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Bacterial bio-cementation can repair space bricks

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This study investigates the potential of Microbially Induced Calcium Carbonate Precipitation (MICP) as a repair technique for consolidated (sintered) bricks made from Lunar Highland Simulant-1 (LHS-1), aiming to extend their functional lifespan in extra-terrestrial conditions. Sintered bricks (compressive strength ~50 MPa) were fabricated with embedded holes, V-shaped notches, and semi-circular notches to simulate structural failure. The compressive strength of these modified bricks was assessed, revealing a significant reduction in strength due to stress concentrations around these cavities. Following this, the cavities were filled with a MICP-based soil slurry, resulting in a notable recovery of compressive strength (~28%–54%), although not to the levels of the original material. Scanning electron microscopy (SEM) analysis demonstrated strong interfacial bonding between the MICP filler and the sintered substrate, indicating the effectiveness of the repair method. Additionally, Digital Image Correlation (DIC) was used to track the crack propagation and growth under the loading conditions. Instances of crack propagation through the MICP interface highlight areas for further investigation. The findings underscore the viability of MICP as a sustainable solution for repairing construction materials, aligning with contemporary practices aimed at enhancing durability and reducing dependency on Earth.

KEYWORDS

biocementation process, lunar regolith simulant, space bricks, lunar habitation, repairing

1 Introduction

The prospect of human settlement on the Moon, the closest celestial body to Earth, rich in material resources, has grabbed the interest of many researchers (Crawford et al., 2016). Insights into the lunar structure through the Apollo and Soviet Luna missions and the presence of water in the form of ice by Chandrayaan-1 has fueled research in this direction (Goswami and Annadurai, 2009). While these missions have laid the foundation for lunar exploration by understanding its structure and conditions, scientists are now interested in the prospect of a long-term stay on the moon through the construction of infrastructure. With the launch of the Artemis series of missions, the National Aeronautics and Space Administration (NASA) aims to return people to the moon and establish long-term settlements (Creech et al., 2022). The success of Artemis Phase I and Chandrayaan-3's historic touchdown at the southernmost point on the moon has taken us a step closer to achieving the same (Kanu et al., 2024). China has also successfully executed several phases of the Chang'e (CE) mission to acquire samples from the far side of the Moon and use probes to detect ice at the South Pole (Lin et al., 2024). However, to make these lunar explorations sustainable and feasible, one needs to exploit the local resources present on the Moon, termed *in situ* resource utilization (ISRU) (Sanders and Larson, 2011).

One bountiful local resource on the moon is the unconsolidated and fine-grained lunar regolith covering the lunar surface and the underlying bedrock (Lucey et al., 2006; McKay et al., 1991). This regolith, rich in SiO_2, is formed due to the crushing of the anorthositic and basaltic rocks through micrometeorite bombardment and space weathering (Meurisse et al., 2017; Papike et al., 1982). Much of the research in constructing lunar habitats is now focused on using these local resources to circumvent transportation limitations (Kumar et al., 2020). The regolith's heterogeneous mineral composition depends on whether it is from the mare region containing ancient soil or from the heavily cratered highland area with younger, less weathered soils (Isachenkov et al., 2022). Various soil simulants replicating the regolith of the lunar mare and highland regions have been developed based on their composition and particle characteristics (Toklu and Akpinar, 2022). These simulants can be used as raw materials for construction after their binding and consolidation (Farries et al., 2021) using various mechanical (Farries et al., 2021; Phuah et al., 2020; Taylor et al., 2018), chemical and biological (Castelein et al., 2021; Roberts et al., 2021; Toutanji et al., 2005; Roedel et al., 2014) methods. Among these, sintering-based techniques, such as laser, microwave, spark plasma, solar, and furnace-based, are the most potent, giving strong final structures (Gupta et al., 2024a). Our lab has previously demonstrated the use of sintering to consolidate lunar and martian soil simulants and termed these sintered bricks as "synthetic space bricks" (Gupta et al., 2024a; Gupta et al., 2024b).

Although sintered bricks have a good compressive strength, they need to withstand the extreme environmental conditions of the moon. The lack of heat insulation due to the absence of an atmosphere makes the surface temperatures on the moon vary greatly between 224°F on a lunar day and −298°F on a lunar night (Harrell et al., 2021). In addition, there is a constant threat of both primary and secondary meteorites, which have caused the craters characteristic of the moon (König, 1977). These conditions could make the sintered bricks prone to fractures, making them less durable and sustainable for long-term settlements on the moon. This necessitates the need to look for repair strategies to increase the shelf-life of these bricks. For the repair of terrestrial concrete bricks, different fibers and polymers have long been explored (Dry, 1994; Van Tittelboom et al., 2016; Yang et al., 2009). Recently, bio-mineralization has been investigated as an alternative for making self-healing concrete structures (De Muynck et al., 2008).

