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Use of bio-cementation for prevention of coastal erosion against wave attacks

Utilisation de bio-cémentation pour la prévention de l'érosion côtière contre les attaques de vagues

Mohammad Abu Obeida & Mohamed A. Shahin
School of Civil and Mechanical Engineering, Curtin University, Australia, mohammad.abuobeida@hotmail.com

Liang Cheng
School of Environment and Safety Engineering, Jiangsu University, China

ABSTRACT: This paper investigates the use of "bio-cementation" via microbial-induced calcite precipitation (MICP) for prevention of coastal erosion of sandy slopes against wave attacks. Bio-cementation via MICP is an emerging and promising technology that proved to be efficient for stabilisation of sandy soils. It is a naturally driven biological technique that employs bacteria to hydrolyse urea, producing carbonate ions that react with a calcium-rich solution (calcium chloride) to produce calcium carbonate (calcite) which precipitates in the soil matrix and binds soil particles together, leading to improved soil strength. This presents an experimental laboratory approach that looked at the ability of MICP to prevent cross-shore erosion due to surging waves in shallow waters generated in a tilting acrylic flume apparatus, and the results showed that MICP was able to limit coastal erosion to around 11% and thus demonstrated the potential of this technology as a means to coastal protection and disaster mitigation in marine environments. Also, a new promising and innovative modification of MICP treatment was evaluated by exploring the viability of using seawater as a sole calcium source to replace commercial calcium chloride in producing calcium carbonate, leading to potential cost savings.

RÉSUMÉ: Cet article s'intéresse à la "bio-cimentation" par précipitation microbienne de calcite (MICP), une application qui a pour objectif la prévention de l'érosion côtière contre les attaques de vagues. La bio-cimentation via MICP est une technologie émergente et prometteuse qui s'est avérée efficace pour la stabilisation des sols sableux. C'est une technique naturelle qui utilise des bactéries hydrolysant l'urée et produisant des ions carbonate qui réagissent avec une solution riche en calcium (chlorure de calcium) pour produire du carbonate de calcium (calcite). La calcite ainsi produite précipite dans la matrice du sol et lie les particules du sol ensemble, conduisant à une meilleure cohésion. Ce papier présente une approche de expérimentale permettant d'examiner la capacité du MICP à prévenir l'érosion transfrontière due aux vagues déferlantes dans les eaux peu profondes générées dans un appareil à canal acrylique inclinable, et les résultats ont montré que le MICP était capable de limiter l'érosion côtière à environ 11%. Cette technologie a le potentiel d'être utilisée comme moyen de protection côtière et d'atténuation des catastrophes dans les environnements marins. En outre, une nouvelle modification prometteuse et innovante du traitement MICP a été évaluée en explorant la viabilité de l'utilisation de l'eau de mer comme seule source de calcium pour remplacer le chlorure de calcium commercial dans la production de carbonate de calcium, conduisant à des traitements plus économiques.

KEYWORDS: Bio-cementation, microbial-induced calcite precipitation, soil stabilisation, coastal erosion, wave attack.

1 INTRODUCTION

Coastal erosion is a global problem that has drastic impacts on beaches and coastal regions across the globe. This issue is exacerbated by the sea-level rise due to climate change, often causing the damage to key infrastructure and ecosystems. Sea level rise alters the location of the coastline, moving it landward along contours that are low lying, therefore exposing new areas and landform to erosion (Committee on Mitigating Shore Erosion along Sheltered 2007). A study by The Climate Council (2014) found that on average, for every metre of sea-level rise, sandy shorelines recede by 50-100 metres. According to the Australian Bureau of Statistics (2001), it was found that more than 85% of Australians live within 50 kilometres of the coastline of Australia. Moreover, more than half of Australia's coastline, approximately 31,000 km, is potentially vulnerable to recession (The Climate Council 2014). Such numbers and vulnerability call for means to mitigate and control coastal erosion.

