Proceedings of ISERME 2025
19-20 September 2025
https://doi.org/10.31705/ISERME.2025.4

Comparative Analysis of Beachrock Cementation Mechanisms in Sri Lanka: Toward Biomimetic Engineering Solution

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Abstract
Beachrocks are intertidal coastal sediments formed mainly through carbonate cementation, and these sedimentary structures can be seen along the coastlines of Sri Lanka due to the prevailing tropical climate. Beachrock occurrences and formations in Sri Lanka are underexplored, despite their potential for biomimetic ground improvement. This study investigates the formation mechanism and engineering relevance of beachrocks in Chilaw and Uswetakeiyawa, focusing on the mineralogical and elemental characteristics to support nature-based ground improvement applications. Analytical methods employed included Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDX), Fourier Transform Infrared Spectroscopy (FT-IR), and X-ray Diffraction (XRD). The evidence suggests that beachrocks in both the localities consist mainly of quartz grains cemented by High Magnesium Calcite (HMC) with micritic coating and scalenohedral terminations, show evidence of carbonate cementation by mixed marine and meteoric water, and biological activity. Contrasting with Aragonite-rich beachrocks in Southern Sri Lanka, these findings highlight regional variations in cementation and formation mechanisms. Further exploration is recommended with additional geochemical analysis, tests of strength, petrographic thin sections, and geochronological dating, to help establish an integrated basis for understanding beachrock formation and its application to nature-based ground improvement techniques.

Keywords: Carbonate cementation, Ground improvement, Mineralogical analysis, Elemental composition

1 Introduction

Beachrocks are unique coastal formations formed by the lithification of beach sediments by precipitation of calcium carbonate cement. These structures often comprise sand, shells, and small pebbles that bind collectively to solidify into rock [1],[2]. This natural process provides insights into coastal geomorphology as well as information on coastal sedimentary processes. Beachrock is typically formed at a tropical or subtropical shoreline where warm seawater promotes the conditions necessary for the precipitation of $CaCO_3$ [2]. Moreover, these typically occur in the intertidal zone where they could be subjected to tidal fluctuations [3]. The occurrence of beachrock on sandy beaches in these climates emphasizes the influence of regional temperature and seawater chemistry on its origin. [3] states that, over 90% of beachrocks are distributed between the proximity of 40°N and the Tropic of Capricorn. They further show that beachrocks were not primarily near the equator. Most of them were found in areas further from the equator, including Area A (Figure 1), where it shows that beachrocks do not occur only in places with warm air or sea temperatures. According to [1], [4], and [5], beachrock formation occurs through six distinct processes. Those are precipitation from sea water, precipitation from fresh water, CO_2 degassing, biological processes, sea water–fresh water mixing, and physico/chemical factors. Some beachrock sites have developed from more than one mechanism [4].

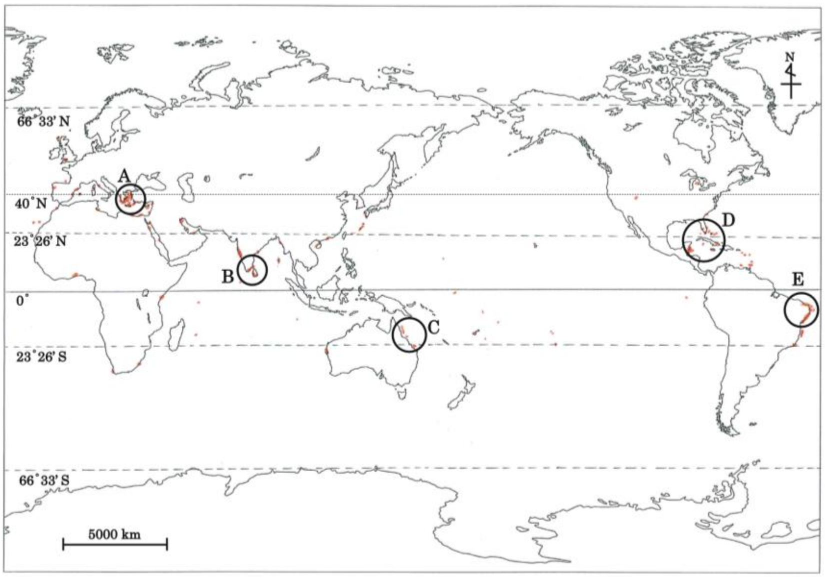

Figure 1: Global distribution of beachrocks [3]