Biomineralization through Microbially Induced Calcium Carbonate Precipitation (MICP) is a particularly promising area of research, which utilizes microorganisms to produce calcium carbonate as a binding agent in construction materials (Dhami et al., 2013; Dikshit et al., 2023; Zhu and Dittrich, 2016). This process relies on certain microbial metabolic activities, such as urea hydrolysis, iron and sulfite reduction, methane oxidation, photosynthesis, and the carbonic anhydrase pathway (Jain et al., 2021; Mwandira et al., 2023), which facilitate the precipitation of calcium carbonate from soluble calcium sources (De Muynck et al., 2008; Zhang et al., 2023). Among these, ureolysis by certain urease-producing bacteria, including *Bacillus sphaericus, Bacillus megaterium, Bacillus cereus* and *Sporosarcina pasteurii* has been extensively explored (Kho et al., 2024; Wang et al., 2012). These bacteria can hydrolyze the urea present in their extracellular environment, converting it to carbonate and ammonia. When calcium ions are present in the surrounding media, they get deposited on the negatively charged surface of these bacteria and react with the carbonate ions, thus forming calcium carbonate precipitates (Mwandira et al., 2023; Wu et al., 2021) (Figure 2B). Previous studies from our lab have used MICP for consolidating lunar and martian soil simulants to make 'space bricks' with a significant structural strength (Dikshit et al., 2021; Dikshit et al., 2022). Recognized as a sustainable alternative to traditional cement-based options, MICP addresses environmental concerns by reducing carbon emissions and enhancing sustainability (Zhang et al., 2023; Wiktor and Jonkers, 2016). It is an energy-efficient method and can be proposed as a cost-effective solution for construction challenges both on Earth and in space (Haouzi and Courcelles, 2018; Gebru et al., 2021). The ingredients required for bacterial growth and bio-cementation are substantially lesser than those used in traditional binders like cement. Water is vital in ureolysis and will be necessary for subsequent binder-based consolidation. Recent research focuses on extracting water from the lunar surface (Yanwei et al., 2024; Metzger et al., 2021; Kleinhenz and Paz, 2020; Sowers and Dreyer, 2019). Researchers are also attempting to produce plants in the lunar regolith, which may lead to future extraction of guar gum powder on the lunar surface (Hosamani et al., 2024; Duri et al., 2022; Caporale et al., 2023), and this will reduce resource dependency on Earth.

MICP's effectiveness in repairing both natural and simulated cracks in terrestrial brick materials has been previously demonstrated (Ortega-Villamagua et al., 2020; Hermawan et al., 2023; Wiktor and Jonkers, 2011), significantly improving their mechanical properties such as compressive strength and water resistance. These studies indicate that MICP-treated consolidates exhibit higher failure loads than untreated specimens, underscoring its potential as a sustainable repair technique—particularly relevant in extraterrestrial settings where resource availability is limited. In addition, we have previously demonstrated that supplementing the soil with biopolymers such as guar gum and xanthan gum can significantly improve the strength of the final construction materials formed (Dikshit et al., 2022) due to their effective binding activities (Gupta et al., 2025; Sujatha and Saisree, 2019; Chang et al., 2015). The calcium carbonate produced through MICP serves as both a filler and a cementing agent, effectively decreasing porosity and durability by filling voids, repairing cracks, and thus enhancing the mechanical properties of construction materials (Mu et al., 2021). Although there is extensive research on using MICP for consolidation and making self-healing terrestrial bricks, its healing ability in lunar bricks has not yet been explored.

The present work studies the possibility of using MICP-based slurry (via ureolysis pathway) to repair fractures in sintered bricks made from lunar soil simulant. Our findings show a significant increase in the compressive strength of the fractured lunar bricks upon filling the cracks with MICP-based slurry. Further, the interfacial bonding between the filler and brick and the crack propagation patterns are also evaluated to gain insights into the binding efficacy. We propose that MICP can serve as a sustainable solution for enhancing the practical utility of lunar bricks for long-term human settlement in extraterrestrial habitats.

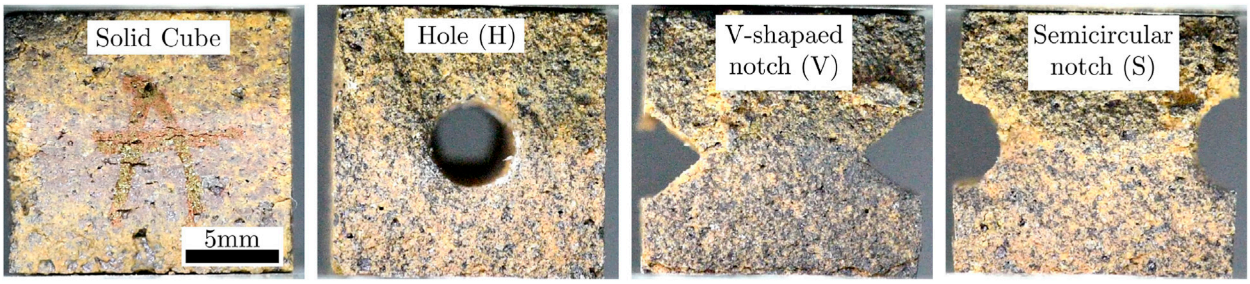

FIGURE 1
Illustration of the sintered solid and geometrically modified bricks (GMBs).

2 Materials and methods

2.1 Lunar soil simulant

The Lunar Highland Simulant (LHS-1), which accurately replicates the lunar regolith, was procured from Exolith Lab (Space Resource Technologies), Florida, USA (Isachenkov et al., 2022). LHS-1 comprises 75% anorthosite, 24% glass-rich basalt, and a small percentage of olivine, pyroxene, and ilmenite. The size of grain particles of LHS-1 ranges from 0.4 μm to 1,000 μm with an average of 88 μm.

2.2 Preparation of sintered specimen

In this investigation, we employed a sintering method for brick fabrication, as detailed in our previous work (Gupta et al., 2024a; Gupta et al., 2024b).

