96 [5]. To activate the $CaCO_3$ formation by bacteria Bacillus sp., the specimens were cracked first with a load of approximately 40% of its splitting tensile strength after 7 days of soaking in water. Then, the cracked specimens were soaked again in water for 28 days as crack-healing time before being tested to obtain the concrete splitting tensile strength.

The test begins by providing a center line on each side of the cylinder end to ensure that the cylinder was placed really centric on the loading plate, then plywood pads were provided along the longitudinal side of the cylinder before applying a compressive load. Loading was carried out continuously with a constant loading speed ranging from 0.7 to 1.4 MPa per minute until the cylindrical specimen was collapsed [5]. The setup of splitting tensile strength testing is given in **Fig. 1**. The concrete splitting tensile strength is calculated using Equation (6) as follows:

$$f_t = \frac{2P}{\pi D t} \tag{6}$$

where P is the maximum load (kN), D is the diameter of cylinder specimen (mm), and t is the height of cylinder specimen (mm).

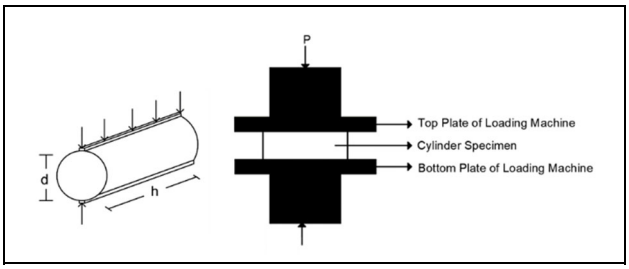

Figure 1. Setup of Splitting Tensile Strength Testing

3 Results and discussions

3.1 Effect of bacterial concentration on splitting tensile strength

Based on the research results, it can be seen that the ureolytic bacteria Bacillus sp. from local landfill Gampong Jawa Banda Aceh could be used effectively as crack-healing in high-strength concrete. After being imposed an initial cracking load of an average of 42.507% from the splitting tensile strength of the control high-strength concrete without bacteria, the increase of strength in the bacterial concrete after crack remediation reached an average of 65.295% of the splitting tensile strength of the control high-strength concrete.

The amount of the splitting tensile strength of high-strength concrete at the initial cracking load and at the ultimate load for varying concentrations of bacteria + precursor + nutrients of 1.27% (bacteria concentration 0.50%); 1.53% (bacteria concentration 0.60%); and 1.79% (bacteria concentration 0.70%) respectively can be seen in **Table 1**. The initial crack load in high-strength concrete with bacterial concentrations of 1.27%, 1.53% and 1.79% is 44.517%, 50.058% and 32.946% respectively of the splitting tensile strength of control high-strength concrete of 5.395 MPa. It was difficult to make the initial crack load same for all variations in bacterial concentration because the splitting tensile strength test of concrete used a manually controlled hydraulic compression testing machine. Meanwhile, the ultimate splitting tensile strength of high-strength concrete with bacterial concentrations of 1.27%, 1.53%, and 1.79% respectively reached 53.086%, 74.569%, and 68.230% of the splitting tensile strength of control high-strength concrete.

Table 1. Splitting Tensile Strength of High-Strength Concrete with Varying of Bacterial Concentration at Initial Cracking and Ultimate Load

No.	Bacterial Concentration (%)	Splitting Tensile Strength (MPa)		Comparison of Ultimate Splitting Tensile Strength to Control Specimen (%)	Crack-Healing Efficacy (%)
		At Initial Cracking	At Ultimate Load		
(1)	(2)	(3)	(4)	(5)	(6) = (4)/(3)
1.	1.27% (Bacteria 0.50%)	2.402	2.864	53.086	119.23
2.	1.53% (Bacteria 0.60%)	2.701	4.023	74.569	148.94
3.	1.79% (Bacteria 0.70%)	1.777	3.681	68.230	207.15

According to **Table 1** it can be seen that the increase in the strength of high-strength concrete after crack healing process by Bacillus sp. bacteria was greater at higher concentrations of ureolytic bacteria. At the bacterial concentration of 1.27% the increase in splitting tensile strength at ultimate load compared to the initial cracking load was 0.462 MPa, at bacterial concentration of 1.53% it was 1.322 MPa, and at bacterial concentration of 1.79% it reached 1.904 MPa.

