Microbial healing of nature-like rough sandstone fractures for rock weathering mitigation

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Abstract

Rock weathering fractures in nature are complex and fracture healing is an effective strategy for rock weathering mitigation. This study is a first attempt to apply microbially induced calcium carbonate precipitation (MICP) technology in the healing of nature-weathering-like rough fractures (NWLRF). Sandstone was studied as an example due to its wide distribution as construction, sculpture and monument materials all over the world. To achieve a high healing efficiency, a repeated mixture injection strategy was proposed. Based on a series of laboratory MICP injection experiments on four types of NWLRF, we systematically explored the fundamental micro-healing mechanism and the influence factors including fracture aperture, characteristics of branch fractures, and cementation solution concentration. Experimental results demonstrated that MICP healing with the repeated mixture injection strategy had the ability to efficiently heal the penetrated NWLRF well with length in centimeter scale and aperture in millimeter scale, but cannot heal the non-penetrated branch fractures under low injection pressure. The repeated mixture injection strategy furtherly achieved a high apparent fracture healing ratio and a significant reduction of transmissivity. The apparent fracture healing ratios of all main fractures were higher than 80% and the maximum was 96.3%. Fracture transmissivity was reduced by at least three orders of magnitude from about $1 \times 10^{-4}$ m²/s to less than $1 \times 10^{-7}$ m²/s, and the highest reduction reached to four orders of magnitude. For the aspect of the effects, larger cementation solution concentration, finer aperture and penetrated branch fracture were beneficial to improve the healing effect. Moreover, the MICP healing mechanism with high fracture healing ratio and significant reduction of transmissivity on sandstone NWLRF was also analyzed. The research results have important theoretical significance and technical guidance value for the disaster prevention and mitigation of rock weathering.

Keywords Sandstone · Weathering fractures · MICP · Bio-healing · Fracture transmissivity · Weathering mitigation

Introduction

Rock weathering is a common geological phenomenon. It often destroys stone cultural relics and geological remains, and affects the stability of rock slopes. Rock fracture is regarded as the first way for rainwater to infiltrate into the rock, and is considered as the dominant effect in accelerating weathering process through freeze–thaw cycles, chemical and biological erosions, etc. (McKay et al. 2009; Sel and Binal 2021).

Several researchers have pointed out that permeability reduction by healing fractures is a useful strategy for weathering mitigation, and developed various types of chemical healing materials (Cardiano et al. 2005; Guo et al. 2009; Worthington et al. 2016; Liu et al. 2018; Zhang et al. 2018; Gao et al. 2020). Classified by chemical composition, chemical healing materials can be divided into inorganic materials...
and organic materials. However, both the two types of healing materials are not always preferable in site applications due to some disadvantages. For example, Portland cement as the most widely used inorganic material is difficult to penetrate into the microfractures due to its large particles, thus leading to poor healing effect. Other inorganic materials with low viscosity normally cannot form effective bonding strength among fractures. Organic materials usually have poor weathering resistance and durability (Naeimi and Haddad 2020). In addition, the consumption of these traditional healing materials is often accompanied by high carbon emissions and environmental pollution risk. It thus important to propose a new method with low viscosity, high bonding strength, good weathering resistance and durability, and low carbon emission and eco-friendly.

Since microbially induced calcium carbonate precipitation (MICP) has been widely applied for the improvement of soil foundation, it has been proven to be a novel, green, effective, and sustainable geotechnical engineering technology (Ivanov and Chu 2008; DeJong et al. 2010; Van Paassen et al. 2010; Al Qabany and Soga 2013). However, only a small number of researchers have attempted to verify the feasibility of healing rock fractures using MICP technology by exploring the hydraulic and mechanical performances. According to the literature review, these researches can be divided in to three scales including small-scale, borehole-scale, and field scale.