The current mitigation strategy implemented to prevent coastal erosion includes the use of hard engineering techniques such as seawalls and groynes. Although these techniques may be effective in preventing coastal erosion, they are often non-environmentally friendly, costly and make the beach aesthetically unpleasing (Gracia et al. 2018). Another strategy involves the use of soft engineering techniques such as beach nourishment, which can be environmentally friendly but require frequent maintenance. It is therefore evident that a more sustainable method of coastal erosion mitigation is essential to protect coastal regions.

The process of Microbially Induced Calcite Precipitation (MICP) is an emerging method of biological soil treatment that has recently undergone rapid development. This soil stabilisation technique involves the utilisation of urease-active bacteria to produce calcium carbonate, which binds the soil particles together, increasing the soil shear strength while retaining sufficient permeability (Bernardi et al. 2014; Achal and Mukherjee 2015). MICP has displayed potential for application as an effective mean for controlling coastal erosion in the marine environment (Salifu et al. 2016). Recent findings showed that MICP-treated soils showed greater resistance against erosional waves in the tilting flume than non-treated samples (Shahin et al. 2020). The traditional method of MICP involves the use of calcium chloride as the source of calcium ions, while recently alternative sources of calcium have been considered, including the use of calcium ions found in seawater (Cheng et al. 2014).

This paper aims to investigate the effectiveness of using seawater as a source of calcium ions in the process of MICP for coastal erosion protection. The paper further investigates the effectiveness of traditional MICP treatment when natural beach sand is used. The paper finally investigates how well the traditional methods of treatment, and the more recently emerging method of using seawater as a source of calcium ions in MICP, act as a means to prevent coastal erosion.

2 MATERIALS AND METHODS

2.1 *Beach sand*

Silica sand is often used in the literature for MICP, due to being readily available and closely resembling sandy soils of coastal regions (e.g. Cheng and Cord-Ruwisch 2012; and Cheng and Shahin 2016). It is therefore apparent that further research is required using natural beach sand, which would further enhance the ability of MICP to be feasible for field-scale application of coastal erosion protection. In this study, both silica sand and beach sand from Western Australia were used. The grain size distributions of the sand used were identified through sieve analyses conducted in accordance with Australian Standards AS1289.3.6.1 (2009). Figure 1 displays the particle size distribution curves of the sand used, classified as SP (poorly graded sand).

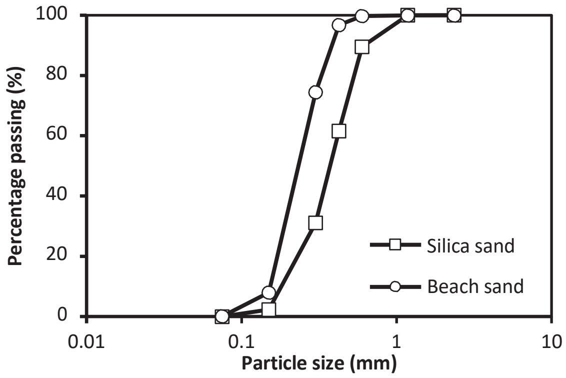

Figure 1. The particle size distribution of silica sand and beach sand.

2.2 *Bacterial culture, seawater and traditional cementation solutions*

The urease active bacteria used in the current study were *Bacillus sp*. DSM 23526, which has been demonstrated to survive and flourish in a high salinity environment (Cheng et al. 2014). The bacteria were cultivated in a sterile aerobic batch growth medium consisting of 20 g/L yeast extract, 18 g/L of ammonium sulfate and 0.1 mmol/L $NiCl_2$, at a pH value of 9.25. The bacteria were then inoculated by adding 1% (v/v) of the pure stain inoculums into the conical flasks containing the growth medium, which were consequently placed in a water bath shaker set to 30 ^oC for 48-72 hours. The optical density (OD_{600}) of collected bacterial culture varied between 2 and 2.5 and the urease activity was approximately 10 U/mL (1 U = 1 mol urea hydrolyzed per minute).

