Investigation of Natural Beachrock and Physical–Mechanical Comparison with Artificial Beachrock Induced by MICP as a Protective Measure against Beach Erosion at Yogyakarta, Indonesia

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Abstract: Typically, the mitigation of coastal erosion is achieved by amending surface conditions using materials, such as concrete. The objective of this study is to evaluate the feasibility of constructing artificial beachrocks using natural materials (e.g., microbes, sand, shell, pieces of coral, and seaweed, etc.) within a short time, and to propose the method as a novel strategy for coastal protection. Initially, a survey on resistivity and a multichannel analysis of seismic waves (MASW) were conducted along the coastal lines to characterize and elucidate the subsurface structure of existing beachrocks in the Southeast Yogyakarta coastal area, Krakal–Sadranan beach, Indonesia. The field survey on natural beachrocks suggested that both resistivity and shear wave velocity were higher in the deeper deposits compared to the underlying unconsolidated sand layer within a depth of approximately 1.5 m and covering an area of 210.496 m² for the α-section and 76.936 m² for the β-section of beachrock deposit. The results of the sand solidification test in the laboratory showed that treated sand achieved unconfined compressive strength of up to around 6 MPa, determined after a treatment period of 14 days under optimum conditions.

Keywords: beachrock; resistivity; MASW; physical properties; mechanical properties; microbial-induced carbonate precipitation

1. Introduction

The coastal zone comprises a narrow strip of coastal lowlands and a vast area of coastal waters. It has become an important site for extensive and diverse economic activities. The rise in sea level, which is attributed to global warming, has resulted in coastal sand drainage around the world, thus mean sea level will result in the retreat of unprotected coastline [1,2]. One of the common methods of preventing coastal erosion is covering the surface of the sandy beach with concrete. However, this method has a significant impact on the environment and destroys the surrounding landscape. Beachrock is a sedimentary rock that occurs in the intertidal zone of sandy beaches, mainly in the
tropics and subtropics [3]. It is composed of the same material as the surrounding beach, and most of the cement material is carbonated. Most of the research on beachrock is related to its geological or chemical properties, and there is very little literature on the underground structure of beachrock. There have been a few cases of electrical exploration on Thassos Island, Greece [4]. To elucidate the formation process of beachrock, it is important to understand the structure of its underground and surrounding area. Kubo et al. [5] investigated beachrock on Yagaji Island, Okinawa, Japan, using a direct current (DC) electrical survey on a seismic surface and showed the results of the structure around the seashore to a depth of more than 10 m. Insufficient data in the South East Asian country related to recent beachrock sedimentary is a challenge for further study because of the weathering process is extremely rapid, especially is intertropical areas. This study serves as a pilot research study on the beachrock sedimentary processes at intertropical areas and compares the rock properties of the artificial beachrock, which is fabricated using the microbiologically induced carbonate precipitation (MICP) method, as a solution to coastal erosion as new revetment technology with a self-repair function. Upon receiving successful results following MICP treatment using marine ureolytic bacterium for the desired engineering application, further studies were carried out to (i) examine the underground structure of natural beachrock based on a geophysical survey, (ii) develop a 3D beachrock structure, and (iii) identify the physical and mechanical properties, such as porosity, compressional wave (P-wave) velocity ($V_P$), shear wave (S-wave) velocity ($V_S$), and strength characteristics of artificial beachrock. These properties were relatively comparable with those of natural beachrocks and were significantly determined by the precipitated crystals based on the MICP treatment.

Figure 1. Data recorded at Krakal–Sadranan α-section: (a) Filtered shot gather records; (b) f-v diagram for each data in (a).

2. Krakal–Sadranan Beachrock Characteristics

The coast of Krakal–Sadranan, Yogyakarta, Indonesia (Supplement Figure S1) has a steep slope (~12.33°) with a tidal range of 12 m, which made the sedimentary process in this coastal region thicker than lowland beaches, which consist of silica sands. Beach slope was measured from the...
shoreline to the lowest level of the tidal sea-level change around 30 m from the shoreline, approximately (Figure S2). The tidal of littoral zone provides strong sea wave energy to erode the beach. The energy comes from crashing ocean waves that break on the beach in the breaker zone that is not too far from the coastline. Waves break in a water depth about 0.78 times to the breaking wave depth \((= 0.78 \times h_b, h_b \text{ is the breaking wave depth})\) \([6,7]\). The mean value 0.78 is based on the critical ratio between wave height and depth; in this research, approximately 2.1%, with the wave depth around 2–2.7 m, respectively. The result of the wave energy, as well as the sharp, heterogeneous rocks, is the formation of an irregularly shaped beach at Sadranan. Grains of sediment along Krakal and Sadranan beaches are largely bright-colored along most of the coastline as a result of the deposition of the eroded seabed on the beach, and uniformly graded with a mean particle size of 0.9 mm for coarse sand \([8,9]\). The sediment result in this research is mainly composed of coral, skeletal fragment, Foraminifera, and Mollusca, among which \(Baculogypsina sphaerulata\) is dominant.

