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Mechanical Performance of Bacterial Self-Healing Rigid Pavement with Recycled Brick Aggregates

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ABSTRACT

Previous studies have demonstrated the effectiveness of microbially stimulated calcite precipitation (MICP), produced by specific bacterial species such as Bacillus spp. , as a crack repair agent in cementitious materials. To explore its potential applications, this research investigated the effect of a bacteria-based self-healing agent on concrete containing recycled brick aggregate. The study involved isolating and culturing bacteria, identifying their species, inducing cracks, adding the bacteria, and measuring the repair efficacy of Bacillus spp. Specifically, isolated bacteria were added to samples of solid pavement composed of recycled brick aggregate, and cracks of varying sizes were created. Using 16S RNA sequencing, the characteristics of Bacillus spp. were determined. The bacteria were identified as alkaline and heat-tolerant, with amplified fragments measuring 1500 base pairs. Statistics revealed that self-healing does not always occur at the highest bacterial concentrations. Bacillus spp. produced the greatest amount of calcite at an optical density (OD600) of 1.0.X-ray diffraction (XRD) analysis indicated that Bacillus spp. can form two major components of calcium carbonate: calcite and aragonite. These results suggest that optimal bacterial concentration is necessary for effective repair, as varying calcite depositions were observed in concrete samples with different bacterial concentrations

Keywords: Microorganisms, Calcite precipitation, Self-healing concrete, Bacillus spp., Recycled brick aggregate.

1. INTRODUCTION

Concrete is a key component of the building industry because of its affordability, accessibility, and ease of casting. Compared to other building materials, it is also stronger, more manageable, fireproof, and has a high compressive strength. Concrete is prone to cracking and is weak under tension **(Ivaškė et al., 2023; Vijay et al., 2017)**. Concrete cracks could reduce the material's longevity. Microcracks might harm the reinforcement if they spread and develop into it, as well as the concrete itself. Monitoring cracks in concrete structures

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and taking steps to prevent their progression have become increasingly common; these actions are essential for the prompt repair and long-term durability of concrete infrastructure and buildings **(Meraz et al., 2023)**.

There are several methods for fixing cracks, but they are expensive and time-consuming. One of the new techniques for concrete's capacity to self-heal cracks is the use of bacteria incorporated in the material. Researchers in the fields of biotechnology and civil engineering sciences have recently made creating self-healing concrete technology a top priority **(Khaudiyal et al., 2022; Nodehi et al., 2022; Qian et al., 2021)**. Multiple studies have been conducted in recent years on bacterial concrete **(Almosawi and Ibraheem, 2025)**. This innovative technology uses the metabolic processes of bacteria to precipitate Calcium Carbonate in cracked concrete, which may mend them on its own. Multiple investigations have indicated that the spores of bacteria may remain alive for over 200 years when placed in extreme circumstances, and hence, they can satisfy the requirements for the necessary service life of structural concrete **(Siddique and Chahal, 2011; Shukla *et al.*, 2020; Jogi and Lakshmi, 2021; An et al., 2021; Su *et al.*, 2021; Alzard *et al.*, 2022; Amran *et al.*, 2022; Nameh et al., 2025).** This innovative biomaterial, capable of self-healing and compatible with the concrete matrix, substantially decreases CO_2 emissions and maintenance expenses **(Sangadji, 2017)**. The majority of mineral-producing bacteria are found in a range of severe settings, including alkaline lakes, plants, and soil. Their ability to adapt to their environment allowed them to live in concrete paste. An eco-friendly and natural approach to crack therapy is microbial-induced calcite precipitation (MICP) **(Algaifi et al., 2021)**.

