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REPAIR OF CRACKS IN CONCRETE WITH THE MICROBIAL-INDUCED CALCITE PRECIPITATION (MICP) METHOD

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Abstract

In this study, the microbiologically-induced calcium carbonate precipitation (MICP) method was employed to examine its potential for repairing cracks in concrete. In addition, specific gravity and porosity values were measured to examine the effect of calcite formations on concrete surfaces and microstructures. Bacteria-supplemented concrete repaired cracks up to 0.4 mm wide by filling them with CaCO3. Furthermore, this study not only examined the healing of the width but also the length of cracks. However, as the width of the treated cracks decreased, their length increased. This indicated that the MICP treatment is more effective in a limited crack range. Specific gravity values increased, and porosity values decreased in concrete supplemented with calcifying bacteria. SEM analyses showed that calcite is a bacterial product that forms a very tight bond with a cement gel and that calcite fills visible cracks and voids and creates more of a void-free and undamaged concrete structure.

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Key words

- Crack repair,
- Self-healing,
- Bacterial concrete,
- MICP,
- Porosity.

1 INTRODUCTION

Concrete is the construction material most preferred due to its low cost, desirable visuality, ease of production, high durability, and compressive strength. It is exposed to various external factors and forces throughout its service life. These forces often cause cracks, spills, and separations on concrete surfaces. Cracks formed on a concrete surface are classified as structural cracks (due to design errors, its application, and inspection problems) and non-structural cracks (quality of the material used, freezing/thawing, ambient conditions, reactions, chemical effects, additional loads, and other environmental factors). Although the compressive strength values desired are achieved in structural concrete today, cracks still occur due to the reasons listed above and damage the durability properties of the concrete. Therefore, treating cracks encountered on a concrete surface appropriately is a necessity because cracks formed as a result of this damage are known to negatively affect the mechanical properties and durability of concrete (Yıldırım and Ozhan, 2023). Although cement offers autogenous improvements in cement-based composites, such improvements are limited in width (Danner et al., 2019; Wang et al., 2014b) and mechanisms proposed. There was no effect of varying silica fume (4%, 12%). Materials used to repair concrete cracks are usually polymer or cement-based products but repairs with these materials are costly. Such repairs result in extra costs to the structure over the long run (Muhammad et al., 2016; Van Breugel, 2007). In addition, cement and similar materials used for crack repairs and long service life cause high CO_2 emissions. However, the concrete's composition contains natural components, not CO_2-generating emissions, except for cement. Researchers have thus started to use the microbial calcification method (MICP) as an autonomous healing strategy, as it is a more natural, environmentally-frien-

dly, and economical method (Bachmeier et al., 2002; Choi et al., 2017; De Muynck et al., 2008; Jongvivatsakul et al., 2019; Van Tittelboom et al., 2010; Wu et al., 2019).

Carbonate mineralization is a frequently observed mechanism in nature. For example, the growth of corals, seashells, the protective shells of some animals, and bones are formed or regenerated as a result of bio-mineralization. The formation of bacterial calcium carbonate depends on the metabolic activity of bacteria (Hammes et al., 2003). Feeding the bacteria to increase its metabolic rate also increases carbonate mineralization. Many bacteria in nature can hydrolyze urea to form calcification. The production of calcium carbonate ($CaCO_3$) by bacteria can be considered as an ideal process for MICP. The bacterial urease enzyme initiates carbonation (Equation 1). In the presence of calcium ions and suitable environmental conditions, calcium carbonate is formed (Equation 2). The suitable conditions may depend on many variables, such as the type of bacteria, ambient temperature, pH value, oxygen and calcium concentration in the environment (Okwadha et al., 2010). Calcium carbonate formed as a result of this reaction is known to have a high degree of purity (Beveridge, 1988).

