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# A STUDY OF THE FORMATION MECHANISM OF BEACHROCK IN OKINAWA, JAPAN: TOWARD MAKING ARTIFICIAL ROCK

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**ABSTRACT:** Beachrock is coastal sediment that has been cemented mainly by calcium carbonate within the intertidal zone in tropical and subtropical regions. Man-made beachrock has the potential to inhibit coastal erosion. Considering this important application, we performed field investigations and laboratory tests to understand the formation mechanism of beachrock in Nago, Okinawa, Japan. We performed a needle penetration test, microbial population count and urease activity test, and conducted elemental and mineral analyses of the beachrock and sand. Some microorganisms at the site showed urease activity and the beachrock cement comprised high Mg calcite (HMC). Our investigation showed that evaporation of seawater and/or urease activity of bacteria may have resulted in precipitation of HMC, leading to formation of the beachrock, with partial solidification of some sandy specimens.

*Keywords: Beachrock, Formation Mechanism, Cement, Microorganism, Urease Activity*

## 1. INTRODUCTION

On the world's coasts, erosion is a significant problem. To preserve coastlines, various countermeasures are used to combat coastal erosion. These include construction of artificial reefs, headlands, detached breakwaters and hard shore protection, all of which control the amount of drift sand and/or beach nourishment and sand bypassing, thus overcoming shortages of drift sand. However, these solutions are expensive, and require long time periods for implementation, as well as the engineering of large amounts of materials, especially for heavyweight sand coasts [1], [2].

We consider here a new method to protect coastlines – the use of artificial rock that auto-repairs by means of sunlight, seawater, and bacteria. Our model of artificial rock is beachrock. Beachrock is a type of sedimentary deposit that generally occurs on tropical and subtropical beaches as a result of intertidal lithification of loose beach sands and gravels by carbonate cementation [3]. Beachrocks around the world have been reported to form over several thousand years [4] owing to interactions among sand supply, cement precipitation from seawater and coastal erosion by ocean waves. Therefore, it may be possible to slow the erosion of coasts by making man-made beachrock from coastal sands. Because this artificial rock is made of local materials, it has the potential to be an eco-friendly product.

In this study, we examined the formation mechanism of beachrock in Okinawa, Japan, because understanding this mechanism is an important step in making artificial beachrock. As part of this analysis, we performed a needle penetration test, determined the viable bacterial count, conducted a urease activity test and performed elemental and mineral analyses of the beachrocks and sand. Our focus is on the cement formation mechanism of beachrock, which occurs in the intertidal zone. Cement type and content have the potential to influence the strength of the material; hence, detailed knowledge of beachrock cements is valuable for producing a man-made equivalent. In addition, we conducted laboratory solidification experiments using local bacteria.

## 2. STUDY SITE AND METHODS

### 2.1 Study Site

The geology of Sumuide, Nago, Okinawa, Japan (Fig. 1) comprises limestone and calcarenite of the Quaternary Ryukyu Group [5]. The location is 26° 40' 74" N and from 126° 00' 73" to 126° 00' 74" E.

### 2.2 Needle Penetration Test

At the site, needle penetration inclination ($N_P$) values of some beachrock samples were measured five closely spaced points at each location by using a needle penetration device (SH-70, Maruto Testing Machine Company, Tokyo, Japan). Samples measured exposed beachrock at the shoreline (two test sections) and buried beachrock underneath the coastal sand (one test section). Unconfined compressive strength, $q_u$, was estimated from $N_P$ by