The seawater cementation solution utilised in this study comprised of natural seawater obtained from Coogee Beach in Cockburn Western Australia, which was mixed with urea to obtain a 60 mM and 120 mM urea concentration in solution. Traditional cementation solution was also utilised and comprised of calcium chloride and urea, which made-up 1 M cementation solution. Testing involving traditional cementation solution was used to compare results obtained from beach sand with that of silica sand from previous studies on the use of MICP as a coastal erosion mitigation strategy.

2.3 *Preparation of sand samples*

2.3.1 *Beach profile mould*

The profile mould utilised for the placement of sand profiles in this work was similar to that used previously in studies undertaken by Shahin et al. (2020). The profile mould comprises square, clear acrylic walls of 200 mm dimensions displayed in Figure 2. Clear acrylic walls allow for the ability to view the sand's reaction when tested against erosion.

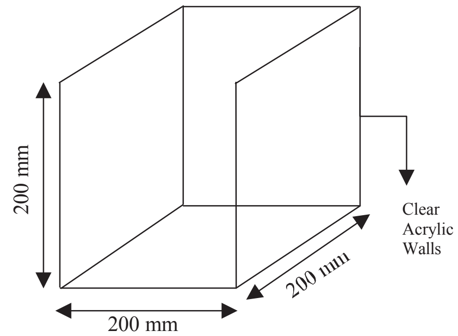

Figure 2. Soil profile mould dimensions.

2.3.2 *Bio-cementation soil treatment*

With the assembly of the soil profile mould comprising clear acrylic walls, the sand had liquid reagents (bacteria and cementation solution or seawater) added to ensure it was at the optimum moisture content found from the Standard Proctor Compaction Test. Following the procedure undertaken by Shahin et al. (2020), the sand was filled in the mould in five lifts, with each lift compacting the soil to 95% of its maximum dry density. The slope angle chosen for the soil profile was 30 degrees. Following the compaction of the sand in equal layers, the surface was cut to 30 degrees, as such a slope angle represents the maximum angle of repose when the soil used was saturated. Thus, with the use of seawater cementation solution and by immersing of the sand mould in the cementation solution, it was deduced that a 30-degree slope angle was the most appropriate slope angle for the case of this research.

The first method of treatment conducted on Sample S1 for both beach sand and silica sand was premixing method, whereby the bacteria and traditional cementation solution were added into the soil through mixing. The bacteria were mixed into the bulk of the soil, using natural beach sand or silica sand. The cementation solution contained 1M calcium chloride and 1 urea. The sample was left to cure in the open air for two weeks before being tested for erosion in the tilting flume.

The second method for Sample S2 involved the use of beach sand to create 2 cm thick calcite crust on top of the sand profile through the use of the spraying method. The MICP treatment comprised of 210 ml of 1 M cementation solution and 70 ml of bacteria. The bacteria were initially sprayed onto the sand surface and allowed to settle before the cementation solution comprised of 1 M calcium chloride and 1 M urea, which was subsequently sprayed onto the surface. The sample was left to cure in the open air for two weeks before testing for erosion in the tilting flume.

The third method of treatment for Samples S3 and S4 involved the use of seawater as the only calcium source. During the treatment, the bacteria were mixed with 50 mM of calcium chloride to produce bio-flocculants which could be retained well in sand. The bacteria culture was subsequently added to the beach sand and thoroughly mixed to achieve uniform calcite precipitation within the soil matrix. The sample was then assembled at 30-degree slope after being compacted to 95% of its maximum dry density. Bacteria were resprayed on the surface weekly for the duration of the curing. Moreover, the use of Geo-fabric was adopted before being placed in the seawater cementation solution. The beach sand was simply mixed with bacteria and the geo-fabric ensured that the slope was maintained before the urea reacting with the bacteria, and hence the sample gaining strength through forming calcite. The soil strength gain was evident through the formation of a crust on the surface of the samples, depicting that the samples were sufficiently strong and can sustain their slope without the use of geo-fabric. However, to ensure consistency and reduce disturbance to the samples, the geo-fabric was kept throughout the curing duration and was only removed once the curing period of 6-weeks was reached.

