GAS Journal of Engineering and Technology

(GASJET)

Volume- 01 | Issue- 01 | 2024 Homepage: https://gaspublishers.com/gasjet-home/ ISSN: 3048-5800

Experimental Study on the Strength of Concrete Joint Reinforced by Microbially Induced Calcium Carbonate

Muhammad Saqib Hanif

School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China

DOI: 10.5281/zenodo.11216818

Abstract: The microbially induced calcium carbonate precipitation (MICP) technique is a developing soil and rock reinforcement technique. In order to improve the reinforcement influence of MICP on concrete joints in a saline-alkaline environment, direct shear tests on concrete cracked samples reinforced by microbially induced calcium carbonate were conducted. The strengthening effects of Sporosarcina pasteurii on the shear strength of concrete joints were comprehensively evaluated. Samples of sandstone with rough surfaces were prepared and reinforced by MICP. The shear strength characteristics of rock joints reinforced by CaCO3 were then deeply assessed by laboratory tests. The results showed that the acclimated Sporosarcina Pasteurii has good reinforcement performance in saline-alkaline conditions. In the saline-alkaline environment, the shear strength of concrete joints repaired by microbially induced calcium carbonate significantly increased. The ultimate shear-strength concrete joint reinforced by MICP rose with the curing time, but its strength developed quickly in the early stage and slowly in the later stage of the experiment. The peak shear strength of cemented concrete joints increased significantly compared to uncemented concrete joints. The current research idea could be a benchmark for applying the MICP technique in repairing the joints of concrete.

Keywords: Concrete crack, MICP, Direct shear test, Shear strength, Curing time

INTRODUCTION

In the civil engineering field, concrete has many benefits such as good durability, high compressive strength and low price. It is the most extensively used construction material worldwide and plays a remarkable role in hydraulic engineering, foundation engineering, bridge engineering, tunneling and underground space technology. The compressive strength character of concrete changes under various loading conditions and cracks (Xiang et al. 2022) and the restoration of strength is required to increase the life of concrete structures (Lu et al. 2023). In addition, concrete is easy to fracture or crack under different seismic and static loads because of its low tensile strength and brittleness (Xiang et al. 2024). These surface cracks speed up the ingression of destructive media inside the concrete resulting in the corrosion of steel bars, which inevitably reduces the strength and the durability of concrete structures (Lu et al. 2022; Turner et al. 2023). For that reason, it is necessary to repair concrete cracks effectively. So, the treatment and reinforcement of cracks in concrete is a vital means to control the damage.

Since the rate and cementing strength of carbonate crystallization generated by MICP technology can be artificially controlled, the resulting crystals can replace traditional cementing materials under certain conditions (Zhang et al. 2023b; Zhang et al. 2024b). At present, microbial grouting technology based on MICP technology has been widely used in soil, rock and concrete reinforcement, especially in the repair of concrete cracks (Chen et al. 2024; Yan et al. 2024). There are few reports about the application of MICP in concrete technology, and it is mainly concentrated in the field of seepage treatment. Intarasoontron et al. (Intarasoontron et al. 2021) analyzed the change of the permeability coefficient of concrete joints before and after reinforcement through MICP technique, and the results showed that the permeability coefficient of joints after MICP reinforcement was significantly reduced, and MICP technology has a good repairing effect. Fan et al. (Fan et al. 2023) conducted MICP repair and filling tests on sandstone specimens with fractures by using Bacillus pasteurii, and the

results showed that the test strength of concrete cracks treated with MICP increased significantly. Nasser et al. (Nasser et al. 2022) used plexiglass to prepare simulated joint samples with Barton standard profile features and a gap width of 1.5 mm and studied the influence of joint surface roughness on the amount of calcium carbonate deposition in the MICP process. Ariyanti et al. (Ariyanti et al. 2023) studied the permeability of cracks reinforced by MICP by conducting microbiological grouting reinforcement tests on split single-fissure limestone in Brazil. Although the researchers have made a preliminary exploration of the use of MICP technology for concrete seepage treatment, the research results on the mechanical properties of MICP-reinforced concrete are rarely reported.

Sporosarcina Pasteurii and other bacteria have been selected to repair concrete cracks in alkaline environments (Gao et al. 2023). The principle of this technique is that the domesticated germs can better acclimate the saline and alkaline environments. At present, there are few studies have been conducted on this topic (Mondal and Ghosh 2019; Zhang et al. 2023a). Therefore, it is a challenge, how to make acclimate bacteria to properly grow and produce sufficient amount of $CaCoO_3$ saline and alkaline conditions and make their repair effect on rough concrete cracks reach or even exceed the neutral environment is the focus of this research. This paper intends to use microbial domestication methods in the field of biological research to achieve this goal. Microbial domestication, also known as the behaviour of domesticating microorganisms, refers to the addition of environment-targeting materials or substrates in bacterial culture medium so that germs can adapt and depend on the substrates of the environment, hence that they could also display the working characteristics and good growth (Mondal and Ghosh 2019; Zhang et al. 2023a). These results provided a solid foundation for the reinforcement of fractured rocks by using the MICP technique. Furthermore, previous studies mostly improved the impermeability constant, and unconfined compressive strength and reduced the porosity of different fractured rock masses in alkaline environments. However, the shear displacement and peak shear strength of concrete are mostly controlled by the strength of joints. So, the research on the reinforcement of cracked concrete with the MICP technique in a saline environment is still missing.

In this research, a new multi-gradient artificial acclimation experiment of Sporosarcina Pasteurii in a saline environment, the combined direct shear test was carried out to improve the strength of the cracked concrete. Sporosarcina Pasteurii was first domesticated by the method of five-gradient saline-alkaline conditions, and then its reinforcement effects on cracked concrete were evaluated by direct shear tests. The subsequent applications of the MICP technique provided a good reference to reinforce the cracked concrete in a saline-alkali environment.

