Review on the potential application of bacterial cementitious composites in Indonesia

R Linda¹, H Prabowo²* and I Indrayadi³

¹Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Tanjungpura, Pontianak, Indonesia
²*Laboratory for Construction, Innovative Structures, and Building Physics, Politeknik Negeri Pontianak, Pontianak, Indonesia
³Department of Architecture, Politeknik Negeri Pontianak, Pontianak, Indonesia

E-mail: prabowoherry@polnep.ac.id

Abstract. Cementitious composites are common construction material for infrastructures. Their abundant resources are one of the reasons why they are widely consumed. The drawback of these materials is its brittle nature resulting in unavoidable cracking problems in the infrastructures. Further, the crack will initiate the corrosion of steel reinforcement and reduce structural durability. Calcium carbonate precipitating bacteria are the potential to heal the cracks in the cementitious composite if they are selected and treated carefully. This paper reviews different types of bacteria applied in concrete, and the methods can be used as a healing agent. This study recommends using bacterial cementitious composites as self-healing material, surface treatment, and crack healing agent.

1. Introduction
Cementitious composite plays an essential role as the most used material for infrastructures. Its low tensile strength property leads to the tension crack propagation. This condition allows for harmful liquids and gases to enter the material, resulting in steel reinforcement corrosion and durability problems [1]. Cementitious composite can be classified into three categories based on the aggregate composition. They are concrete (containing coarse and fine aggregates), cement mortar (only containing fine aggregates), and cement paste (containing no aggregates) [2].

The new emerging bacterial technology gives hope to overcome the brittle nature of cementitious composites. Research shows that bacteria from the genus Bacillus can precipitate calcite when inserted into concrete [3]. The calcite has known to be excellent in mechanical and thermal compatibility with cementitious materials [4].

In Indonesia, the research in bacterial cementitious composites is still rare. This paper reviews the state-of-the-art development of bacterial cementitious composites in Indonesia. The aspects addressed including the type of bacteria used, the source of bacteria, mixture proportion and specimens, mechanical properties, physical properties, and chemical properties. The possible applications are also presented.
2. Material and method of bacterial cementitious composites
The material used for bacterial cementitious composites consists of the bacteria and composite compound. Bacteria related parameters, among other types of bacteria, bacterial concentration, nutrients, incubation method, and sources. The cementitious composites' parameters include the type of cement, fine aggregate, coarse aggregate, and filler. The ratio of fine aggregate, coarse aggregate, and filler are associated with the mixture proportions. The specimens' parameters are the type, size, and type of test performed. The method used in this research is literature review which is shown in Figure 1.

2.1. Bacteria used
Bacteria are simple single-cell organisms presented in most places on earth. There are roughly five nonillions \((5 \times 10^{30})\) bacteria on earth [5]. The bacteria inserted into the concrete should withstand its high alkali environment [6]. Most of the reported bacteria used as bacteria-based crack healing are coming from the genus Bacillus. Bacillus is a Gram-positive, rod-shaped bacteria. The species of Bacillus used in Indonesia can be listed in Table 1.
Table 1. Different bacteria used.

| Bacteria           | Bacterial Concentration (cell.mL⁻¹) | Nutrients (gL⁻¹) | Incubation       | Source                        | Reference |
|--------------------|-------------------------------------|------------------|------------------|-------------------------------|-----------|
| Bacillus subtilis  | 10⁴                                 | 5 peptone, 5 NaCl, 3 yeast | 125 rpm, 24 hours | Nutrition and food center, UGM | [7]       |
|                    | 10⁵                                 |                  |                  |                               |           |
|                    | 10⁶                                 |                  |                  |                               |           |
| Bacillus altitudinis | -                                  | 5 peptone, 5 NaCl, 3 yeast | 125 rpm, 24 hours | Mountain limestone, Central Java | [8]       |
| Lysinibacillus macroides | 1.25x10⁵ | 5 peptone, 5 NaCl, 3 yeast | 28°C, 3 days     | Jombblang Cave Soil and Stalagmite, Yogyakarta | [9]       |
| Bacillus sp.       | 1.75x10⁷                            | 20 urea, 49 chloride | 150 rpm, room temperature | Mountain limestone, Southeast Sulawesi | [10]      |
|                    | 3.50x10⁷                            |                  |                  |                               |           |
| Bacillus sp.       | -                                   | 1 calcium lactate pentahydrate, 1.5 nutrient broth | 0.600             |                               | [11]      |

