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DEVELOPMENT OF A LITERATURE-BASED DATABASE ON BEACHROCK FORMATION IN TROPICAL ASIA

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ABSTRACT: Global beachrock (BR) distribution, characteristics, and formation mechanisms remain subjects of ongoing debate. A comprehensive database that compiles all documented BR occurrences is essential for improving our understanding of BR formation processes and BR spatial patterns. However, no up-to-date unified global database currently exists. This study takes the first step toward addressing this gap by developing a regional database focusing on the tropical Asian region. A systematic literature review was conducted, resulting in the compilation of 122 documented records of BR occurrences. The collected records were then analyzed to determine spatial patterns, regional variations, BR composition, cements, and cementation mechanisms. The findings reveal that BR formations are concentrated mainly in certain coastal areas, especially the East China Sea (Western Japan), whereas many other areas remain poorly documented or entirely unstudied. The composition of BR particles varies according to local environmental and geological conditions. Cement analysis records reveal that aragonite and High Magnesium Calcite are the dominant types. Cementation occurs through seawater precipitation, microbial activity, and freshwater processes, with seawater precipitation being the most prevalent mechanism. The findings serve as a baseline framework, contribute to the development of a global BR database, and provide insights into BR formation processes in tropical regions.

Keywords: Asian tropical coasts, Carbonate cements, Cementation, Sedimentary rocks, Spatial pattern

1. INTRODUCTION

In general, beachrocks (BR) are naturally consolidated shoreline sedimentary formations typically found in tropical and subtropical regions, particularly within intertidal and supratidal zones [1]. BR commonly occurs parallel to the present shoreline and often displays distinct layering or banded sequences with associated textural laminations. These bands generally dip gently seaward, following the beach slope, although in some locations BR orientations differ from the modern shoreline due to post-depositional processes. BR bodies vary widely in scale, ranging from small patches to extensive outcrops extending several kilometers, and can be either friable or well-cemented [2,3,4]. BR are composed of beach-derived sediments including sand and gravel from siliciclastic, bioclastic, or volcaniclastic sources bound together through rapid cementation. This cementation is mainly driven by the precipitation of carbonate minerals, predominantly High-Magnesium Calcite (HMC) and Aragonite (Ar) [5,6].

Numerous global studies on BR indicate that over 90% of BR occurrences are concentrated between 40°N and the Tropic of Capricorn (~23°S) [7]. However, more recent research has identified sporadic occurrences in temperate and colder regions (at higher latitudes), challenging the traditional view that BR formation is limited to tropical and subtropical areas [1,8]. In tropical and subtropical settings, BR typically forms as extensive, shore-parallel ledges with relatively uniform distribution, supported by stable, low-energy beach conditions and high temperatures that promote rapid cementation. In contrast, temperate BR commonly occurs as isolated concretions buried deeper within the beach profile, reflecting more variable environmental conditions, including shoreline instability and episodic erosion [1]. These contrasting characteristics highlight that many questions remain regarding the global distribution and characteristics of BR. Much of the existing research is highly case-specific. Earlier researchers, such as Russell and McIntire (1965) [9], conducted extensive field campaigns across diverse geographic locations to identify the key processes responsible for BR formation based on field observations. However, many of the general conclusions drawn from the observations have later been found to be invalid in other cases. Hence, the process of BR genesis is not yet fully understood.

A comprehensive database that compiles all documented BR occurrences is essential for advancing our understanding of the global distribution, characteristics, and formation mechanisms of BR. The first global inventory of documented BR occurrences was compiled by Vousdoukas et al. (2007) [6]; however, no up-to-date unified global database currently exists. Creating such a database requires systematic and consistent data collection and analysis on a global scale. This study takes an initial step toward addressing this gap by developing a regional database focused on the tropical Asian region. As tropical Asia contains some of the most potentially significant zones for BR formation, beginning with this region provides a strong foundation for improving our understanding of BR distribution, characteristics, and genesis. The regional insights generated here will serve as an essential basis for future expansion toward a more complete global BR database.