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-} \quad (1)$$

$$CO(NH_2)_2 + Ca^{2+} + 2\,H_2O + \text{cell} \rightarrow 2NH_4^+ + CaCO_3^{2-} + \text{cell} \quad (2)$$

The biological calcification created by bacteria is shown schematically in **Fig. 1.**

Filling the voids and cracks of concrete with calcium carbonate produced by bacteria is remarkable. Cracks filled with $CaCO_3$ formed as a result of Equations 1 and 2 are also important for reinforced concrete structures, because 80% of all structures in the world are reinforced concrete structures and must therefore be protected against corrosion through cracks (Joshi et al., 2017). In concrete repair studies using the MICP method, the bacillus genus of bacteria is particularly preferred, because this genus can preserve itself for up to 200 years unless there is an undesirable off-limit condition (Wang et al., 2014a). Considering the long service life of building materials, it is important that bacteria can survive for a long time when used in a material. Any bacteria that have the ability to produce calcite, a long-living alkali-resistant substance, can be used as an additive in concrete. Bacillus species with spore stages in their life cycle are perfect candidates for such applications of MICP.

Various methods are used for bacteria supplementation in concrete mixtures. These methods include spraying, injection, and its direct addition to a mixture. The most effective and practical method is its direct addition to a cement mixture because both external and internal cracks can be treated without the need for any additional treatment (Le Metayer-Levrel et al., 1999). Therefore, in the present study, *Bacillus megaterium* was directly supplemented in concrete mixtures. This method was successfully used in crack repair applications, and the concrete cracks were healed by filling them with $CaCO_3$(Chintalapudi et al., 2017; Feng etal., 2021; Van Tittelboom et al., 2010; Wiktor and Jonkers, 2011; Zhang et al., 2017). In bacterial concrete, self-healing behavior positively altered other properties such as compressive strength, water absorption, and permeability, as well as crack repair (Andalib et al., 2016; Krishnapriya et al., 2015).

However, MICP is still a developing treatment technique. This study examined bacterial self- healing not only in the width but also in the length of cracks. Therefore, the effetive width and length of the cracks were also examined. In addition, the effectiveness of the MICP treatment, depending on the curing time, was investigated by examining the cracks on the bacterial concrete samples that were cured for different amounts of days. In addition, the effect of calcite formed by Bacillus megaterium, one of the bacteria with the highest urease capacity, on the specific gravity and porosity level of concrete was investigated. The image of this bacterial product

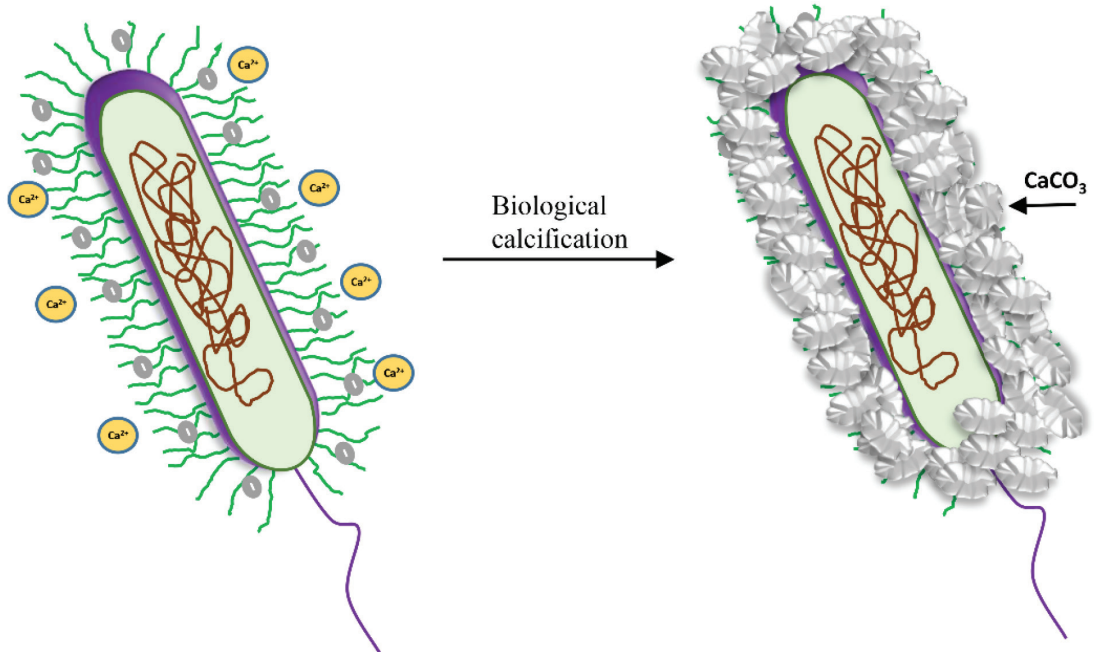

Fig. 1 *Schematic representation of microbially-induced calcite precipitation by bacteria.*

calcium carbonate, was examined under a scanning electron microscope (SEM), and its compatibility with the concrete matrix was observed.