Additionally, it increases the material's tensile strength **(Jogi and Lakshmi, 2021)**. MICP prolongs the life of structures by repairing concrete cracks and lowering the permeability of water and chloride ions to harmful elements. Understanding how microorganisms precipitate calcium carbonate (calcite) and the conditions that may limit their effectiveness is crucial, given the wide range of applications **(Tang and Xu, 2021)**. It is well known that Bacillus species are the most capable of producing urease and spores **(Wong et al., 2024)**. The non-pathogenic bacterium Bacillus sp. is very resistant to harsh environments and grows best at a pH of 9.0. Our knowledge of the mechanics of precipitation among microorganisms has been constrained by the majority of research **(Schuab et al., 2021; Rauf et al., 2020)** that has employed a range of techniques to introduce bacteria into concrete or mortar. The goal of this study is to identify the ideal concentration of *Bacillus spp.* to manufacture the urease enzyme for calcite precipitation, with a focus on bacteria that can thrive in alkaline environments and survive in extremely high temperatures (thermophilic) **(de Brito et al., 2021; Javeed et al., 2024)**. According to **(Talaiekhozan et al., 2014)**, thermophilic bacteria can endure temperatures ranging from 45°C to 122°C. In this study, concrete incorporating recycled brick aggregates was used, where the mixing water was replaced with a bacterial solution of *Bacillus spp.* , with the aim of evaluating their efficiency in calcite precipitation and enhancing the self-healing capability of concrete cracks. Thermophilic bacteria were selected for use in this investigation due to their high propensity for surviving in strongly alkaline environments, vulnerability to activation upon exposure to water, and capacity for high-temperature survival. The bacteria operate as a catalyst to change ammonia into calcite, the substance that seals the crack, by their urease activity **(Castro-Alonso et al., 2019)**.

This study also investigates the impact of bacterial growth on mortars at different bacterial concentrations.

2. MEDIA PREPARATION

Alkaliphilic bacteria were screened from 10 local sites, the neighbors of Baghdad city, and the debris sample. All of the collected about 50 g of stake soil was carried to the sterile zip-lock bag and brought to the laboratory in a refrigerator, then still under refrigeration after isolation and identification **(Ahmed et al., 2007)**.
The modified culture medium was formulated with nutrient broth and sterilized by autoclaving at 121 °C for 15 min. Urea stock solution was produced by dissolving 100 g of urea in 500 mL of distilled water and sterilized with a membrane filter (0.45 μm) as urea was heat-labile and could be degraded on autoclaving. Then 25 mL of the urea solution was added to 25 mL of nutrient broth and agar (2%) when solid media were needed **(Ezzat and Ewida, 2021)**. The solidified medium was autoclaved at 121 °C for 20 min (sterilization pressure), the pH was adjusted to 9, and then it was cooled before use.
Microorganisms were isolated from the soil by serial dilutions (1:10) and homogenizing 90 mL of 0.1% peptone water with 10 g of soil samples. The suspension after shaking was allowed to sediment and replicate dilutions (1:10) were made with supernatant. Dilutions (0.1 mL) of all samples were plated on urea agar plates. The plates were incubated (37 °C for 24–48 h) and observed at intervals. Individual colonies were picked, purified by several rounds of restreaking on urea agar. Colonies were then observed on the basis of morphology and Gram-stained reactions.

2.1 Isolation and Identification of Bacteria

Bacterial colonies that were isolated and cultured were microscopically analyzed after incubating for 18 h by making a Gram stain to separate the morphology of the bacteria and determine bacterial cells based on their Gram reaction in light microscopy **(Cowan and Steel, 1993)**. The isolation was excised with the Genomic DNA Extraction kit, followed by amplification and analysis on agarose gel. The NCBI-GenBank database BLAST tool was used to get the bacterial sequence and compare it with entries in the GenBank Database. The fish were put on dishes with bacteria, and the results were expressed in colony-forming units per milliliter; the concentration of solution was 10^7 cells/ml and 10^{10} **(Tawfeeq and Ahmaed, 2023)**.

2.2 Gram Staining

On a glass slide, a lapful of the bacterial culture was spread out and allowed air to dry. After that, the crystal violet solution was applied to the slide for a minute. The slide was drained and cleaned with tap water. After adding Gram's iodine solution, the mixture flooded for a minute. Tap water was used to rinse and drain the slide. For ten seconds, three drops of 95% alcohol were poured onto the slide, and then they were removed with tap water. The slide was then washed off with tap water after being submerged in safranin solution for 30 seconds. A light microscope (LEICA) was used to view the slide in order to examine the characteristics of the bacteria **(Tilli, 2022)**.