MICROBIAL DOMESTICATIONS

In this particular research, Sporosarcina Pasteurii was the first artificially domesticated through the five-gradients technique under saline environment conditions. Fan et al. (Fan et al. 2023) pointed out that the main salts in saline-alkali areas are Cl^- and SO_4^{2-}, and the salinity of groundwater can reach up to 4%, while that of the surface can reach 20%. The medium solution was prepared according to the data in Table 1 and the pH value of the medium was adjusted to 9 according to the main components and contents of saline soil in the Ningxia region measured by Zhang et al. (Zhang et al. 2024a). All chemical materials of the Saline medium are presented in Table 1. A saline water was prepared here using a pH of 8.1 and salinity of 33%.

Table 1: Saline medium components

Material	Content（g/L）
NaCl	10
$MgSO_4$	1.20
KCl	1.12
$MgCl_2$	1.71
Peptone	15
Beef extract	5

This research scheme aims to adopt the five-gradient domestication of Sporosarcina pasteurii bacteria in saline conditions. The acclimated medium was prepared as follows: First, according to prior studies (Chuo et al. 2020; Omoregie et al. 2017), an artificial medium was designed as presented in Table 2. Then, the pH of the medium was set to 8.1. The final acclimated medium was prepared by adding 20 g sterilized urea in each medium as shown in Fig. (2). The domestication procedure under various domestication ways is clearly described in Fig. (2)

Table 2: Different domestication test schemes

Test scheme	Conical number	Acclimation medium volume (mL)	
		Saline medium	Conventional medium
Five-gradient domestication	A	20.0	80.0
	B	40.0	60.0
	C	60.0	40.0
	D	80.0	20.0
	E	100.0	0.0

The particular domestication method is divided into three acclimation schemes:

Five-gradient acclimation: 1 mL of microbes was put in bottle "B" diluted to 1/5 and containing 100 mL of saline medium. At this stage, bacteria were cultured in the bottle for 48 h and then taken out for use (Fig. 1). Add 1 mL bacterial solution from bottle "B1" to bottle "B2" containing 100 mL NaCl and saline medium diluted to 2/5, and take it out after culture for 48 h. Add 1 mL of bacterial solution from bottle "Bn" to bottle "C" containing 100 mL of NaCl and saline-alkaline medium diluted to 3/5, and take it out after culture for 48 h as shown in Fig. 1. From bottle "C1", add 1 mL of bacterial solution to bottle "Cn" containing 100 mL of NaCl and saline-alkaline environment diluted to 4/5, and take it out from bottle after culture for 48 h. 1 mL of bacterial solution in bottle "D" was added to bottle "Dn" containing 100 mL of acclimation medium, which was removed after culture for 48 h. At this time, the bacteria in the conical bottle "Dn" were five gradient-acclimated bacteria.

In addition, the microbes were expanded in each stage of concentration several times during the domestication process and the concentration of the bacterial solution was measured carefully. The bacterial solution achieved from two different cultures did not change significantly after the concentration. The domestication process of the next concentration was completed and at this time, the urease activity of the microbes was measured. The detail of the three-gradient domestication scheme in a saline environment is presented in Fig. (1). At this stage, the medium was diluted to 1/3 and 2/3 (Fig. 1). In the case of the three-gradient domestication scheme, enzyme activity was measured in the initial stage (Fig. 1).

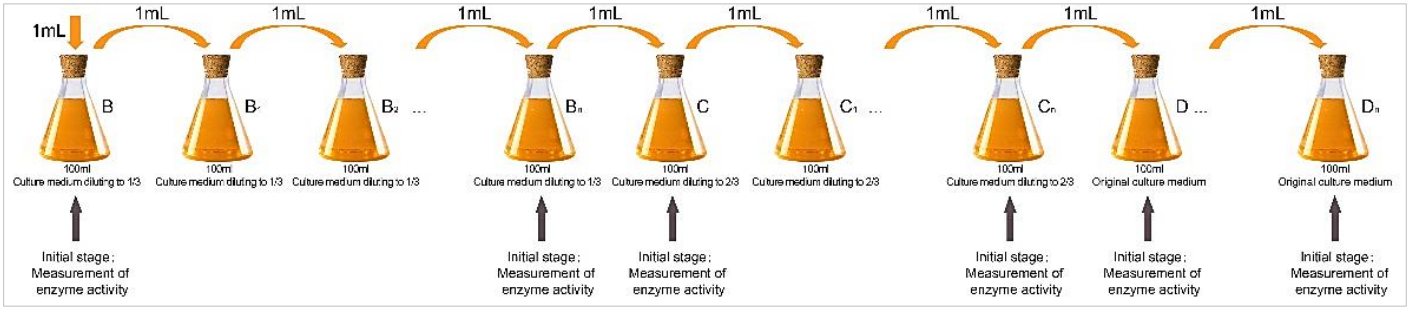

Figure 1. *Five-gradient domestication scheme in the saline environment*

The domestication conditions of Sporosarcina Pasteurii are as follows: NaCl 10 g/L, urea and beef extract 5 g/L. The volume of pasteurii immunization is 2.0 ml per 100 ml. After immunization, the medium is kept in the mixture for 48 hours at 30°C, and the rocker speed is 150 r/min. The bacterial solution concentration was estimated at regular intervals during the cultivation process; OD600 (1.39) was selected to describe the concentration, which is the solution absorbance at the wavelength of 610 nm. The medium solution was prepared according to the data in Table 2 and the pH value of the medium was adjusted to 8.1 according to the main components and contents of saline conditions. In the saline environment, the growth rate of Sporosarcina Pasteurii is shown in Fig. (2). According to Fig. (2), the growth rate of microbes consists of four stages. First is the bacterial adjustment period, second is the rapid breeding period, third is the steady growth period and fourth is the slow decay period.

