Journal of the Civil Engineering Forum, January 2024, 10(1):31-38
DOI 10.22146/jcef.6454
Available Online at https://jurnal.ugm.ac.id/jcef/issue/archive

Biomineralization Grouting for Beach Sand Cemented with MICP

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SUBMITTED 14 December 2022 **REVISED** 21 October 2023 **ACCEPTED** 02 November 2023

ABSTRACT Microbial-induced carbonate precipitation (MICP) is an environmentally friendly approach that relies on the production of calcium carbonate by microorganisms to construct or reinforce coastal structures. In order to address the disadvantages of current coastal countermeasures techniques, MICP is a cost-effective solution that can be used to repair and restore coastal habitats damaged by human activities. The resulting structures formed through MICP are strong and durable, providing long-term protection against erosion and flooding caused by storms or rising sea levels. Biominerals, including calcium carbonate or calcium phosphate, are used to create complex composites with organic molecules by combining the strength of inorganic materials with the versatility and biocompatibility of organic macromolecules. It is of the utmost importance to investigate the functionality of MICP and scale up its deployment in various fields in order to thoroughly assess the instrument's application. Coastal erosion has been a severe concern in archipelagic countries. Therefore, this study explored the Miyazaki coast in Japan and the Yogyakarta coastline in Indonesia to minimize coastal erosion using MICP. The bacteria found in Miyazaki (Sporosarcina species) and the Yogyakarta coast (Pseudoalteromonas tetradonis) were used in the experiment. As a result, the sample treated with a gradual injection of the cementation solution achieved about 6 MPa UCS after 21 days of treatment. The objective were investigated the potential biotreatment with original sand materials and to evaluate the long-term durability under saturated conditions. For these purposes, the MICP-treated sand columns were subjected to series of compression tests and wet-drying (WD) durability analysis.

KEYWORDS Coastal; Erosion; MICP; Biomineral; Durability

1 INTRODUCTION

Erosion of sandy beaches is a widely recognized problem not only in Japan but also in Indonesia, characterized as an archipelagic country. Over the years, this erosion has led to the formation of beach cliffs, with the roots eroded by relentless waves. This virtuous circle of beach cliffs collapsed, and the retreat became more serious. As beach recedes, it loses the ability to protect the hinterland from disasters including storm surges and waves. In addition, erosion of the coastal cliffs is common in construction facilities such as toll roads in Miyazaki, Japan, and ports in Yogyakarta, Indonesia, showing the need for countermeasures. This problem is reportedly affecting approximately 75% of the global shorelines (Pilkey and Cooper, 2014; Rangel-Buitrago et al., 2018). An additional 2 billion people worldwide are expected to be living in coastal regions in the next 30 years, possibly peaking at 11 billion in 2100. This substantial increase implies that about 1 billion people in low-lying coastal cities will face escalating risks from climate-induced hazards by mid-century (Adger et al., 2005; United Nations, 2022; Pörtner et al., 2023). Furthermore, coastal zone monitoring based on aerial data, satellite, or field investigation is an important task in environmental protection and fundamental coastal management.

Sand pack construction method (Figure 1) offers an effective means of preventing or suppressing the receding of coastal cliffs by putting sand in a large fiber bag, burying it under, and nourishing beach behind. This method ensures that nourishment does not recede even in the face of a typhoon. However, a significant challenge arises from the