2.3 Urease Test

The ability of thermophilic Bacillus sp. To hydrolyse urea and generate ammonia and carbon dioxide was determined using the urease test. The constitutively expressed enzyme urease hydrolyses urea to produce ammonia and carbon dioxide **(Dowdy and Srubar, 2023)**.

$(NH_2)_2 CO + H_2O \rightarrow CO_2 + 2NH_3$ (1)

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

2% urea and phenol red, a pH indicator, are both present in the urea test media. As the pH increases as a result of ammonia synthesis (pH 8.2), the color shifts from yellow (pH 6.8) to vivid pink. In addition to encouraging bacterial growth, this medium makes it possible to identify urease activity for the creation of calcite Eq. (2) **(Mahmud et al., 2022).**

2.4 Genomic and Bacterial Identification

Isolates of Bacillus sp. Was forwarded to a third-party sequencing company for bacterial identification. Electrophoresis on a 1% TAE agarose gel was used to analyze the amplified samples for 60 minutes at 100V. The DNA marker in this investigation was 1Kbp (kilobase pair), and the primers utilized were F27 and R1492 **(Tamura et al., 2007)**.

2.5 Mixing and Testing for Bio-concrete

There were two types of concrete mixtures, including one that contained OPC to produce with the same setting time as that of UHPC and the other that had a lower content than UHPC. Moreover, the mixer was a liquid, which is an ice cream base mixed B with Bacillus spp. Or dissolved in culture medium. At a couple of cell densities (10^7 and 10^{10} cells/mL) in this case serving as a replacement for water, depicted in **Fig. 1**. The constituent volumes in 1 m^3 were recorded as follows: cement = 380 kg/m^3, fine aggregate = 787 kg/m^3, coarse aggregate =1024 kg/m^3 and bacterial medium = 165 L/m^3.

Figure 1. Components of concrete mix.

Compressive strength of the concrete specimens was determined by 150×150× 150 mm cubes, tensile strength with cylindrical specimens (d = 100 mm; h = 200 mm) and flexural strength via 100×100×400 mm beams. These were evaluated at 7, 28 and 56 days of age. The Ultrasonic pulse velocity (UPV) is a non-destructive testing (NDT) technique used for the measurement of how fast an ultrasonic wave passes through a material. Concrete and other construction materials are continuously tested for quality and soundness, while their mechanical properties are analysed. At 24-48 hours post bacterial culture, a SEM test was performed to evaluate the bacterial aggregation 48 hours at 37°C post inoculation on two concrete samples, namely with and without bacteria, which were analysed by SEM examination after 28 days of casting to determine the effect of bacteria on the structure of concrete. The SEM test of bacterial aggregation after the period of t = 48 h/37 °C was carried out. A small amount of material was extracted and coated with a gold layer, then the SEM apparatus was used at numerous magnifications (from 250–120,000 times).

2.6 XRD Analysis

The Analytical Pert PRO XRD equipment (USA) was used to perform the XRD analysis at 40kV and 30mA. The crystalline phases of the calcium carbonate crystals that developed in concrete were characterized using XRD analysis.

3. RESULTS AND DISCUSSION

3.1 Bacterial Identification

By using the dilution streaking method, two thermophilic isolates (*Bacillus spp.*) were cultivated on NA media. Following a 24-hour incubation period at 50°C, colonies of *Bacillus spp.* Were observed to be yellowish, uneven, raised, and undulated in shape. Following a 24-hour incubation period at 50°C, **Fig. 2** shows Bacillus sp. On the NA plate media **(Nakajima et al., 2005)**.

Figure 2. *Bacillus spp.* On Nutrient agar that was modified with urea.