As demonstrated in the previous work (Dikshit et al., 2022), 1% (w/w) guar gum (GG) powder was added as a binder to LHS-1. Subsequently, 15 mL of DI (de-ionized) water was thoroughly mixed with every 100 g of LHS-1 to form the mixture. This mixture was then die-cast with a load of 10 tonnes in a prismatic cavity with a square cross-section of 15 mm sides to form cubical samples with side 15 mm (density of LHS-1 is 2.2 g/cc, this implies that ~8 gms of this mixture is required to form a cube of 15 mm side). Using cylindrical molds, a similar methodology was employed to fabricate discs with a diameter (D) of 15 mm and a thickness (t) of 6 mm ± 1 mm for the Brazilian disc test, and a prismatic mold was used to fabricate cuboidal samples of width (b) 18 mm, height (d) 18 mm and a length (L) of 65 mm for flexural testing. Geometrically modified bricks (GMBs) were fabricated to simulate the damage in the bricks, for which 3D-printed cores made of polylactic acid (PLA) with circular (5 mm diameter), semi-circular (5 mm diameter) and triangular (equilateral triangle with 5 mm side) cross-sections were placed to form the desired cavity in the samples. The circular cross-section core was positioned centrally to form a cylindrical hole (H), while the semi-circular and triangular cores were placed on the sides to create semi-circular (S) and V-shaped notches (V), respectively. These samples were then placed in a muffle furnace (Delta Power Systems) for sintering. The solid cubical and GMBs have been illustrated in Figure 1. Figure 2A gives an overview of the manufacturing process used to make sintered bricks. First, the as-cast samples were heated to 600°C for 1 h with a heating rate of 5°C/min. This stage removes any volatile substances from bricks along with guar gum and the 3D-printed cores made of PLA. This step confirms that guar gum does not contribute to the sintering process of the regolith; its role is limited to providing structural integrity to the green part before sintering. In the next stage, the temperature was raised to 1200°C with the same heating rate, and the bricks were soaked for 4 h. This ensures that the samples undergo liquid state sintering, as the melting point of the basalt content is approximately 1160°C. In the last stage, the temperature was brought down to room temperature with a ramp-down speed of 4°C/min.

2.3 Microbial cultures and MICP-based slurry

Sporosarcina pasteurii (Miquel) Yoon et al. ATCC®11859™ obtained from American Type Culture Collection (ATCC) was revived using NH4-YE medium containing 1 g/L ammonium sulfate and 2 g/L yeast extract in 0.13 M tris buffer (pH = 9) as recommended by ATCC. Synthetic media containing 1 g/L glucose, 1 g/L peptone, 5 g/L sodium chloride, 2 g/L monopotassium phosphate was added in 100 g of Lunar highland simulant (LHS-1) and supplemented with 1% guar gum (GG). The contents were mixed thoroughly and autoclaved at 121°C and 15 psi pressure for 30 min 3% urea, 10 mM $NiCl_2$, and 100 mM Calcium lactate were added into the mixture after autoclaving to prevent their degradation and mixed well. Approximately 30% (w/v) of bacterial culture with 0.8 O.D at 600 nm in NH4-YE liquid medium (pH = 7) was inoculated into the soil mixture, and the contents were mixed well to get a consistent slurry, as shown in Figure 2B. This MICP-based slurry was used to fill the holes, and semi-circular and V-shaped notches were made in the sintered bricks. Control fillers without bacteria and guar gum were also used to fill these cavities (n = 4). These bricks were incubated for 5 days at 32°C followed by drying in a hot air oven (BioBee, India) at 60°C. The dried bricks were then subjected to microstructure analysis through SEM imaging (Carl Zeiss AG - Ultra 55, Germany) and mechanical characterization, as described in the following sections.