2.2. Cementitious composite ingredients

The cementitious composite compounds are mixture of cement, fine aggregate, coarse aggregate, filler, and water. The cement used is Ordinary Portland Cement (OPC) Type I as per SNI 15-2049-2004 [12] and Portland Pozzolana Cement (PCC) as per SNI 15-0302-2004 [13]. The fine and coarse aggregate shall conform to SNI 03-1750-1990 [14]. The filler used is Pulverized Fly Ash (PFA) and Volcanic Ash (VA). The VA was obtained from Mount Kelud, West Java, Indonesia. Table 2 shows the material components used.

Table 2. Cementitious composite ingredients.

| Type of cement | Fine aggregate | Coarse aggregate | Filler | Reference |
|----------------|----------------|------------------|--------|-----------|
| OPC            | Sand           | -                | PFA    | [7]       |
| OPC            | Sand           | Coarse aggregate | VA     | [8]       |
| PPC            | Sand           | Crush rock 20 mm/ Crushed Hydroton 10 mm | VA     | [9]       |
| Cement         | Sand           | -                | -      | [10]      |
| OPC            | -              | -                | -      | [11]      |
2.3. Mixture proportion and specimens
The ingredient of cementitious composites is mixed based on specific mix design. The material proportion (the ratio between cement, fine aggregate, coarse aggregate), water-cement ratio (W/C), and amount of filler used is given in Table 3. Based on the mixture proportion, the specimens are cast into certain shapes. These specimen shapes are adjusted to the mechanical tests carried out. The specimen, size, and type of test are in Table 4.

### Table 3. Mixture proportions.

| Proportion | Fine Aggregate | Coarse Aggregate | W/C | Filler (by weight of cement) | Reference |
|------------|----------------|------------------|-----|-----------------------------|-----------|
| 1          | 3              | -                | 0.485 | 20%                        | [7]       |
| 1          | 2              | 3                | 0.5  | 0 – 2%                      | [8]       |
| 1          | 2              | 3                | 0.65 | 25 – 50%                    | [9]       |
| 1          | 1              | -                | -    | -                           | [10]      |
| -          | -              | -                | 0.5  | -                           | [11]      |

### Table 4. Specimens’ sizes and types.

| Type of specimen | Size (mm) | Type of test | Reference |
|------------------|-----------|--------------|-----------|
| Mortar           | 50x50x50  | Compressive strength, flexural test, water permeability | [7] |
|                  | 60x60x220 |              |           |
|                  | Ø110 – thick 20 |              |           |
| Concrete         | Cylinder  | Compressive strength | [8] |
| Concrete         | ASTM C31/ C31M | Compressive strength | [9] |
| Mortar           | 100x100x100 | Compressive strength | [10] |
| Cement paste     | Ø45 – thick 22.5 | Compressive strength | [11] |

3. Discussion on the Properties of Bacterial Cementitious Composites
The properties of bacterial cementitious composites addressed include the mechanical properties, physical properties, and chemical properties. The mechanical properties are characterized by a compressive strength test. Physical properties are observed visually and by using SEM. Meanwhile, the chemical properties are identified by using XRD, EDX, and acid titration.

3.1. Mechanical properties
The mechanical properties addressed are based on compressive strength tests. Table 5 describes the correlations of bacterial concentration and specimen age to the increase of compressive strength. The compressive strength of the specimen tends to increase as the rise of bacterial concentration. There is a trend that the specimen compressive strength is stronger as the specimen age increasing.