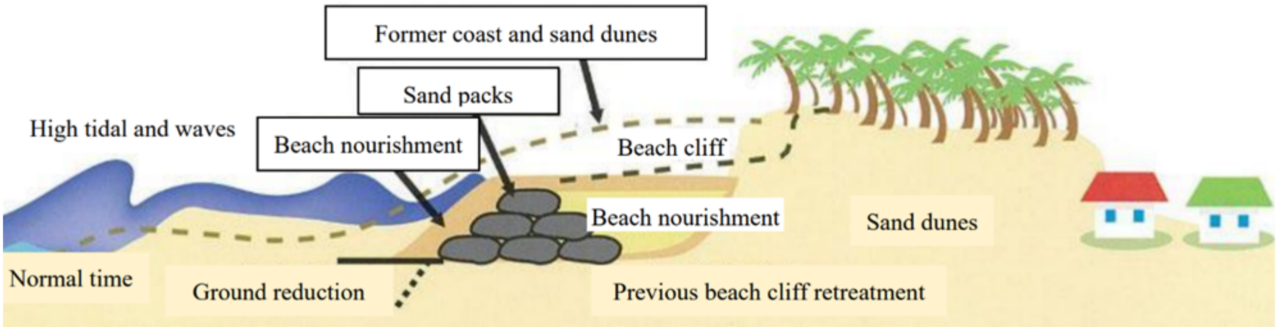

Figure 1 Sand packs method illustration

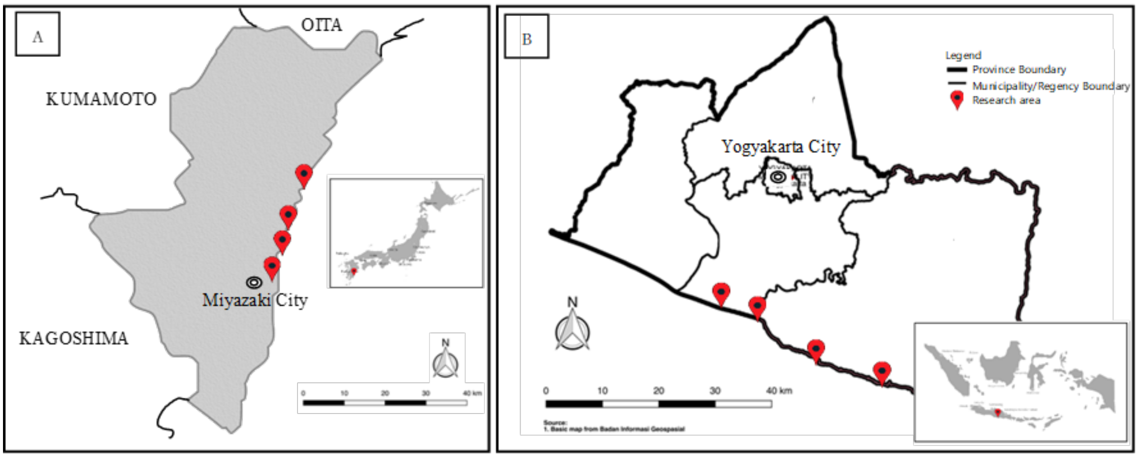

Figure 2 (A) Location map of Miyazaki in Japan and (B) Location map of Yogyakarta, Indonesia

potential damage to sandbag due to the outflow of beach nourishment embankment resulting from continuous storms/typhoons. To address this, several measures have been implemented, specifically in Miyazaki Japan, such as adopting a method that does not easily damage the seams of the bag material. By strengthening the above measures, a more effective strategy can be developed for preventing the receding of cliffs in the future. A promising green method based on recent studies is MICP (microbial-induced carbonate precipitation). MICP is a relatively innovative technique developed through biological processes, in which the production of calcium carbonate bio-cement relies on the performance of microbial urease (DeJong et al., 2010; e Portugal et al., 2020). The bacteria-origin enzyme catalyzes the hydrolysis of urea into ammonium ions and carbonates Eq. (1), which precipitates in the presence of calcium ions Eq. (2). This process forms connections between soil particles, increasing the overall shear strength.