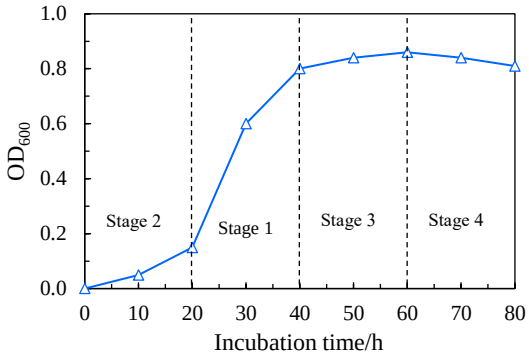

Figure 2. *The growth rate of Bacillus Pasteurii under the saline-alkaline environment*

MICP PROCESS BASED ON UREA HYDROLYSIS

Currently, available MICP methods include urea hydrolysis (Sun et al. 2023), denitrification chemical reaction, ferric iron reduction and sulfate reduction (Cao and Zhang 2023). Among them, urea hydrolysis has a simple reaction mechanism and can Generate large amounts of 〖CO〗_3^(-2) calcium in a short time, a reaction to generate calcium carbonate crystals. It is widely used due to its advantages such as easy control of process and gelling strength. The MICP reaction process based on urea hydrolysis is divided into two steps: The first step is to use urease produced by the metabolic activity of microorganisms to convert urea into Hydrolyzed NH4 and 〖CO〗_3^(-2); The second step is to add soluble calcium salt solution of 〖Ca〗^(+2) and 〖CO〗_3^(-2) generated in the first step reaction and combine to form a precipitate CaCO3.

The deposition process of calcium carbonate on the surface of microbial cells (Xiang et al. 2023). First, the positively charged 〖Ca〗^(+2) in the solution is adsorbed onto the negatively charged microbial cell wall, while the microorganisms use urea as a nitrogen source through its metabolic activities, it produces a large amount of highly active urease, converting urine into Hydrolysis of phytozoin produces NH4 and 〖CO〗_3^(-2) (Khoshtinat 2023). Secondly, adsorption on 〖Ca〗^(+2) the outer surface of microbial cells is decomposed by hydrolysis of urea Come 〖CO〗_3^(-2). Reaction occurs, with cells as nuclei, around the cells calcium carbonate crystals precipitate (Lee et al. 2024); finally, as calcium carbonate crystallizes. The number of organisms continues to increase, and cells are gradually wrapped, causing microorganisms too difficult to transport nutrients required for metabolic activities, which ultimately leads to the microbial cells gradually dying.

According to the turbidimetric method, the amount of germs can be indirectly articulated by calculating the total absorbance of the solution of the bacteria. The absorbance is generally based on the concentration of the bacterial cell, which is related to the turbidity of the microbe's solution. In the current research scheme, the total absorbance and the number of cells were estimated with the help of a spectrophotometer (OD600) at the wavelength of 500 nm. The urease activity of germs and the concentration of the cultured solution reached the stable stage easily under each of the five-gradient acclimation schemes. Also, reproduction characteristics, urease activity and growth of strains are significant parameters that affect the yield of CaCO3. In the process of urea hydrolysis, the change in bacterial solution conductivity is directly correlated with the amount of hydrolysis. The change of the conductivity per minute can be used to determine the urease activity. At room temperature, 5 ml of germ solution with stable concentration was mixed with 55 ml of urea solution. Then, a conductivity meter was used to monitor the change in electrical conductivity within 5 minutes. To obtain urease activity, the average value per minute was converted into hydrolyzed urea (Mm) according to a previous study (Jiang et al. 2024). To facilitate the study on the urea decomposition ability of unit species, the unit urease activity was μM urea hydrolysed · min−1 · OD−1. The specific calculation formula is shown in formula (1).

$$\underset{(\mu\text{M urea hydrolysed} \cdot min^{-1} OD_{600}{}^{-1})}{Unit\ urease\ activity} = \frac{Urease\ activity\ \ (\mu M\ urea\ hydrolysed \cdot min^{-1})}{Bacterial\ concentration\ \ (OD_{600})}$$

The Production Rate of Calcium Carbonate

The calcium carbonate precipitation technique is a multifaceted procedure which needs a enough number of carbonate and calcium ions, depending on pH, the concentration of calcium, available nucleation sites and dissolved inorganic carbon (Zhang et al. 2024b). Some scholars stated that temperature has a remarkable effect on the performance and growth of Sporosarcina Pasteurii bacteria, particularly at the temperature of 10~37 °C (Chen et al. 2024; Yan et al. 2024). During the test, considering the ambient temperature that may be encountered in the actual project, this section discusses the influence of temperature on the MICP performance of the acclimated Bacillus pasteuris. Two cases of 10ºC and 30ºC are considered in the test. Carbonate production after MICP under different domestication culture schemes was calculated. The detailed method was as follows:

The bacteria under different salt and alkali concentration acclimation culture schemes were expanded culture, 150 r/min, 48 h later removed for use. The MICP calcification test was carried out in a tissue culture tube with a sealing film, and 20 mL gel liquid was prepared, in which urea and calcium chloride had an equal molar number of 0.5M. The reaction temperature was controlled at 30ºC after mixing the gel liquid with the bacterial liquid at the same volume ratio. After 6 days of reaction, the mass of calcium carbonate was weighed and the yield was calculated as follows:

The reacted mixed solution was filtered, and water was added to the glass tissue culture tube and filtered twice. Then the tissue culture tube and filter paper were dried in the oven at 110ºC. The tissue culture tube and filter paper were taken out after 24 hours and weighed to obtain the mass M_1. The tissue culture tube and filter paper were first picked with hydrochloric acid washed with water and then dried in the oven at 110ºC to obtain the mass M_2. The difference between M_1 and M_2 is the mass of $CaCO_3$. On the other hand, the speculative mass of $CaCO_3$ was gained by multiplying the concentration of calcium ions with the volume V. The actual yield amount of $CaCO_3$ is a ratio between the produced amount of $CaCO_3$ and the theoretical amount of $CaCO_3$.