2 MATERIALS AND PREPARATION OF SAMPLES

2.1 Microorganisms, growth conditions and media

Bacillus megaterium, which was selected as the bacterium identified to have a high degree of urease activity, was obtained from the Culture Collection of Refik Saydam Hygiene Institute (Ankara, Turkey). The cells were maintained at -80°C in 50% (v/v) glycerol and cultured on agar nutrient plates at 30°C for 24 h. Pure colonies were transferred into sterile nutrient broth media, and the culture was incubated at 30°C with agitation at 150 rpm for 24 h. To carry out the experiments, a nutrient broth-urea (NBU) medium (8 g nutrient broth, 2% urea solution and 25 mM $CaCl_2$) was used as described by (Achal et al., 2009), and the final pH of the medium was adjusted to 8.0.The nutrient broth was autoclaved at 121 °C for 15 minutes and supplemented with a filte -sterilized 2% urea solution and 25 mM $CaCl_2$.

2.2 Concrete materials and proportion of mix

CEM I 42.5R Portland type cement was used in all the mixtures. The aggregates were prepared and used in accordance with TS 706 EN 12620 standards (TS 706 EN 12620+A1, 2009). The specific gravity of the coarse aggregates used was 2.75, and the specific gravity of the fine aggregates was 2.65. Tap water was used in all the mixtures. The water/cement ratio in the concrete mixture is 0.45. The weights of the materials used in the mixtures for 1 $m^3$are given in Tab 1.

Tab. 1 *Composition of the concrete mixture*

Materials	Volume(kg/m^3)
Cement	195
Water	433
8-16mmaggregate	618
4-8mmaggregate	353
0-4mmaggregate	766

2.3 Preparation of concrete sample

The production of the concrete was performed in accordance with TS 802 standards (TS 802, 2016).Two types of concrete were produced in this study, i.e., bacterial concrete (BC) and the control concrete (CC). In the bacterial concrete, the bacterial cells with a density of 3×10^6cells/mL were inoculated into the NBU medium while making curing water for the concrete samples. No bacteria were added to the curing water in the control concrete. Except for the bacteria inoculation, the production conditions and materials were exactly the same. Fresh mixtures were poured intomolds (100 x 100 x 100 mm) and removed from the molds after 24 hours. The samples were kept in the curing liquid (the NBU medium) for the days of the experiment (28 and 90 days). Three replicates from each type of concrete were used for each experiment.

3 TEST AND METHODS

3.1 Generation and healing of cracks

It was expected that the cracks would be healed as long as the required nutrients and oxygen were taken by the bacteria present on the surfaces of the crack (Seifan et al., 2017). The 7-day concrete samples cured in the curing liquid (NBU medium) were cracked using a compressive strength press. The cracks were generated on three replicates from each series. The range of the width of the cracks generated on the concrete was between 0.1 - 0.5 mm (Fig. 2). For this crack formation, the compressive strength value of the concrete was determined first. Then, 90% of this compressive stress was loaded on the concrete samples, and cracks were formed. The cracked concrete was placed back into the NBU me-dium and cured for 28 days and 90 days. At the end of 28 and 90 days, the changes in the crack structures were recorded by photographing them. At the same time, CC and BC samples with out any cracks were also kept in the same NBU medium as controls. The medium liquid was renewed every 28 days.