This study aimed to investigate the feasibility of biocement treatment using original sand materials and evaluate the long-term durability under saturated conditions. For these purposes, MICP-treated sand columns were subjected to a series of compression tests and wet-drying (WD) durability analyses. The observations were conducted in Miyazaki and Yogyakarta shoreline (Figure 2) with the indigenous strain of isolated bacteria from the local sediment.

$$\mathrm{CO(NH_2)_2} + 2H_2O \xrightarrow{\text{Urease}} \mathrm{2NH_4^+} + \mathrm{CO_3^{2-}} \tag{1}$$

$$\mathrm{CO_3^{2-}} + \mathrm{Ca^{2+}} \xrightarrow{\text{(Bacterial cell)}} \text{Cell-CaCO}_3 \tag{2}$$

2 MATERIALS AND METHODS

2.1 Characteristics of soil

The particle distribution of local beach sands used in the experiments is shown in Figure 3. The local beach sand was uniformly graded with a mean particle size of 0.9 mm for Yogyakarta coral and 0.6 mm for fine sand. On the other hand, Miyazaki Bay

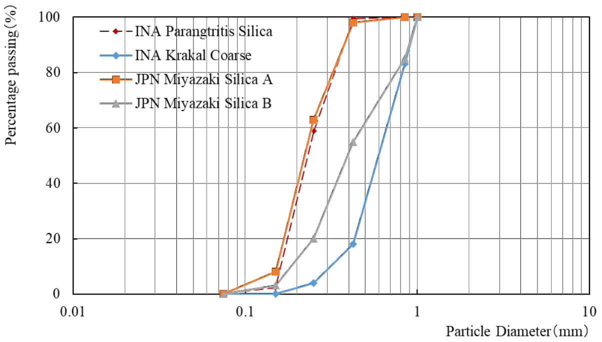

Figure 3 Particle size distribution of local beach sand from Miyazaki Bay, Japan, and Yogyakarta coast, Indonesia

consisted of particles sized 0.9 mm for fresh silica sand A and 0.7 mm for B. Sand was sterilized, and hand packed into a 50-mL syringe (mean diameter, D_{50} = 3 cm and height, h = 10 cm). The investigation of Yogyakarta beach sediment and the detailed characteristics of sand followed the methodology outlined in a previous study (Daryono et al., 2020*b*).

2.2 Isolation and Characteristics of Bacteria

The ureolytic bacteria used in this study were Sporosarcina sp. and Psedoalteromonas tetradonis. Sporosarcina sp., a motile rod-shaped Gram-positive species (1.3–4.0 µm long; 0.5–1.2 µm in diameter), was isolated from Miyazaki. Meanwhile, Psedoalteromonas tetradonis from Yogyakarta coast is gram-negative, strictly aerobic, motile with one polar flagellum, rod-shaped, and 0.5–0.8×1.0–1.5 µm when in the exponential growth phase. A detailed isolation process had been described thoroughly in a previous study (Gowthaman et al., 2020; Daryono et al., 2020*b*).

2.3 MICP Treatment

The barrel part of a 50 mL disposable syringe (30 mm in diameter) was used as the mold to shape and compact sand into columns. For each specimen, 60 g of local sand was added. To prevent sand from being washed out during treatment, the bottom of the barrel was lined with a filter paper piece before filling the mold. Similarly, a filter was used to reduce the adverse effect of large organic particles in the nutrient broth on carbonate precipitation. The two-phase injection strategy adopted in this study was in accordance with a previous study (Gowthaman et al., 2020; Daryono et al., 2020*a*).

The two-week treatment could be considered as two cycles of injection, initiated by 12 mL injection of bacteria culture solution (OD_{600} = 1.5–2) on the first day followed by a one-week treatment with 12 mL of cementation solution every 24 h.

2.4 Evaluation Methods

2.4.1 Unconfined Compression Test

The cementation strength of the specimens was examined using a needle penetration device/soft rock penetrometer (SH-70, Maruto Testing Machine Company, Tokyo, Japan). This device was developed in Japan for predicting UCS of soft, weak, to very weak rocks and cemented soil specimens. The specimen was horizontally positioned, and the needle of the device penetrated the cylindrical surface at three locations (at the distance of 1 cm (top), 3 cm (middle), and 5 cm (bottom) measured from the column top). The penetration resistance (N) and depth (mm) were measured simultaneously (Supplement A).