The main objectives of this study are: (1) to compile and develop a regional database of documented BR occurrences in the tropical Asian region; (2) to identify spatial patterns and regional variations in BR distribution and characteristics; and (3) to analyze BR composition, cements, and cementation mechanisms based on documented records.

2. RESEARCH SIGNIFICANCE

The BR distribution, characteristics, and formation mechanisms remain subjects of ongoing debate. A comprehensive database that compiles all documented BR occurrences is essential for improving our understanding of BR formation processes and BR spatial patterns. However, no up-to-date unified global database currently exists. This study takes the first step toward addressing this gap by developing a regional database focusing on the tropical Asian region. The findings serve as a baseline framework, contribute to the development of a global BR database, and provide insights into formation processes in tropical regions.

3. METHODOLOGY

A systematic literature review was conducted to compile documented BR occurrences within the tropical Asian region. The summary of methodology is illustrated in Fig.1 below.

The methodology followed a structured approach consisting of identification, screening, eligibility assessment, geospatial verification, data analysis, and database development. In the identification stage, a comprehensive search of *Scopus* and *JSTOR* databases, covering publications from 1960 to 17 March 2025, was performed using the keywords "beachrock," "beach-rock," and "beach rock," which yielded 320 publications (n=320). During screening, publications reporting BR occurrences within the tropical Asian region (~23°S to ~30°N) were selected, and duplicates were removed, resulting in 68 publications for further evaluation. Eligibility assessment was then conducted using defined criteria: inclusion of peer-reviewed, English-language journal articles or review papers documenting BR occurrences, and exclusion of studies lacking full-text access or sufficient descriptive information. Following this step, 44 studies were deemed eligible.

For geospatial verification, the reported coordinates of BR occurrences were confirmed using *Google Earth* and *ArcGIS*, and when coordinates were missing, they were estimated using maps, site descriptions, and contextual geographic information. The verified records were analyzed to extract information on sediment composition, cement types, cementation mechanisms, and spatial patterns.

3.1 Resource Availability

The compiled Tropical Asian Region Beachrock Database (TARBD) is publicly accessible via **https://doi.org/10.5281/zenodo.17759821**.

4. RESULTS AND DISCUSSIONS

4.1 Beachrock Occurrences and Literature

A total of 122 records of BR occurrence records were compiled from 44 published studies across the

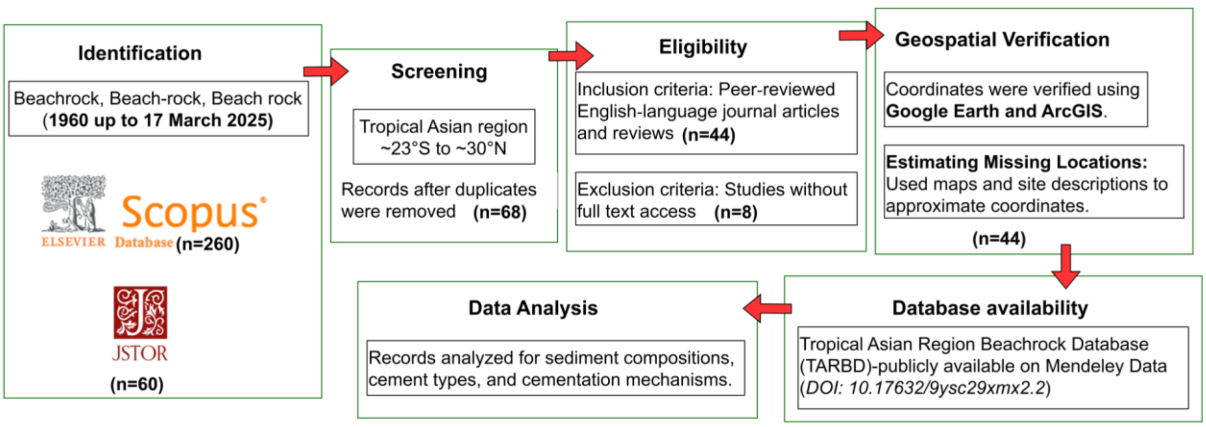

Fig.1 Methodology flowchart

tropical Asian region. Fig. 2 presents the decadal comparison between documented BR occurrences and BR-related scholarly publications. The number of publications shows a steady increase, reaching its peak between 2010 and 2019. BR occurrence records also rise noticeably after 2000, indicating improved reporting and expanded field investigations. The research gap noted by Vousdoukas et al. (2007), who highlighted the limited number of studies from tropical regions, appears to have narrowed [6]. The marked increase in publications after 2007 suggests that this gap is progressively being addressed.