A 1000x magnification light microscope (LEICA) was used to observe the Gram stain. Both isolates were found to be Gram-positive bacteria. Bacillus species had a rod-like morphology and were purplish blue in color. The morphology of the Gram-positive bacteria *Bacillus spp.* Is depicted in **Fig. 3**. Gram-positive bacteria have thick peptidoglycan coatings in 90% of their cell walls, which enable them to live in their surroundings. The bacteria had a purple shape. Gram-negative bacteria are characterized by their high lipid content, thin peptidoglycan coatings (10% of wall thickness), and pink shape **(Kamalakkannani and Nandhini, 2021).** The results of the urease test are displayed in **Fig. 4**.

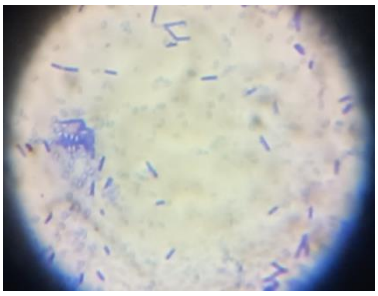
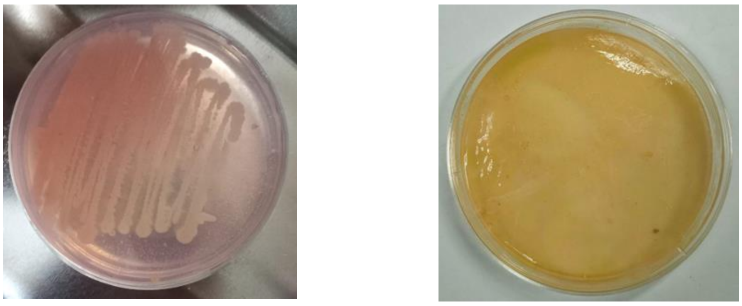


Figure 3. Purple-stained Gram-positive bacterium *Bacillus spp.*

Using this method, bacteria that could produce calcite through urea activity were found—both *Bacillus spp.* Bacterial cultures turned pink (fuchsia) after a 24-hour incubation period at 50°C. As a result, *Bacillus spp.* Exhibit positive urease activity reactions. The bacterium was urease-negative since the pH of the culture media for the control sample was lower than 7. Based on the findings, it is reasonable to assume that urease activity will lead to increased calcite synthesis.



(a) (b)

Figure 4. (a) Positive reaction of bacteria Bacillus spp. , (b) Negative media without bacteria.

3.2 Genomic and Bacterial Identification

Electrophoresis using 1% TAE agarose gel at 100V for 60 minutes was used to analyze the samples. A 1Kbp (kilobase pair) DNA marker was used to compare the lengths of the DNA fragments. Both *Bacillus species* have DNA that is roughly 1,500 bp in size. Based on the blast results on the NCBI GenBank Database website, they were identified as Bacillus thermoaerophilus. A picture of the PCR gel electrophoresis of six strains of bacteria as shown in **Fig. 5**. This result agreed with **(Al-Hejjaj et al., 2020)**.

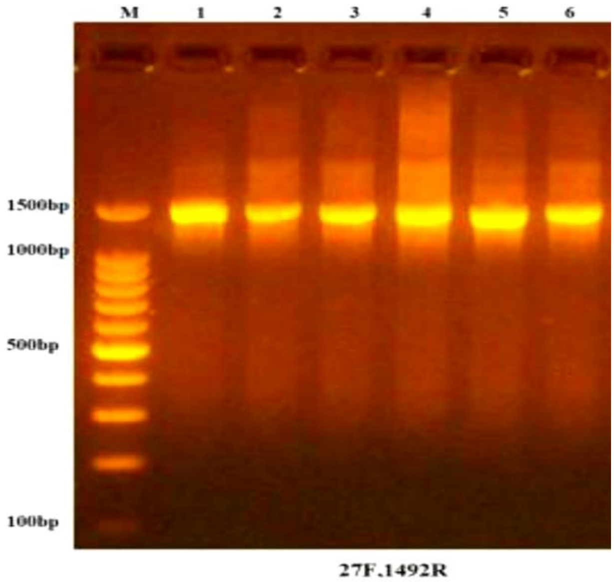


Figure 5. Image of PCR Gel Electrophoresis of six strains.