2.4.2 Effect of wetting and drying (WD) cycles on the durability

WD cycles were performed in accordance with the method suggested in ASTM (2003). Each cycle consisted of immersing the specimens in room-temperature water (25 ± 1 °C) for 6 h, followed by a minimum of 42 h oven drying at 70 ± 1 °C. Specimens were subjected to a total number of 14 cycles. Finally, the dry mass was recorded to evaluate the amount lost.

3 RESULTS AND DISCUSSIONS

3.1 MICP on Local Beach Sand

The reactant and the bacteria cell concentration were two primary factors that influenced the degree and the homogeneity of strength increment throughout the treatment depth. The local strength of sand specimens was subjected to treatment conditions considering these two parameters as shown in Figure 4.

The cementation reagent used contained equimolar concentrations of urea and $CaCl_2$, consistent with Daryono et al. (2020*b*,*a*). When two sam-

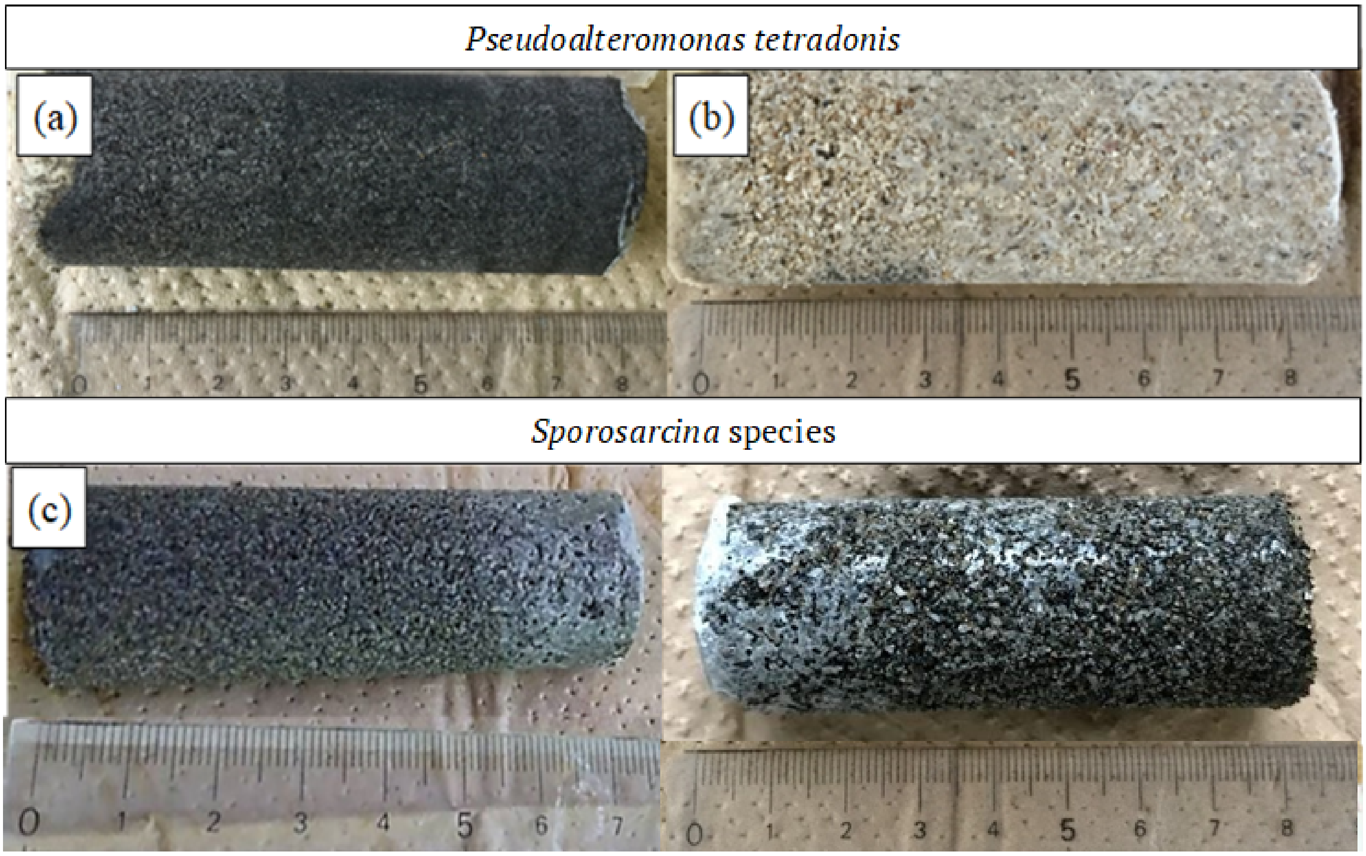

Figure 4 (a) Solidified sample with fine silica sand Yogyakarta, (b) solidified sample with coral Yogyakarta sand, (c) solidified sample with Miyazaki silica A sand and (d) Miyazaki silica B