In the Sri Lankan context, studies have been done in the southern and southwestern parts of the country. According to [5], most of the southern and southwestern sandstone-type beachrocks are composed of silica-rich grains cemented together by carbonated cement. [6] conclude that beachrock from some locations in the southern coastal region mainly consisted of Aragonite, which is similar to most of the potential sites in the world. However, the proper formation mechanism of beachrock in Sri Lanka remains undefined, with no detailed understanding of the mineralogical and elemental characteristics. Except southern coast, no detailed investigations were conducted in other coastal regions in Sri Lanka. Therefore, this research primarily focuses on the northwestern and western coastal areas, which have not been previously studied.

Through field observations and employing advanced analysis techniques like Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Spectroscopy (EDX), Fourier Transform Infrared Spectroscopy (FT-IR), and X-ray Diffraction (XRD), this study establishes mineralogy and the elemental composition of the beachrocks.

There are conventional soil improvement methods used to enhance soil properties using mechanical or chemical action. But conventional techniques have several significant drawbacks, often involving high costs, a long period for construction, and the need for many engineering materials. This research aims not only to determine the precise formation mechanism of Sri Lankan beachrock, focusing on Chilaw and Uswetakeiyawa coastlines, but also to open up the prospect for bio-mimetic applications for an effective ground improvement practice, merging geotechnical engineering with sustainable solutions.

2 Methodology

2.1 Study Area

2.1.1 Chilaw

Beachrock samples were randomly collected from 7 sampling locations (Table 1) along the tide line, covering a stretch of approximately 7 km from Welihena to Chilaw Sand Spits, (Figure 2) in the vicinity of the Chilaw lagoon. The study area is situated in the intermediate zone between the dry and wet zones of the western low country of Sri Lanka.

Table 1: Coordinates of sampling locations along the Chilaw coast

Location ID	Latitude	Longitude
CH 1	7.54389	79.78896
CH 2	7.564047	79.78812
CH 3	7.592622	79.78626
CH 4	7.575327	79.78732
CH 5	7.574527	79.78741
CH 6	7.606638	79.78632
CH 7	7.607297	79.78637