For the small-scale conditions, a series of planar flow experiments were carried out on varying smooth single artificial fractures by etching the fractures using transparent rock-like materials or rock materials (Mountassir et al. 2014; Minto et al. 2016; Deng et al. 2019; Peng et al. 2020). Borehole-scale experiments were mainly radial flow experiments conducted on single artificial rock fractures constructed by hydraulic fracturing or saw cutting (Phillips 2013; Phillips et al. 2013; Tobler et al. 2018). Moreover, Cuthbert et al. (2013) presented a first field experiment applying MICP to reduce a single dolomite fracture permeability approximately 25 m below ground level. Other researchers, i.e., Cunningham et al. (2014), Phillips et al. (2016), Phillips et al. (2018), and Kirkland et al. (2020) furtherly performed MICP field healing experiments on subsurface single fractures near wellbores for wellbore integrity purpose.

In these studies, all researchers adopted a similar injection strategy, namely repeated bacterial injection strategy to ensure an even calcium carbonate precipitation. The repeated bacterial injection strategy means that injecting bacterial suspension (BS) first, followed by the cementation solution (CS, Ca\(^{2+}\) and urea), and the injection process was repeated several cycles until the experiment was completed. These studies also showed that MICP had great potential to heal smooth single rock fractures in small-laboratory-scale or to reduce hydraulic properties of single rock fractures.

For the horizontal smooth single fractures, gradual reduction in fracture apertures due to calcium carbonate precipitation was the main healing mechanism (Mountassir et al. 2014; Minto et al. 2016). It was influenced by hydrodynamics (i.e., velocity, flow rate, and aperture) and the properties of the BS and the CS. Moreover, during the repeated bacterial injection process, the precipitation rate of calcium carbonate near the inlet area was slightly higher than other areas (Minto et al. 2016). The precipitated calcium carbonate will initially block the fractures near the inlet area. Part of the CaCO\(_3\) crystals could bridge across the fracture aperture and form a hydraulic barrier, resulting in a significant reduction in the hydraulic conductivity. Other part far away from the inlet area would not be filled well enough to form an effective hydraulic barrier. Ultimately, the precipitated calcium carbonate reduced fracture to a number of smaller tortuous pathways along the upper and lower fracture surfaces (Tobler et al. 2018).

However, shallow ground weathering fractures in nature are not only more in quantity but also more complex in geometry than these studied smooth single fractures, such as varying surface roughness, abrupt changes in aperture and existing branches (Du et al. 2022). To date, there is limited information related to the MICP healing performance on shallow ground weathering fractures in nature, the feasibility and the underlying healing mechanism remain poorly understood, which are essential criteria to be investigated for weathering mitigation. It is well known that the MICP performance and efficiency of fracture healing are mainly controlled by the injection strategy. Tobler et al. (2018) pointed out that healing efficiency was a major challenge for the widely used repeated bacterial injection strategy. The dominant reason is that bacteria were difficult to be attached on the smooth fractures firmly, and most of the bacteria were washed away during the subsequent injection of the CS. It is also important to note that during the repeated bacterial injection process, the precipitation rate of calcium carbonate near the inlet area was slightly higher than other areas in smooth fractures. This phenomenon will be more severe in weathering fractures. The precipitated calcium carbonate will initially block the fractures near the inlet area with smallest aperture quickly. Other fractures far away from the inlet area are thus not filled well enough to form an effective hydraulic barrier. These require that the injection strategy proposed for weathering fractures should have high healing efficiency.