Considering the dimensions of the container, approximately 7.5L of seawater was mixed with 27 and 54 g of urea to obtain 60 and 120 mM urea concentrations, respectively. This concentration was deemed appropriate as it allowed for complete calcite precipitation due to the concentration of calcium and magnesium in seawater being approximately 10 and 50 mM, respectively. It was however found that by increasing the urea concentration from 100mM to 200mM the solid content of the precipitate doubles, hence, causing weight increase in the calcite precipitates. Therefore, Sample S3 was tested with 60 mM urea concentration and S4 with 120 mM urea concentration to determine the effect of doubling the urea concentration on the calcite precipitation and samples slope stability.

Sample S5 also involved the use of the spray method, where this sample was treated five times before testing for erosion in the tilting flume. The different samples and methods of treatment are displayed in Table 1.

Table 1. Different methods used for MICP treatment and curing periods.

Sample Number	Method of MICP Treatment	Curing Period	Urea [mM]
S1	Bacteria and cementation solution premixed into the beach sand	2 weeks	1000
S2	Use of spray method to spray bacteria and cementation solution onto the surface of the sample (one treatment)	2 weeks	1000
S3	Premixing beach sand with bacteria and immersing in seawater cementation solution, with weekly re-application of bacteria	6 weeks	60
S4	Premixing beach sand with bacteria and immersing in seawater cementation solution, with weekly re-application of bacteria	6 weeks	120
S5	Use of spray method to spray bacteria and cementation solution onto the surface of the sample (five treatments)	5 Days	1000

2.3.3 *Measurement of Calcium Carbonate*

The methodology used to determine the $CaCO_3$ content across the sand samples followed the same procedure used by Cheng et al. (2013). This method involves collecting 0.5–2 g dry sub-samples from different regions across the sample and adding 2ml of 2 M Hydrochloric acid. The reaction between $CaCO_3$ and HCl produces carbon dioxide, which is measured using a U-Tube manometer under standard conditions of 25°C and 101.325 kPa atm. The CO_2 is subsequently converted to $CaCO_3$ using a pre-determined linear relationship. Due to calcite being naturally present in beach sand, smaller quantities of 0.1–0.5 g of treated beach sand were used for calcite testing to ensure the accuracy of the results.

Calcite testing of seawater cured Samples S3 and S4 was limited to just the surface of the samples. The top crust of the slope was deemed as the more critical factor for erosion resistance of the seawater cured samples. Weekly bacteria reapplication was the key to ensure this was achieved, and as such the focus was to achieve the top layer resistance of the sample through calcite formation. Calcite testing was therefore performed on a thin layer of the crust obtained from both samples after the curing period was complete.

2.4 *Erosion testing*

2.4.1 *Wave testing parameters*

All samples were tested against erosional waves in the tilting flume shown in Figure 3. The speed of the rotating arm was adjusted to ensure that the required wave parameters were produced. The wave parameters have been adjusted to match breaking shallow-water waves. The height of the wave was equivalent to three-quarters of the water depth, i.e. height ≥ ¾ depth (The University of Hawaii 2018). A wave height of 4 cm was therefore adopted to produce a shallow water breaking wave. This was used as the basis to obtain the wave parameter for erosional waves; the wave height and depth were 4 cm and 5 cm, respectively. The wavelength was 2.5 m with a frequency of 3 seconds.

Figure 3. Tilting flume used for erosion testing.