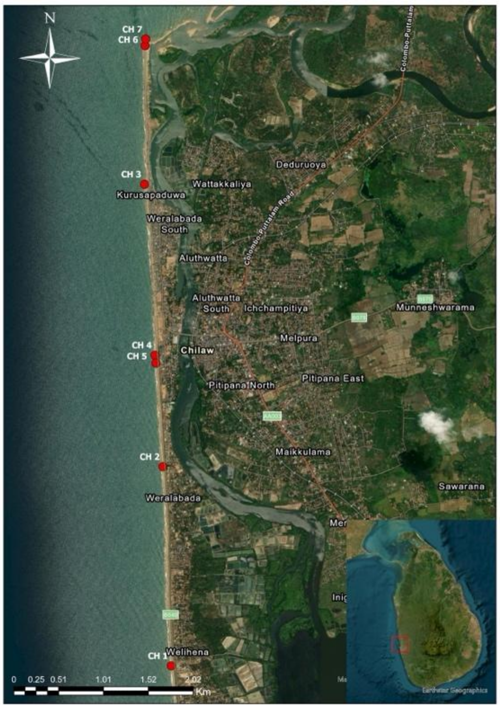

Figure 2: Sampling locations along the Chilaw coast

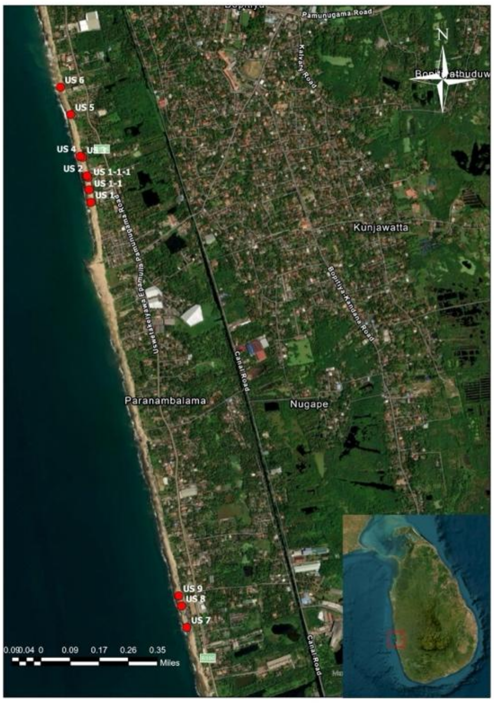

Figure 3: Sampling locations along the Uswetakeiyawa coast

2.1.2 Uswetakeiyawa

The study area spans approximately 2.5 km along the tide line in Paranambalama, Uswetakeiyawa. A total of 11 sampling locations (Figure 3 and Table 2) were identified for the random collection of beachrock samples.

Table 2: Coordinates of sampling locations along the Uswetakeiyawa coast

Location ID	Latitude	Longitude
US 1	7.071397	79.85117
US 1-1	7.07194	79.85108
US 1-1-1	7.072467	79.85104
US 2	7.07254	79.85098
US 3	7.073334	79.8508
US 4	7.073384	79.8507
US 5	7.075185	79.85029
US 6	7.076366	79.84985
US 7	7.053037	79.8553
US 8	7.053963	79.85508
US 9	7.054397	79.85496

2.2 Sample collection and preparation

In each location, approximately 100g of beachrocks were collected into plastic bags and transported out of the sites. Before testing, samples were air-dried at room temperature, and any algae and weathered surfaces were removed. In the laboratory, the rock samples were crushed into small pieces by a sledgehammer, and the pieces were powdered using a Temma Mill and sieved to obtain a particle size not greater than 63µm. Powder samples were used for mineralogical analysis in XRD, FT-IR, and elemental analysis in EDX. Crushed rock pieces, approximately 1 cm × 1 cm in size, were prepared to perform SEM-EDX, aiming to identify petrographic characteristics and determine surface elemental measurements.

2.3 SEM-EDX

SEM uses a focused high-energy beam of electrons to generate high-resolution images of the surface morphology of the sample. The surfaces of the prepared seven beachrock chip samples (four Chilaw and three Uswetakeiyawa) were observed microscopically and elemental composition was determined using EDX available in the Department of Materials Science and Engineering, University of Moratuwa.

2.4 FT-IR

The functional groups and chemical bonds of minerals are qualitatively determined by the

Bruker Alpha series FT-IR instrument available in the Department of Materials Science and Engineering, University of Moratuwa. The mineral analysis was performed according to the KBr pellet technique. For each sample, the spectra were taken in the region of 4000-400cm^{-1}, with Transmittance (%) being the y-axis and wavenumber (cm^{-1}) being the x-axis.

2.5 XRD analysis

Eight beachrock samples (CH 1, CH 2, CH 5, CH 6, CH 7, US 7, US 8, and US 9) were analyzed by Rigaku Ultima IV (Bruker Ultima IV) multipurpose XRD system, which is available at the Research Laboratory, Department of Nano Science Technology, Wayamba University of Sri Lanka. The analysis was carried out at room temperature, with CuKα radiation with a beam diameter of 10 mm at a scanning rate of 5° 2θ/min and a step size of 0.02° 2θ, ranging from 5° to 70°. Qualitative mineralogical analysis of the beachrock samples was determined, with the standard interpretation procedures of XRD using Match! software for phase identification.