Beachrock is a carbonate sedimentary product, and its sedimentary characteristics were examined in this study. It has an anchoring effect in dynamic islands and provides protection from erosion. A lot of information regarding its origin and properties remains either unknown or the subject of continued debate. Outcrops of beachrock sediment are valuable records of the past climate of low-lying reef islands, which are generally found in the tropics and subtropics area and mostly in warm seawater \([10–13]\). In Indonesia, the beachrock plays the role of protecting the coastline from storms, and there are also examples in eastern Kume Island and the Great Barrier Reef in Australia \([14,15]\).

Table 1 summarizes the results of physical and mechanical tests conducted on the beachrock whose geological formation was similar to that in Japan \([16,17]\). According to previous research, the beachrock was formed only a few thousand years ago, and as its ages, the \(V_p\), \(V_s\), and mechanical strength increase. Suzuki et al. \([18]\) explained the relationship between the age of beachrock formation and the strength based on Okinawa beachrock properties. In particular, the mechanical compressive strength is 3.7 to 17 MPa, which is similar to the strength of sedimentary rocks from the late Miocene to Pliocene.

![Table 1. Comparison of beachrock properties between Japan and Indonesia.](image)

| Sample | Japan Beachrock | Indonesia Beachrock |
|--------|-----------------|---------------------|
|        | OK-A | OK-B | OK-C | OK-D | 1-A | 1-B | 1-C | 2-A | 2-B | 2-C |
| Saturated density (g/cm\(^3\)) | 2.06 | 1.97 | 2.49 | 2.27 | 1.84 | 1.92 | 1.84 | 1.80 | 1.69 | 1.81 |
| Porosity (%) | 11.1 | 25.4 | 3.7 | 27 | 10 | 12 | 11 | 14 | 14 | 13 |
| One axis compressive strength (MPa) | 11.14 | 19.91 | 31.11 | - | 7.87 | 14.47 | 15.89 | 6.07 | 3.717 | 10.77 |
| P-wave velocity (km/s) | 3.50 | 3.69 | 4.07 | 2.29 | 3.76 | 4.41 | 4.06 | 4.66 | 3.85 | 4.35 |
| S-wave velocity (km/s) | 2.34 | 2.31 | 2.51 | 1.33 | 2.49 | 2.79 | 2.79 | 2.92 | 2.33 | 2.70 |
| Dynamic Poisson ratio | 0.096 | 0.178 | 0.193 | 0.245 | 0.11 | 0.16 | 0.09 | 0.18 | 0.21 | 0.19 |
| Geological age (vBP) | 1370 | 1250 | 2300 | - | - | - | - | - | - |

*OK = Okinawa.

3. Materials and Methods

3.1. Drone Photogrammetric Data Processing

Aerial photos were obtained from selected sites at Krakal–Sadranan Beach (Supplement Material Figure S1). In this case, a GoPro HERO 6 camera attached to a DJI Phantom 3 and equipped with a 3D gimbal to minimize shaking was used for the drone photogrammetry. The Agisoft software was used to evaluate surface changes and conduct spatial analysis, such as geomorphological surfaces of the south Yogyakarta shoreline (Supplement Material Figure S2). Identification of the shoreline differences based on interactive 3D geospatial data was conducted and compared with the literature information \([19,20]\). Further study may conclude the propagation of the intertropical shoreline based on the beachrock role by comparing the data from this research with present geospatial data.