3.3 Formation of Calcite in Cracked Specimens

After injecting bacteria into cement specimens for 56 days, the crack closure was seen using a Microscope Digital at 1000x magnification. The specimens' cracked mouth showed the development of white precipitation. **Fig. 6** of Bacillus spp. Demonstrate that the amount of calcite precipitation varied in each specimen with a different OD600 concentration. When bacteria are encapsulated within a spore or carrier, they typically exhibit a greater capacity for crack healing compared to vegetated bacteria. Similar morphology was also obtained in research by **(Khaliq and Ehsan, 2016)**. For example, *Bacillus spp.* Bacteria, protected by a bacterial carrier, can repair a 0.79 mm crack in concrete, highlighting the enhanced crack-healing capabilities of well-protected bacteria **(Han et al., 2022)**. Urea, which yields (4.7grams) of nitrogen. This sum is approximately one-third of the nitrogen produced by each individual on an everyday **(Mahmud et al., 2022)**.

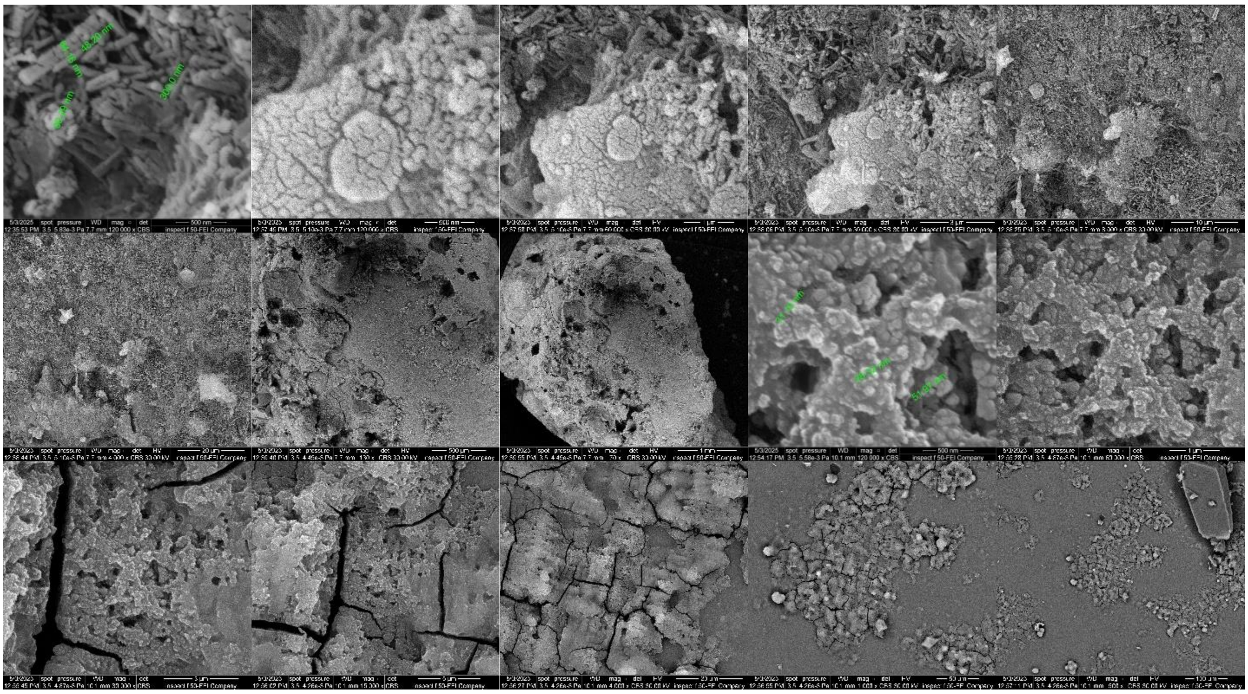
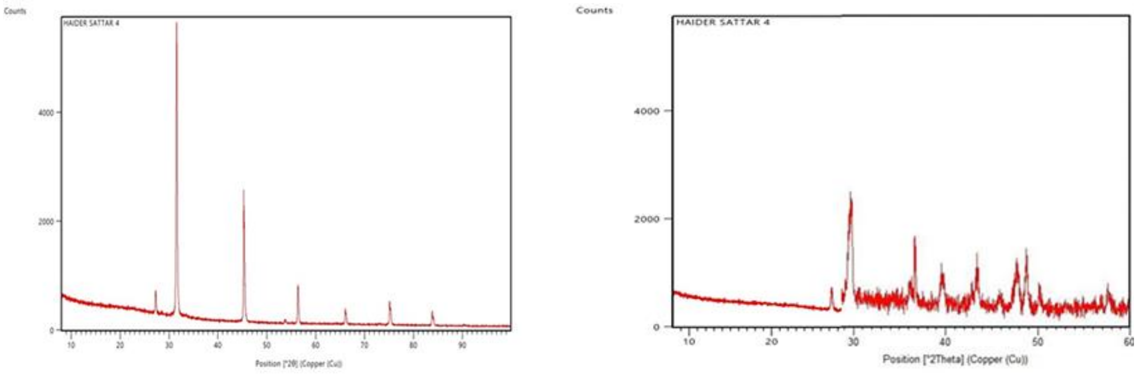