3 Results

3.1 SEM imagery

SEM images of the beachrock samples tells about the morphology and evidence of cementation of the beachrock surface. From the SEM images of Chilaw and Uswetakeiyawa samples (Figure 4), Authors were able to identify the presence of bridge cement, meniscal cement, and micritic cement coatings, which are key textural features of carbonate cementation. These identifications suggest that the cementation occurs through carbonate cementation. Also, in the SEM images of both regions, High Magnesium Calcite (HMC) with scalenohedral terminations were identified.

3.2 SEM - EDX

SEM-EDX analysis helps to distinguish the type of cementation. In (Table 3) Chilaw samples, an average of 18.37% of Ca, 10.49% of Si, and a very small percentage of other major elements are present in the samples. In Uswetakeiyawa samples, an average of 19.22% of Ca, 15.97% of Si, and a smaller percentage of other elements are present in the samples. This shows that both samples contain calcium-rich material and silica-rich materials. The average $MgCO_3$ mol% of Chilaw beachrock samples is 22% and of Uswetakeiyawa is 18% (>4 mol%) and in both locations' beachrocks consist of HMC as per [4].

3.3 FT-IR

By comparing the observed frequencies of Chilaw and Uswetakeiyawa samples with the previous literature [7], [8], and [9], minerals such as Quartz, Chlorite, Feldspar (Orthoclase, Albite, and Microcline), Clay minerals (Kaolinite and Montmorillonite), and Carbonate minerals (Calcite, Aragonite, and Dolomite) were qualitatively identified. The observed frequencies are reported in Table 4. Apart from these minerals, some frequencies were observed that indicate the presence of organic materials.

3.4 XRD analysis

The XRD patterns of the samples, analyzed using Match! Analysis shows the presence of Quartz and Carbonate minerals (either Mg Calcite or Kutnohorite) in both Chilaw and Uswetakeiyawa regions. Quartz is consistently dominant, and the other identified minerals present in minor amounts including, Aragonite, Periclase, and Spinel. The presence of Magnesium Calcite (MC) is further confirmed by SEM imagery. Figure 5 shows the analyzed pattern of CH 5 with identified minerals.

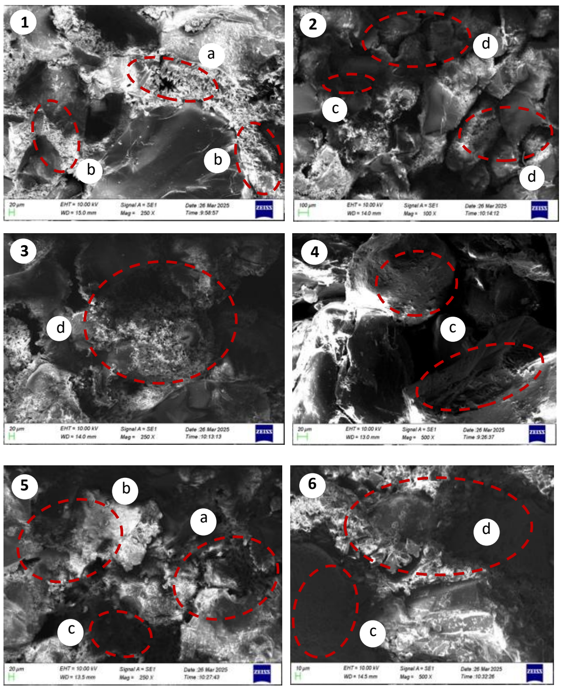

Figure 4: SEM images of Chilaw (subfigures 1-4) and Uswetakeiyawa ((subfigures 5-6) beachrocks. Marked features in the images include: (a)bridge cement with needle-like crystals, (b)meniscal cement, (c)micritic coating, (d)HMC with scalenohedral terminations