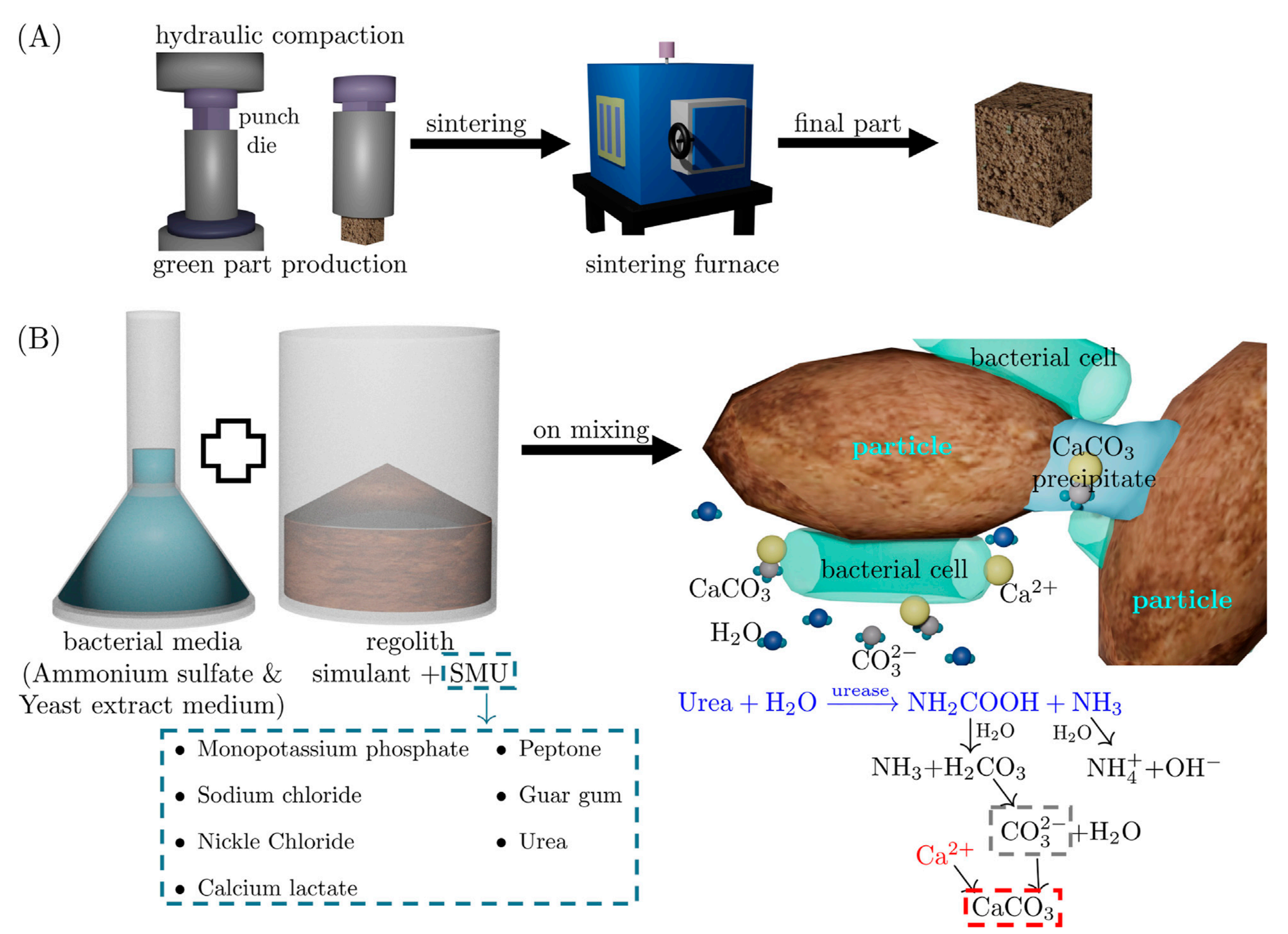

FIGURE 2
Schematic representation of the manufacturing process. Panel **(A)** illustrates the die compaction of guar gum (GG) mixed with Lunar Highland Simulant (LHS-1), which is hydraulically compacted at a load of 10 tons, followed by sintering in a muffle furnace for 4 h at 1200°C. Panel **(B)** depicts the process of MICP and the subsequent formation of bacteria-mediated $CaCO_3$ precipitate.

2.4 Post processing characterization

The integrity of the consolidated bricks was assessed by measuring the unconfined compressive strength (UCS) according to ASTM C109 standards under quasi-static conditions on a Universal Testing Machine (UTM) (Instron 5,697), employing a load cell capacity of 30 kN. The specimen dimensions were kept smaller than ASTM standards because of practical constraints. Compression tests were carried out for the control samples (sintered samples without holes and notches), and GMBs (with holes and notches), and the samples were repaired using MICP (as filler material). Cubical samples of dimension 15 mm ± 1 mm were used to test the filler material. Additionally, to measure the tensile and bending properties of the sintered bricks, a Brazilian disc test was performed as per ASTM D3967 standard, and a sintered beam was subjected to a three-point loading, respectively, on UTM. The load cell capacity was 2 kN and a 0.5 mm/min loading rate. The strength was calculated as averages from a minimum of four samples, accompanied by standard deviation as error bars. Furthermore, to get an insight into the mechanical behavior of bricks under the sudden impact, the compression test was conducted at three different loading rates: 0.5, 5, and 50 mm/min.

Furthermore, Digital Image Correlation (DIC) was performed on the samples to monitor crack propagation during tensile testing and repairing-based analysis, using the Ncorr software package (Blaber et al., 2015), with MATLAB version 2021a. Image sequences for the DIC analysis were obtained using a Digital Single-Lens Reflex (DSLR) camera (Nikon-D850) at a frame rate of 30 frames per second.

3 Results

3.1 Mechanical properties of the sintered bricks

The mechanical properties of the bricks determine their strength and ability to withstand loads and stresses in construction applications. The tensile strength of the sintered bricks was measured indirectly from the Brazilian disc test, with the maximum load converted into tensile strength using $\sigma_t = 2P_{max}/\pi Dt$, where P_{max} represents the maximum load prior to failure, while D and t denote the diameter and thickness of the specimen, respectively. Similarly, the flexural strength (σ_f) was

TABLE 1 Mechanical properties of sintered bricks.

Mechanical property	Strength (MPa)
Compressive strength (σ_c)	50.7 ± 6.5
Tensile strength (σ_t)	5.9 ± 1.1
Flexural strength (σ_f)	10.8 ± 0.6

calculated as $3P_{max}l/2bd^2$, where l, b, and d refer to the sample's length, width, and height, respectively. The results from the compression testing of sintered cubical bricks, Brazilian disc test (tensile strength), and three-point bend test (flexural strength) of cuboidal sintered bricks are summarized in Table 1.

In addition to quantitative measurements, the failure modes and crack patterns observed during testing are illustrated in Figure 3. The blue arrows in the figure indicate primary crack propagation paths, highlighting the typical behavior of the bricks under applied loads. This information can help develop methods to engineer or steer crack paths.

The tests conducted at three different loading rates: 0.5, 5, and 50 mm/min showed no significant change in either compressive or tensile strength with these loading rates. As shown in Figure 4, both

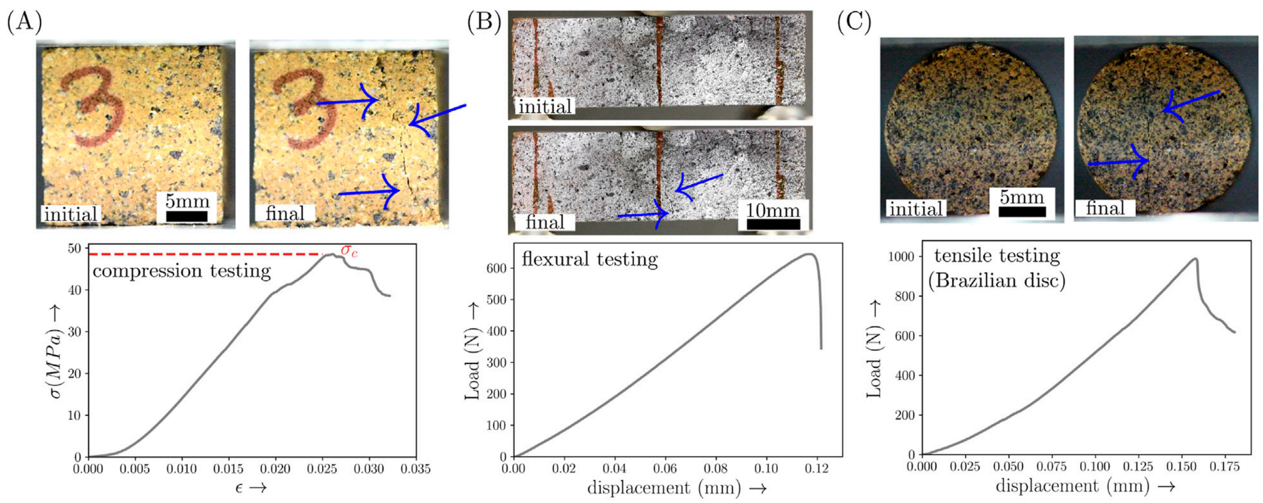

FIGURE 3
Failure modes of bricks under different loading conditions: **(A)** compressive loading, **(B)** three-point loading (flexural test), and **(C)** tensile loading (Brazilian disc configuration).