Figure 6. Image of Calcite Precipitation of Bacillus sp.

3.4 XRD Analysis

On the interior surfaces of the concrete cracks depicted in **Fig. 7**, calcium carbonate crystal XRD patterns (dominant peak) were found. All of the bacterium isolates had both vaterite and calcite phases. It was found that each bacterial sample had a varied ratio of calcite to vaterite phases.



(a) (b)

Figure 7. (a) XRD pattern of Standard concrete mix without bacteria; (b) XRD pattern of calcium carbonate crystals formed by *Bacillus spp.*

According to the results, when compared to the standard (calcium carbonate) powder, the thermophilic bacteria *Bacillus spp.* (Areurinibacillus thermoaerophilus) displayed a similar peak ratio between calcite (29.3°) and 99aterite (25°) as shown in **Fig. 7(b)**. Bacillus sp. Was able to create calcite and vaterite phases, according to their XRD patterns. The primary components of calcium carbonate were these two phases **(Rodriguez-Blanco et al., 2011; Ni et al., 2008)**. In addition, the peak ratio displayed a peak that was comparable to the calcium carbonate standard.

3.5 Compressive Strength

The results of the compressive strength tests at 7, 28, and 56 days for both the reference and bio-concrete mixtures, which include bacterial concentrations of 10^{10} and 10^{7} and coarse recycled aggregate (RBA) at 10% and 20%, are displayed in **Tables 1 to 4** and percentage increase relative to the mixture without adding bacteria . The main causes of the decrease in compressive strength when recycled brick aggregate is used in place of natural coarse aggregate are the brick aggregate's increased porosity, increased water absorption, and decreased mechanical strength. These elements reduce the concrete's total compressive load-bearing capability by weakening the interfacial transition zone and increasing interior voids **(Chahal et al., 2012)**. The maximum percentage increase in compressive strength sample is 16.7% at 7 days, 25.8% at 28 days, and 35.8% at 56 days for concrete mix without RBA and with a concentration of 10^{10} compared with the reference mix. Bacterial concrete has a higher compressive strength than normal concrete. Another researcher arrived at a similar conclusion **(Afifudin et al., 2011)** .

Table 1. Compressive strength at 7, 28, and 56 days for the reference mix and the mix containing bacteria at a concentration of 10^{10}.

Mix ID	Mix Description	Compressive Strength (Mpa)		
		7 days	28 days	56days
R.M	Reference mix	32.4	38.8	39.7
C 10^{10}	Bacteria at a concentration of 10^{10}	37.8	48.8	53.9
RBA 10%	Natural C.A volume replacement by RBA 10%	29.00	35.20	36.30
C 10^{10} RBA 10%	Bacteria at a concentration of 10^{10} natural C.A volume replacement by 10%RBA	31.73	42.14	46.16
RBA 20 %	Natural C.A volume replacement by RBA 20%	24.70	30.90	31.24
C 10^{10} RBA 20%	Bacteria at a concentration of 10^{10} natural C.A volume replacement by 20%RBA	26.60	36.44	39.05

Table 2. The percentage increase in compressive strength of bio mixes containing bacteria at a concentration of 10^{10} is compared to that of the counterpart without added bacteria.