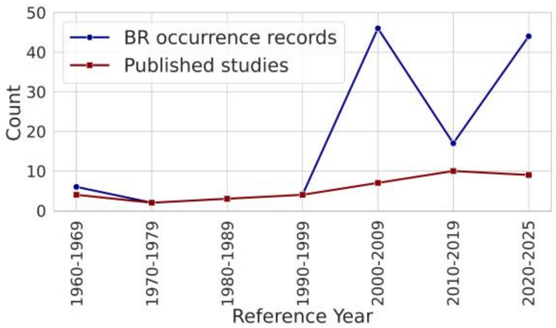

Fig. 2 Comparison of decadal trends in documented BR occurrence records and the number of scholarly publications on BR

Fig. 3 illustrates the distribution of BR literature across the tropical Asian region. India has the highest number of BR-related publications, whereas Bangladesh shows the lowest level of representation.

4.2 Beachrock Spatial Distribution

A spatial distribution map of the 122 BR occurrence records was created in *ArcMap 10.8.2* to visualize and verify the geographic coordinates of each documented site. Fig. 4 represents the spatial distribution of the 122 BR occurrence records. Fig. 5 highlights areas of higher occurrence density, primarily concentrated in the East China Sea (Western Japan), as identified through hot spot analysis.

In addition to research limitations, several natural and anthropogenic factors contribute to the lack of recognized BR sites. Naturally, rising sea-levels can submerge BR formations, making them difficult to access or observe, while wind-driven sediment accumulation may bury them beneath surface layers leading to seasonal exposure. Human activities such as coastal development, dredging, sand mining, and constructions may have disturbed or destroyed BR before they are documented. Furthermore, legal restrictions in protected, historical, or conservation areas may limit scientific access, as regulations