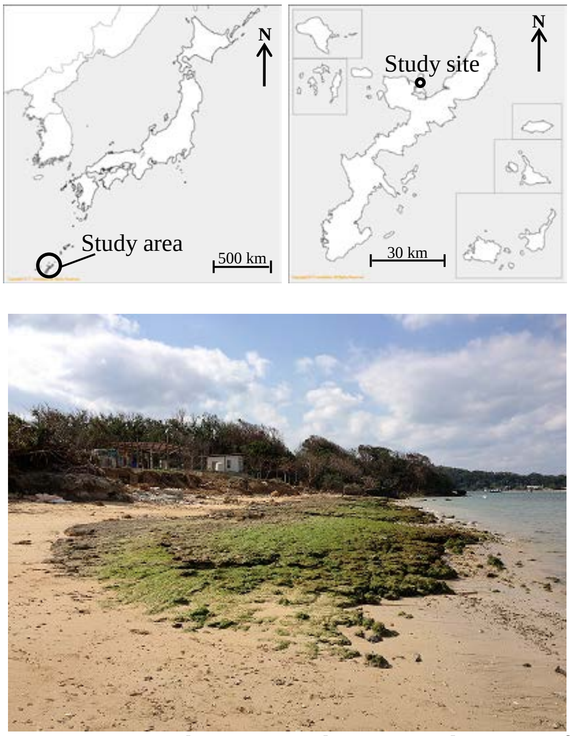


Fig. 1 Maps showing study site and view of exposed beachrock.

the correlation chart of $N_P$ and $q_u$ described in the instruction manual.

### 2.3 Microbial Population Count

Seawater, some beachrock samples, and sand at both sites were sampled in sterile test tubes and refrigerated at 4 °C in our laboratory. Subsequently, 1.0 g of each sample was mixed with 9 mL of artificial seawater or saline solution, and 10 µL of the supernatant was added to ZoBell2216E medium (for marine bacteria) or polypeptone-yeast extract medium [6] (for viable bacteria). After inoculation, the media were incubated at 25 °C for 7 days. Subsequently, each population (colony count) was counted by the plating method.

### 2.4 Urease Activity Test

We isolated colonies from the sand adjacent to the beachrocks using ZoBell2216E medium. Each colony was mixed with 20 mL of solution (25 g/L $CO(NH_2)_2$ and 20 mL/L cresol red solution with distilled water) in a 20 mL bottle. Under sealed conditions, the samples were left standing at 45 °C for 2 hours. To determine whether the colonies have urease activity, we observed the solution color after 2 hours. For cresol red, a change from yellow to purple can be observed from pH 7.2 to pH 8.8. Those samples that changed to purple were measured for their pH values. For comparison, a non-bacterial sample also was measured.

### 2.5 Elemental Analysis and SEM Observations

Samples of exposed beachrock, buried beachrock, and adjacent sand were analyzed by X-ray fluorescence analysis (XRF). The surfaces of the samples were observed microscopically and elemental measurements were made using scanning electron microscopy (SEM) (SuperScan SS-550, Shimadzu Corporation, Kyoto, Japan) and energy-dispersive X-ray spectroscopy (EDX) (SEDX-500, Shimadzu Corporation).

### 2.6 Mineralogical Analysis

The same samples used for XRF and EDX analyses were further subjected to mineralogical study using X-ray diffraction (XRD) (MultiFlex 2kW, Rigaku Corporation, Tokyo, Japan) with Cu-Kα radiation, with 2θ between 5 and 70°.

## 3. RESULTS

### 3.1 Needle Penetration Test

The $q_u$ values of exposed beachrocks were larger than those of buried beachrock (Table 1). This result is similar to that of Vousdoukas et al. [4]. Furthermore, to the best of our knowledge, this study is the first to report $q_u$ of buried beachrock. Only three previous studies from Japan and Scotland [7]–[9] have addressed the mechanical properties of exposed beachrocks.

Table 1 Unconfined compressive strength, $q_u$ of the beachrocks estimated by the needle penetration test, and microbial population counts.

| Test Section | Needle Penetration test | | Microbial population count | |
|---|---|---|---|---|
| | $N_P$ N/mm | $q_u$ MPa | Marine $\times 10^4$ CFU/mL | Viable $\times 10^4$ CFU/mL |
| Seawater | - | - | 1.3 | 0 |
| Exposed Beachrock 1 | 80±22 | 28±6.9 | 410 | 45 |
| Exposed Beachrock 2 | 51±12 | 19±4.7 | 1500 | 8.15 |
| Buried Beachrock | 8.9±5.4 | 3.4±2.2 | 460 | 13.6 |
| Sand | - | - | 500 | 5.4 |

### 3.2 Microbial Population Count

For each sample, marine microbial populations showed viable values (Table 1). Bacterial morphologies and colors differed on ZoBell2216E medium and polypeptone-yeast extract medium (e.g. Fig. 2). The populations in the beachrock samples tended to be smaller than bacterial populations reported from soil ($10^6$ to $10^{14}$ $g^{-1}$) [10], but larger than in the seawater, despite the fact that the beachrock is washed by seawater every day. Therefore, this result suggests that the microbiological properties of the beach at this site affect beachrock formation.