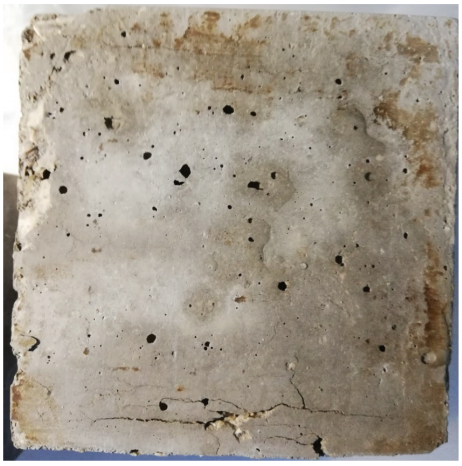

Fig. 2 *The cracks generated on the concrete surface.*

3.2 Specific gravity

Since the products formed in the pores and cracks on the surface of the concrete, it was expected to form a filled structure; specific gravity tests were applied to determine the rate of the filling. According to Equation 3, the weights of the concrete samples in the saturated water weights were measured, and the specific gravity of each specimen was determined.

$$\delta = \frac{(Wsat)}{(Wsat - Wwat)} \tag{3}$$

where: δ is the specific gravity; Wwat is the weight in water of the saturated sample; and Wsat is the weight in air of the saturated sample.

3.3 Porosity

The porosity was measured to determine the effect of bacterial products formed in theconcrete samples cured for 28 days. After 28 days of curing, the saturated in water and oven-dry weights of the CC and BC concrete samples were determined. The porosity values were obtained with the use of Equation 4.

$$P = \frac{(Wsat - Wdry)}{(Wsat - Wwat)} \quad (4)$$

where: P is the apparent porosity; (%) Wwat is the weight of the saturated concrete sample in water; Wsat is the weight of the saturated concrete sample; and Wdry is the weight of the oven-dried concrete sample.

3.4 Scanning electron microscopy (SEM)

The SEM analysis was conducted with the use of a Zeiss / Gemini 300 Scanning Electron Microscope (BTU, Turkey). Fragments taken from the bacteria-supplemented concrete samples were examined. The widths of these structures were between 5-15 mm. The samples were dehumidified and vacu-umed before the SEM analysis was performed.

4 RESULTS AND DISCUSSION

4.1 Formation of $CaCO_3$ and Healing of Cracks

To monitor the calcium carbonate production of the bacteria, the bacteria-supplemented concrete samples cracked by applying stress were cured for 28 days and 90 days. The control concrete (CC) and bacterial concrete (BC) samples were also treated the same with the bacteria-supplemented concrete samples. $CaCO_3$formations were not observed in the CC samples. However, $CaCO_3$products were formed in the crack-free BC concrete samples (Fig. 3). We found that the bacteria added to the concrete mixtures led to calcification after curing. We also observed that the $CaCO_3$on the concrete samples tended to form calcification in the pores of the concrete samples. At the same time, the calcification products were firmly attached to the concrete samples and were difficult to scrape o

Despite the decreased rates of calcification during the incubation, the bacterial calcification formations continued to occur after 28 days. When the surface of the 7-day, 90-dayuncracked, and 100 mm-wide BC samples were compared, the surface of the sample in the 90-day uncracked sample became filled due to the calcification of the bacteria (Fig. 4). The 90-day bacterial activity was apparent as more whitish areas were on the sample compared to the 7-day samples.

After cracks were formed on the BC and CC concrete sam-ples by applying compressive stress on the seventh day of the curing, the concrete samples were further cured for 28 and 90 days. During the curing process, the crack healing process was observed by photographing it. It is well known that even