3.2 Geoelectricity survey (dipole–dipole).
where $\Delta V$ is the measured potential, $I$ the transmitted current, and $K$ the geometrical factor expressed as:

$$K = \frac{2\pi}{|V_A - r_M|} - \frac{1}{|V_A - r_N|} - \frac{1}{|V_B - r_M|} + \frac{1}{|V_B - r_N|}$$

The apparent resistivity is defined so that it is equal to the true resistivity in a homogeneous half-space [21]. In this survey, we used Syscal Junior (IRIS Instrument) within a 1-m space of electrode interval. The spikes used as electrodes (about 5 mm in diameter and 15 cm in length) were driven 10 cm into the outcrop of beachrocks along the shoreline with a hammer. The $\alpha$-section was represented by 22 electrodes along line-1, 73 electrodes along line-2, and 21 electrodes along line-3. The $\beta$-section was represented by line-4, which was lined with 26 electrodes and line-5 lined with 39 electrodes.

3.2. Multi Analysis of the Seismic Surface (MASW)

We calculated the $V_S$ profiles using the multichannel analysis of surface waves (MASW), originally introduced by Park et al. [23,24]. This method is still being developed and has been used in several areas [25–27]. By using $f$-$v$ stack, the variation of MASW acquisition geometries to provide $f$-$v$ stack from recorded traces data in space-time (x-t) and frequency-phase velocity (f-v) domain. Identical equipment was used to analyze MASW and seismic refraction: we used the Doremi Seismograph (SARA Instrument) with 24 geophone channels in two wire line cables. The measurement applied the same procedure as the geoelectricity array. MASW data were acquired using eight 4.5 Hz geophones recorded with an own-constructed data logger. The data record was set to 7200 data for 24 channels per second, and geophone spacing was set to 0.5 m. An example of measured MASW data is obtained at point line 2, especially at four-shot gathers recorded with the source at 3-m offset. These shot gathers
were then Butterworth bandpass filtered (3–45 Hz), especially for removing the power frequency of 50 Hz, which dominantly influenced the data (see Figure 1a). The data were then collected from f-v, via remapping them in f-k (frequency–wavenumber) domain, (see Figure 1b). In the f-v domain, all shots appeared to be consistent for each data set. The f-v diagrams in Figure 1, b were then stacked manually to improve the quality of data and suppress the inconsistent noise closures (see Figure 2a). By using this f-v data stack, we easily collected the data and ran it through the program to compute interpolation and smoothing values. The selected data was then automatically inverted using the SeisImager module (WaveEq) to produce the \( V_S \) profile (see Figure 2b).

3.3. Physical Properties of Beachrock

For further analysis, the beachrock sample was investigated in a laboratory to identify the rock properties and strength of the sedimentary mechanism as a parameter for developing artificial beachrock. For the laboratory tests, beachrock samples were gathered at two points: one about 0-m east from the western edge of the \( \alpha \)-line (Sample 1), and the other between the \( \beta \) and \( \gamma \)-line of the beachrock outcrop (Sample 2). The samples were then brought to the laboratory and trimmed into rectangular parallelepipeds using a rock-cutting machine. Sample 1 had a 3-cm diameter and was 6-cm long, and Sample 2 was of the same size for coring. First, the specimens were soaked in artificial seawater in a vacuum (Aquamarin: Yashima Pure Chemicals Co., Japan) for 24 h. Then, the \( V_P \), \( V_S \), and mass of the specimens was tested during natural evaporation. Once the evaporation process slowed down, the specimens were heated to and maintained at 40 °C in a constant-temperature drying oven. Finally, tests were concluded by heating the specimens to 110 °C for 24 h. The P-wave and S-wave velocities were measured twice at each water content level (SonicViewer-SX; OYO Corp., Japan).

Compressional wave velocity (P-wave velocity) and shear wave velocity (S-wave velocity) were measured, and ambient pressure on cylindrical samples with a diameter of around 3 cm and a length of up to 6 cm cut at frequencies of 500 kHz was determined. The velocity of an ultrasonic wave in rock samples is related to its elastic coefficients, internal structure, and density. Moreover, the typical shear wave velocities of the soil states, ages, and behavior were compared to aid in the design of the triaxial testing program. Target shear wave velocities, \( V_P \) and \( V_S \), were chosen to represent the following different soil states and behavior of material [28,29].