2.4.2 *Testing methodology*

This marked the final stage by which each of the samples was placed in the tilting flume for testing against breaking shallow-water waves. The mass of the samples was measured before being placed in the tilting flume to record the initial mass and to allow for the measuring of the mass eroded in the flume. The samples were then left in the flume for 1-hour and photos were taken periodically to note the changes within the sand profile. Subsequently, the samples were then removed from the flume and left to drain for 24-hours before measuring their mass to determine the mass of sand eroded.

3 RESULTS AND DISCUSSION

3.1 *Beach sand cementation against erosion*

Sample S1 (for both silica sand and beach sand) was treated with a single premixing treatment, where the bacteria and traditional cementation solution were premixed into the soil matrix. Through the calcite testing, it was proven that this method of treatment produced uniform calcite throughout the soil matrix. Sample S1 displayed signs of strength and improvement through the hardening of the surface and overall soil matrix. Figure 4 shows the results of the erosion testing conducted for the full 1-hour, and the change in mass was equivalent to only 17.5% erosion for the beach sand and 14.5% erosion for the silica sand. This portrays that the method of premixing has been effective in minimising erosion in both natural beach sand and silica sand.

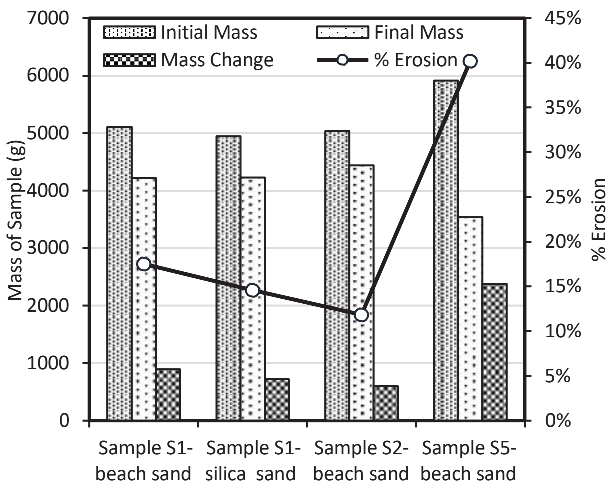

Figure 4. Erosion test results of beach sand and silica sand treated with MICP using cementation solution.

For silica sand, the change in mass was calculated as 15%, indicating that only a small proportion of sand was lost due to erosion. It is clear from Figure 5 that the slope profile of S1-silica sand after testing has not collapsed seriously. The surface profile after erosion testing indicates a relatively good distribution of calcite throughout the sand sample. There were, however, small areas with minimal or no calcite as the sand in these areas was removed during testing, leaving isolated areas of voids which are highlighted in Figure 5. Previous MICP research carried out by Shahin et al. (2020) found that internal erosion was the major problem when MICP was only applied to the soil surface. This was due to swash water travelling between the sides of the profile mould and sand slope, washing out the untreated sand underneath the bio-cemented layer. This phenomenon was not observed for natural sand, as indicated in Figure 5, which displays profiles of erosion for Samples S1-beach sand and S1-silica sand before and after the wave attack. Although calcite uniformity was achieved, it is evident that a greater amount of bacteria and cementation solution is required to achieve greater resistance against erosion, when the method of premixing is used on natural beach sand.

3.2 *Premixing vs surface treatment*

As seen previously in Figure 4, Sample S1-beach sand (premixing) displayed a weaker resistance to erosion compared to Sample S2-beach sand (surface spraying). As shown in Figure 5, erosion testing in the flume displayed that the slope of S1-beach sand displayed lower resistance compared to S2-beach sand). This was particularly evident during the first 10-minutes of testing and is because S2-beach sand had a higher quantity of bacteria and cementation solution applied to just the surface compared to S1-beach sand, showing greater signs of strength during the testing.