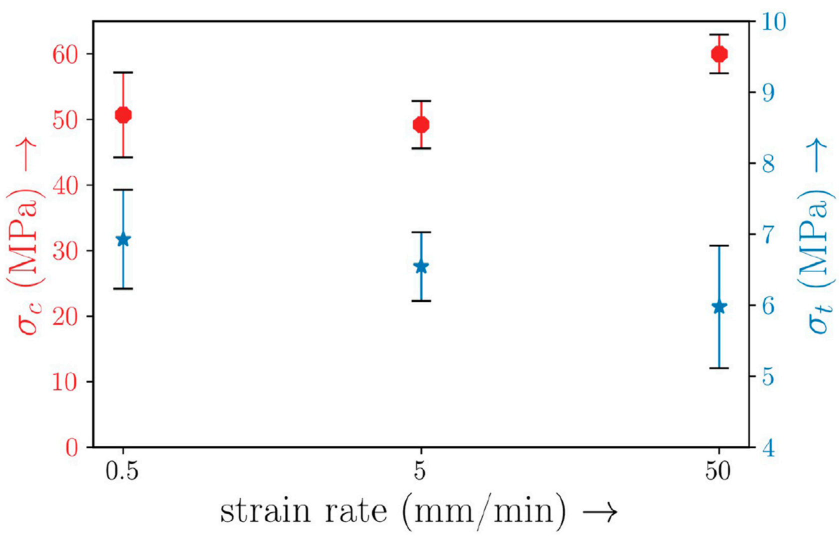

FIGURE 4
Compressive (blue) and tensile (red) strength of the sintered bricks under various strain rates (0.5, 5, and 50 mm/min). Strength values are averaged over four specimens, with standard deviation represented as error bars.

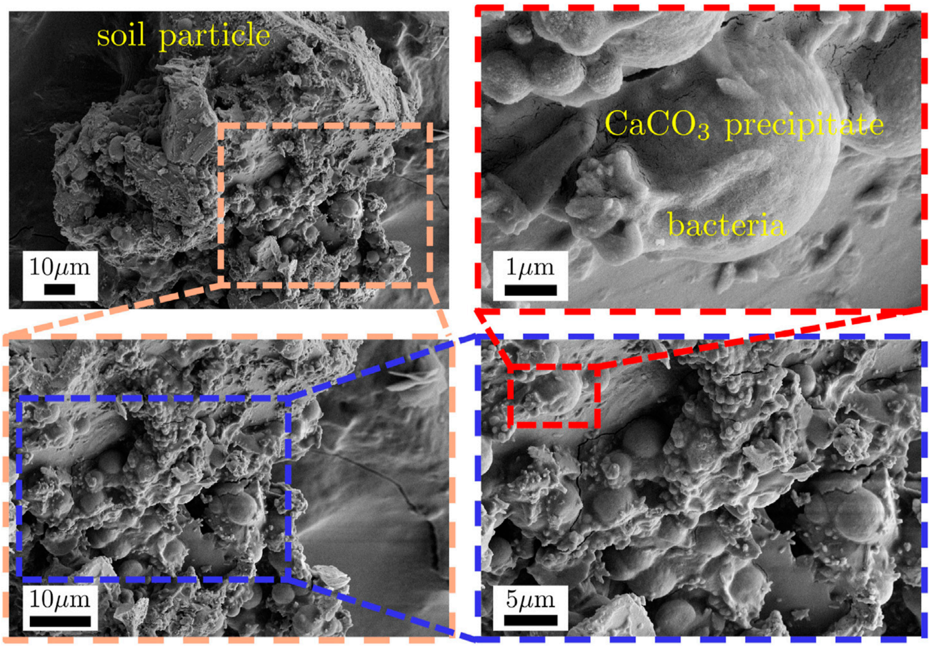

FIGURE 5
SEM micro-graph of bacteria-mediated $CaCO_3$ precipitation on the surface of soil particle.

compressive and tensile strength values remained relatively consistent across the different loading rates tested.

These results were used as a baseline to evaluate GMBs, which simulated damage. Compression tests on the GMBs revealed a significant reduction in strength. Figure 6D summarizes the results obtained from these tests. These results confirm that the GMBs that simulate damaged bricks are considerably weaker than the unaltered solid bricks, indicating the need for repair for prolonged use.

3.2 Brick repair using MICP-based slurry

Using lunar bricks for extraterrestrial construction requires them to withstand the impacts of meteors and other threats in these extreme environments. As a result, repairing them to restore their structural integrity and strength becomes crucial for building sustainable structures for long-term settlement. In this context, we used a MICP-based approach to repair the intentionally fractured bricks as described in Section 2.3. The details of these investigations are presented in this section.

3.2.1 Calcium carbonate precipitation in the soil particle

MICP exploits the natural processes of microorganisms to facilitate the precipitation of calcium carbonate, which can fill the damaged areas within the bricks. *Sporosarcina pasteurii* is a microbe very well known for its ability to precipitate calcium carbonate ($CaCO_3$) through the ureolytic pathway (Ghosh et al., 2019; Ma et al., 2020). The overall biochemical reactions involving ureolysis and the subsequent precipitation of calcium carbonate are shown in Figure 2B. The bacterium metabolizes urea to produce ammonia and raises the surrounding medium's pH, thereby shifting the equilibrium towards carbonate ion formation (Wu et al., 2021). In addition to the enzymatic activity, the bacterial cells also serve as nucleation sites, promoting calcite precipitation (Wang et al., 2024). The morphology of the calcite crystals and bacterial cells can be seen in the SEM micrographs, as illustrated in Figure 5, indicating successful biomineralization through the microbial process. We have previously presented a detailed analysis on calcium carbonate precipitation, including XRD and TGA analysis and polymorph characterization (Dikshit et al., 2022). However, we established that the fraction of polymorphs doesn't play any significant role in the overall strength of the consolidate (Dawara et al., 2022).