ples injected with 0.5 M cementation solution were considered, it was clear that the specimen with bacteria injected twice showed significantly greater strength compared to the specimen injected only once (at the beginning). According to previous reports, it was deduced that higher concentrations of bacteria populations enhanced the amount of $CaCO_3$ precipitate and, ultimately the results of MICP treatment.

To study the effect of the initial concentration of resources, beach sand was subjected to preliminary MICP treatment. As shown in Figure 4, significant improvements were observed, resulting in an estimated UCS of approximately 16 MPa. This estimation was based on the needle penetration test, with a maximum load of 100 N, and the results were subsequently validated through the uniaxial compression test (Supplement A). To further confirm the strength, an axial UCS test based on a 400 N load was conducted for the material after treatment with MICP (Figure 5).

Due to the very small particle size, the penetration rate of cementation media was low compared

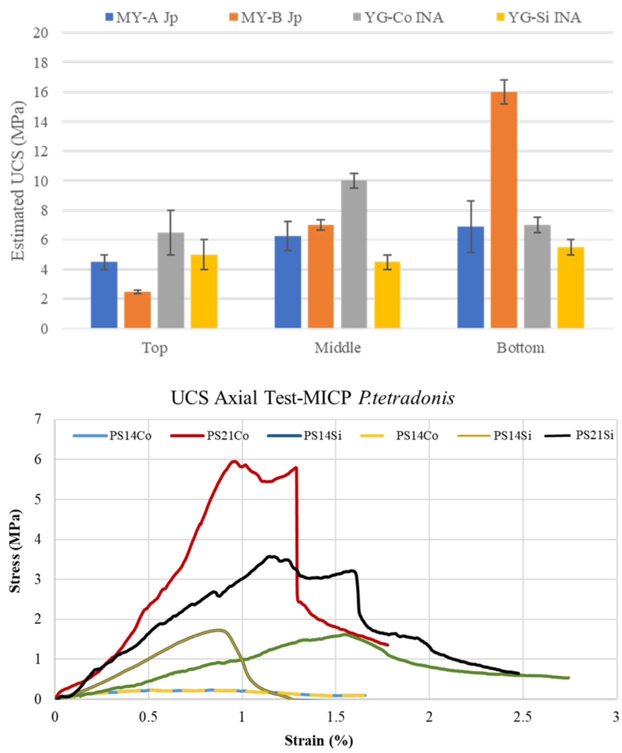

Figure 5 (Above) Estimated UCS based on Needle Penetration Test and (Below) UCS test with 400N load under Pseudoalteromonas tetradonis solidification with local Indonesia beach sand