Cracked Concrete Sample

Ordinary Portland Cement with 53-grade is used to make cracked concrete samples as shown in Fig. 3. Fine aggregate and gravel with a fineness modulus of 2.7 and particle size of 5–31.5 mm were used in sample preparation. The cracked concrete cube was 100 mm × 200 mm × 100 mm and the size of the crack was 2 mm. The compressive strength test was conducted after 7 days, 14 days and 28 days of curing. A rough crack was made with a grinder tool as shown in Fig. 3. Water cement ratio w/c ratio = 0.49, Water = 220 kg/m^3, Cement = 450 kg/m^3, Sand = 615 kg/m^3, coarse aggregate = 1200 kg/m^3, Compressive strength = 32.1 MPa.

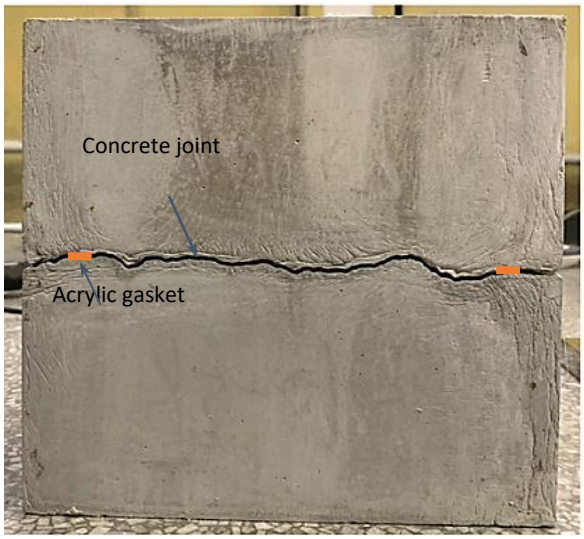

Figure 3. *Artificial concrete crack specimens*

An acrylic gasket of 5 mm×2 mm×1 mm (length × width × thickness) is inserted into 4 corner points of the upper and lower parts of the joint to form a cavity with a height of 1 mm, where the repair test reacts. One side of the cavity perpendicular to the joint direction of the specimen is kept unsealed and used as an inlet for subsequent infusion of bacterial fluid and nutrients, while the other three sides are sealed with glass glue. After the glass glue solidifies, check the tightness of the reaction channel and fill the leak until the cavity no longer leaks.

Sporosarcina Pasteurii

Sporosarcina pasteurii domesticated by method of five-gradient saline-alkali concentrations was expanded for culture. After 48 h of culture at 150 r/min in the incubator, it was taken out for use. The OD600 was 1.37 which was measured by UV spectrophotometer. Saline-alkali gelling liquid with 0.5M/L concentration of urea and calcium chloride is used to provide a nitrogen source for microbial growth and a calcium source for cementation products for the MICP process. The reaction solution was prepared by mixing the bacterial solution with the gelling solution according to the volume ratio of 1:1.

EVALUATION METHODS

Macroscopic Observation

In this paper, the visual observation technique was adopted to observe the changes around the cracked surface during the repair and curing period. The morphology of the germs concentration in the concrete crack was measured using a scanning electron microscope (SEM). X-ray diffraction (XRD) and Energy Dispersive Spectrum (EDS) were selected to match the composition of $CaCO_3$ in concrete cracks before and after repair.

Water Absorption Test

To check the water penetration through a sealed crack, capillary water absorption experiments were carried out on the samples. All cracked concrete samples were dried at 105 ^{o}C. One side of the sample was watertight with wax to properly assess the effect of water absorption. Subsequently, the initial mass of the sample was recorded as m_0. The repair surface of all concrete samples was downward and partly immersed in water. The samples were taken out from the water for measurement of the water penetration after immersion of 1, 2, 3, 8, 15, 24, 36 and 48 h. After removing the surface water, the mass of all specimens was weighed as m.

Chloride Penetration Test

The chloride penetration experiments were conducted to assess chloride penetration in the repair crack. The unrepaired surface and repaired crack were taken as the test surfaces for chloride penetration. An adequate portion of the penetrable wiper was attached as a chloride solution carrier to the cracked surface. An arrangement of the germs solution drying-wetting cycle was designed with 3 days of drying and 3 days of wetting. The adhered wiper was moistened, during the wetting period, with 6% of the microbe's solution and repeated every 9 h to confirm the same wet form at the surface of the concrete crack.

The above steps constitute the MICP test process in concrete cracks. The prepared MICP cemented cracks were divided into 3 groups, which were cured at 30^{o}C for 7, 14 and 28 days, respectively, and used for subsequent laboratory direct shear tests. In addition, for comparative analysis, uncemented concrete cracked specimens were prepared for direct shear test.