Mix ID	The % increase in compressive strength at 7 days	The % increase in compressive strength at28 days	The % increase in compressive strength at 56days
C 10^{10}	16.67%	25.77%	35.77%
C 10^{10} RBA 10%	9.41%	19.72%	27.16%
C 10^{10} RBA 20%	7.69%	17.93%	25.00%

Table 3. Compressive strength at 7, 28, and 56 days for the reference mix and the mix containing bacteria at a concentration of 10^7.

Mix ID	Mix Description	Compressive Strength (Mpa)		
		7 days	28 days	56 days
R.M	Reference mix	32.4	38.8	39.7
C 10^7	Bacteria at a concentration of 10^7	37.8	48.8	53.9
RBA 10%	Natural C.A volume replacement by10% RBA	29.00	35.20	36.30
C 10^7 RBA 10%	Bacteria at a concentration of 10^7 Natural C.A volume replacement by 10% RBA	30.98	40.43	44.06
RBA 20 %	Natural C.A volume replacement by 20% RBA	24.70	30.90	31.24
C 10^7 RBA 20%	Bacteria at a concentration of 10^7 natural C.A volume replacement by 20% RBA	26.28	35.14	37.50

Table 4. Percentage increase in compressive strength of bio mixes, including bacteria at a concentration of 10^7 compared to mixes without added bacteria.

Mix ID	The % increase in compressive strength at 7 days	The % increase in compressive strength at28 days	The % increase in compressive strength at 56days
C 10^7	10.80%	20.62%	32.75%
C 10^7 RBA 10%	6.83%	14.86%	21.38%
C 10^7 RBA 20%	6.40%	13.72%	20.04%

Followed by the concrete mixture with 10% RBA and a concentration of 10^{10}, where the compressive strength improved by a percentage of 9.4% at 7 days, 19.7% at 28 days, and 27.2% at 56 days compared with the concrete mixture with 10% RBA but without bacteria.
The lowest percentage of increase in compressive strength was for the concrete mixture with 20% RBA and a concentration of 10^{10}, where the compressive strength improved by a percentage of 7.69% at 7 days, 17.9% at 28 days, and 25% at 56 days compared with the concrete mixture with 20% RBA but without bacteria.
When bacteria at a concentration of 10^7 were introduced to the concrete mixture containing 10% (RBA), the percentage of enhancement in compressive strength decreased in comparison to bacteria at a concentration of 10^{10}. The enhancement rates were observed as follows in comparison to the concrete mixture containing 10% RBA without bacterial addition, increasing by 10.8%, 20.6%, and 32.8% after 7, 28, and 56 days of curing, respectively.
The percentage of enhancement in compressive strength decreased to the minimum level of the prior mixture when bacteria were included at a concentration of 10^7 into the concrete mixture containing 20% recycled coarse material. This contrasted with the combination containing 20% recycled coarse aggregate, which was devoid of bacteria and exhibited percentage increases of 6.8%, 14.9%, and 21.4% at 7, 28, and 56 days, respectively.
The enhancement in compressive strength in all prior mixes resulted from the sealing of cracks and the formation of bio-calcium carbonate crystals, resulting from bacterial metabolic processes inside the concrete. Calcite was deposited in the concrete's pores, strengthening the Interfacial Transition Zone (ITZ), which enhanced the microstructure and concrete density. Bacteria may enhance the strength of concrete by elongating the C-S-H gel chain, which raises the degree of cement hydration reaction **(Joshi et al., 2016)**. According to the Iraqi General Specifications for Roads and Bridges (R10) the concrete used for rigid

pavement must achieve a minimum compressive strength of 300 kg/cm^2 (≈30 Mpa) at 28 days, based on the obtained test results, the compressive strength of the concrete meets the requirements of the Iraqi General Specifications for Roads and Bridges (SORB) for rigid pavement.