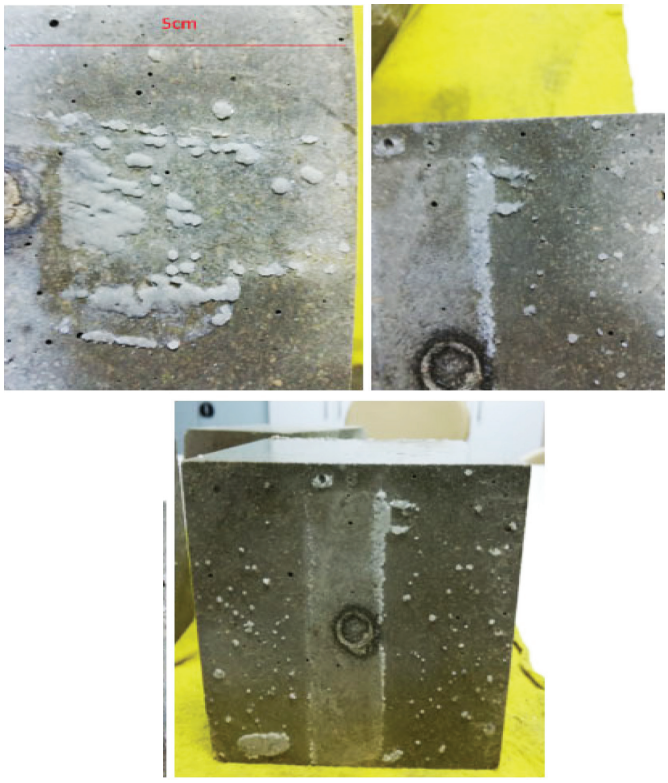

Fig. 3 *$CaCO_3$ products formed on the surface of the 28-day BC concrete samples.*

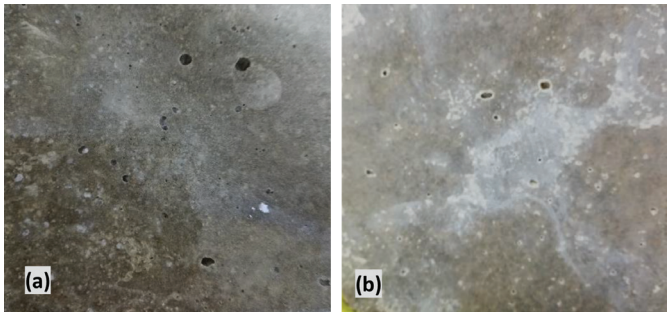

Fig. 4 *Formations on the surface of the 7-day (a) and 90-day (b) BC concrete samples.*

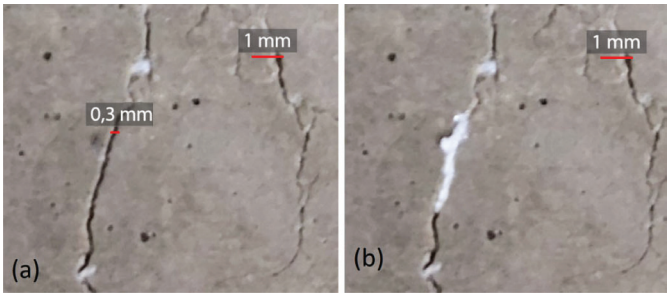

Fig. 5 *Healing of crack (0.3mm) after 28 days of curing: (a) initial (b) final.*

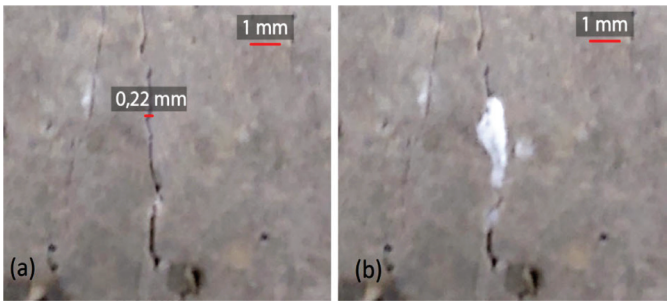

Fig. 6 *Healing of crack (0.22mm) after 28 days of curing: (a) initial (b) final.*