Direct Shear Test

The rock joint specimens used in this laboratory direct shear test are divided into two categories: the first one is the uncemented concrete specimens with a width of 1mm; The second one is the MICP cemented concrete specimen. YZW30 rock shear test system was used for the direct shear test (Fig. 4). The tertiary normal stress (σn) is proposed, whose values are 0.05σn, 0.1σn and 0.2σn, respectively, corresponding to the tertiary normal stress conditions of low, medium and high. In the test, the axial stress was generated at a loading rate of 0.2 kN/s. The tangential stress is generated by the displacement control bottom at the rate of 0.2 mm/min. The test is stopped when the shear displacement reaches 10% of the length of the specimen. The number of experimental groups of 2 types of sandstone joint specimens in this direct test is summarized in Table 3.

Figure 4. *YZW30 computer-controlled rock stress direct shear apparatus*

Table 3: Summary of shear tests performed on three kinds of artificial cracked concrete specimens

Specimen type	Curing time/day	Test quantity			Total Quantity
		$0.05\sigma_c$	$0.1\sigma_c$	$0.2\sigma_c$	
Uncemented	—	1	1	1	3
	7	1	1	1	3
Cemented	14	1	1	1	3
	28	1	1	1	3
	7	1	1	1	3
	14	1	1	1	3
	28	1	1	1	3
	7	1	1	1	3
	14	1	1	1	3
	28	1	1	1	3

RESULT AND DISCUSSION

Surface Observations

Throughout the crack repair procedure, it was noticed that white microbes were consistently created and slowly gathered on the surface. Observations of the surface for both test specimens indicated that the surface crack could be fully healed and blocked by the end of the scheduled repair period. Fig. 5 shows the progress of concrete crack repair by using MICP. As can be seen in Fig. 5, white microbes slowly collected from the bottom to the top of the concrete crack during the repair. This phenomenon is mainly due to gravity, which causes the deposit of germs from the bottom surface of the crack. Furthermore, surface observations analysis in Fig. 5 revealed that it takes 11 to 13 days for the five-gradient domestication scheme to heal the crack. It has been observed that the amount of $CaCO_3$ grown in the concrete crack, using a five-gradient domestication scheme, is limited. On the other hand, the proposed method ensures that the solution of $CaCO_3$ retained in the wiper is sufficient and could flow inside the crack by diffusion process. As a consequence, the biochemical reactions associated with the MICP technique are endorsed, causing more effective and faster repair of cracks compared to other methods (Chuo et al. 2020; Omoregie et al. 2017).

Figure 5. *MICP cemented joint specimen*

Analysis of Filling Materials

The morphology and phase composition of filled $CaCO_3$ were analysed through a Scanning Electron Microscope (SEM) coupled with energy-dispersive X-ray Spectrometry (EDS) and X-ray diffraction (XRD). SEM images of the fillers at the cracks of the specimens are shown in Fig. 6. Both the white spores had different particle sizes and sphere-shaped

morphologies. The Potassium Magnesium Phosphate (MKPC) encapsulated spores group had an average particle size of 3-4 μm, and the spheres were more dispersed. On the other hand, the SC encapsulated spores group had an average particle size of 2-3 μm, and most of them were clustered together.

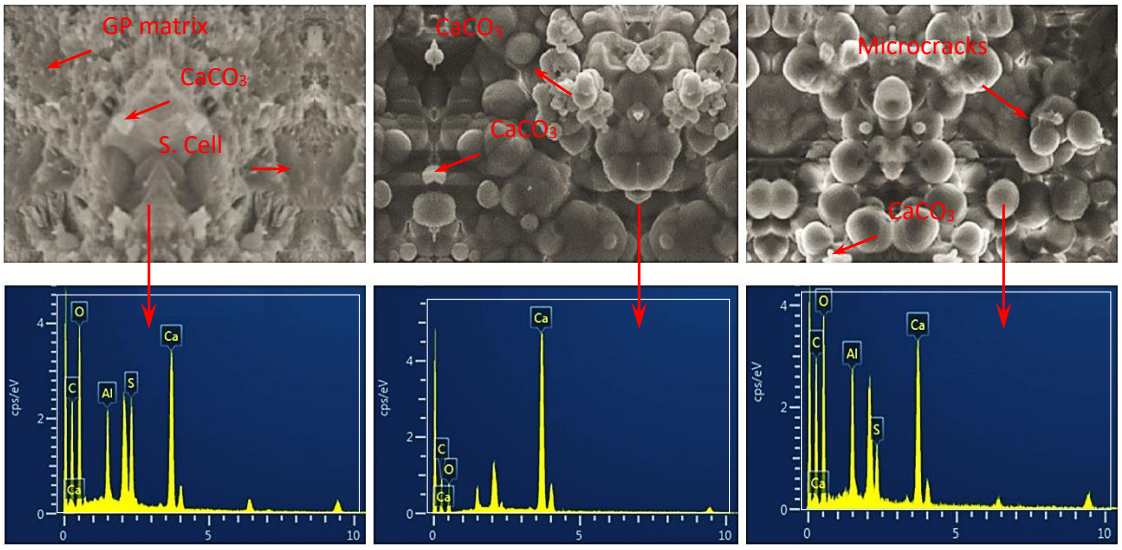

Figure 6. *EDS and morphologies spectrums of the materials in the concrete crack at different curing times. (a) 7 days, (b) 14 days and (c) 28 days.*