Sandstone is a wide-spread construction, sculpture and monument materials all over the world. These sandstone constructions, sculptures and monuments are facing serious weathering hazard, and weathering fracturing is one of the important diseases (Turkington and Paradise 2005). It is thus necessary and urgent to study the healing problem of sandstone weathering fractures.
Therefore, this study took sandstone as an example, and was a first attempt to investigate the hydraulic performance of adopting MICP to heal nature-weathering-like rough fractures (NWLRF) and to reveal the corresponding micro-healing mechanism. A repeated mixture injection strategy (detailed information can be found in Section of injection strategy) was proposed and a series of laboratory MICP injection experiments were carried out on four types of NWLRF including single fractures with broad aperture, single fractures with fine aperture and multiple fractures with penetrated branch fracture and non-penetrated branch fracture. The four types of NWLRF were prepared using a cyclic thermal shock processing method which was widely used to generate new random and rough cracks of rocks rapidly (Bruel 2002; Dong et al. 2019). The reasons can be explained as the fact that thermal stress induced weathering was an important source of rock weathering when subjected to periodic rapid temperature changes (McKay et al. 2009). The cyclic thermal shock processing method can simulate the thermal stress induced weathering process, and the generation speed of NWLRF is faster than other physical and chemical weathering effects such as freeze–thaw cycles and chemical erosion. By observation at macroscale and hydraulic tests, the spatial distribution of the calcium carbonate precipitation, apparent fracture healing ratio and fracture transmissivity reduction were evaluated, which are key aspects controlling the effect of rock weathering mitigation. In addition, the effects of fracture aperture, CS concentration, branch fracture and healing mechanism were discussed. The research results have important theoretical significance and technical guidance value for the disaster prevention and mitigation of rock weathering.

Materials and methodologies

Materials

The sandstone used in this study was a type of fine green sandstone with grain size varies from 0.2 to 0.5 mm. It was collected from Longchang, Sichuan province, China. The mineral composition of the sandstone was 62% quartz, 18% feldspar, 16% kaolinite, and 4% mica. The density was 2.23 g/cm³ and P-wave velocity was 2.6 km/s. There were no distinct layering or laminations observed from the collected sandstone block.

Sporosarcina pasteurii (ATCC 11859), a type of bacteria which can efficiently produce urease and has high urea hydrolysis performance, was used as urease-producing bacteria in this study (Cheng et al. 2020; Liu et al. 2020). To initialize the growth of bacterial colonies, the pure bacterium strain was rehydrated in the solid ammonium yeast extract (NH₄-YE) medium for 24 h followed by low-temperature storage in Petri dishes at 4 °C (Liu et al. 2020). The liquid culture medium prepared for culturing bacteria consists of 15.73 g/L Tris base, 10 g/L ammonium sulfate and 20 g/L yeast extract and was sterilized in an autoclave at 121 °C for 20 min. Then, the bacteria were inoculated in the liquid culture medium and cultured in the flask inside an incubator at a rotation speed of 200 rpm under a constant temperature of 30 °C for 24 h. Finally, the bacteria in the exponential growth phase with high urease activity were collected. The optical density (OD₆₀₀) of the collected BS varied between 1 and 1.2, and the urease activity was 11 mM hydrolyzed urea/min.

CS is a mixture of equimolar calcium chloride and urea with 3 g/L nutrient broth. In this study, two types of CS concentration including 0.1 M/L and 0.5 M/L were adopted to investigate the influence of the CS concentration on the MICP healing process and the spatial distribution of the calcium carbonate.

Sample preparation

The schematic diagram of sample preparation process including three steps is shown in Fig. 1.

Firstly, three standard size cylindrical sandstone samples of 5 cm in diameter and 10 cm in height were cored from a same sandstone mass. Secondly, samples were heated in a high-temperature furnace at 600 °C for 1 h, and then were moved to 20 °C water for rapid cooling (Dong et al. 2019). The cyclic thermal shock processing was repeated until 1 mm aperture fracture appeared on sample surface. Thirdly, the standard size samples with various of NWLRF were cut into small size sub-samples with a thickness of 1 cm along length direction. Samples contained single fracture with broad aperture, single fracture with fine aperture, and multiple fractures with branch fractures were selected as the typical experimental samples. To consider both penetrated branch fracture and non-penetrated branch fracture conditions, two branch fractures in one of the multiple fractures sample (M1) were both sealed and one branch fracture was sealed and the other one was not sealed in another multiple fractures sample (M2). The sealed locations can be found in Fig. 1 marked with red points.

Finally, four types of sandstone samples with NWLRF were prepared to simulate the typical shallow ground weathered sandstone in nature. Each type of samples was prepared in duplicate (see Fig. 1). The physical dimension of the samples was 5 cm in diameter and 1.0 cm in height. According to the theory of fracture roughness (Barton and Choubey 1977), the fracture roughness coefficients (JRC) of the all samples were about 18–20. Typical samples of each fracture type were shown in Fig. 1 as examples.