3.4. Artificial Rock Development Based on Microbial Induced Carbonate Precipitation (MICP) Method

Ureolytic bacteria, specifically the \textit{Psedoalteromonas tetradonis} genus, were extracted from natural beachrock and used in the development of artificial rock. The local beach sand used in the experiments was uniformly graded with a mean particle size of 0.9 mm for coarse sand and 0.6 mm for fine sand. The sand was sterilized, and hand packed into a 50-mL syringe (mean diameter, \( D_{50} = 3 \) cm and height, \( h = 10 \) cm), followed by the gentle injection of bacteria and a solidification solution, as illustrated in Figure S3 (Supplementary Material). Initially, a bacteria suspension was injected and allowed to sit in the column for 2 h, after which a solidification solution was injected. This was repeated every 24 h for 14 days. Additionally, two sets of biocementation experiments were conducted under conditions designed to mimic the possible conditions for in-situ injection of treatment solutions. In the first set of experiments, coarse local sand whose main constituent was skeletal shell carbonate was used, while the other set of experiments contained iron–silica fine sand from fluvio–volcanic sand of the Young Merapi deposit. Both injection conditions with 2 mL of cementation solution (Table 2) were left above the surface of the sand to mimic saturated conditions. This procedure is called the immersed method. Control tests were also conducted following the same procedures but without the addition of bacterial cells. Rock property testing, such as \( V_P \) and \( V_S \) wave propagation and the unconfined compressive strength (UCS) of the cemented samples was measured through a uniaxial compression test which was conducted on the specimen using an Instron universal tester (manufactured by INSTRON, 5586) to determine the strength of the biocemented sand. The axial strain rate was 0.1 mm/min. However, a uniaxial compression test was conducted using a table-top type high-capacity compression tester.
(manufactured by Seikensha Co., Ltd., T266-31100) for specimens with a low degree of consolidation (UCS of 1 MPa or less). The test period was conducted on 7th, 14th, and 21st, when the whole began to solidify, and the change over time of UCS under each test condition was grasped to compare with natural beachrock properties.

**Figure 3.** Electrical and multi analysis surface wave results of α-section. (a1) the resistivity of line 1, (b1) the MASW of line 1, (a2) the resistivity of line 3, (b2) the MASW of line 3, (a3) the resistivity of line 2, (b3) the MASW of line 2.
Table 2. Standard composition of cementation solution 0.5 M (solvent in artificial seawater).

| Reagent              | Content (g/L) |
|----------------------|---------------|
| Nutrient broth       | 3.0           |
| NH₄Cl                | 10.0          |
| NaHCO₃               | 2.12          |
| Urea, Co(NH₂)₂      | 18.02         |
| CaCl₂                | 33.3          |

Figure 4. Three dimensional of beachrock model calculation based on geophysical statistical anomaly data from electrical resistivity and multi analysis surface wave of α-section.

4. Results and Discussions

4.1. Geophysics Measurement

Figure 3 shows the apparent resistivity distribution of each survey line, as indicated by the electric survey method. As a general trend, the apparent resistivity at 1 m in the shallow layer was slightly high (9.65 to 16.3 Ωm), and a section of the surface layer of the α-section had the highest resistivity (46.7 to 78.7 Ωm). Below this level was a low resistivity layer of 1 to 5 Ωm. The beachrock sedimentary value of the β-section was 9.65 to 16.3 Ωm, with the highest being 46.7 to 78.7 Ωm. Furthermore, when the depth exceeded 4 m, the apparent specific resistance tended to increase gradually. The MASW method adopts the conventional linear receiver array and mainly attempts to use the surface waves generated from natural beachrock. This method uses the passive remote method to overcome limitations, such as the inconvenience in field operations, by foregoing the accuracy (usually less than 10%) of the Vₛ evaluation and dominance of noise data. In this method, the array can be set along a shoreline, and the survey can continue in a roll-along mode for the purpose of two-dimension Vₛ profiling. Using a land streamer for the array can improve survey speed by as much as a few orders of magnitude. In addition, an active impact (e.g., using a sledgehammer) can be applied at one end of the array to trigger a long
recording (e.g., 60 s). This can result in a combined active–passive analysis of surface waves to obtain both shallow (e.g., 1–20 m) and deep (e.g., 20–100 m) \( V_S \) information simultaneously (Figure 3). As a general trend, the S-velocity on the wavelength side was 300 to 600 m/s, but on the longer side of the wavelength, the phase velocity increased to 400-550 m/s. For each survey line, a band of 10 to 100 Hz was analyzed in the dispersion curve. Figure 3(a1–a3) show the resistivity cross-sections of each survey line when, on the other hand, Figure 3(b1–b3) show the S-wave velocity cross-sections. In general, both cross-sectional views were well aligned, with a surface resistivity of approximately 1 m, a slightly higher resistivity layer, a lower resistivity layer, and a lower portion. It had a three-layer structure with a high resistivity layer (high-speed layer). In other words, there was a slightly higher velocity layer of 300 to 350 m/s on the surface layer where the distance between line-1 and line-3 from 0 to 3 m, which was the beachrock outcrop, was exposed on the surface, and the distance of line-2 was 0 to 2 m on the \( \alpha \)-section.