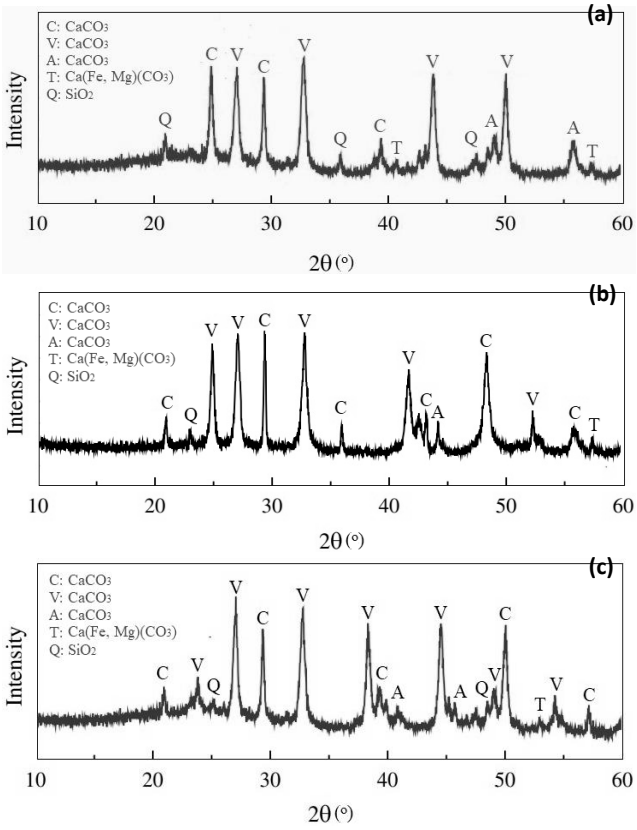

Figure 7. *XRD patterns of the materials in the concrete crack at different curing times. (a) 7 days, (b) 14 days and (c) 28 days.*

The EDS spectrum of precipitations showed that the key elements were O, Ca, and C indicating that the filling spores on the surface of the concrete crack area were $CaCO_3$. Fig. 7 shows that the main product was $CaCO_3$ with Vaterite (V) Calcite (C). The calcium carbonate formed by the microbially induced technique has a higher bonding strength with the shear strength of concrete cracks. But, the height of the bonding film could reach the micrometer level. These findings confirm that the five-gradient domesticated $CaCO_3$ is not only a good bonding material between the two surfaces of the concrete but also a good cementing ability.

Shear Displacement

The specimens with joints repaired by strains cultured with a five-gradient domestication scheme were subjected to direct shear tests after 7 days, 14 days and 28 days of curing at normal stress (σ_n) of $0.1\sigma_c$ and $0.2\sigma_c$ (Fig. 8). The shear displacements and shear strength curves under third-order normal stress were plotted in Fig. 8. From Fig. 8, all shear stress-displacement curves have obvious peak points. The whole shear stress-displacement curve could be divided into three parts: pre-peak climbing section, post-peak falling section and residual stage (Fig. 8ab). The shear stress corresponding to the peak point is the ultimate shear strength of concrete joints under normal stress conditions. But, the residual shear stress is the residual shear strength. In addition, the repair ability of the strains after five-gradient domestication was the best, indicating that the strains after domestication by this method can be well adapted to the saline-alkali environment, have a good connection effect on concrete joint specimens and can improve their shear strength to a certain extent. The shear stress-displacement curves of MICP cemented concrete crack obtained by a five-gradient domestication scheme after 7 days, 14 days and 28 days of curing are shown in Fig. 8. As can be seen from Fig. 8, the peak shear strength of the cemented joint increases with the extension of maintenance time.

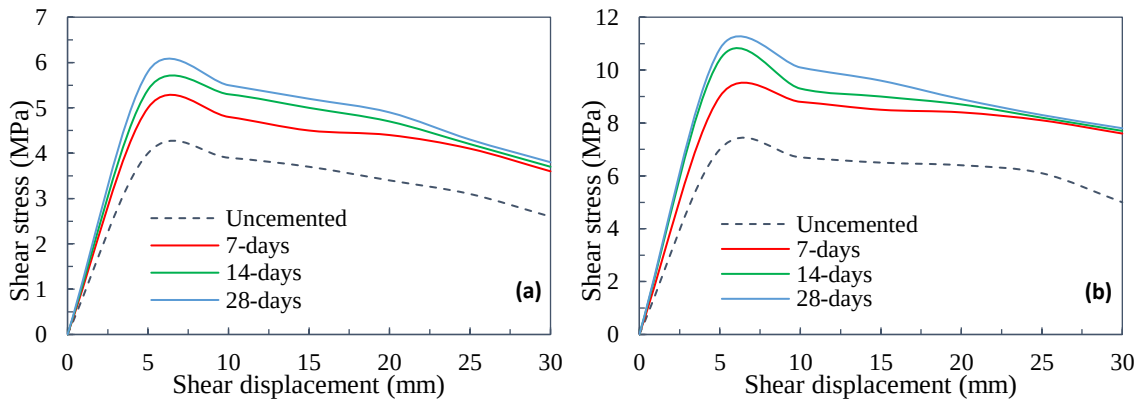

Figure 8. *Shear stress-displacement curves of $CaCO_3$ cemented concrete crack at different curing times, (a) $\sigma_n = 0.1\sigma_c$ and (b) $\sigma_n = 0.2\sigma_c$*

Peak Shear Strength

The relationship between the ultimate shear strength of the joint and curing time is plotted in Fig. 9 to assess the strengthening effect of $CaCO_3$ on the strength of concrete crack. As shown in Fig. 9, At a five-gradient domestication scheme (normal stress $\sigma_n = 0.2\sigma_c$) the peak normal stress increased rapidly in the initial stage of restoration. This is because the productive rate of calcium carbonate gradually slows down with the consumption of nutrients and the decline of bacteria in the environment without supplemental nutrients and bacterial solutions. As a result, the ultimate shear strength rises gradually with the rise of curing time (Fig. 9). The repair ability of the strain was significantly inhibited by the saline-alkali environment, resulting in little improvement in the peak shear strength after repair. Furthermore, the peak shear strength of the joint repaired after 28 days of curing significantly improve the shear strength of the joint to a certain extent, indicating that the bacteria can gradually adapt to the saline environment under five-gradient acclimation. These results prove that the five-gradient acclimation scheme is better than that of other methods.