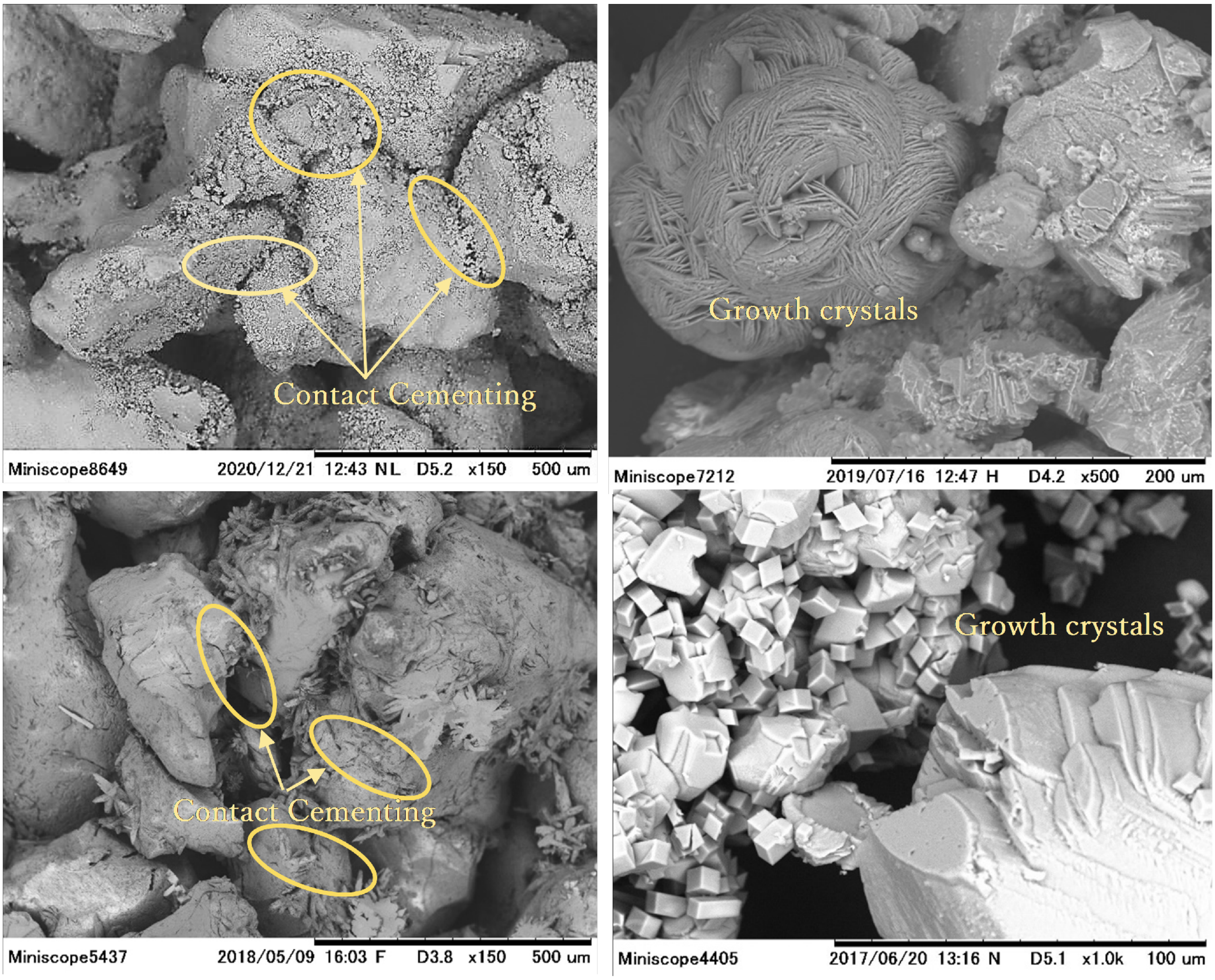

Figure 6 SEM images of treated sand with MICP

to coral sand samples. This factor could lead to a reduction in the bacteria process and a slower hydrolysis. Consequently, $CaCO_3$ precipitation decreased and UCS value was lower in the fine sand compared to coral or glass bead samples. This showed that the particle size was mainly affected by the solidification of the sample. Based on the results, strength enhancement achieved through MICP process was primarily influenced by the presence of calcium chloride.