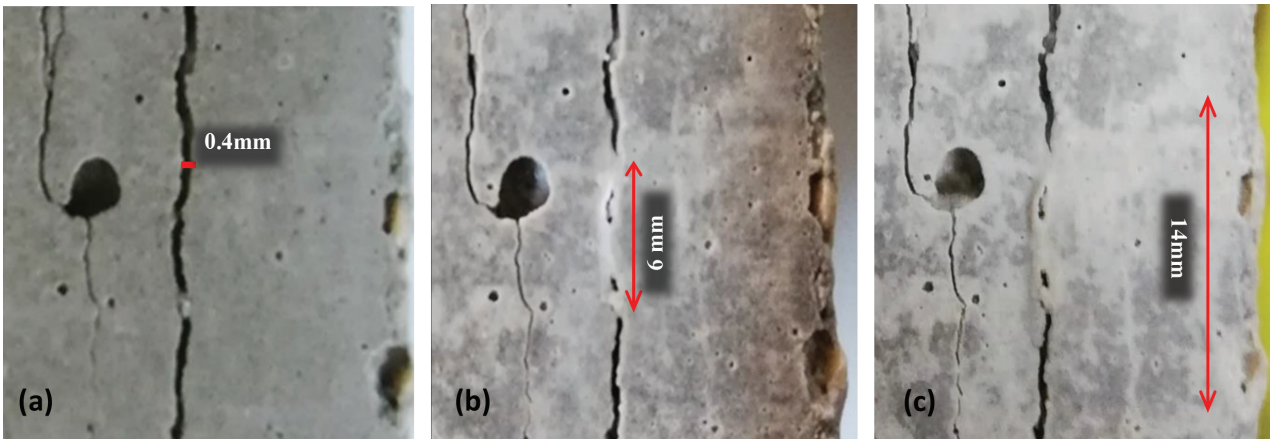

Fig. 7 *Initial (a), 28-day (b), and 90-day appearance (c) of a 0.4 mm wide crack on the surface of BC.*

cracks that do not pose a risk in terms of structural safety can cause durability problems over the longterm. Therefore, the healing of the various sizes of the crack widths is important. We observed that 28 days were enough to heal cracks of 0.3mm (Fig. 5) and 0.22mm (Fig. 6).

The initial, 28-day, and 90-day states of the cracks were examined in all the concrete samples to determine the long-term changes in the crack healing processes. The widest crack width repaired in this study was 0.4 mm and is shown in Fig. 7. Significant mprovements in the healing of the crack were observed as early as 28 days (Fig. 7b), and a more general improvement was detected in the 90-day cured concrete samples (Fig. 7c). Acceptable improvements were particularly observed within the 14 mm-long region on the surface of the edge of the concrete sample. The voids and cracks in those structures were filled with calcite, and a white surface was formed. It was also observed that the color of the concrete sample turned from gray to whitish, indicating heavy calcification. Also, Qian et al. (2021) repaired cracks with a width close to the width of the cracks healed in our study using MICP.

Fig. 8 presents another concrete sample whose long-term behavior was examined. On this other concrete sample there were two 7 mm (0.20 mm width) and 15 mm (0.12 mm width) long cracks (Fig. 8). After 28 days, these two cracks had healed. In Fig. 8 (c), it was seen that the microstructures and micro cracks on the concrete sample were mostly filled with calcite. Similarly, to other cured concrete samples, the surface color turned white. In addition, it was also found that as the width of the crack increased, the length of the healed crack decreased. The longest healed crack was observed to be 0.12 mm wide, where the amount of the width was most restricted. Thus, the MICP treatment was found to be more effective in more limited crack ranges .

In previous studies (Yildirim et al., 2023; Qian et al., 2021), it had been observed that similar widths of cracks had been repaired with the MICP method. Slight differences were mainly attributed to different species of bacteria and to the conditions present in healing the cracks. Chintalapudi et al. (2017) used Bacillus pasteurii as a biological agent in their study and observed healing in cracks in 56 days. Van Tittelboom et al. (2010) used Bacillus sphaericus in their study and also used different media for the bacterial activity. These factors had an impact on the closure of the cracks. Zhang et al. (2017) reported that bacterial cultures and conditions were effective in a crack closure. In the study of Wiktor et al. (2011), healing of cracks at the end of 100 days were observed. Feng et al. (2021) achieved the final healing of cracks after 28 days of the application of the MICP. In this study, although the crack closure was higher in the first 28 days, it continued for 90 days, but the type of bacteria and medium used must be considered.

The cracked and uncracked concrete samples were compared in terms of the $CaCO_3$ products, and it was observed that the $CaCO_3$ formations were primarily encountered in cracks. Such formations play a great role in the effectiveness of crack treatment. H_2O (water) and O_2(oxygen) could pass more easily through the cracks by the capillary route, thus creating better conditions for the bacteria there.