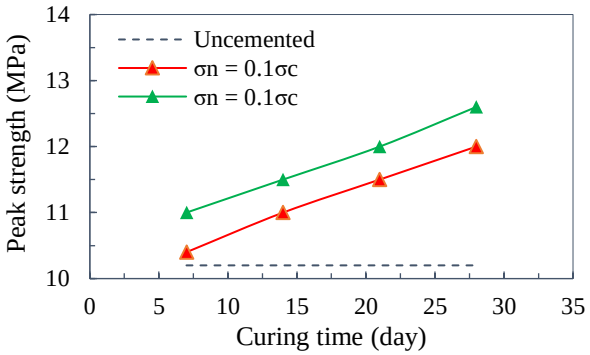

Figure 9. *Variation of peak shear strength of MICP cemented concrete joints at different curing times*

The relationship between peak shear strength and normal strength of the joint is plotted under different curing times as shown in Fig.10. As the normal stress increased the peak strength of the concrete joint also increased linearly (Fig. 10). It was close to the repair strength of the conventional environment, indicating that the effect of five-gradient acclimation was better than that of other methods. In this research, the CaCO3 formed by germs has a good bonding strength with the concrete. Microbially CaCO3 not only increased the shear strength of cracked concrete but also has a better cementing ability.

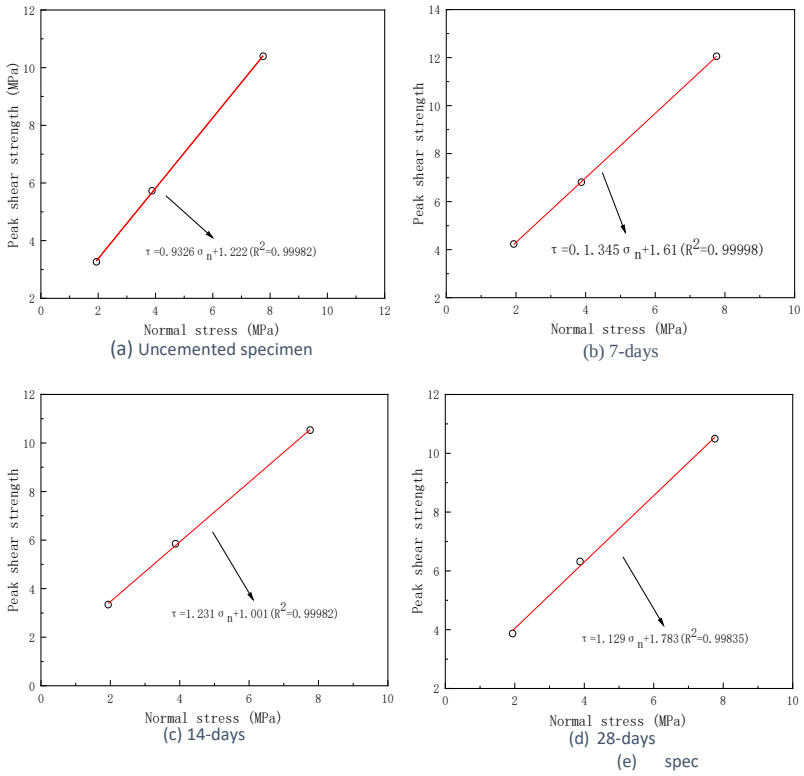

Figure 10. *Fitting curves of shear strength parameters of concrete MICP cemented joint at different curing days*

CONCLUSIONS

In this particular research, Sporosarcina Pasteurii was first domesticated in a saline environment. Then, the cementation effect of domesticated bacteria on the shear strength of concrete joints was analysed through laboratory tests. The main conclusions are drawn as follows:

1. In the five-gradient domestication process, the morphology of Sporosarcina Pasteurii was meaningfully decreased, but good adaptability to saline conditions. Meanwhile, the saline water conditions provided more Magnesium and Calcium ions, which promotes productive rates of carbonate during the cementation after 28 days of curing.
2. The concentration of bacterial fluid after five-gradient acclimation in saline water can reach more than 94% of that in a neutral condition. The productive rate of CaCO3 after interaction with cementing fluid was significantly increased compared with that in a neutral environment,
3. The acclimated Sporosarcina Pasteurii has good temperature adaptability and good MICP performance at 10~30 °C. In the saline environment, both the carbonate production and the shear strength of concrete joints after MICP consolidation were higher, and the bacteria with five-gradient acclimation had a better crack-sealing performance.
4. The peak shear strength of the cemented joint increased with the curing time, but the strength developed quickly in the early stage and slowly in the later stage. Compared with uncemented concrete joints, the peak shear strength of MICP cemented joints was significantly higher.

ACKNOWLEDGEMENT

The author would like to thank Southwest Jiaotong University, Chengdu 610031, China for research and funding.

REFERENCES

Ariyanti, D., Sasongko, N.A., Fansuri, M.H., Fitriana, E.L., Nugroho, R.A. & Pratiwi, S.A. 2023. Retrofitting of concrete for rigid pavement using bacterial: A meta-analysis. Science of the Total Environment, 166019.

Cao, D. & Zhang, B. 2023. Study on bonding strength, chloride penetration resistance, and microstructure of adhesive interface for the old concrete repaired by alkali-activated materials. AIP Advances, 13.

Chen, H.-J., Lo, Y.-H., Tang, C.-W. & Chang, H.-W. 2024. Applying Microbial-Induced Calcium Carbonate Precipitation Technology to Improve the Bond Strength of Lightweight Aggregate Concrete after High-Temperature Damage. Applied Sciences, 14, 1416.