The fracture parameters including length, aperture and area were determined by a “Crack Image Analysis System”
(CIAS) using microscope photos. CIAS, a software developed by Tang et al. (2008) was widely used to quantify the soil fracture parameters including length, aperture and area with a calculation accuracy of 0.01 mm (Tang et al. 2010; Liu et al. 2013). The length, aperture and area of the fracture of each sample determined by the CIAS are shown in Table 1.

**Injection strategy**

To achieve a high healing efficiency, a repeated mixture injection strategy was adopted in this study. The repeated mixture injection strategy means that BS and CS solutions are mixed in equal volume, and half hour static period is conducted before injection. Ever one knows that when BS and CS solutions are mixed prior to injection, calcium carbonate precipitation begins almost immediately in the mixture, leading to clogging of the inlet ports. The half hour static period was conducted for the adequate deposition of the rapidly formed CaCO$_3$ crystals. The clean supernatant was used as the bio-cement solution for injection.

To reduce the effect of sample thickness, the (main) fractures remained vertical during injection process. The upper fractures were the solution inlet and the lower fractures were the outlet as shown in Fig. 1. Prior to injection, samples surfaces were covered with soft silicone film and acrylic glass plate, and were clamped with clamps to prevent surface leakage. In this study, 0.5 L BS and 0.5 L CS were used for each sample to ensure sufficient clean supernatant to completely heal each fracture. Previous study demonstrated that MICP can successfully be used to grout a fracture under constantly flowing conditions (Minto et al. 2016). Thus, a constant flow

![Fig. 1 Schematic diagram of MICP healing experiment on nature-weathering-like rough fractures including sandstone sample preparation, injection strategy and characterization of fracture healing performance](image)

| Fracture type               | Sample notation | Fracture name | Length (mm) | Aperture (mm) | Area (mm$^2$) |
|-----------------------------|-----------------|---------------|-------------|---------------|---------------|
| Broad aperture single fracture | B-1             | Main fracture | 55.76       | 0.74          | 38.00         |
|                             | B-2             | Main fracture | 56.21       | 0.71          | 37.06         |
| Fine aperture single fracture | F-1             | Main fracture | 54.77       | 0.41          | 21.17         |
|                             | F-2             | Main fracture | 59.70       | 0.37          | 20.34         |
| Multiple fracture           | M-1             | Main fracture | 60.19       | 0.74          | 44.83         |
|                             |                 | Branch fracture 1 | 25.29   | 0.22          | 5.21          |
|                             |                 | Branch fracture 2 | 28.40   | 0.27          | 7.06          |
|                             | M-2             | Main fracture | 57.70       | 0.73          | 43.08         |
|                             |                 | Branch fracture 1 | 31.20   | 0.31          | 9.20          |
|                             |                 | Branch fracture 2 | 28.69   | 0.38          | 11.21         |

Note: B-1, F-1, M-1 were treated by 0.1 M/L CS, and B-2, F-2, M-2 were treated by 0.5 M/L CS
rate of 20 ml/min was adopted to inject the supernatant under a room temperature of 30 °C until substantial clogging occurred.

**Characterization of fracture healing performance**

Healing performance on NWLRF is evaluated from four aspects including calcium carbonate distribution, morphology features of calcium carbonate on fracture surfaces and across the fracture aperture, apparent fracture healing ratio, and the changes of fracture transmissivity before and after MICP healing.

Calcium carbonate distribution was directly observed by microscope and was verified by the inside calcium carbonate distribution through opening the fracture.

The morphology features of calcium carbonate on fracture surfaces and across the fracture aperture were characterized by microscope photos.

