Research Brief https://doi.org/10.31705/BPRM.v5(2).2025.20

Beachrocks Reveal Blueprint for Coastal Sustainability:

An Attempt to Explore Natural Cementation Characteristics

Beachrocks may look like just hardened sand on the shoreline, but globally, they tell a fascinating story about how nature turns sand into stone. Beachrocks are found along tropical and subtropical coastlines worldwide, exhibiting strong variation in composition and cementation characteristics [1]. In Okinawa, Japan, beachrocks exhibit extremely high calcium carbonate ($CaCO_3$) content, indicating that cementation is dominated by precipitation from seawater [2]. In contrast, locations such as Ishikawa in Japan, St. Martin's Island in Bangladesh, and Bozcaada in Turkey contain higher silica (SiO_2) content, suggesting a combination of processes influenced by varying local sediment supply and limited carbonate cementation [2],[3]. These compositional differences indicate that beachrock formation cannot be explained by a single process but instead involves complex interactions among seawater chemistry, freshwater mixing dynamics, biological processes, climate, and geological conditions.

In this context, recent studies emphasize the growing importance of nature-based and bio-inspired solutions for sustainable coastal protection and ground improvement, particularly under increasing climate-driven coastal vulnerability. However, despite extensive global research on beachrock formation, significant knowledge gaps remain in understanding region-specific cementation mechanisms, especially along the northwestern and western coasts of Sri Lanka. Moreover, the role of biologically mediated carbonate precipitation in beachrock formation and its potential translation into engineered ground-improvement techniques remains underexplored. Addressing these gaps is essential to align beachrock research with current sustainability-driven engineering needs.

Against this background, the composition of Sri Lanka's beachrocks reflects a wide variety of formation environments. Aragonite-rich beachrocks along the southern coast are likely dominated by direct seawater precipitation [4]. In contrast, nearly equal proportions of CaO and SiO_2 observed along the northwestern coast at Chilaw suggest cementation through the mixing of marine and freshwater. Silica-rich beachrocks exposed along the western coast at Uswetakeiyawa represent formation mechanisms comparable to those reported from Bangladesh, Japan, and Turkey.

Detailed investigations of beachrocks in the Chilaw and Uswetakeiyawa regions were therefore conducted to better understand their cementation characteristics and formation processes. In general, quartz grains are cemented by high-magnesium calcite (HMC; $(Ca,Mg)CO_3$) exhibiting scalenohedral crystal morphologies, characterized by sharply pointed, multi-faced

crystal terminations. Such scalenohedral HMC crystals indicate rapid carbonate precipitation under supersaturated pore-water conditions, commonly associated with marine–meteoric water mixing environments. The presence of meniscal and micritic cement coatings within the matrix further indicates combined meteoric vadose and marine influences.

Additionally, the occurrence of micritic carbonate coatings and traces of organic matter within the cement matrix indicates biologically mediated cementation, potentially involving microbial degradation of organic material and microbially induced carbonate precipitation (MICP). Overall, the formation of beachrocks in these regions reflects a cooperative interplay between marine-freshwater mixing and biologically influenced carbonate precipitation, demonstrating nature's intrinsic capability to stabilize loose coastal sediments.

The mechanisms through which beachrocks form provide valuable insights into natural cementation and stabilization processes. Unlike conventional soil-stabilization methods that rely heavily on cement or synthetic chemicals, beachrocks demonstrate how sediments can be naturally bound through interactions among water, minerals, and biological activity. Replicating such processes could support the development of environmentally friendly ground-improvement and coastal protection techniques with reduced carbon footprints.

Finally, comparative studies of beachrock formations in Sri Lanka, Japan, Bangladesh, and South Africa provide valuable natural analogues for resilience-based coastal engineering solutions that operate in harmony with ecological systems. The next time one steps onto an unusually hard patch of sand along a shoreline, it may well represent a segment of a global archive of beachrocks, a natural coastal phenomenon with promising implications for sustainable engineering practices.

Fig. 1 : Aragonite-rich southern coast beachrocks

Fig. 2 : CaO and SiO_2 equally dominant northwestern coast beachrocks exposed in Chilaw

Fig. 3 : Silica-rich western coast beachrocks exposed in Uswetakeiyawa

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