Figures 6 and 7 display the side profile of Sample S2-beach sand throughout the erosion testing. Although Sample S2 only had a single MICP treatment, the long curing period allowed for greater calcite precipitation between the sand particles. The maximum quantity of calcite was able to be achieved given the greater curing timeframe. This was reflected through the behaviour of Sample S2-beach sand against erosional waves. Furthermore, with the treatment being applied to the surface, the calcite precipitation occurred mostly at the surface of the sample. As such, Sample S2-beach sand had greater resistance against waves in the flume during the first ten minutes of testing. Figure 7 also displays the side profile of Sample S5-beach sand after erosion testing. The most likely explanation of Sample S5-beach sand having the highest percentage of sand erosion (40%) is the cracking of the top bio-cemented layer of the sample, and separation from the sand underneath. Erosion testing displayed the path taken by sand eroding from the sample. It was clear that the cracking of the bio-cemented layer of the sample resulted in a preferential pathway for the sand particles to erode from the top of the sample to the bottom. This leads to clear gaps developed in the core of the sample, allowing for an easier and preferential pathway for sand particles to erode. It can also be seen that the top layer near the bottom of the slope was maintained, and the gap developed between the top layer and the sand beneath allowed for a higher amount of sand to be eroded. In contrast, there was no evidence of internal erosion occurring in Sample S1-beach sand treated with mixing method.

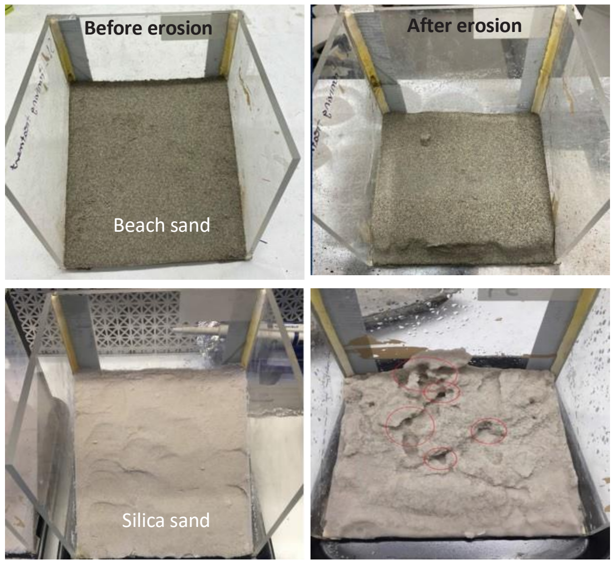

Figure 5. Slope surface profile of Sample S1 (beach sand and silica sand) before and after erosion tests.

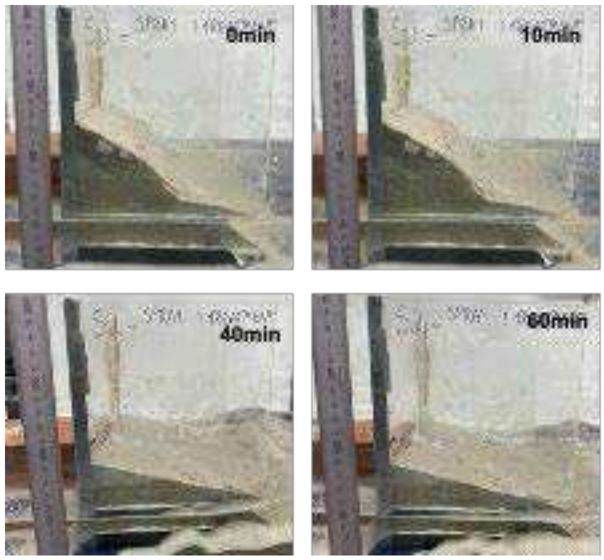

Figure 6. Erosion testing of Sample S2-beach sand.

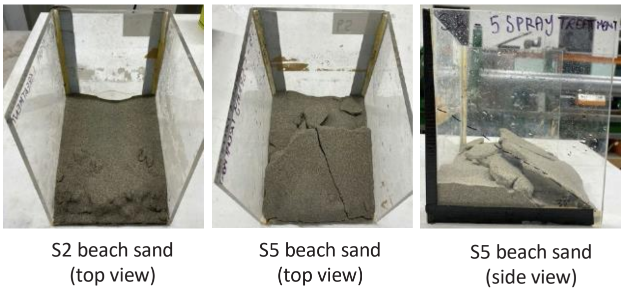

Figure 7. Slope surface profile of Samples S2-beach sand and S5-beach sand after erosion tests treated with surface spray method.