Table 3: SEM – EDX results of analyzed Chilaw and Uswetakeiyawa samples

Sample	Elemental Weight Percentage (%)									
	CK	OK	NaK	MgK	AlK	SiK	ClK	CaK	TiK	FeK
CH 2	11.75	53.28	4.66	3.16	3.35	7.07	2.12	12.23	0.18	0.97
CH 5	4.43	46.79	0.67	3.20	2.62	7.10	0.09	20.80	7.49	6.70
CH 7	1.63	53.75	0.38	2.40	1.24	17.29	0.16	22.04	-	0.86
US 7	1.52	50.90	-	1.85	1.05	22.41	-	20.89	-	1.23
US 8	4.14	47.88	0.47	2.85	1.46	15.42	0.21	23.15	1.94	2.26
US 9	3.10	43.89	1.16	2.73	4.20	10.09	0.64	13.62	11.59	8.96

Table 4: Observed absorption frequency for Chilaw and Uswetakeiyawa beachrocks in the region 400-4000 cm^{-1}

Quartz	Feldspar			Clay minerals		Carbonate minerals			Chlorite	Organic materials
	Orthoclase	Albite	Microcline	Kaolinite	Montmorillonite	Calcite	Aragonite	Dolomite		
454	431	421	428	432	876	1428	1084	2523	440	2885
461		427	464	3402	877	1431			442	2920
511		722	465	3405	878	1432				2924
691		788		3431		1433				
692		790		3433		1795				
792				3436		1800				

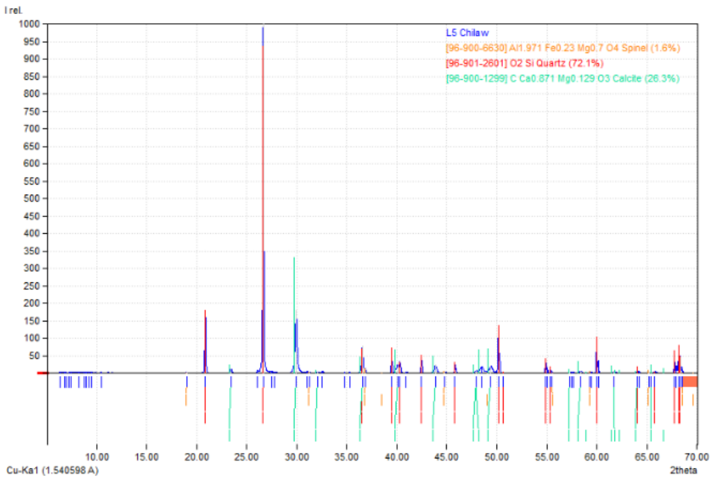

Figure 5: Analyzed XRD pattern of Chilaw (CH 5) sample using Match! software

4 Discussion

4.1 Morphology and surface nature of beachrocks

In Uswetakeiyawa, from location US 1 to US 6, beachrocks begin to appear at US 1, where the rock beds are almost flat, very hard, and form outcrops approximately 15 meters wide, extending for over 1 kilometer (Figure 6a). The thickness of the exposed outcrops varies across different locations. At US 1, beachrocks appear as isolated patches (Figure 6b), while at US 2, the thickness of the exposed beachrock is less than 10 cm (Figure 6c). Further along at US 5, the thickness increases to more than 12 cm (Figure 6d). At location US 1-1, two stacked beachrock beds were observed (Figure 6e). At US 2, the beachrocks are composed of beach sediments with larger particle sizes (Figure 6f). In locations US 5 and US 6, the surrounding sand is black, and black patches and bedded layers were visible within the beachrocks (Figure 6g). A notable discontinuity was also observed along the strike direction at this location. From US 7 to US 9, the exposed beachrocks are cemented sandstone. In these areas, the black sand and black patches present where in earlier locations were absent. However, a long discontinuity along the strike direction was still visible (Figure 6h). The surface texture of the exposed beachrocks in these locations differs noticeably from those at US 1 to US 6 (Figure 6i), although they are also composed of beach sediments with large particle sizes (Figure 6j).In Chilaw, beachrocks begin to appear at location CH 1 and extend up to CH 7, covering a distance of more than 7 kilometers, with an outcrop width of approximately 5 meters (Figure 7a, b). The exposed beachrock thickness in this region is greater than that observed in the Uswetakeiyawa area (Figure 7b). In most locations, the beachrocks are fractured and dip into the sea (Figure 7c, d). Cementation processes are still occurring on the surfaces of previously formed beachrocks, where seaweed and algae colonies have developed on the exposed rock surfaces (Figure 7e)