Chuo, S.C., Mohamed, S.F., Mohd Setapar, S.H., Ahmad, A., Jawaid, M., Wani, W.A., Yaqoob, A.A. & Mohamad Ibrahim, M.N. 2020. Insights into the current trends in the utilization of bacteria for microbially induced calcium carbonate precipitation. Materials, 13, 4993.

Fan, Q., Fan, L., Quach, W.-M., Zhang, R., Duan, J. & Sand, W. 2023. Application of microbial mineralization technology for marine concrete crack repair: A review. Journal of Building Engineering, 69, 106299.

Gao, R., Ma, J., Liu, G., Chen, H., Wen, J. & Wang, J. 2023. Optimization of deposition process for a productive and cohesive bio-CaCO3 to repair concrete existing cracks. Applied Microbiology and Biotechnology, 107, 3479-3494.

Intarasoontron, J., Pungrasmi, W., Nuaklong, P., Jongvivatsakul, P. & Likitlersuang, S. 2021. Comparing performances of MICP bacterial vegetative cell and microencapsulated bacterial spore methods on concrete crack healing. Construction and Building Materials, 302, 124227.

Jiang, Z., Hong, S., Fu, C., Li, Q., Tang, K. & Yan, W. 2024. Effect of NaCl solution wet-dry cycles on pore structure and oxygen diffusivity of axial tensile fatigue damaged concrete. Journal of Building Engineering, 108881.

Khoshtinat, S. 2023. Advancements in Exploiting Sporosarcina pasteurii as Sustainable Construction Material: A Review. Sustainability, 15, 13869.

Lee, D.-K., Shin, K.-J. & Lee, K.-M. 2024. Evaluation of crack width and self-healing performance of concrete based on fluid flow characteristics: Comparison between water permeability test and gas diffusion test. Construction and Building Materials, 411, 134118.

Lu, C., Ge, H., Li, Z. & Zheng, Y. 2022. Effect evaluation of microbial mineralization for repairing load-induced crack in concrete with a cyclic injection-immersion process. Case Studies in Construction Materials, 17, e01702.

Lu, C., Li, Z., Wang, J., Zheng, Y. & Cheng, L. 2023. An approach of repairing concrete vertical cracks using microbially induced carbonate precipitation driven by ion diffusion. Journal of Building Engineering, 73, 106798.

Mondal, S. & Ghosh, A.D. 2019. Review on microbial induced calcite precipitation mechanisms leading to bacterial selection for microbial concrete. Construction and Building Materials, 225, 67-75.

Nasser, A.A., Sorour, N.M., Saafan, M.A. & Abbas, R.N. 2022. Microbially-Induced-Calcite-Precipitation (MICP): A biotechnological approach to enhance the durability of concrete using Bacillus pasteurii and Bacillus sphaericus. Heliyon, 8.

Omoregie, A.I., Khoshdelnezamiha, G., Senian, N., Ong, D.E.L. & Nissom, P.M. 2017. Experimental optimisation of various cultural conditions on urease activity for isolated Sporosarcina pasteurii strains and evaluation of their biocement potentials. Ecological Engineering, 109, 65-75.

Sun, X., Wai, O.W., Xie, J. & Li, X. 2023. Biomineralization To Prevent Microbially Induced Corrosion on Concrete for Sustainable Marine Infrastructure. Environmental Science & Technology, 58, 522-533.

Turner, R., Castro, G.M., Minto, J., El Mountassir, G. & Lunn, R.J. 2023. Treatment of fractured concrete via microbially induced carbonate precipitation: From micro-scale characteristics to macro-scale behaviour. Construction and Building Materials, 384, 131467.

Xiang, J., Qiu, J., Wu, P., Zhang, Q., Song, Y. & Yang, L. 2024. Autolytic capsules incorporating alkali-activated slag system for self-healing cementitious composites. Cement and Concrete Composites, 147, 105439.

Xiang, J., Qiu, J., Yuan, L., Wu, J. & Ma, Z. 2023. Characterization and role analysis of bacteria types in self-healing behaviour of cemented paste backfill. Journal of Building Engineering, 75, 106964.

Xiang, J., Song, Y., Shu, H., Li, Z., Qiu, J. & Gu, X. 2022. Expanded polystyrene (EPS) particles as a carrier to improve the growth of microorganisms in concrete. Journal of Cleaner Production, 369, 133363.

Yan, Y., Liu, W., Li, Z., Jia, G., Zhang, Y., Ma, G. & Gao, Y. 2024. Mechanical properties and frost resistance of self-healing concrete based on expanded perlite with different particle sizes as microbial carrier. Construction and Building Materials, 422, 135450.

Zhang, J., Deng, J., He, Y., Wu, J., Simões, M.F., Liu, B., Li, Y., Zhang, S. & Antunes, A. 2024a. A review of biomineralization in healing concrete: Mechanism, biodiversity, and application. Science of the Total Environment, 170445.

Zhang, K., Tang, C.-S., Jiang, N.-J., Pan, X.-H., Liu, B., Wang, Y.-J. & Shi, B. 2023a. Microbial-induced carbonate precipitation (MICP) technology: a review on the fundamentals and engineering applications. Environmental Earth Sciences, 82, 229.

Zhang, S., Wang, S., Ahmed, Z. & Zhao, X. 2023b. A Novel Mathematical Model for Repairing Rough Cracks Using the Microbially Induced Carbonate Precipitation (MICP). Sustainability, 15, 13122.

Zhang, Y., Liu, Y., Sun, X., Zeng, W., Xing, H., Lin, J., Kang, S. & Yu, L. 2024b. Application of microbially induced calcium carbonate precipitation (MICP) technique in concrete crack

repair: A review. Construction and Building Materials, 411, 134313.