Apparent fracture healing ratio ($R$) was used in this study to evaluate the healing performance instead of the whole fracture healing rate which is very difficult to be determined quantitatively and accurately. $R$ was defined as the percent surface fracture space filled by calcium carbonate after MICP healing. It can be calculated by the fracture area before and after the MICP healing, as shown in Eq. (1).

$$R = \frac{S_B - S_A}{S_B} \times 100\%$$  \hspace{1cm} (1)

where $S_A$ is the fracture area after MICP healing (mm$^2$), $S_B$ is the fracture area before MICP healing (mm$^2$).

Fracture transmissivity ($T$, m$^2$/s) describes the ability for fluid flow within the plane of the rock fracture and is defined as the in-plane permeability multiplied by the fracture thickness. $T$ was determined by fracture transmissivity test with constant water head in this study. To simulate the infiltration of water caused by rainfall, a relatively small constant head pressure of 3.5 kPa was used. Prior to the test, samples were immersed in water for 24 h to achieve saturation situation, reducing the impact of initial water content on the measurement results. In this study, cubic law was used to determine the $T$. Cubic law was widely used for laminar flow in fractures which was also called parallel plate model (Brown 1987). Normally, flow rate ($Q$, m$^3$/s) can be calculated by Eq. (2), and $T$ can be calculated by Eq. (3) (Witherspoon et al. 1980). Substitute Eq. (2) into Eq. (3), $T$ can be calculated by $Q$, $L$, $\Delta h$, and $W$ as shown in Eq. (4).

$$Q = \frac{W}{L} \left( \frac{\rho g}{12 \mu} \right) b_h^3 \Delta h$$  \hspace{1cm} (2)

$$T = \frac{Q L}{\Delta h W}$$  \hspace{1cm} (4)

where $L$ is the fracture length (m), $W$ is the width in the direction normal to fluid flow (m), $\rho$ is fluid density (kg/m$^3$), $g$ is acceleration due to gravity (m/s$^2$), $\mu$ is fluid dynamic viscosity (kg/(ms)), $\Delta h$ is the head loss (m), $V$ is fluid velocity (m/s), and $h_h$ is hydraulic aperture (m).

**Results**

**Distribution of calcium carbonate**

After MICP healing, apparent distribution of white calcium carbonate on fracture surface was clearly observed as shown in Fig. 2a. Figure 2a shows that precipitated calcium carbonate filled all the fractures well except non-penetrated branch fractures of multiple fracture samples M-1 and M-2. For the non-penetrated branch fractures, only small amounts of calcium carbonate were observed near the main fractures. This indicates that MICP technology can heal penetrated rough weathering main and branch fractures well with length in centimeter scale and aperture in millimeter scale, but cannot heal the non-penetrated branch fractures with low injection pressure. The apparent distribution of calcium carbonate of each sample was verified by the internal calcium carbonate distribution across fractures as pointed out in Fig. 2b.

**Morphology features of calcium carbonate**

Microscope photos of the overall surface fractures (Fig. 3a) show that the precipitated calcium carbonate in main fractures and penetrated branch fractures are dense and stable after transmissivity test. Meanwhile, it is important to note that un-healed areas with different shapes, sizes and depths were distributed in the fracture. For example, the shallow un-healed area (indicated by the white dotted oval in Fig. 3a) and deep un-healed area (indicated by the red dotted oval in Fig. 3a) are the two typical types. The comparison of each subgraph indicates that there were more un-healed areas, especially in the deep part of the fracture, in the samples with broad aperture healed by low concentration CS solution, i.e., B-1 and M-1. Moreover, small amounts of loose calcium carbonate can be observed in the non-penetrated branch fractures.

Some typical microscope photos of precipitated calcium carbonate at fully filled areas, un-healed areas and non-penetrated branch areas were presented on Fig. 3b. Calcium carbonate at fully filled areas were dense and had great numbers of small voids among them (Fig. 3b-1). These dense
calcium carbonate consisted of small round CaCO₃ crystals and bonded firmly with each other together, completely filling the fracture aperture and bridging across the both fracture surfaces. This type of micro-morphology feature was most evident on samples B-2, F-2, F-2 and M-2. Calcium carbonate at shallow un-healed areas also consisted of small round CaCO₃ crystals, and looked slightly looser than that at fully filled area (Fig. 3b-2). For deep un-healed areas, calcium carbonates were distributed in clusters on both fracture surfaces and looked much looser than those at fully filled areas and at shallow un-healed areas (Fig. 3b-3). These two types of micro-morphology features at un-healed fracture areas were most evident on samples B-1 and M-1. At non-penetrated branch areas of samples M-1 and M-2, a small number of granular calcium carbonates were attached to both fracture surfaces (Fig. 3b-4).