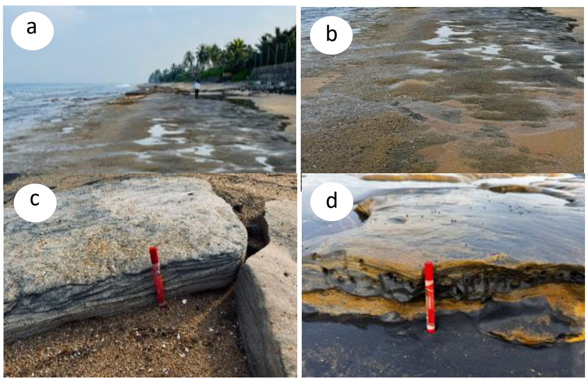

Figure 6: Exposed beachrocks in Uswetakeiyawa

Figure 7: Exposed beachrocks in Chilaw

4.2 Elemental and mineralogical analysis

The presence of meniscal cement, and micritic cement coatings indicates that the formation mechanism may be through the meteoric vadose carbonate cementation [10]. Also, in the SEM images of both regions, HMC with scalenohedral terminations were identified. The presence of HMC or Aragonite and bridge cement indicates that the formation may be from the precipitation of marine water [4]. From the SEM-EDX analysis, we confirmed the presence of carbonate-rich materials in the beachrocks. Additionally, XRD and FT-IR results supported the presence of HMC. Also, the presence of organic materials through

FT-IR results indicates there are possible effects from microorganisms [5]. By combining these observations and results, we suggest that the formation mechanism of beachrock is through the mixing of marine and freshwater, and biological processes.

4.3 Beachrock compositions around the World and in Sri Lanka

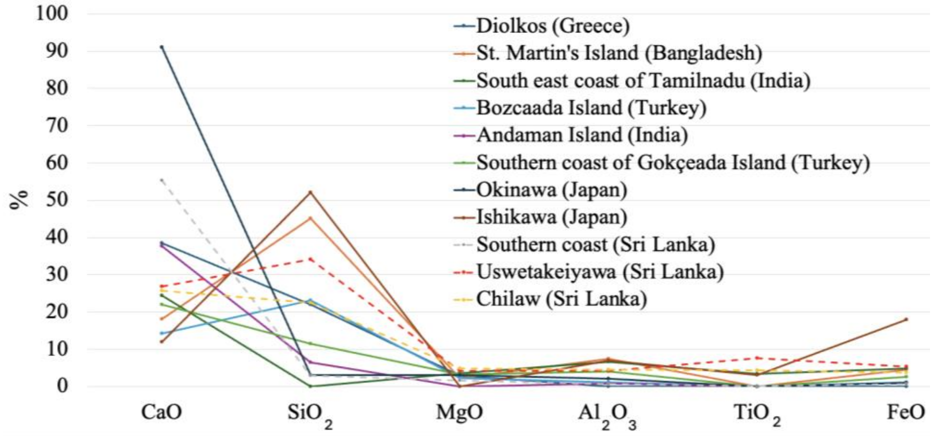

Figure 8: Comparison of beachrock compositions from this study and previously published studies [2], [3], [4], [6], [9], [10], [11] and [12]

If we consider the beachrock composition around the world with Sri Lankan Chilaw, Uswetakeiyawa and Southern coast beachrocks (Figure 8), in Okinawa (Japan), the beachrocks contain a very high CaO% (nearly 90%) compared to the composition in other countries [4]. This suggests that the cementation occurs through the $CaCO_3$ precipitation. Beachrock occurrences in Ishikawa (Japan), St Martin's Island (Bangladesh) [12], and Bozcaada Island (Turkey) contain a higher SiO_2% than CaO%. Also, from the graphs, we can get information that the composition of beach rocks within a country can vary significantly.