4. CONCLUSIONS

The direct incorporation of bacteria significantly enhanced the mechanical properties, including compressive strength, splitting tensile strength, and flexural strength. The enhancement in strength relative to the reference mix fluctuates according to the proportion of coarse recycled brick aggregate (RBA), the concrete's age, and the amount of bacteria present. Practical experiments indicated that a formulation with 10% (RBA) yielded superior outcomes compared to a mixture with 20% (RBA). Regarding the age of the concrete mix, 56 days yielded the greatest enhancement rate, followed by 28 days, and subsequently 7 days. Consequently, the age of the concrete correlates positively with the rate of enhancement. Regarding bacterium concentration, it was shown that 10^{10} was more effective than 10^{7} cells/ml**.** The self-healing process of concrete was observed by SEM investigation and ultrasound tests. The healing of concrete is ascribed to the deposition of $CaCO_3$ and the closure of cracks via the metabolic processes of bacteria.

Credit Authorship Contribution Statement

Hayder Sattar Faraj: Conceptualization, Laboratory experiments, Data analysis, Writing – original draft. Hayder Amer Al-Baghdadi: Conceptualization, Supervision, Methodology guidance, Review and editing. Asmaa Sabah Ahmaed: Conceptualization, Supervision, Methodology guidance, Review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial or personal interests that could have appeared to influence the work reported in this paper.

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الأداء الميكانيكي للرصف الصلب ذاتي الشفاء المعتمد على البكتيريا والمحتوي على ركام الطابوق المعاد تدويره

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الخلاصة

أظهرت الدراسات السابقة فاعلية تقنية الترسيب الحيوي للكالسيت المحفَّز ميكروبيًا(MICP) ، الناتجة عن أنواع بكتيرية محددة مثل .Bacillus sp، بوصفها عاملًا لمعالجة الشقوق في المواد الإسمنتية. وانطلاقًا من استكشاف إمكانات تطبيقها، بحثت هذه الدراسة تأثير عامل شفاء ذاتي قائم على البكتيريا في خرسانة تحتوي على ركام الطابوق المعاد تدويره. تضمّن العمل البحثي عزل البكتيريا وزراعتها، وتحديد نوعها، وإحداث شقوق في النماذج الخرسانية، ثم إضافة البكتيريا وقياس كفاءة الإصلاح التي يحققها .Bacillus sppوقد أُضيفت البكتيريا المعزولة إلى نماذج رصف صلب مكوّنة من ركام الطابوق المعاد تدويره، مع إحداث شقوق بأحجام مختلفة. وباستخدام تقنية تسلسل 16 S RNAجرى تحديد خصائص .Bacillus spp، حيث تبيّن أنها بكتيريا قلوية ومقاومة للحرارة، مع أجزاء مضخَّمة بطول 1500 زوج قاعدي. وأظهرت النتائج الإحصائية أن ظاهرة الشفاء الذاتي لا تتحقق بالضرورة عند أعلى التراكيز البكتيرية. إذ سجّلت أنواع .Bacillus sppأعلى كمية من ترسيب الكالسيت عند كثافة بصرية (OD600) مقدارها 1.0. كما بيّن تحليل حيود الأشعة السينية (XRD) قدرة .Bacillus sppعلى تكوين مكوّنين رئيسين من كربونات الكالسيوم، وهما الكالسيت والأراغونيت. تشير هذه النتائج إلى ضرورة تحديد تركيز بكتيري أمثل لتحقيق كفاءة إصلاح فعّالة، نظرًا لتباين معدلات ترسيب الكالسيت الملحوظة في النماذج الخرسانية ذات التراكيز البكتيرية المختلفة.

الكلمات المفتاحية: الكائنات الحية الدقيقة، ترسيب الكالسيت، الخرسانة ذاتية الشفاء، .Bacillus spp، ركام الطابوق المعاد تدويره.