3.2.2 Mechanical characterization of bricks repaired using MICP-based slurry

With the aim of restoring the brick strength, the MICP-based slurry was filled into the central hole, the V-shaped and semi-circular notches. Previous studies from our lab have reported that MICP-based bricks made using LHS-1 show a compressive strength of ~5 MPa (Dikshit et al., 2021; Dikshit et al., 2022). The repaired GMBs with holes, semicircular notches, and V-shaped notches showed 28%, 14%, and 55% increases in their compressive strength, respectively, under the same loading conditions, as seen in Figure 6D. This indicates that the strength of the GMBs improves after repair, although it does not fully recover to the level of solid brick samples.

The observed increase in strength can be attributed to the mechanism of MICP, which facilitates calcium carbonate precipitation within the holes and notches. This process not only fills cavities but also reinforces the surrounding material through additional bonding. Indeed, previous studies have demonstrated

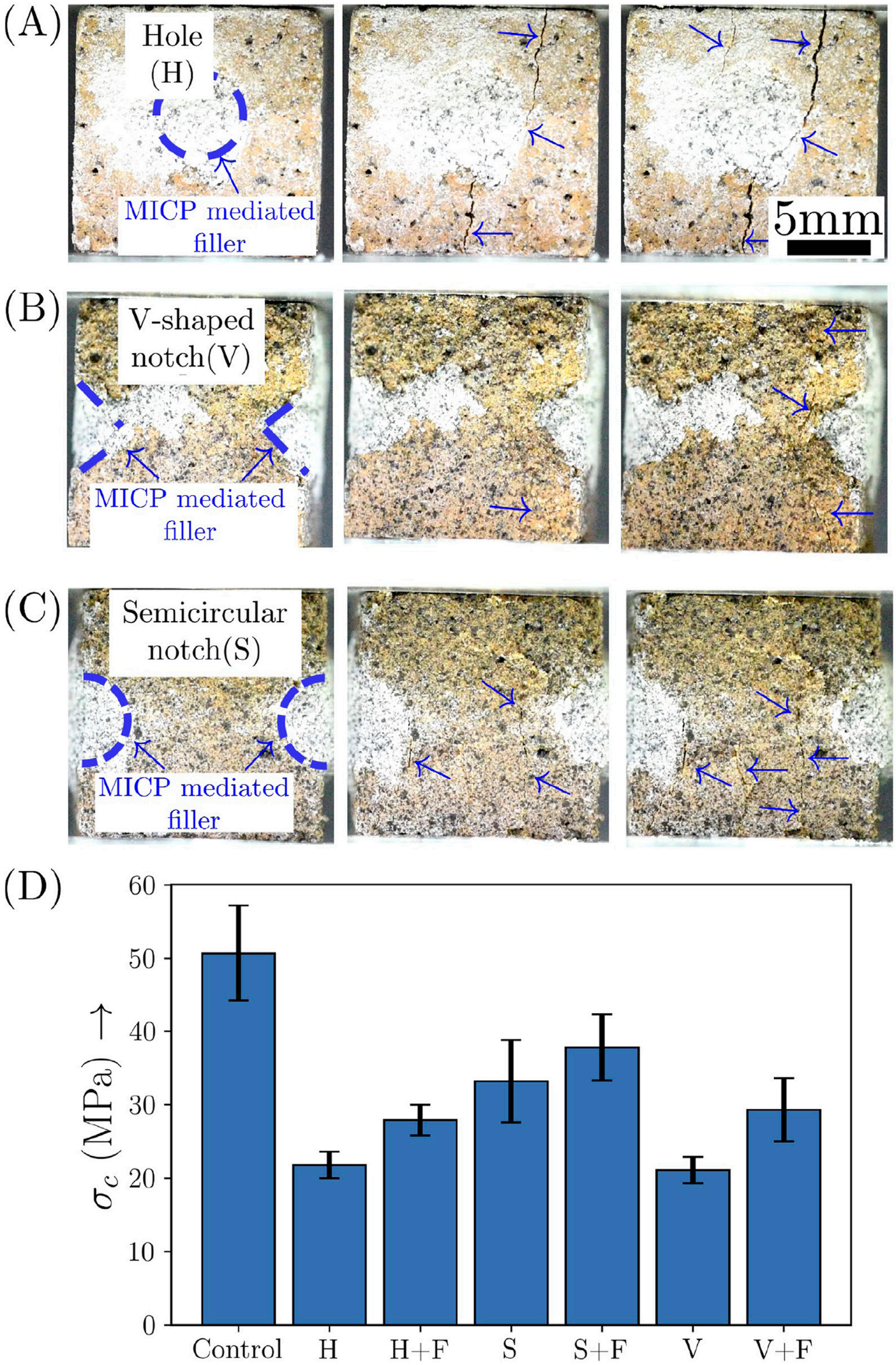

FIGURE 6
Failure patterns and crack paths in GMBs repaired with MICP-based slurry. Panels **(A–C)** illustrate the repaired GMBs with holes (H), V-shaped notches (V), and semi-circular notches (S). The three side-by-side frames represent initial loading conditions, intermediate stages showing crack propagation, and final failure stages. Panel **(D)** presents compressive strength measurements for bricks with and without filler conditions, averaged over four specimens with standard deviation indicated as error bars.