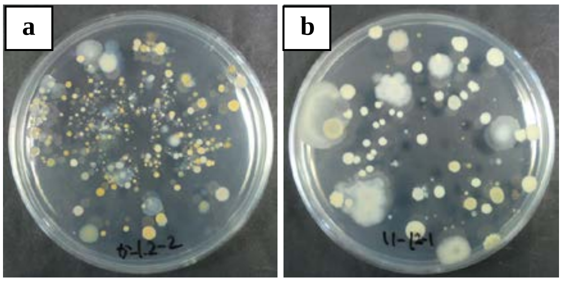


Fig. 2 Microorganisms in exposed beachrock 1 on (a) ZoBell2216E medium and (b) polypeptone-yeast extract medium.

### 3.3 Urease Activity Test

About 156 colonies were isolated from the soil near beachrocks. Of these, five colonies changed the solution color to purple after 2 hours at 45 °C, indicating urease activity. Moreover, the pH range of the five samples was 9.0–9.3. In comparison, the pH value of the non-bacterial sample was 7.1.

### 3.4 Elemental Analyses and SEM Observation

Results of XRF analysis of the samples are shown in Figure 3. All samples were composed mainly of CaO, and beachrock samples contained more MgO than adjacent sand. By contrast, the sand contained more $SiO_2$.

Subsequently, to identify the beachrock cement, we analyzed sample surfaces by performing SEM-EDX. Figure 4 shows that, only in association with the beachrocks, the microparticulates covered with sand particles and the morphologies (Fig. 4 (b) and (d)) were similar to that of high Mg calcite, HMC [11]. HMC is a polymorph of $CaCO_3$, containing more than 4 mol% $MgCO_3$, or 1.2 wt%. Moreover, the $MgCO_3$ found in the microparticulates was calculated to be 16–18 wt% (>1.2 wt%) based on the Mg percentage about P1–P6 in Figure 5. Therefore, we can conclude that the cement of beachrock at site O is HMC.

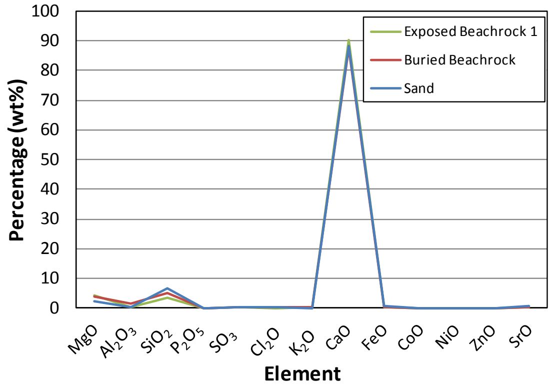


Fig. 3 Elemental percentage of site O samples by using XRF.