These were almost consistent with the position of the slightly higher resistivity layer of 9 to 20 \( \Omega \)m in the resistivity cross-sectional view and were consistent with the beach rock distribution area confirmed in the field. These velocity layers and resistivity layers were thought to capture the vertical distribution of beachrocks, and the thickness of the beachrocks was estimated to be a maximum of 1 m. In particular, the high resistivity layer in the surface layer at a distance of 3 to 44 m from line-2 corresponded to the beachrock distribution area, where the electrode could only be driven in by about 2 cm. This resistivity layer was almost consistent with that of the beachrock shown by David [4], who reported a resistivity of 2–15 \( \Omega \)m and a 1-m thickness and Kubo et al. [5], who reported a resistivity of 4–20 \( \Omega \)m and 1-m thickness. A section with high resistivity (46.6 to 78.7 \( \Omega \)m) was also observed at a distance of 17 to 33 m of the survey line-2, but this can be assumed to correspond to a dry beachrock layer on the ground surface. The pattern of high resistivity value was also observed in other lines of the \( \alpha \)- and \( \beta \)-sections. Refer to the Supplementary Material (Figure S4) for further information about \( \beta \)-sections.

4.2. Three Dimensional of Subsurface Model

The concept of 3D processing entails a combination of processing each line via the drone photogrammetric technique and overlaying digital elevation model data using \textit{ArcGis}. The distance between lines was interpolated with the lines around it. The data input applied in 3-D modeling had four parameters, namely \( x, y, z, \) and \( n \). Coordinates in UTM were labelled as \( x \) and \( y \), indicating the position of the north and east meters. The value of \( z \) as an elevation parameter is not depth because it follows the digital elevation model of topography and geophysics parameters, such as resistivity and surface wave values. This model used \textit{ArcGis} and \textit{Rock Work} to calculate the distribution of beachrock in the Krakal–Sadranan beach, Yogyakarta. The limitation of the value of resistivity and S-velocity taken also applied between 9–78.7 \( \Omega \)m and an S-velocity value between 400–600 m/sec. Based on the calculation, the \( \alpha \)-section covered 210.496 m\(^3\) of beachrock (Figure 4), while the \( \beta \)-section covered 76.936 m\(^3\) (Supplement Material Figure S5).

The average wet density was 1.95 g/cm\(^3\), porosity was 10 to 14%, S-wave velocity was 2.3 to 2.92 km/s (average 2.66 km/s), and the P-wave velocity was 3.35 to 4.41 km/s (average 4.18 km/s). The average dynamic Poisson’s ratio was 0.16, respectively. Compared with the beach rock samples at other points shown in Table 1, these results show a higher porosity and lower values for both P-wave velocity and S-wave velocity compared to Okinawa, Japan samples [17]. Figure 5 shows the results of comparing the properties of beachrocks with other rock types using existing data. The relationship between P-wave velocity and S-wave velocity for sedimentary rock samples in Japan [18] and Indonesia in this research. It can be seen that the elastic wave velocity of the beachrock at this point (2B, 1A, 1C, 2C, 1B, and 2A in the figure) show values similar to those of the early Paleogene until Cretaceous sedimentary rocks. It shows the beachrock distribution in Indonesia has a more compacted crystallization than Japanese Okinawa beachrock, even though the pattern of beachrock samples from both sides were sedimented in the same characteristics (based on dynamic Poisson ration ~0.2) which means it has a
similar porosity. Based on the results, a detailed analysis of carbon dating is needed to prove the actual dating of the beachrock in Indonesia as the most suitable approach for further analysis. In contrast, the subtidal sample probably showed a deeper environment, as indicated by the coexistence of magnesian calcite (Mg-calcite) and aragonite testifying a marine vadose environment [30]. Toward the rim of the cement, high-Mg calcite became progressively less rich in magnesium, which is attributed to sitting at the meteoric vadose zone (Figure 6).

**Figure 5.** Comparison of the geophysical properties of the sedimentary rocks and beachrocks based on compressional wave (P-wave) velocity and shear wave (S-wave) velocity.