3.2 Effect of bacterial concentration on crack-healing efficacy

The ureolytic bacteria Bacillus sp. can function as internal catalyst for crack-healing in high-strength concrete. Calcium carbonate ($CaCO_3$) formed by the ureolysis process of Bacillus sp., which were encapsulated in diatomaceous earth pellets, could close the cracks that arose and could produce higher splitting tensile strength after the crack-healing process for 28 days compared to the splitting tensile strength when the initial cracking load was applied. This can be seen clearly in **Table 1** and **Fig. 2**. By the concentration of Bacillus sp. along with precursors and nutrients of 1.79% (bacteria 0.70%), a concrete crack-healing efficacy of 183.98% was achieved (see **Table 1**). By achieving strength reaching 75.23% of the control high-strength concrete specimens, it could be concluded that the ureolytic bacteria Bacillus sp. were effective as a crack-healing catalyst.

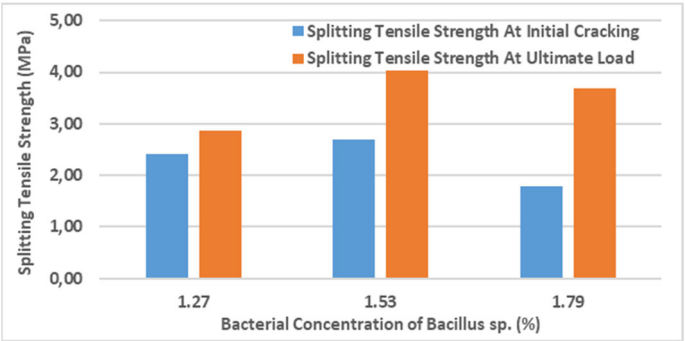

Figure 2. Splitting Tensile Strength at Initial Cracking and Ultimate Load

3.3 Calcite ($CaCO_3$) development on concrete cracking

The self-healing ability of cracks in high-strength concrete by ureolytic bacteria Bacillus sp. was influenced by the concentration of bacteria used. The higher the bacterial concentration, the more $CaCO_3$ (calcite) was formed to close the cracks. Visual observation of the formation of Calcium Carbonate in high-strength concrete cylindrical specimens observed at 7 days, 14 days, 21 days and 28 days during crack-healing process for the three variations in bacterial concentration is given in **Fig. 3**. From **Fig. 3** it can be seen that in the largest concentration of bacteria, i.e., 1.79% (bacteria concentration 0.70%), eventhough large macro cracks had already formed when the initial crack load was applied, the bacteria Bacillus sp. could still produce $CaCO_3$ (calcite) to completely close the crack.

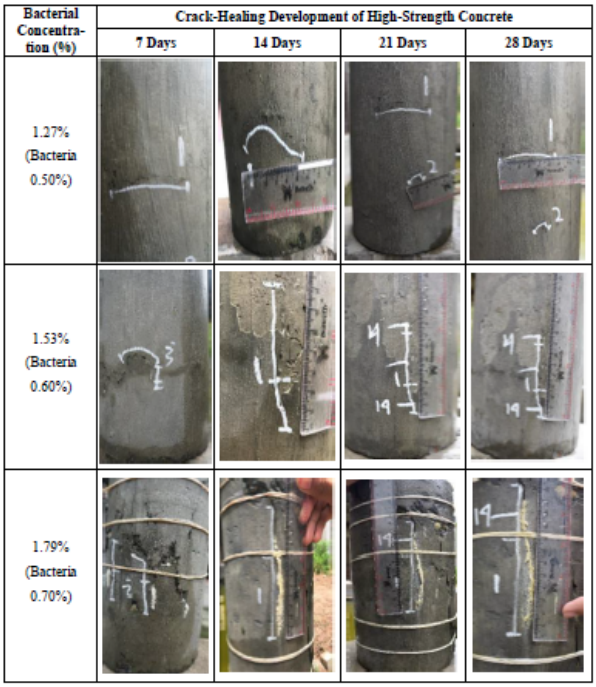

Figure 3. Crack-Healing Development by Bacteria Bacillus sp. During Remediation

4 Conclusions

According to the results of this research, it could be concluded that the use of ureolytic bacteria Bacillus sp. from local landfill Gampong Jawa Banda Aceh encapsulated into diatomaceous earth could function effectively as an internal crack-healing of high-strength concrete. The bacterial concentration has a significant effect on the increase of splitting tensile strength of high-strength concrete after crack remediation, in which the higher the bacterial concentration, the more $CaCO_3$ was formed to close the cracks, and the greater the efficacy of crack-healing. The highest bacteria concentration, i.e., 1.79% (Bacillus sp. bacteria concentration 0.70%) yielded the largest high-strength concrete crack-healing efficacy, i.e., 183.98% reaching the splitting tensile strength of 75.23% compared to the control high-strength concrete specimen.

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