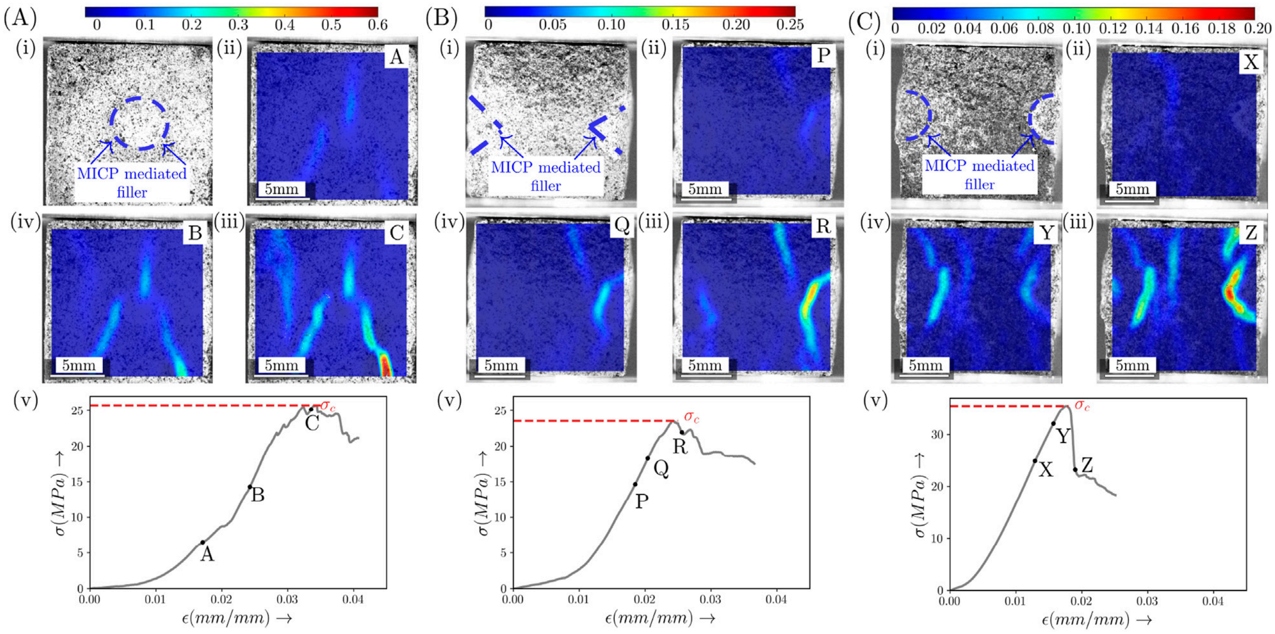

FIGURE 7
DIC analysis of the repaired GMBs. Panels **(A–C)** depict MICP filling in circular holes (H), V-shaped notches (V), and semi-circular notches (S) cavities of sintered brick specimens, respectively, under loading conditions. The (i) panels show brick under loading while (ii), (iii), and (iv) show the DIC color contours strains in x-direction (ϵ_{xx}). The (v) panels depict the stress-strain plots during compressive loading with points marking specific time points corresponding to crack sequences. The colored bar on top of the images represents the strain intensity spectrum.

that MICP effectively enhances mechanical properties by sealing cracks and reducing porosity, thereby improving overall durability (De Muynck et al., 2008; Zhang et al., 2023; Mu et al., 2021).

Further, to understand crack initiation and failure mechanisms in these bricks, videos were recorded during the strength tests. The image series showed that upon application of the MICP-mediated filler to the GMBs with a central hole and V-shaped notch, the cracks propagated through both the filler material interface and into the surrounding brick material rather than the interface between the two, as can be seen in Figures 6A, B. This indicates a strong interfacial bonding, increasing the overall strength of the bricks upon repair. Conversely, for semi-circular notches, initial cracks appeared near the notch; however, significant failure occurred at the center as loading increased (Figure 6C).

3.2.3 DIC for failure analysis

To identify the crack propagation path and to corroborate our observations, we performed Digital Image Correlation (DIC) analysis on the samples from the image sequences that we generated through the recorded videos. The results are presented in Figure 7, which show the crack initiation and propagation patterns within the repaired bricks. Cracks were initiated at locations of high-stress concentration for both fillers at central holes and V-shaped notches on the sides of bricks; however, for semi-circular notches at the sides, initial cracks appeared within the bulk material itself.

Additionally, to better understand how the filler influences the overall material performance, the interfacial bonding between the MICP filler and the sintered specimen was investigated through Scanning Electron Microscopy (SEM) analysis. As shown in Figure 8A, there is evidence of robust interfacial bonding, with insets highlighting detailed views of the interface. To support this, Figure 8B reveals instances where cracks penetrate and extend through the MICP interface. MICP can, therefore, serve as a viable solution for enhancing the durability and lifespan of these construction materials. However, instances of crack propagation through the repaired regions suggest the need for continued investigation into optimizing repair strategies to enhance the durability and performance of MICP-treated materials.

4 Discussion

This study highlights the potential of MICP as an effective method for repairing sintered bricks in extraterrestrial construction applications. The mechanical testing demonstrated that the formation of holes and notches in the bricks significantly reduced their compressive strength. However, the subsequent application of MICP-mediated slurry led to a notable strength recovery. This enhancement can be attributed to the precipitation of calcium carbonate, which not only fills the cavities but also reinforces the surrounding material through improved interfacial bonding. Research carried out with the consolidation of terrestrial soils via MICP by Dhami et al. (2016) shows the dependence of the strength on the grain size, and the larger grains show poor strength. In our previous work (Kumar et al., 2020), we characterized calcite precipitation using various calcium sources, such as calcium lactate, calcium acetate, calcium chloride, and calcium nitrate, among which calcium lactate showed the highest calcite precipitation, followed by calcium chloride. We have also demonstrated the effect of varying