**Figure 6.** Schematic illustration of coastal zones, cement fabrics, and mineralogy-formation environments of the beachrocks (M.H.W: high water level, M.T.L: mean tidal water level, M.L.W: low water level).

### 4.3. MICP of Artificial Rock Properties

Natural beachrock found in nature mostly consists of carbonate bridged material cementation, organic matter, such as skeletal fragments, and also other sources of rock dependent on geological
settling in that area. Therefore, artificial cement formed by mixing seawater and a solution containing \( \text{CO(NH}_2\text{)}_2 \) and \( \text{CaCl}_2 \) was injected into the sand with culture bacteria as the solidification nutrient for the cementation process [31]. Fifteen MICP treated specimens were subjected to undrained shear under different loading paths, including a mixture of both species, similar to the drained test series described previously. The test results indicate that as with the drained specimens, the total stress path influences the constitutive behavior of the cemented soil with small deviations in effective stress paths. A column solidification test was conducted for the purpose of achieving strength in megapascal (MPa), which is feasible as a shoreline development method. A column solidification test was conducted over a period of 25 days owing to the accumulation of carbonate cement, which might get clogged in the sample, under a 37 °C curing temperature, and with injection of solidified solution at one-day intervals which resulted in a 0.5-M \( \text{Ca}^{2+} \) concentration of solidified solution. The results indicate that the UCS values increased with the decrease in particle size in the uniformly graded sands. The average UCS axial load (Figure 7) estimated close to the surface of fine sand and coarse sands (\( D_{50} \) of 0.87 mm and 0.2 mm) were 2.87 MPa and 5.7 Mpa, respectively. The UCS values and the calcium carbonate content of coarse and fine sands reported herein are in a good agreement with the results reported by Cheng and Cord-Ruwisch [32]. Basically, coarse sands have high permeability that leads to the high liquid infiltration compared to the fine sands. In contrast, fine sand exhibited significant improvement in UCS with the depth, which could be due to the increased capillary effect along the sample depth. The higher capillary forces in fine sand tended to retain a certain amount of cementation solutions close to particle contacts, resulting in higher deposition of calcium carbonate and exhibiting higher UCS.

**Figure 7.** Comparison of the unconfined compressive strength (UCS) axial load between (a) natural beachrocks and (b) artificial rock based on the microbially induced carbonate precipitation (MICP) method with x-ray computed tomography (X-ray CT) scan images of porosity.
The results of the tests on bioclogging and biocementation (Table 3) can be monitored in real-time using seismic velocity and resistivity measurements [28,33]. Shear wave velocity (S-wave) test results were used to develop a correlation to the precipitated calcite mass, and this enables the prediction of changes in porosity, density, and shear modulus during treatment [31]. Shear wave velocity is used to nondestructively monitor the change in small-strain stiffness during shearing, which provides an indication of cementation degradation as a function of strain level. Because shear wave velocity is influenced by both the level of cementation and the change in effective mean stress during shearing, the normalized shear modulus is used to evaluate the degradation of cementation during shearing [28]. Biocementation in a change from a shear wave velocity of 140 m/s to an average of 600 m/s, compared with this research a shear wave around 510 m/s to 1330 m/s. Compression wave velocity (P-wave) measurements can be determined under different saturation conditions and used in combination with S-wave measurements to observe how the Poisson’s ratio evolved during treatment [33].

Table 3. Rock properties of artificial beachrock using the microbially induced carbonate precipitation (MICP) method.