3.2 Microscale Properties of MICP-Treated Sand

The SEM images of uniformly graded sands are shown in Figure 6, demonstrating that the calcium carbonate preferentially precipitated at particle contacts, a phenomenon known as contact cementing. Generally, bacteria cells prefer to position themselves in smaller surface features such as near particle-particle contacts compared to the surface due to the reduced shear and a higher availability of nutrients (DeJong et al., 2010). Furthermore, the matrix support, namely growth from particle surface into pore space to create bridges between particles, was barely observed in sands treated by percolation in this study. As the particle size of sand reduced from 1.6 mm to 0.2 mm, the SEM images showed an increase in precipitated carbonate content. Due to the high retention of bacteria cells and less permeability, the crystallization was higher in coarse compared to silica sand.

The applications of MICP on very fine soils are

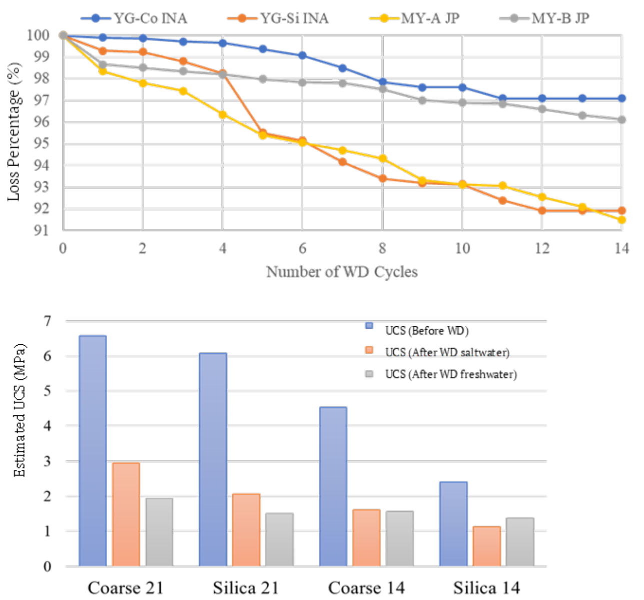

Figure 7 (Above) Average mass loss of the specimens subjected to WD cyclic treatments and (Below) The variation of estimated UCS before and after the exposure of cyclic WD tests

typically limited due to the restricted rate of permeability, which often results in prolonged infiltration times for the reactants (Mortensen et al., 2011). The free passage of the bacteria might be also inhibited due to the small pore throat size of fine soils (Cheng et al., 2017). However, the presence of a certain quantity of fine particles may enhance MICP responses compared to gravel-sand mixtures, which are not stabilized under MICP processes (Kalkan, 2020; Mortensen et al., 2011; Feng et al., 2017).

3.3 Cyclic WD analysis

The physical damage during cyclic tests was evaluated by the mass loss of the specimens, which was carefully measured after every cycle, and no structural damages or considerable changes in temperature were observed. Figure 7 shows the cumulative mass loss of the specimens with the increasing number of WD cycles. The results s that the specimens experienced an average mass loss ranging between 3 to 9 % by the end of 14 cycles. This was consistent with the mass loss reported for phosphate cement specimens under similar WD actions (Gowthaman et al., 2022).

The level of cementation appeared to have influenced the rate of mass loss. After the 14 WD cycles, mass loss of the silica sand specimens amounted to 9%, similar to the fresh beach sand from Miyazaki (JPN Miyazaki Silica A). This suggests that the varying cementation level can either increase or decrease the resistance to aggregate loss. As the crystallization process had already begun during the percolation phase (Whiffin et al., 2007), not all the precipitated carbonates contributed to the contact cementation. A considerable quantity would either crystallize randomly on the soil grains or set on the already formed bridges. It was observed that the physical and mechanical behaviors were significantly influenced by WD cycles. Both mass loss results showed a deterioration in the performance of specimens. The short-term deterioration mechanism could be explained by the evolution of calcium carbonate precipitates during MICP process. The calcium carbonates were initially induced as irregular precipitates (non-crystalline), continued to grow with time, and transformed subsequently into regular crystals (calcites) in the aqueous media. The induced non-crystalline precipitates tend to stabilize on soil surfaces before transforming to crystalline structures. Figure 8 is representative of bacteria strain in this research trendlines with the previous researcher using the common MICP bacteria, Sporosarcina species.