The macro-healing features of the precipitated calcium carbonate inside the fractures were also investigated by microscopic observation. Typical microscope photos are shown on Fig. 3c. A lot of small voids at fully filled areas (Fig. 3c-1) and sparse granular calcium carbonates at non-penetrated branch areas (Fig. 3c-4) were also observed. Meanwhile, round bubble-like voids (Fig. 3c-2) and long bubble-like voids (Fig. 3c-3) were discovered inside the fractures. The surfaces of both types of bubble-like voids were smooth, which were the main difference from those of un-healed areas.

### Apparent fracture healing ratio

Grayscale images of samples before and after MICP healing are showed in Fig. 4. Figure 4 indicates that all the fracture areas were significantly reduced except non-penetrated branch fractures of multiple fractures samples M-1 and M-2. The detail information of fracture area of samples before and after MICP healing can be found in Table 2 as well as Fig. 5a, b.

The apparent fracture healing ratios (Fig. 5c) of main fractures in all samples are higher than 80%. Samples healed by 0.5 M/L CS have slightly higher apparent fracture healing ratios than those samples healed by 0.1 M/L CS. When healed by the same CS concentration, apparent fracture healing ratios of samples with fine aperture fracture are slightly greater than those samples with broad aperture fracture. For single fracture, fracture healing ratio can reach up 87.7% (sample F-2). For multiple fractures, the existing of penetrated branch fracture promoted the performance of healing. For example, the apparent fracture healing ratios of sample M-1 are 83.6% (main fracture), 15.4% (non-penetrated branch fracture 1),
and 41.3% (non-penetrated branch fracture 2), while the apparent fracture healing ratios of sample M-2 increase to 96.3% (main fracture), 60.9% (non-penetrated branch fracture 1), and 99.1% (penetrated branch fracture 2).

Compared to the previous 67% fracture healing ratio achieved using the repeated bacteria injection strategy (Tobler et al. 2018), the repeated mixture injection strategy had better healing performance.

**Fracture transmissivity**

Fracture transmissivities of various samples before and after MICP healing are showed in Fig. 6. Before MICP
healing, fracture transmissivities of all samples close to the order of $10^{-4}$ m$^2$/s and samples with fine aperture fracture have slight lower values. After the MICP healing, the fracture transmissivity decreased by at least three orders of magnitude from about $1 \times 10^{-4}$ m$^2$/s to less than $1 \times 10^{-7}$ m$^2$/s, and the maximum reduction reached to four orders of sample F-2 (Fig. 6). For the same aperture, the fracture transmissivity of samples healed by 0.5 M/L CS (samples B-2, F-2, and M-2) were about 2–3 times higher than those healed by 0.1 M/L CS (samples B-1, F-1, and M-1), indicating that the 0.5 M/L CS had better healing performance on NWLRF in this study conditions. This
consists with the results of apparent fracture healing ratios that samples healed by 0.5 M/L CS have higher apparent fracture healing ratios and more dense calcium carbonate precipitation.

**Discussion**

**Fracture healing mechanism**

According to the experimental results and correlation analysis, a hypothesis of the MICP healing mechanism on NWLRF is proposed and its schematic diagram can be found in Fig. 7. It consists of three main steps.