### Table 5. Mechanical properties (compressive strength).

| Bacterial concentration | Specimen age (day) | Increase (%) | Reference |
|-------------------------|--------------------|--------------|-----------|
| $10^3$                  | 3                  | 17.97        | [7]       |
|                         | 7                  | 21.40        |           |
|                         | 28                 | 25.38        |           |
|                         | -                  | 18           | [8]       |
| $1.2 \times 10^5$       | 28                 | -10.56       | [9]       |
| $3.5 \times 10^7$       | 7                  | 37.37        | [10]      |
|                         | 28                 | 59.98        |           |
| -                       | 0.109              | -            | [11]      |
3.2. Physical properties
The physical properties are observed visually and through Scanning Electron Microscope (SEM). The examined specimens show calcite (calcium carbonate, CaCO$_3$) precipitation in the crack. The crack width of less than 0.2 mm can be self-sealed by concrete itself. For the crack, more than 0.2 mm, concrete fails to heal the gap autonomously. This kind of calcite precipitation will be beneficial to prevent harmful materials from entering. Table 6 presents the type of instrument, a physical characteristic observed, and optimum cell concentration used.

| Observation instrument | Physical characteristic | Optimum cell concentration (cell.mL$^{-1}$) | Reference |
|------------------------|-------------------------|--------------------------------------------|-----------|
| SEM                    | Calcite precipitation   | $10^5$                                     | [7]       |
|                        | Concrete absorption     | -                                          | [8]       |
| SEM                    | Calcite precipitation   | $1.2 \times 10^5$                          | [9]       |
|                        |                        | $3.5 \times 10^7$                          | [10]      |
| Visual                 | Calcite precipitation   | -                                          | [11]      |

3.3. Chemical properties
The instruments used to observe the chemical properties are X-Ray Diffraction (XRD), Energy Dispersive X-ray spectroscopy (EDX), and acid titration. XRD analysis is used to study the crystalline phase present in the materials and to reveal chemical composition. EDX is used to analyze element content and characterize chemical composition in the samples. Acid titration is used to determine the concentration of acid in the sample qualitatively. The results of the observed chemical characteristics to their corresponding observation instrument can be seen in Table 7.

| Observation instrument | Chemical characteristic | Optimum cell concentration (cell.mL$^{-1}$) | Reference |
|------------------------|-------------------------|--------------------------------------------|-----------|
| XRD, EDX               | Better crystallinity    | $10^5$                                     | [7]       |
|                        | Alkali condition        | -                                          | [8]       |
| Acid titration         |                         | $1.2 \times 10^5$                          | [9]       |
|                        |                         | $3.5 \times 10^7$                          | [10]      |
| XRD                    | (Unpublished data)      | -                                          | [11]      |

4. Possible Applications of Bacterial Cementitious Composites
The application of bacterial cementitious composites by far is as a self-healing material. This thing is done by introducing bacteria into concrete during casting. The self-healing mechanism occurs when the crack takes place. H$_2$O and O$_2$ are entering the crack and contact with bacteria in the gap. Afterward, calcite precipitation is induced by the bacteria that will autonomously begin to fill the crack [15].

Besides its application as self-healing material, bacterial cementitious composite is the potential to be implemented in surface treatment and crack healing agents [16]. Recently, a specimen with a surface treatment containing bacteria and nutrients had exhibited better durability in the aspect of
water and chloride permeability [17]. The conventional treatments demonstrate several drawbacks, such as degradation, incompatible thermal expansion, and environmental pollution [18].

A crack healing agent can be obtained by forming bacteria and nutrients solutions. The solution can then be applied in the crack, and calcite precipitation will fill the crack. Research on applying a solution of bacteria and nutrients on a shotcrete specimen seems promising. The 0.2 mm crack was fully mended [19].

The other potential application of the bacterial cementitious composite is coming from its durability properties. The service life simulation on carbonation and chloride ingress mechanisms showed that the bacterial cementitious composite is promising in increasing the durability [20]. This thing will make the bacterial cementitious composite possible to be applied to structures in a harsh environment, for instance, marine structures.

5. Conclusion and Future Study
This work emphasizes the potential application of bacterial cementitious composites in Indonesia. Indonesian biodiversity and a unique environment open a huge opportunity to study different methods based on local resources. The bacteria samples so far were taken from the cave’s soil and stalagmite and also mountain limestone. This study review different types of bacteria used, including Bacillus subtilis, Bacillus altitudinis, Lysinibacillus macroides, and Bacillus sp. This study emphasizes the positive effect of bacteria on the compressive strength of cementitious composites. This study also recommends using bacterial cementitious composites as self-healing material, surface treatment, and crack healing agent. Several issues remaining unaddressed. It is vital to study further the effective and efficient bacterial precipitation, type of curing, different environment exposure, sulfate attack, and carbonation mechanisms.