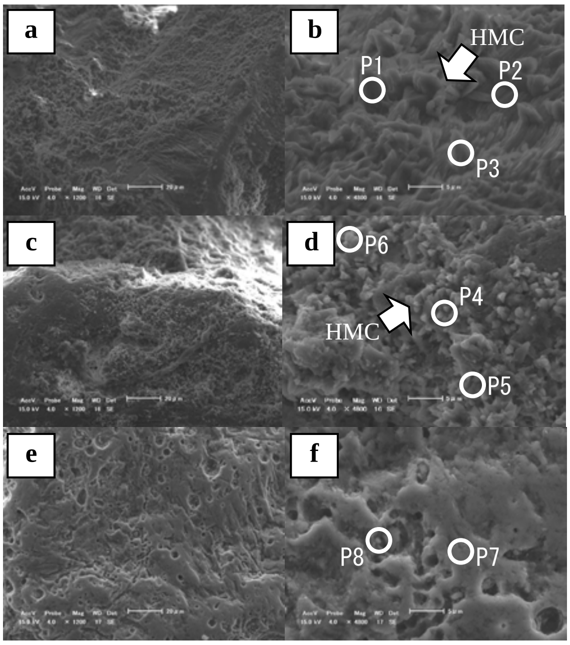


Fig. 4 SEM images of the samples. (a), (b): exposed beachrock 1 (×1200, ×4800), (c), (d): buried beachrock (×1200, ×4800), (e), (f): sand in site O (×1200, ×4800).

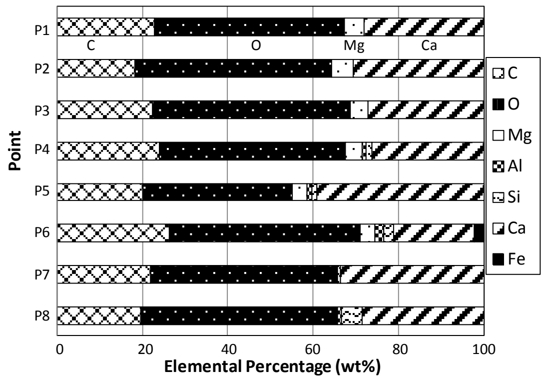


Fig. 5 Elemental percentage from P1 to P8 of Fig. 4 using EDX.

### 3.5 Mineralogical Analysis

The samples contained the following minerals: Mg calcite (MC), aragonite, and quartz (Fig. 6). MC can be divided into HMC and low Mg calcite (LMC). LMC contains less than 4 mol% $MgCO_3$ [4]. The highest peaks (around 30°) of the samples were closer to the peak of HMC than that of LMC, about 2$\theta$ value [12].

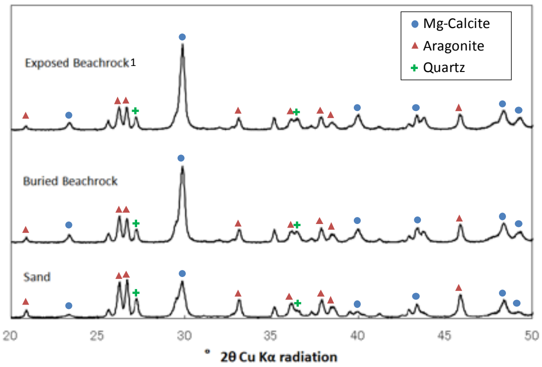


Fig. 6 XRD patterns of (a) exposed beachrock 1, (b) buried beachrock and (c) sand.

## 4. DISCUSSION

### 4.1 Formation Mechanism of the Beachrock

Beachrocks cemented by HMC have been reported at 16 sites [4], [13] around the world, and their formation mechanisms are shown in Figure 7.

We focused further investigations of the beachrock cements on the influence of precipitation from seawater and/or seawater evaporation (PSW), and on surface microorganisms, which we considered as one biological process (BIOL). This is because (1) PSW is the factor most reported to be related to the formation mechanism of beachrock cemented by HMC (Fig. 7) and (2) microbiological

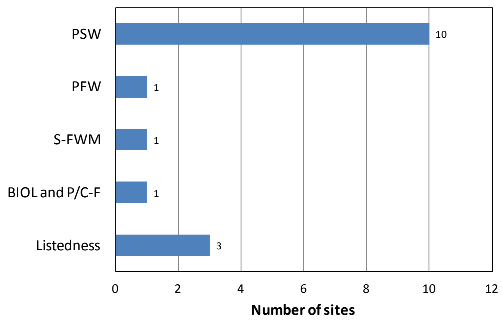


Fig. 7 Formation mechanisms of beachrocks that contain HMC cements. [4], [13] (PSW, Precipitation from seawater/seawater evaporation ; PFW, precipitation from fresh water ; S–FWM, Sea – fresh water mixing ; BIOL, biological processes; P/C–F, Physico/chemical factors)

properties may affect beachrock formation at this study site based on the above microbial population count. Other effects on beachrock formation are outside the scope of this study and require further consideration in the future.