3.3 *Real seawater as cementation agent*

Sample S3 (for both silica sand and beach sand) was treated with real seawater as a cementing agent. In comparison with control samples, the degree of erosion for beach sand and silica sand was reduced from about 50% to 30% and 25%, respectively. This demonstrates the feasibility of mitigating beach erosion by wave using seawater as the only MICP commentating agent. This result also confirms that MICP treatment is more effective in improving the resistance of silica sand to wave attack than beach sand (Figure 8). With natural beach sand being utilised in this study, it is common for organic matter and impurities to be present within the soil matrix. As such, this could potentially result in weaker calcite bonds formed compared to artificial silica sand. It was found that the seawater treated Samples S3 and S4 exhibited similar behaviour against erosional waves, with Samples S3 and S4 producing 29.5% and 31.4% erosion, respectively.

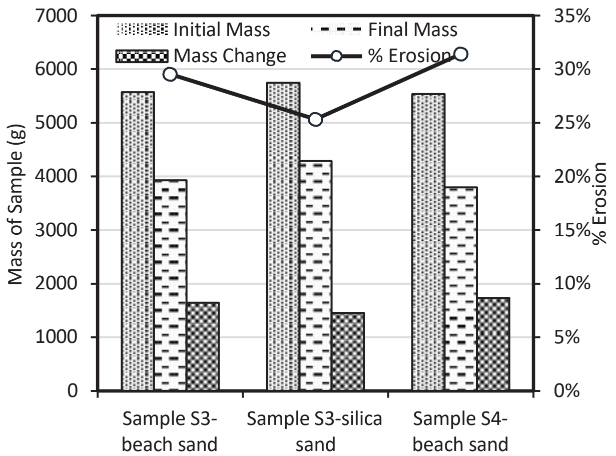

Figure 8. Erosion test results of beach sand and silica sand treated with MICP using real seawater as cementation agent.

Although the degree of erosion was decreased for the sand slope treated with real seawater, it was clear (Figure 9) that there was cracking within the 2 mm crust formed on Sample S3 (for both beach sand and silica sand). However, the calcite crust on the slope surface was weak and washed away by the generated waves. This can be explained by the low shear strength between the sand particles, and the lack of bonding between the calcite crust and the sand underneath. It was also clear that there was some resistance by the top 2 cm surface of the slope but was insufficient to prevent the waves from washing away the beach sand. As such and as the waves travelled up and down the slope of the sample, more sand was washed away in the process. This portrays that the calcite bonds formed between the beach sand particles were weak and unable to withstand the generated waves in the flume. The shear strength of the sand particles was not sufficient to resist the waves which broke the calcite bridges formed between the sand, eroding the sand in the process. As explained in the literature, the mechanical properties of sand, including strength, is mainly impacted by the effective point-to-point contacts between the sand particles caused by the formation of calcite (Ismail et al. 2002). Due to the low concentration of calcium ions in seawater and the number of applied treatments, likely, the formed calcite bonds did not have sufficient strength to completely prevent the erosion of the sample. This suggests that a long-term treatment to produce sufficient calcite crystal bonding from seawater is essential to improve the sand slope stability under wave attacks.