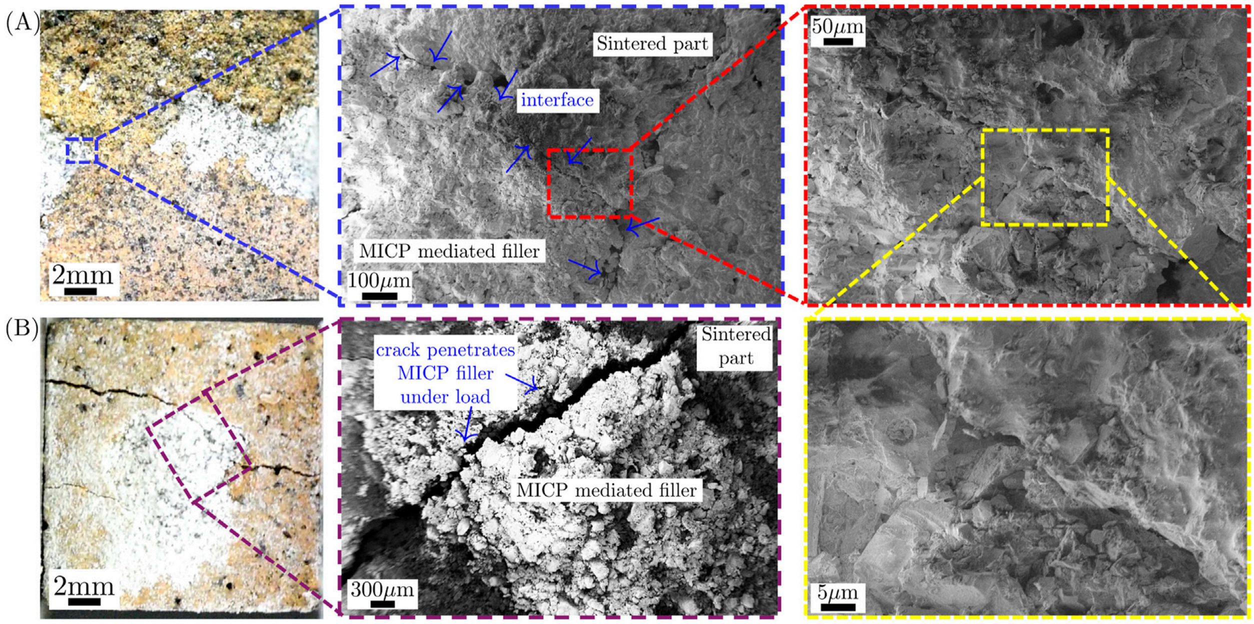

FIGURE 8
Interfacial bonding of MICP-mediated slurry with sintered parts. Panel **(A)** illustrates the bonding characteristics, with insets providing a magnified view of the interface. Panel **(B)** depicts instances where cracks penetrate and traverse the MICP interface. The first big brick image shown in both panels was taken with a DSLR camera and kept to show the location from where SEM micrographs were obtained.

the composition of urea, pH, temperature, and biopolymer content on the precipitation and, subsequently, on the compressive strength of the consolidates. Additionally, we demonstrated that using admixtures like guar gum and nickel chloride supplements enhances the binding properties and reduces the porosity (measured using micro-CT), which is one of the major parameters in governing the compressive strength of consolidate (Dawara et al., 2022). As opposed to this, the control filler samples without the bacteria and guar gum could only fill the cavities but not reinforce the strength.

However, the increased strength observed in the repaired bricks did not reach the levels of the unfractured bricks, indicating that MICP-based slurry can effectively extend the functional lifespan of damaged structures but not restore their strength. This is particularly relevant in construction applications where maintaining structural integrity is crucial. The ability to repair rather than replace damaged components aligns with sustainable practices, thereby reducing waste and minimizing resource consumption.

Additionally, SEM analysis provided valuable insights into the bonding mechanisms between the MICP filler and the sintered brick substrate. The strong interfacial bonding observed suggests that MICP can facilitate durable repairs. Nevertheless, instances of crack propagation through the MICP interface underscore the need for further investigation. Understanding these failure mechanisms is essential for optimizing repair strategies and enhancing overall material performance. At the same time, certain limitations of MICP through the ureolysis pathway, such as the release of ammonia, raising environmental concerns, and the sensitivity of the process to temperature, pH, aeration, and nutrient availability, leading to variability in compressive strength need to be addressed for the successful implementation of the process for space brick repair. One solution could be to co-culture with ammonia utilizing microbes to mitigate the ammonia released.

Future studies should consider the long-term durability of MICP repairs under varying environmental conditions, including moisture exposure, high strain rate loading, vacuum, radiation exposure, and temperature fluctuations. In our recent trials, we have exposed that consolidated material to different temperatures ranging from 100°C to 175°C. It produces the same strength, which implies that once the bonding is complete, the lunar surface temperature does not alter the strength. Investigating these factors will yield a comprehensive understanding of how MICP-mediated repairs perform over time, ultimately informing best practices for their application in real-world scenarios. Such research will be critical for advancing sustainable construction techniques, particularly in extraterrestrial environments where resource availability is limited and structural resilience is paramount.

5 Conclusion

This study demonstrates the feasibility and effectiveness of using MICP to repair sintered lunar bricks. The systematic approach employed revealed that while initial damage significantly compromised the bricks' mechanical properties, subsequent repair using MICP-based slurry resulted in a meaningful recovery of their compressive strength (about 28%–55%).

The findings highlight the potential of MICP as a sustainable solution for extending the service life of construction materials, aligning with contemporary efforts to enhance material resilience and reduce environmental impact. The strong interfacial bonding observed through SEM analysis further supports the viability of this method; however, challenges related to crack propagation through repaired areas warrant additional research.

Overall, this investigation contributes valuable insights into innovative repair techniques for extraterrestrial construction materials, emphasizing the importance of integrating biological processes. Future work should focus on optimizing MICP applications and exploring their effectiveness across diverse environmental conditions to realize their full potential in practical applications.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

NG: Data curation, Investigation, Methodology, Writing–original draft. RK: Data curation, Investigation, Methodology, Writing–original draft. AN: Data curation, Investigation, Methodology, Writing–original draft. KV: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing–original draft. AK: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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