In the initial stage of injection, bacteria in bio-cement solution were attached to the both fracture surfaces through two ways. One way was to rely on the penetration of the bio-cement solution to carry the bacteria into the tiny pores near the fracture surface, so that the bacteria were trapped in the tiny pores. The other way was that the bacteria were attached to the fracture surface by their own electrostatic charge attraction. Due to the rough fracture surface and abrupt changes in aperture, the attached bacteria were unevenly distributed along the length of the fracture. The reason was the fact that solution flow rate in different locations were different (Mountassir et al. 2014). As shown in Fig. 7a, at the convex, the flow rate slowed down, thus more bacteria could be attached than other locations. Because of using the repeated mixture injection strategy, the existence of the CS allows more bacteria to be attached firmly to the pores or the fracture surfaces during the subsequent calcium carbonate precipitation.

The second step was the precipitation process of calcium carbonate. Due to more attached bacteria in the MICP process, the repeated mixture injection strategy accelerated the precipitation rate of calcium carbonate on the fracture surface than the repeated bacteria injection strategy. Especially at the convex, calcium carbonate precipitation was relatively faster because there were more bacteria (see Fig. 7b). As more calcium carbonates were precipitated at the convex,
more bacteria were furtherly attached to these CaCO$_3$ crystals. This mutually promoting process finally induced a rapid precipitation of calcium carbonate along the fracture length and formed many narrow necks (see Fig. 7b).

The third step was the clogging process and further bonding process of calcium carbonate. The clogging process was caused by the calcium carbonate particles pre-produced in the bio-cement solution. As the bacteria in the supernatant gradually produced urease, calcium carbonates were also gradually produced in the bio-cement solution. Compared to the calcium carbonate produced by bacteria attached to the fracture surface, this portion of calcium carbonates were loose with small particles (a few microns to tens of microns) and migrated with the bio-cement solution inside the fractures. When the fracture apertures at narrow necks were reduced to a few tens of microns, these calcium carbonate particles pre-produced in the bio-cement solution will clog the necks immediately. Soon afterwards, more calcium carbonate particles partly filled the un-healed areas quickly. It agreed with a previous study (Saada et al. 2006) which pointed out that a solution was able to penetrate pore space if the pore space size was 1.5–2.5 times greater than that of the largest solid particle of the solution. At this time, these fast-filling calcium carbonates were still loose and combined

Fig. 5 Fracture area calculated by crack image analysis system of samples a before MICP healing, b after MICP healing, and related e apparent fracture healing ratio
into discontinued un-healed area of different shapes, sizes and depths in the fracture as shown in Fig. 7c. The bio-cement solution was still able to penetrate these calcium carbonate particles and subsequently bond them together by inducing new calcium carbonate precipitation. As a result, fast-filling calcium carbonates were firmly bonded with each other and completely closed up the fracture, providing a stable hydraulic barrier.

The formation of bubble-like voids was accepted to be related to the presence of gas bubbles due to their smooth surface. On the one hand, the gas might come from the air mixed during the injection process (Tobler et al. 2018). On the other hand, the gas might be related to the biogas produced by bacterial activity. Biogas was a type of gas produced through microbial reactions under certain conditions, such as carbon dioxide (CO₂) and nitrogen (N₂) gas (Rebata-Landa and Santamarina 2012; He et al. 2014). It was believed that the hydrolysis of urea by bacteria produced carbon dioxide (CO₂) and ammonia gas (NH₃) as shown in Eq. (5), which were not all involved in the formation of calcium carbonate or dissolved in water (Seifan and Berenjian 2019; Choi et al. 2020; Almajed et al. 2021), and the undissolved part formed gas bubbles inside the fractures (see Fig. 7b). When gas bubbles appeared, calcium carbonates precipitated around them, eventually forming round bubble-like voids. In some cases, some small gas bubbles merged into large and long bubbles, thus forming long bubble-like voids (see Fig. 7c).