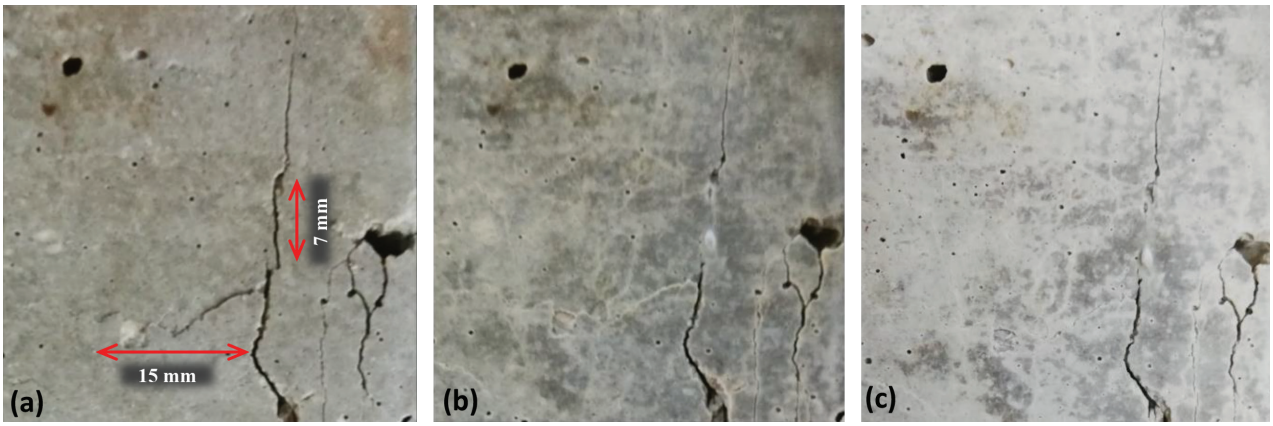

Fig. 8 *Initial (a), 28-day (b), and 90-day (c) appearance of crack generated on the BC specimens.*

Owing to these better conditions, the bacteria in the cracks use their microbial enzymes to create $CaCO_3$ (Jonkers and Thijssen, 2010; Ujike et al. 2010). Likewise, in our study, while the calcite formed in the uncracked concrete samples was dispersed in the voids and on the surface, it was formed primarily on the cracks in the concrete samples. In previous studies, it was reported that these calcites formed on concrete surfaces and that the filled-in cracks improved the mechanical properties and durability of the concrete. (Reddy and Revathi, 2019; Yildirim et al., 2023; Özhan et al., 2020).

4.2 Specific gravity

Calcium carbonate ($CaCO_3$) produced by the MICP method occurs in micro cracks and on surfaces, thereby creating an extra filling in a concrete sample. Therefore, the specific gravity values of the cured concrete samples increases. The specifi gravity values of the concrete samples were calculated with the use of Equation 3 and the weights provided in **Table 2**. The specific gravity was calculated as 2.32 for the BC concrete samples and 2.30 for the CC concrete samples. The bacteria-induced $CaCO_3$ formations yielded this change in the specific gravity. Thus, it was observed that the bacteria generated a heavier and fuller volume. Fuller concrete volumes are known to have higher strengths and are more impervious to water. In this respect, it is important that calcite be formed in an amount that will increase the specific gravity o the concrete.

Tab. 2 *Weights of the control and bacterial concrete*

Sample	Wsaturated (g)	Wwater (g)	Wdry (g)
CC	2411	1364	2299
BC	2435	1386	2336

4.3 Porosity

A more void-free structure is possible by filling the pores with the $CaCO_3$ produced by the bacteria. The values given in Table 2 were used in Equation 4 to estimate the porosity values. The average porosity value was estimated at 10.72% for the CC samples and 9.43% for BC concrete samples. As a result, the calcifying bacteria also had an effecton the surface porosity of the concrete samples. The more void-free structures on the concrete samples after curing were also detected on the porosity levels. Our results clearly show that the $CaCO_3$ formed reduced the porosity values and filled the structure. In line with this study, the studies of Siddique et al. (2016) and Rao et al. (2017) showed that calcite produced by bacteria reduces porosity values. Porosity is crucial for the service life of concrete, as it is a property of concrete that primarily affects its water absorption properties.

4.4 Scanning electron microscopy (SEM)

The $CaCO_3$ formations created by the MICP method were examined under SEM. The crystallized structure of the calcium carbonate is clearly shown at 50X and 200X magnifications in Figs. 9 and 10. It is a stable product thanks to its crystalline structure.