| Sample | Sand Type | Saturated Density (g/cm³) | Porosity (%) | Expectation Strength (MPa) | P-Wave Velocity (km/s) | S-Wave Velocity (km/s) | Dynamic Poisson Ratio |
|--------|-----------|---------------------------|--------------|-----------------------------|------------------------|------------------------|----------------------|
| VB-14 Unsaturated | Quartz Silica Sands | 1.60 | 37% | 1.01 | 1.12 | 0.77 | 0.05 |
| PS-14 Unsaturated | | 1.63 | 34% | 2.33 | 1.20 | 0.84 | 0.01 |
| MIX-14 | | 1.56 | 30% | 1.48 | 0.97 | 0.68 | 0.02 |
| OC-21 | | 1.56 | 36% | 0.54 | 0.82 | 0.57 | 0.05 |
| PS-14 | | 1.53 | 30% | 1.57 | 0.73 | 0.51 | 0.04 |
| MIX-21 | | 1.65 | 29% | 3.19 | 1.00 | 0.69 | 0.06 |
| PS-21 | | 1.81 | 24% | 3.73 | 1.78 | 1.24 | 0.02 |
| PS-14 Unsaturated | | 1.42 | 32% | 2.40 | 1.31 | 0.88 | 0.09 |
| PS-21 Unsaturated | | 1.74 | 28% | 5.79 | 1.82 | 1.27 | 0.03 |
| MIX-21 | Coarse Limestone Sand | 1.66 | 33% | 3.20 | 1.94 | 1.33 | 0.05 |
| OC-21 | | 1.58 | 43% | 1.78 | 1.07 | 0.72 | 0.07 |
| PS-25 | | 1.63 | 26% | 1.39 | 1.68 | 1.13 | 0.09 |
| PS-14 | | 1.46 | 31% | 1.58 | 1.04 | 0.73 | 0.01 |
| PS-21 | | 1.60 | 29% | 2.46 | 1.48 | 1.01 | 0.07 |

Permeability of the fractured rock after biotreatment decreased between 2 and 4 orders of magnitude and the sandstone core withstood three times higher well bore pressure than during the initial fracturing event showing that MICP is applicable for the bioclogging (biosealing) of the fractured rocks [34]. Porosity is the amount of voids in a material. The porosity after MICP treatment had a porosity larger than natural beachrock found in the site study, and an additional tomography scan beneath sands particle was conducted to show the distribution of porosity of natural beachrock versus artificial rock based on MICP (Figure 6). The porosity content of beachrock (10–15%, approximately) in treatment sands significantly increases the number of particles in contact by bonding with the sand grains (30~45%) because of the meniscus bridge crystallization not present in natural beachrock. It can be observed that the fine matrices’ content plays a very important role in support by enabling intermediate support to form bridges among the carbonate crystals that have grown in void spaces, thus, strengthening the force chain of the treated matrix. It should also be stated here that the MICP technique is limited due to the limited rate of permeability that generally takes a much longer time to infiltrate the reactants [35]. Further, free passage of the bacteria might be inhibited due to the small pore throat size of fine soils [32], which mostly contain calcium carbonate compounds, such as vaterite, aragonite, and/or calcite, without magnesium mineral enrichment from the seawater supply [8,9].

5. Conclusions

As a result of conducting electrical and surface wave surveys on sandy beaches, we found the following:
• Beachrock found in this area were precipitated beneath beach sand, which is a wave erosional product, and then solidified beneath that formation, floating between limestone bedrock and beach sands formation, based on a greater value from resistivity and S-wave velocity in the formation layers.

• Resistivity, thickness, and S-wave velocity of the beachrock increases as it gets closer to the coastline. The maximum thickness of the beachrock at this point is about 1 m based on calculations; the α-section covers 210.496 m$^3$, while the β-section covers 76,936 m$^3$ of beachrock deposit.

• Natural beachrock and artificial beachrocks bore similar results following the MICP process examining properties, such as chemical compounds, meniscus carbonate bridges, and rock properties. However, the strength and porosity of artificial bedrocks were significantly different from those of natural beachrocks, which intensified the carbonate precipitation processes.

• Therefore, the sufficient immersion and evaporation of seawater is an important condition for the solidification of sand to form beachrock.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3263/10/4/0/s1, Figure S1. Aerial photogrammetric of the study area in Krakal–Sadranan, Yogyakarta south coast, Indonesia; Figure S2: Geomorphology zonation of shoreline mapping based on beachrock deposits, (a) α-section and (b) β-section; Figure S3: Syringe cementation test scheme; Figure S4: Electrical and multi analysis surface wave results of α-section. (a1) the resistivity of line-4, (b1) the MASW of line-4, (a2) the resistivity of line-5, and (b2) the MASW of line-5; Figure S5: Three dimensional of the beachrock model calculation based on geophysical statistical anomaly data from electrical resistivity and multi analysis surface wave of β-section.

Author Contributions: L.R.D., K.S., and S.K. performed the measurements; S.K., K.N., and L.R.D were involved in planning and supervised the work; L.R.D., K.S., and A.R. processed the experimental data, performed the analysis, drafted the manuscript, and designed the figures; L.R.D., K.S., and I.S. aided in interpreting the results and commented on the manuscript. All authors have read and agreed to the published version of the manuscript.

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