**Effect of fracture aperture**

The fracture aperture has an influence on the healing performance of MICP. Single fractures with fine aperture have a higher apparent fracture healing ratio than that of single fractures with broad aperture. The reasons can be explained as follows. Healing single fractures with broad aperture
requires more precipitated calcium carbonate to fully fill the fracture, which means more healing cycles are needed. This is consistent with the observation that the injection time for single fractures with broad aperture were longer. As mentioned above, the precipitation rate of calcium carbonate was different at different locations. The longer the injection time, the more heterogeneous the precipitated calcium carbonates. Thus, there were more narrow necks formed. These narrow necks could easily cause clogging, generating un-healed areas with different shapes, sizes, and depths. In addition, flow rate in fine fracture was larger, which made the bacteria more evenly distributed along the fracture surface. This reduced the likelihood of the formation of the narrow necks. Therefore, these two aspects resulted in a higher apparent fracture healing ratio and a lower fracture transmissivity for single fractures with fine aperture.

**Effect of cementation solution concentration**

In general, the larger the CS concentration, the higher the apparent fracture healing ratio and less amount of un-healed areas. Previous studies suggested that high CS concentration would yield large size of calcium carbonate crystals with high calcium carbonate production rate (Al Qabany et al. 2012). This means that compared to low CS concentration, the fractures could be healed more quickly by high CS concentration. Thus, uneven precipitation of calcium carbonate was reduced. When the fracture apertures at narrow necks were reduced to a few tens of microns, those large size of CaCO₃ crystals formed in the bio-cement solution clogged the necks immediately and filled the fractures uniformly. Therefore, samples healed by larger CS concentration had higher apparent fracture healing ratio and lower fracture transmissivity.

**Effect of branch fracture**

In multiple fractures, during the injection process, the main fracture acted as the dominant flow channel, allowing the bio-cement solution to flow preferentially through it. Experimental results indicated that penetrated branch fractures could promote the healing performance such as increasing apparent fracture healing ratio and decreasing fracture transmissivity of the main fractures. This is can be explained as the fact that penetrated branch fractures increased the cross-sectional area of the fractures near outlet. It reduced the flow rate of the bio-cement solution at the bottom main fractures and branch fractures, ensuring the bacteria to be more evenly distributed in these areas. In addition, after the clogging occurred at the necks, the penetrated branch fractures allowed extra clean bio-cement solutions to be injected in to the fractures, even the main fracture was completely closed. The extra clean bio-cement solution induced more calcium carbonate precipitation to fill un-healed areas and made the calcium carbonate bond firmer. While for the non-penetrated branch fractures, due to the air obstruction, only a small amount of the bio-cement solution could be injected into the non-penetrated branch fractures. Thus, it is difficult to form large amounts of calcium carbonate crystals in the non-penetrated branch fractures and it has less influence on the healing process of the main fracture.

**Conclusions**

Four types of NWLRF in sandstone were prepared to simulate the shallow ground weathering fractures in nature, including single fracture with broad aperture, single fracture with fine aperture and multiple fractures with penetrated branch fracture or non-penetrated branch fracture. To have a high healing efficiency, a repeated mixture injection strategy was proposed. According to the analysis of the MICP injection experiment results in laboratory, the main findings are as follows.

1. MICP healing with the repeated mixture injection strategy can efficiently heal penetrated NWLRF well with length in centimeter scale and aperture in millimeter scale but cannot heal the non-penetrated branch fractures under low injection pressure.
2. The repeated mixture injection strategy also ensured that the apparent fracture healing ratios of main fractures were higher than 80% and the maximum value was 96.3%. This is much higher than the healing rate that can be achieved by repeated bacteria injection strategy used in previous studies.
3. Fracture transmissivity could be reduced by at least three orders of magnitude from about $1 \times 10^{-4}$ m²/s to less than $1 \times 10^{-7}$ m²/s, and the highest reduction reached to four orders of magnitude.
4. The MICP healing performance was affected by the fracture aperture, CS concentration, and branch fracture. Larger CS concentration (0.5 M/L), finer aperture and penetrated branch fracture can promote the MICP healing performance.
5. At the convex of fracture, where more bacteria were attached, calcium carbonates deposited more rapidly and as a result preferentially formed narrow necks. Subsequently, the calcium carbonate particles pre-formed in the bio-cement solution resulted in clogging at the narrow necks and promoted further bonding. The above process provided a stable hydraulic barrier and was the healing mechanism for NWLRF in sandstone.
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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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