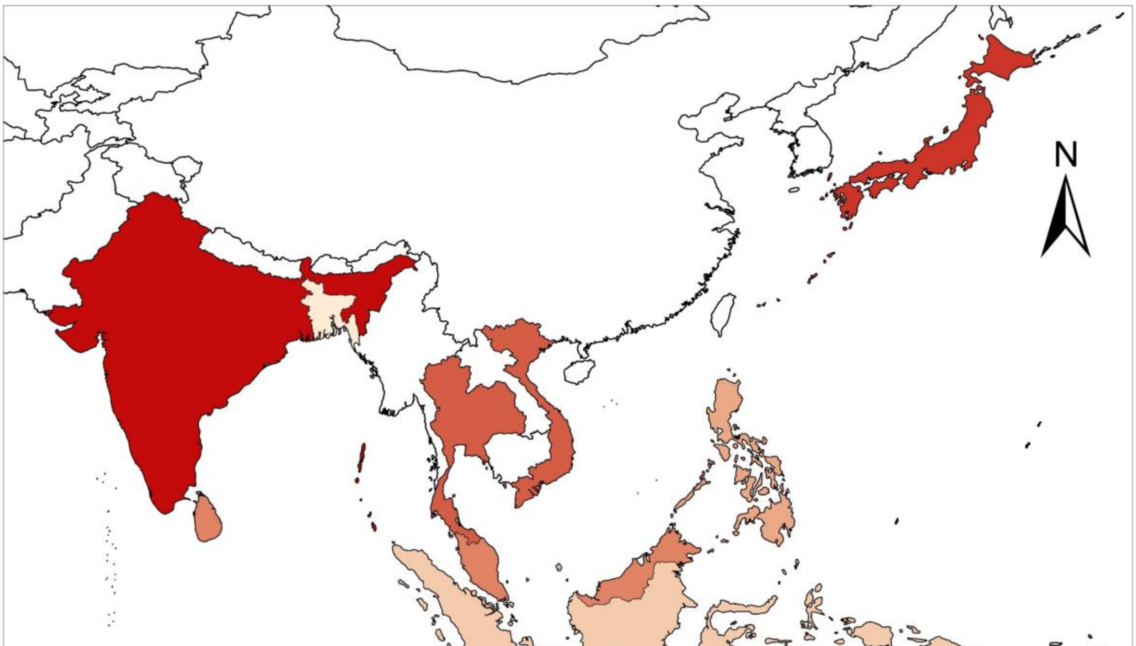

Fig. 3 Distribution of BR literature in tropical Asia

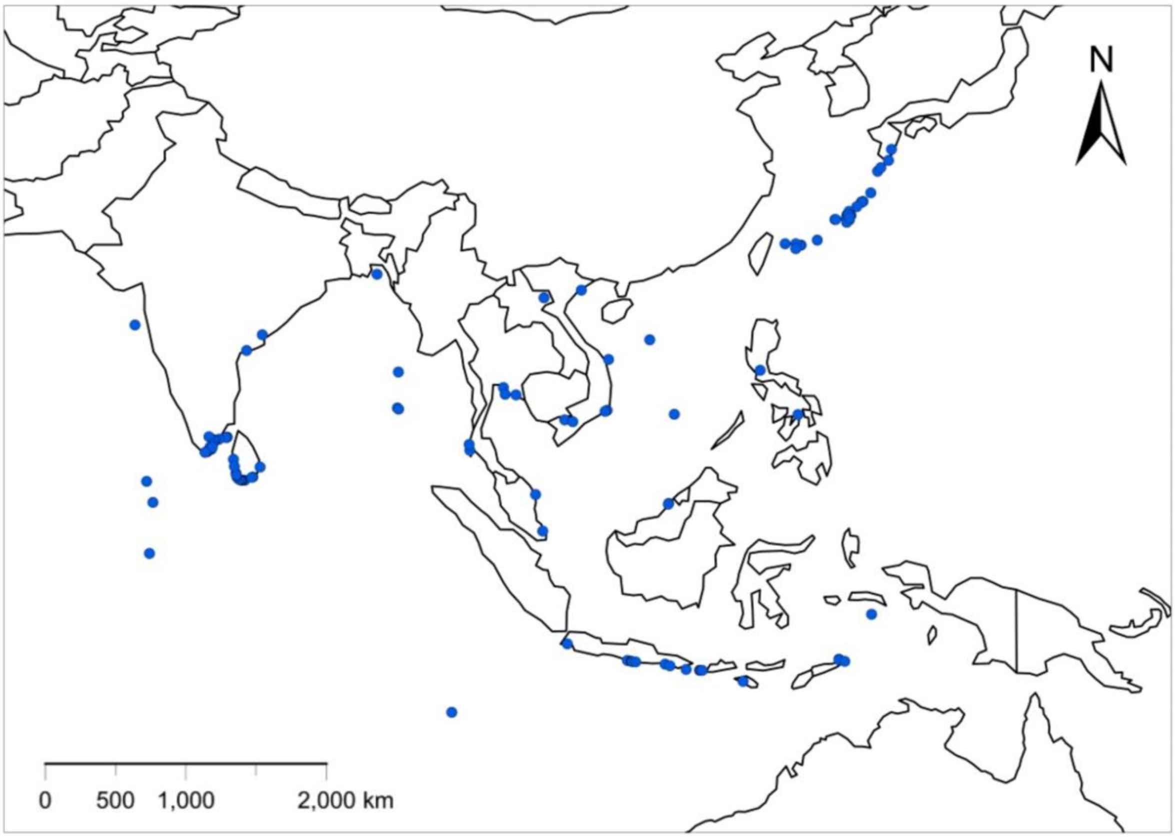

Fig.4 The spatial distribution of reported BR occurrence records

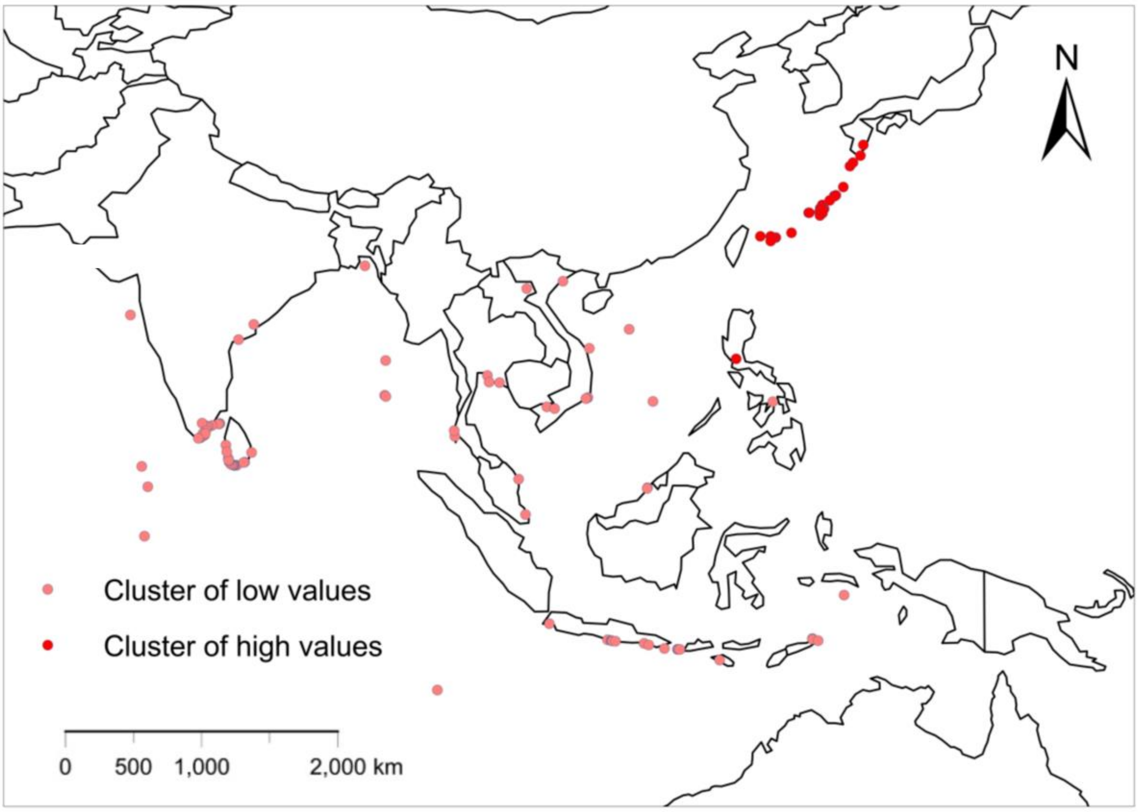

Fig.5 The areas of higher occurrence density, as identified through hot spot analysis

often prohibit the extraction of geological materials to preserve cultural and ecological value.

The distribution of BR occurrences by area or country is presented in Fig. 6.

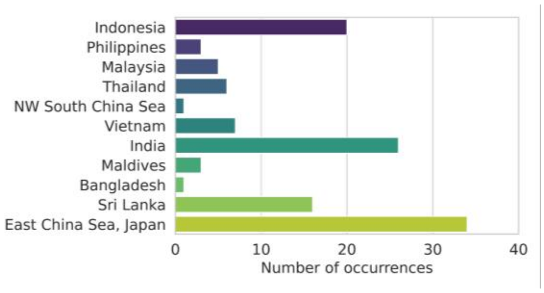

Fig.6 The distribution of BR occurrences by area or country

The East China Sea (Western Japan) has the highest number of occurrences, while Bangladesh and the northwestern South China Sea report the fewest. The absence of documented BR occurrences along the coasts of Brunei, Cambodia, Myanmar, Papua New Guinea, Indonesia, and Singapore likely reflects limited research attention and insufficient field investigations, highlighting gaps in the TARBD.

Fig.7 illustrates the relationship between count of BR occurrences and latitudes. Most reported BR occurrences were associated with coastal regions within latitudes 0–10°N.