In Sri Lankan beachrocks, from the already done research on elemental analysis of beachrock [6], the beachrocks in the southern coast contain a very high amount of CaO%, which suggests that the cementation occurs through the precipitation of $CaCO_3$. In this study, the authors analyzed beachrock samples from Chilaw and Uswetakeiyawa. The Uswetakeiyawa samples exhibit a significantly higher SiO_2 content compared to those from southern coast and Chilaw. This trend is similar to observations from Ishikawa (Japan), St Martin's Island (Bangladesh), and Bozcaada Island (Turkey).

Additionally, the Uswetakeiyawa beachrocks show higher TiO_2 and FeO content than the beachrocks reported from these other locations. In contrast, in the Chilaw region, the CaO and SiO_2 contents are nearly equal.

4.4 Proposed formation mechanisms of beachrocks worldwide

Figure 9 shows the proposed formation mechanisms of beachrocks at 89 sites around the world. Among the proposed mechanisms, the most common is precipitation from seawater, followed by biological processes.

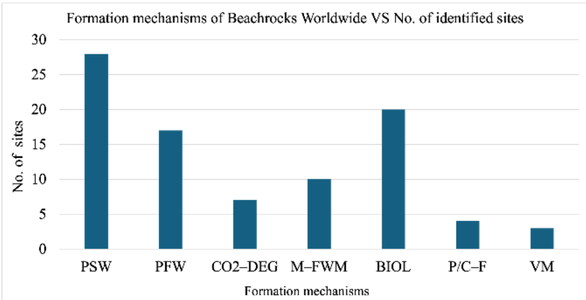

Figure 9: Proposed formation mechanisms of beachrocks at 89 sites around the world, based on data compiled from [1], [2], [4], [5], [10], [11], [13] and [14] PMW: Precipitation from marine water, PFW: Precipitation from fresh water, M-FWM: Marine fresh water mixing, BIOL: Biological processes, CO_2-DEG: CO_2 degassing, P/CF: Physico-chemical factors, and VM: Various mechanisms

5 Conclusion

This research has addressed the knowledge gap associated with the formation of beachrocks in the Chilaw and Uswetakeiyawa regions of Sri Lanka. The combined evidence from SEM images, SEM-EDX, XRD, and FT-IR analyses indicates that both mixing of marine and freshwater and biological processes contribute to the cementation of these beachrocks. Overall, these beachrocks differ from Southern Sri Lankan sites, that is dominated by Aragonite and precipitated from marine water. This observation shows that the composition and formation mechanism of beachrock have varied along the Southern to Western coastal regions of Sri Lanka, and the reasons for this variation need to be confirmed by further studies.

Acknowledgements

The authors wish to extend their gratitude to all who supported this research. Special thanks to Prof. Satoru Kawasaki of Hokkaido University, Japan, for expert guidance. We are grateful to Dr. Ashane Fernando and Dr. Upeka Samarakoon from the Wayamba University of Sri Lanka, and Dr. A.M.P.B. Samarasekara and Dr. D.A.S. Amarasinghe of the Department of Materials Science and Engineering of the University of Moratuwa for providing us with the opportunity and support for laboratory testing and analysis. We are also thankful to Mr. Mihiranga Jayaweera and Mr. Pubudu Gunawardana for their technical support with SEM-EDX and FT-IR analysis, respectively. We thank the Department of Earth Resources Engineering for facilities and staff support, with particular gratitude to Ms. A. Ranjanie Amarasinghe for her invaluable assistance during fieldwork, laboratory testing, and equipment handling.

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