First, with respect to PSW, Raz et al. [14] reported that to better understand the depositional process of high-magnesian calcitic skeletons, they studied the $CaCO_3$ precipitates formed from solutions with Mg/Ca ratios ≥4. We conducted water analyses at the study site by performing ion chromatography (ICS-1000, Dionex Corporation, Osaka, Japan) (Table 2). The molar ratio Mg/Ca of the seawater was approximately 6.3; this ratio satisfies the conditions under which HMC could precipitate. In addition, according to experiments by Kitano et al. [15], sodium citrate and sodium malate favor the precipitation of MC, whereby an increase in concentration of magnesium ion and these organic materials cause formation of Mg-rich calcite. The present study site is rich in organic matter, such as sea algae, shells, corals, and bacteria, which may be sources of citrate and malate.

Table 2 Chemical composition of seawater at the study site.

| $Na^+$ (ppm) | $Mg^{2+}$ (ppm) | $K^+$ (ppm) | $Ca^{2+}$ (ppm) | pH | EC (mS/cm) |
|---|---|---|---|---|---|
| 11000 | 1330 | 486 | 348 | 7.9 | 51 |

A second factor—the microbiological effect—was indicated by the microbial population count and urease activity test. We found five colonies of bacteria exhibiting urease activity in the sand near the beachrock. The bacteria stimulate the hydrolysis of urea, $CO(NH_2)_2$. This reaction leads to an increase in pH and precipitation of $CaCO_3$, as shown Eq. (1) and (2) [16]. At this site, there are abundant organisms, and the mammalia, amphibia and chondrichthyes void urea.

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-}, \quad (1)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \downarrow. \quad (2)$$

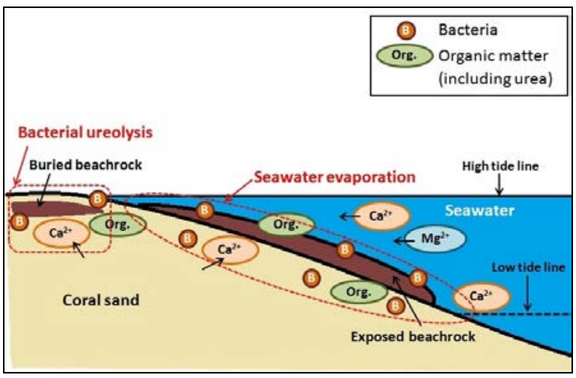

Fig. 8 Proposed formation mechanism of beachrock at the study site.

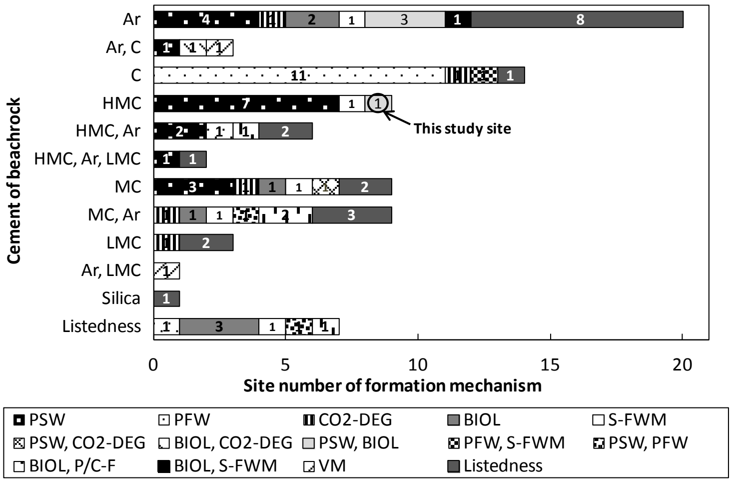


Fig. 9 Cements and formation mechanisms of beachrocks in the world including the study site. [4], [17] (Cement type: Ar, Aragonite; C, Calcite; HMC, High Mg calcite; LMC, Low Mg calcite; MC, Mg calcite; Al, Element of Al; Si, Element of Si. Formation process: $CO_2$–DEG, $CO_2$ – degassing; VM, Various mechanisms.)