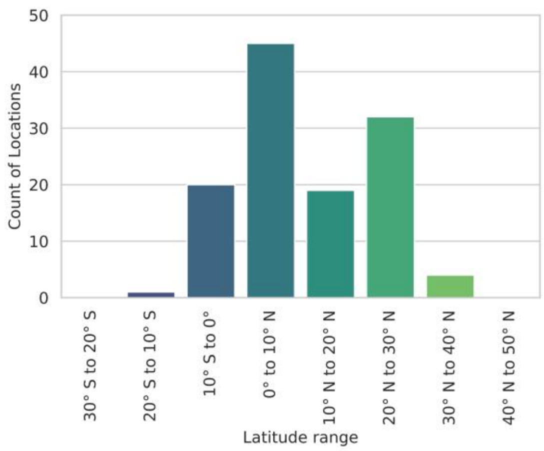

Fig.7 The BR occurrence counts across different latitudes

A notable number of BR occurrences were identified within the 20°S to 40°N latitude range. These findings contribute to a slight increase in the percentage previously reported by Danjo and Kawasaki (2014) [7], who observed that over 90% of global BR occurrences were concentrated between 40°N and the Tropic of Capricorn (~23°S).

4.3 Beachrock Morphology

Tropical Asian BR typically formed between the high and low tide levels, extending extensively along shorelines and often reaching inland, where they were sometimes buried beneath a thin layer of loose beach sediments. These BR formations ranged from small, localized patches of cemented sediments to expansive outcrops extending over several kilometers (Fig.8). The thickness of BR varied considerably, from less than 0.5 m to over 2.5 m. Thicker formations were generally located in areas with a significant tidal range, indicating the influence of tidal dynamics on their development [6].

The morphology of BR varies widely across the tropical Asian region, influenced by factors such as sea-level fluctuations, local environmental conditions, climatic events, tectonic activity, and coastal morpho-dynamics [6,9]. In tectonically active settings like Java, these controls are especially evident: shorelines commonly feature broken and redeposited BR boulders situated close to their original in situ positions. These displaced fragments result primarily from strong wave energy that detaches and shifts the blocks over short distances. Additionally, many BR surfaces exhibit visible splits and fractures, although the separated pieces often remain in place with minimal lateral movement. This demonstrates how dynamic coastal and tectonic processes shape BR morphology at both site-specific and regional scales.

BR exposures typically exhibit clear layering or banded sequences, often accompanied by textural laminations. These bands generally dip gently seaward in alignment with the natural beach slope [6,10]. Stratified BR outcrops (Fig. 9) commonly consist of medium-bedded layers with occasional thin beds and may display continuous or discontinuous graded bedding. Along the coast, these stratified bodies occur in both submerged and subaerial settings and typically extend 10–40 m in width [11].

Fig.9 Visual representation of stratified BR outcrops at Koggala beach, Sri Lanka

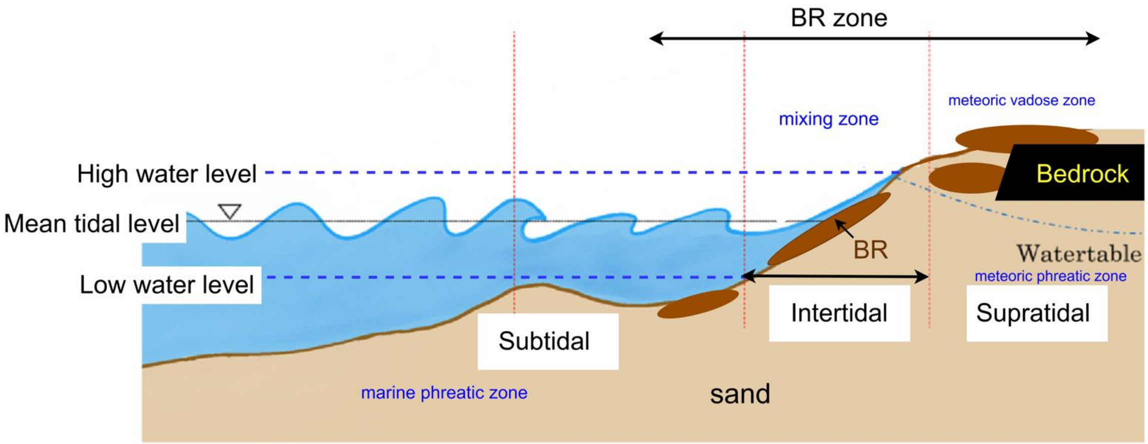

Fig.8 Schematic cross-section illustrating the diagenetic zones within the BR body