Fig. 9 *Microstructure of the calcium carbonate precipitation ($CaCO_3$) on the BC samples at 200X magni ication.*

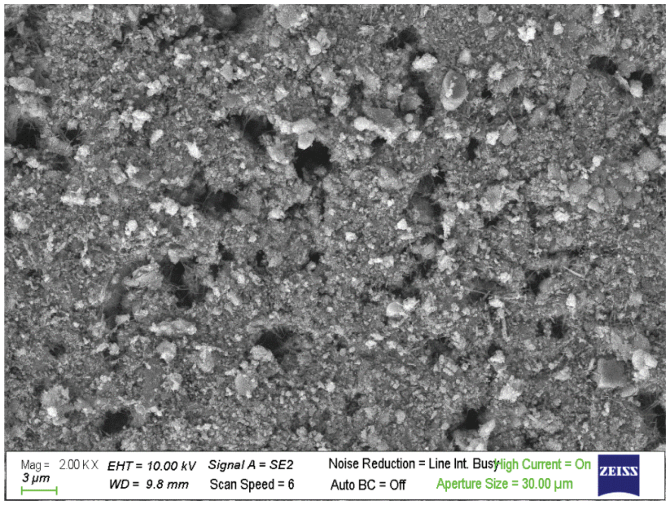

Fig. 10 *Precipitated $CaCO_3$ on the surface of the concrete samples*

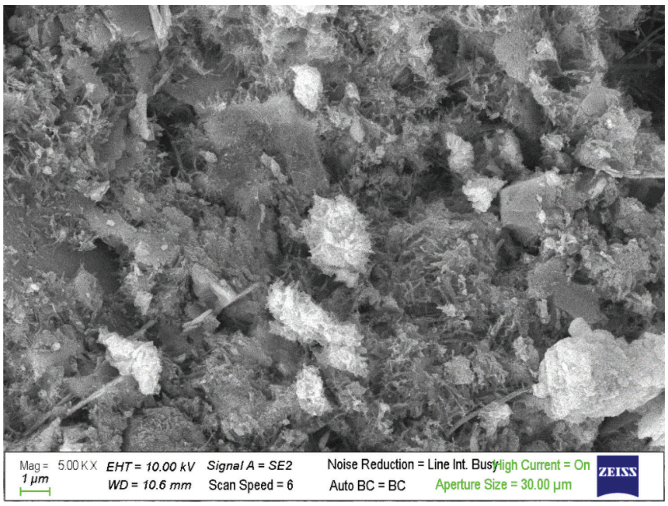

Fig. 11 *Microstructure of bacterial concrete (BC)*

When examined with 5.00KX magnification, the $CaCO_3$ in Fig. 11 revealed itself with its white color. In addition, the structure created with the CSH gels in the photograph and how

it filled the voids at the micro level was remarkable. In addition to filling pores and cracks, a strong bond was observed to have been established in the concrete structure, thanks to its compatibility with the CSH gel.

5 CONCLUSIONS

The addition of bacteria to a concrete mixture as a biological additive has positive effects on concrete structures, i.e., a more filled-in surface and the healing of cracks. The healing of the cracks was observed just a week after the curing process. After 28 days, the various cracks between 0.1 mm and 0.4 mm were completely healed. However, it was determined that the bacteria provided a longer closure at the narrower crack widths. This indicated that the MICP treatment is more effective in a limited crack range. In addition, calcite was formed in the bacterial samples that did not contain cracks, leading to more filled concrete surfaces. It was observed in the precracked concrete samples, that calcite tended to form in cracks, so it was concluded that crack repair could be performed effectively in bacteria-supplemented concrete. Cracks in narrow areas present more surface area for bacterial activity. Moreover, calcite formations were also encountered on the surface and internal structure of the concrete, and such formations increased the specific gravity values and decreased the porosity values of the concrete samples. The microstructure of the calcium carbonate produced by bacteria in the bacterial concrete was investigated under SEM. Depending on the calcium carbonate mineralization, the formations and changes in the microstructure of the concrete were clearly observed. Further research is recommended with the use of different bacterial species and examining the effect of fibers to restrict crack widths.

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