Following the first cycle, mass loss tended to become relatively stable (in another 3–4 cycles), suggesting that the powdery deposits had been totally eroded. WD degradation mechanisms were proposed for geomaterials such as fracture energy reduction, capillary tension decrease, chemical and corrosive deterioration, frictional reduction, etc (Zhao et al., 2017). The short-term deterioration mechanism of MICP-treated soils is more likely to be comparable with carbonate rocks. Ciantia et al. (2015) found the occurrence of instantaneous debonding of depositional bonds in carbonate rocks when subjected to saturation, and a single wetting process caused considerable loss in compressive strength. Ca^{2+} ions can bind more frequently onto the negatively charged cell surface of bacteria than Mg^{2+} due to the greater power for ionic selectivity. Subsequently, the bound cation (metal ions) reacts with anions (carbonate) to form calcium carbonate in an insoluble form. Bacteria cells are very important for the precipitation of $CaCO_3$, due to the ability to provide nucleation sites (heterogeneous nucleation) and affect the specific types of minerals formed (Anbu et al., 2016).

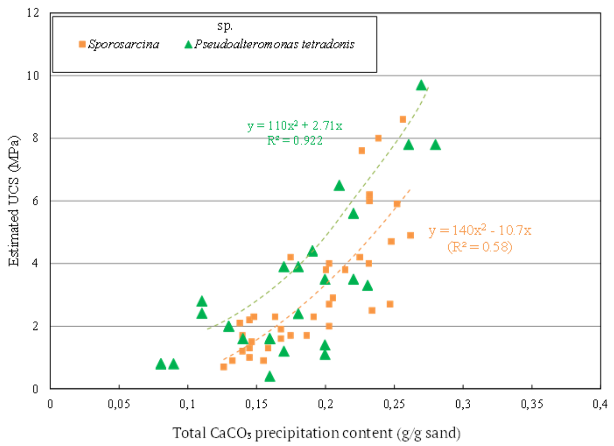

Figure 8 Relationship between estimated UCS versus calcium carbonate content of MICP comparing with previous study

Gowthaman et al. (2022) reported long-term deterioration after 50 WD cycles, where a substantial deformation resembling a cauliflower-like morphology was observed. Detailed analysis confirmed that this deformation did not occur within the matrix. The deformation might have possibly resulted from the development of internal stresses during the cyclic WD process as reported by Li et al. (2019). The difference in the thermal expansion coefficient of calcite and soil material could lead to the development of fatigue stresses during the cyclic WD process (due to temperature change), causing deformation in calcite crystals. Recently, Li et al. (2019) proposed a rotating soak method to promote the uniformity of cementation in specimens by facilitating more nutrition supply and air replenishment in the soil for effective bacteria performance. However, in field implementation, maintaining the saturated flow conditions during the treatment period would be challenging. This process requires hydraulic injection of cementation/biological solutions, extraction of effluent solution, and heavy machinery systems.

4 CONCLUSION

In conclusion, MICP-based bio-cementation was found as a promising alternative countermeasure for coastal erosion, achieving a compressive strength of approximately 6 MPa UCS after 21 days of treatment. As the number of WD cycles increased, the index properties showed that the specimens could withstand the brittleness of the material against physical fatigue stress, particularly in submerged saltwater conditions. This observation suggested that the cyclic WD effects mimicked the environmental stresses experienced over a 14-cycle seasonal year period. Based on the result, MICP biomineralization could improve the local beach cementation against the erosion process for up to 14 years.

DISCLAIMER

The authors declare no conflict of interest.

SUPPLEMENTARY MATERIALS

Supplement A. Needle Penetration Test

ACKNOWLEDGMENTS

The authors extend their heartfelt gratitude to all the individuals and entities involved in this collaborative research conducted between Hokkaido University and NITTOC Construction Ltd.

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