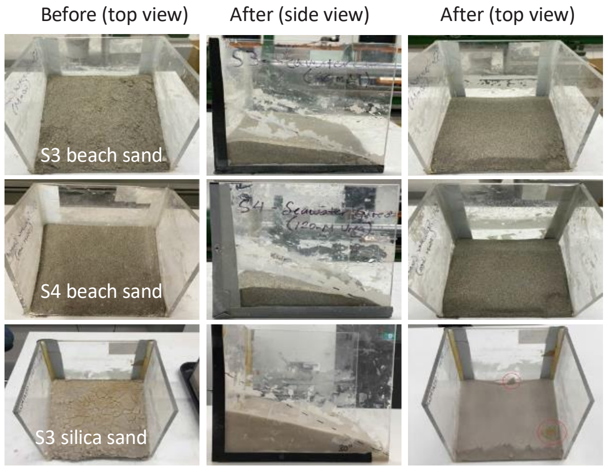

Figure 9. Erosion test results of beach sand and silica sand treated with MICP using real seawater as cementation agent.

3.4 *Effectiveness of using seawater as source of calcium*

One of the main aims of this study is to investigate the effectiveness of using seawater as a source of calcium in MICP for controlling the erosion of natural coastal beach sand. Results obtained from the seawater cured Samples S3 and S4 indicate that seawater can be used as a source of calcium ions in MICP when both natural beach sand and silica sand is utilised. From the erosion testing, it is apparent that the seawater cured samples did not have sufficient strength to completely maintain the slope and resist erosional waves in the flume. However, reduction in erosion for beach sand and silica sand was observed. The resulting erosion outcome suggests that the current curing timeframe (6 weeks) for both samples was deemed not sufficient to form adequately strong calcite bonds between the sand particles, and hence cause a mild increase in the strength and stiffness. It is therefore apparent that seawater can be used in MICP, although the number of applied treatments should be increased to achieve greater resistance against erosional waves.

To better comprehend the effectiveness of using seawater as a source of calcium in MICP, the properties of seawater, mainly the concentration of calcium ions, must be better understood. It is evident from the current study that the process of MICP and calcite formation is possible when seawater is used, and this was depicted through the formation of calcite on the surface of Samples S3 and S4. However, as mentioned previously, seawater has only about 10 mM concentration of calcium ions dissolved in seawater (Cheng et al. 2014). This is a very low concentration of calcium compared to traditional cementation solution utilising commercial calcium chloride as a calcium source (e.g. 100 to 1500 mM). As such, a high number of seawater flushes or long-term submerge is required to achieve similar strength to traditional MICP treatment. In the current study, only 30 flushes were applied to the soil for the seawater cured samples. Cheng et al. (2014) found that between 60 to 80 flushes of seawater are required to cause a significant increase in the soil strength. As such, it is evident that multiple seawater flushes are required to minimise erosion taking place. Also, the slow rate of calcification is further impacted by the decrease in the activity of the bacteria, which was premixed into the soil matrix initially. This was could be mitigated through the weekly reapplication of bacteria.

Another factor impacting seawater cured samples was the seawater temperature. Seawater was collected from Coogee Beach and its temperature was approximately 19^{o}C, as documented by Surf Life Saving (2020). Previous literature has proven the importance and impact of temperature on the strength of MICP-treated soils and calcite formation (Cheng et al. 2016). As such, the low temperatures have likely impacted the process of MICP and calcite formation in seawater cured samples. It is therefore evident that temperature is an essential factor and should be considered in the future when samples are treated using seawater cementation solution.

4 CONCLUSIONS

This paper investigated the use of "bio-cementation" via microbial-induced calcite precipitation (MICP) for prevention of coastal erosion of sandy slopes against wave attacks. By applying the surface spraying method, MICP was able to limit coastal erosion to around 11% using traditional cementation solution as the cementing agent. Also, the viability of using seawater as a sole calcium source to replace commercial calcium chloride for MICP was evaluated, showing an obvious reduction in the degree of erosion from 50% to about 25%. However, a longer treatment period is crucial to achieving calcium carbonate precipitation and sufficient cementation to increase the resistance of sand slopes against wave erosion. Overall, the current work demonstrated the potential of MICP technology as a means of coastal erosion protection and disaster mitigation in marine environments.

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