Some BR units, however, show orientations that differ markedly from the modern beach configuration. Such deviations are often attributed to post-cementation diagenetic alteration [6,10]. Due to constant exposure to waves and sediment movement, BR outcrops undergo progressive modification through fracturing, abrasion, and corrasion. During repeated erosion–accretion cycles, older detached fragments can become reworked and incorporated into younger BR horizons [2,6,10].

The dips of stratified BR beds generally correspond to the coastal slope, typically ranging from 8° to 12° towards the sea, with strikes parallel to the shoreline. Dip variability reflects local conditions such as beach gradient and wave energy [9]. Coastal hydrodynamic intensity—defined as the strength and motion of water along the shore—plays a major role in shaping BR formation, influencing their width, layer thickness, sedimentary structures, and overall developmental patterns [6,9].

On the other hand, BR can be difficult to distinguish from other coastal cemented deposits. Supratidal “cay sandstone” or cayrock forms on reef islands and differs from BR by its horizontal bedding, excellent sorting, and dominant meteoric calcite cement. Aeolianite, another common coastal cemented deposit, is also meteoric-cemented but is identifiable by wind-generated structures such as cross-stratification. Other cemented features such as rampart and boulder rocks, elevated reefs, reef terraces, and lithified layers on tidal flats or shallow seabeds may resemble BR but differ in origin and should not be considered true BR [10].

4.4 Beachrock Components

BR composition in tropical regions largely mirrors the sediment supply of nearby beaches, with most BRs comprising well-sorted marine carbonate grains such as coral fragments, shell debris, and other bioclasts (Fig.10b). These particles typically range from sand to gravel size and are often better sorted than adjacent subtidal sediments. Primary sedimentary structures are frequently preserved within BR, providing valuable clues for reconstructing depositional environments and understanding BR formation processes [1,2,3,6,9].

Layering or banding is a common textural feature and often develops because fine-grained layers undergo faster and more efficient cementation than coarser ones (Fig. 10a). Smaller pore spaces in finer sediments promote quicker precipitation of carbonate cements, producing distinct stratification within the BR [6,9,12]. Occasionally, various anthropogenic or natural artifacts may become incorporated during cementation, as documented in cases such as WWII relics preserved within BR at Enewetak Atoll [10].

In volcanic coastal settings, the composition of BR differs markedly. Instead of marine carbonates dominating the sediment mix, particles derived from volcanic rocks are incorporated. Intense weathering of volcanic materials enhances the release and mobilization of iron, promoting iron-oxide cementation and mineral replacement [13]. This results in characteristic reddish to brown coloration and distinctive cement fabrics, setting volcanic-influenced BR apart from the carbonate-dominated BR typical of tropical regions [2,3,5,6].

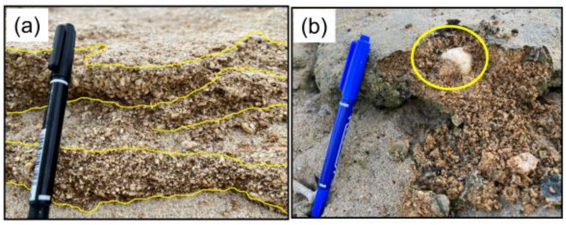

Fig.10 (a) Layered BR outcrop displaying well-defined sedimentary banding formed by differential cementation of fine- and coarse-grained layers, (b) A shell fragment trapped and cemented within the BR matrix, illustrating the incorporation of bioclastic material during lithification.