Moreover, $MgCO_3$ is expected to precipitate with $CaCO_3$. To the best of our knowledge, this is the first time that bacteria exhibiting urease activity have been recorded near beachrock.

Therefore, our investigation into the formation mechanisms of beachrock at this study site (Fig. 8) has shown that the evaporation of seawater and/or the urease activity of microorganisms might have resulted in the precipitation of HMC, leading to formation of beachrock.

Furthermore, we considered the relationship of cements and formation mechanisms of beachrocks around the world, including the present study site (Fig. 9). We found six processes to be reported: PSW; precipitation from fresh water (PFW); $CO_2$–degassing; BIOL; sea–fresh water mixing; physico/chemical factors; and various other mechanisms. Some beachrock sites have developed from more than one mechanism. Moreover, the beachrock examples cemented by calcite tend to have been formed by PFW. In contrast, aragonite and MC tend to have been precipitated from seawater, as beachrock cements. In addition, the beachrocks formed by BIOLs are cemented by HMC, MC and/or Ar (Fig. 9).

### 4.2 Ground Solidification using the Bacteria

We discuss here the tendency for solidification of sand using microorganisms from the study site.

Recently, several investigations of microbial ground improvement technologies have been reported globally. The major cementation method is to stimulate calcium carbonate to precipitate by the ureolytic reaction of *Sporosarcina pasteurii*, a well-known urease positive bacterium [16], [18], [19]. The solidification technique using local bacteria is novel and expandable.

Based on the method of Inagaki et al. [18], we conducted a solidification test using a local microorganism that raised the pH value to the highest with respect to the above urease activity test. The microorganism was estimated as *Paracocus sp.* by the analysis of a partial base sequence of 16S rDNA using the Apollon DB-BA 8.0 database. First, the bacterium was shaken in the ZoBell 2216E culture solution for 3 days at 30 °C. Second, coral sand dried at 110 °C for more than 2 days was added into a 15 mL syringe (inner diameter 15 mm). Third, the culture medium solution and 0.3 equimolar urea and calcium chloride solution were sequentially injected into the syringe and drained up to 1 mL above the top surface of the sand. The specimens were kept in wet conditions throughout. Thereafter, in the same manner, the urea and calcium chloride solution was injected and drained once a day and the syringe test was conducted at 30 °C.

Results indicate that the upper, side portions, and bottom areas of the specimens were solidified after 2 weeks (Fig. 10). The $q_u$ values were estimated, by the needle penetration test, up to 2 MPa. This maximum strength was obtained from a bottom

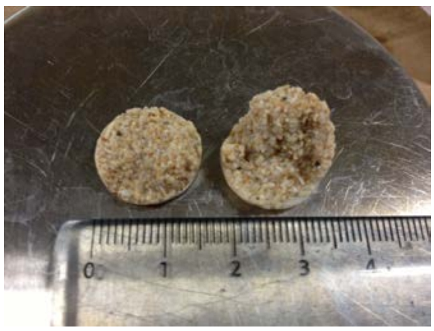

Fig. 10 Solidified parts of sediments using a

bacterium obtained from near the Okinawa beachrocks.

solidified part that was ≤10 mm thick and 54 mm high). To the best of our knowledge, this is the highest $q_u$ measured by all reported solidification methods using local bacteria.

Hereafter, by finding optimal compositions of the solutions and curing temperatures, we plan to make higher mechanical strength materials and larger specimens to create artificial beachrock.

## 5. CONCLUSIONS

We performed needle penetration tests, viable bacterial count and urease activity tests, as well as conducted elemental and mineral analyses of beachrock and sand to investigate the formation of beachrock at Okinawa in Japan. These results revealed a probable formation mechanism.

In particular, evaporation of seawater and/or urease activity of microorganisms may have resulted in precipitation of HMC, leading to formation of beachrock. In addition, the microorganisms partly solidified coral sand specimens.

For future studies, we plan to conduct solidification tests with bacteria and an evaporation test with seawater to create artificial beachrock on a large scale.

## 6. ACKNOWLEDGEMENTS

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