Acknowledgments
The assistance or encouragements from colleagues and extraordinary works by technical staff are gratefully acknowledged.

References
[1] Kumar VR, Bhuvaneshwari B, Maheswaran S 2011 An overview of techniques based on biomimetics for sustainable development of concrete. Current Science; 101(6).
[2] Yanfeng R, Wei Z, Jialiang W, Danna W, Xun Y, Baoguo H 2019 Nanocarbon material-filled cementitious composites for construction applications. In Khan A, Jawaid M, Abdullah I, Asiri MA, editors. Nanocarbon and Its Composites: Preparation, Properties and Applications.: Woodhead Publishing Series in Composites Science and Engineering. p. 781-803.
[3] Lee YS, Park W 2018 Current challenges and future directions for bacterial self-healing concrete. Applied Microbiology and Biotechnology; 102.
[4] Seifan M, Samani AK 2016 Berenjian A. Bioconcrete: next generation of self-healing concrete. Applied Microbiology and Biotechnology; 100(6).
[5] Siddique R, Chahal NK 2011 Effect of ureolytic bacteria on concrete properties. Construction and Building Materials; 25(10).
[6] Bravo F, Silva D, Boon N, Verstraete W, De Belie N 2015 Screening of bacteria and concrete compatible protection materials. Construction and Building Materials.; 88.
[7] Nugroho A, Satyarno I, Subyakto 2015 Bacteria as Self-Healing Agent in Mortar Cracks. Journal of Engineering and Technological Sciences; 47(3).
[8] Purwanto HA, Nugroho A, Aprilin R 2017 Study of Volcanic-Ash-Impregnated-Bacteria Filler to the Compressive Strength of Concrete. In MATEC Web of Conferences 138;
[9] Nugroho A, Sumarno A, Ngeljaratan LN, Zulfiana D, Krishanti NPRA, Triastuti, et al 2019 Self-Healing Concrete Using Bacteria Calcification from Karst Cave Environment. Jurnal Kimia Terapan IndonesiaJune; 21(1).
[10] Susilowati E, Rajiani NA, Hermawan H, Zaeni A, Sudiana IN 2019 The use Immobilized Bacteria-Alginate-Chitin for crack remediation. In IOP Conf. Series: Earth and Environmental Science;

[11] Syarif R, Rizki IN, Wattimena RK, Chaerun SK 2019 Selection of bacteria inducing calcium carbonate precipitation for self-healing concrete application. Current Research on Biosciences and Biotechnology; 1(1).

[12] BSN. SNI 15-0302-2004: Semen portland pozolan. Jakarta: Badan Standardisasi Nasional (BSN); 2004.

[13] BSN. SNI 15-2049-2004: Semen portland. Jakarta: Badan Standardisasi Nasional (BSN); 2004.

[14] DSN. SNI 03-1749-1990: Besar Butir Agegat untuk Aduk dan Beton. Jakarta: Dewan Standardisasi Nasional (DSN); 1990.

[15] Luo M, Qian C 2016 Influences of bacteria-based self-healing agents on cementitious materials hydration kinetics and compressive strength. Construction and Building Materials.; 121.

[16] De Belie N 2016 Application of bacteria in concrete: a critical evaluation of the current status. RILEM;

[17] Joshi S, Goyal S, Reddy MS 2018 Influence of nutrient components of media on structural properties of concrete during biocementation. Construction and Building Materials; 158.

[18] Linwei L, Qiaofeng Z, Zhen L, Ashraf A, Baoguo H 2019 Bacterial technology-enabled cementitious composites: A review. Composite Structures; 225.

[19] Kalhori H, Bagherpour R 2017 Application of carbonate precipitating bacteria for improving properties and repairing cracks of shotcrete. Construction and Building Materials; 148.

[20] Prabowo H 2020 Durability based service life prediction of bacterial concrete. In Journal of Physics: Conference Series, Volume 1469; Bali.