4.5 Cements

Analysis of 81 BR records with complete mineralogical information shows that Ar is the dominant cement type, followed by HMC, whereas silica was identified at only one site, indicating it is a rare cementing agent in tropical BR (Fig. 11). BR cement type depends upon factors like temperature, salinity, pH, and abundance of magnesium in the environment. Calcite occurs in two distinct forms, HMC and Low Magnesium Calcite (LMC), both of which are polymorphs of calcium carbonate ($CaCO_3$). HMC contains more than 1.2 wt.% magnesium carbonate ($MgCO_3$) [6] while LMC contains less than 4 mol% $MgCO_3$. Both HMC and Ar cements predominantly form in the marine-phreatic zone, where continuous saturation promotes rapid carbonate precipitation. They are also occasionally observed in the marine-vadose (wave-spray) zone, where intermittent wetting leads to meniscus and gravitational fabrics as well as whisker-like crystals [6,10].

In contrast, LMC forms in meteoric-phreatic and meteoric-vadose zones, reflecting freshwater influence. Texturally, HMC occurs as micritic groundmass or bladed, fibrous, and peloidal crystals, while Ar typically develops needle-like isopachous fringes or micritic rims. LMC is characterized by dripstone fabrics in vadose settings and blocky crystals under phreatic conditions. Together, these patterns highlight the strong control of hydrological zone and pore-water chemistry on BR cement mineralogy and textures [6,7,10].

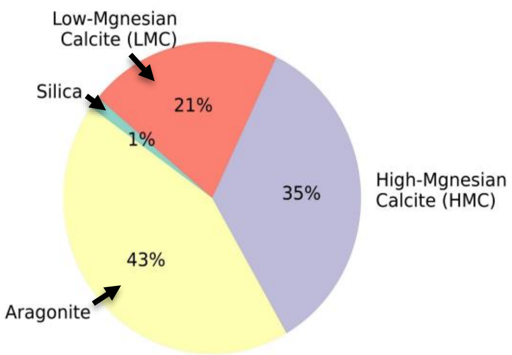

Fig.11 The statistical comparison of cement mineralogy in the tropical Asian region

4.6 Cementation Mechanisms

Among the 122 BR records compiled, only 60 contained complete information on cementation mechanisms (Fig. 12).

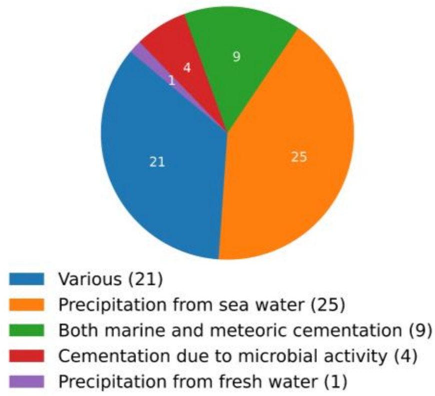

Fig.12 The statistical comparison of cementation mechanisms in the tropical Asian region

Analysis of these data shows that seawater precipitation is the dominant cementation process in the tropical Asian region, reflecting the strong influence of marine-phreatic and marine-vadose conditions on carbonate cement formation. Several sites fall into a 'various' category, where multiple processes such as seawater precipitation, meteoric influences, and microbial activity operate together. This reinforces that no single mechanism can fully explain BR formation.

Current explanations generally fall into two groups: physico-chemical processes, where carbonate precipitates directly from seawater, and biologically induced processes, where microbes promote $CaCO_3$ formation [13]. Although seawater precipitation appears most common in the available dataset, this pattern is partly constrained by the limited number of studies reporting detailed cementation mechanisms.

5. CONCLUSION

By systematically compiling and analysing documented BR occurrences, the study aimed to enhance understanding of beachrock spatial distribution, regional variability, compositional characteristics, and cementation mechanisms. Based on the findings, the following key conclusions can be drawn:

1. The geographical distribution of BR in the tropical Asian region reflects concentrated research in certain coastal areas, while other parts remain poorly studied or lack research entirely.
2. BR ranges in size from small patches to extensive outcrops, including multiple beds, spanning hundreds of meters to several kilometers.
3. The composition of BR particles depends on the local environment and geology.
4. BR cements can form from seawater (marine) or rainwater (meteoric), with different crystal types

and textures depending on where and how they form.

5. No single theory can explain all BR formations; instead, different processes often work together at the same BR site.

6. ACKNOWLEDGMENTS

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