Distribution and cementation characteristics of beachrocks along southern, southwestern and western coast of Sri Lanka

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Abstract

Beachrocks are sedimentary structures where gravelly or sandy beaches have been transformed into rock outcrops formed through precipitation of connective cements amid their interstices. They are well-noted coastal features along the coastal belt of Sri Lanka due to the prevalent tropical climate. This study was aimed at gathering data on surface nature and cementation characteristics of beachrock occurrences along a part of Sri Lankan shoreline through field observations and a series of analyses including X-ray diffraction, X-ray fluorescence, scanning electron microscopy (SEM) techniques and petrographic thin-section analysis. The combined research findings from different techniques are also employed as a preliminary step to determine the formation mechanism of the studied beachrocks. The seaward-inclined low-angle beds running parallel to present shoreline are composed mostly of sandstone with occasional conglomerate. Almost all the beachrocks are made of quartz grains amalgamated by cement. One remarkable feature of Sri Lankan beachrocks is the presence of heavy minerals generally in thin lamina form. The cementing agents are predominantly composed of metastable carbonate phases, high magnesium calcite (HMC) and aragonite (Ar) with varying microfabrics and textures. From SEM examinations and thin-section images, main morphologies identified are acicular Ar, scalenohedral magnesium calcites along with bridge cements and micritic coatings which are typical of a marine-phreatic precipitation with the exception of occasional meniscus cements. Further, the presence of evidences of living organisms may be an indication of influence from the biological aspects which can be confirmed by more detailed analyses.

Keywords Beachrocks · Carbonate cements · Marine phreatic precipitation · Microfabrics and textures · Spectroscopic analysis

1 Introduction

Beachrocks are a type of friable to well-cemented sedimentary formations in which beach sediments including sands and gravels of siliciclastic, bioclastic and volcanoclastic origin are bound together by precipitated carbonate cements usually in intertidal and/or supratidal zone (Ginsburg 1953; Vieira and De Ros 2006; Howie 2009).

The specific formation mechanism of beachrocks is still debated. Some of the theories that have been accepted are direct precipitation of calcium carbonate from beach interstitial waters and/or fresh water, precipitation induced by marine—freshwater mixed systems, CO₂ degassing from coastal water tables (Ginsburg 1953; Russell and McIntire 1965; Scoffin 1970; Hanor 1978) and direct or indirect influence from biological activities (Krumbein 1979; Neumeier 1999; Webb et al. 1999; Khadkikar and Rajshekhar 2003).

The occurrence of beachrocks is significant due to many aspects as indicators of sea-level changes (Mauz et al. 2015), as a recorder of Holocene events including natural disasters (Friedman 2011), ability to act as a natural wave barrier (Chowdhury et al. 1997; Calvet et al. 2003; Voudoukas et al. 2007), their contribution to coastal evolution (May et al. 2012), and as a factor that changes beach morphodynamics and recreational values (Voudoukas et al. 2009).

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The composition of the beachrocks is that it contains all kinds of beach sediments including sand and gravels, rock fragments, shells, coral conglomerates, and even anthropogenic wastes that were present at their time of lithification (Ginsburg 1953; Wagle 1990; Arrieta et al. 2011; Chandrasekaran et al. 2015).

Extensive studies carried out on beachrocks all over the world have shown that tropical and subtropical climates are more preferred for beachrock formation and over 90% of the occurrences are between 40°N and Tropic of Capricorn (Danjo and Kawasaki 2014). However, sporadic occurrences in temperate regions and cold areas have been identified by more recent investigations, thus eliminating the idea that beachrocks are a characteristic feature in tropical and subtropical regions (Kneale and Viles 2000; Cooper et al. 2017). Among various beachrock occurrences in the world, there have been references to abundant existence of beachrocks in Indian Ocean in St Martin's Island—Bangladesh (Chowdhury et al. 1997), Keeling Islands (Russell and McIntire 1965), Andaman and Nicobar archipelago (Chandrasekaran et al. 2015), Mozambique (Siesser 1974), South Africa (Siesser 1974), Seyshelles (Russell and McIntire 1965) and along coasts of India (Wagle 1990; Ravisankar et al. 2012). Although limited to very few investigations and published data, Sri Lanka, an island in Indian Ocean can be considered as a 'hot spot' for tropical beachrocks.

In Sri Lanka, reef-like or small occurrences of beachrocks are exposed in many places along the present coastline in localities along the western, southwestern, southern and eastern coasts. Literature suggests that those formations are similar to what are found in the coasts of Brazil, Uruguay, Venezuela and Hawaiian Islands (Cooray 1968). However, the amount of research dedicated to investigate the Sri Lankan beachrocks so far is negligible and no systematic studies on the cementation characteristics have been carried out.

The beachrock cement composition and morphology is primarily dependent on its diagenetic environment. According to the studies on cementation characteristics of beachrocks, a high inconsistency in fabrics and textures of different beachrock cements and coexistence of different types of cement in beachrock have been found (Vousdoukas et al. 2007). However, major composition of beachrock cements is either calcitic or aragonitic. Although the cementation process and resulting mineralogy are dependent on various physico-chemical factors, such as pH, salinity, temperature and availability of Mg, it is a commonly accepted norm that calcite is derived from meteoric water or a mixture of marine—meteoric water while aragonite is a result of precipitation from sea water and is found generally in marine-phreatic zone (Vousdoukas et al. 2007). Therefore, it is undoubtedly clear that cementation characteristics unravel important evidences about the origin of beachrocks. Further, detailed investigations can be done to examine the

mineralogical and elemental composition of beachrocks using spectroscopic analysis techniques exposing valuable information on the sedimentary environment and the beachrock-formation mechanism.

Therefore, this study is primarily aimed at establishing the existence of tropical beachrocks along a part of southern, southwestern and western coastal belt of Sri Lanka and evaluating the cementation characteristics in detail using spectroscopic methods. Interestingly, to the best of authors' knowledge, there are no other reports published about Sri Lankan beachrocks with this much focus on the cementation.

1.1 Previous findings

Knowledge of the existence of beachrocks in Sri Lanka is very limited especially due to the limited amount of research conducted in this area. Previous researches have designated these as 'coastal sandstones', 'littoral sandstone' and 'sandstone reefs' (Cooray 1968). These discontinuous occurrences are of varying size and extent with local variations in composition. Best exposed occurrences have been reported along western, south western and western coastal belt. According to Katupotha (1989), Sri Lankan beachrocks are primarily made up of biogenic carbonate sands, quartz grains and various types of heavy minerals, ilmenite been prominent in most of the cases (Cooray 1968). However, embedded shells can be found while calcareous algae are also present on the surface of exposed portion of the beachrocks (Katupotha 1989, 2003). Radiometric dating obtained from C14 dates on samples of beachrocks obtained from west coast of the island has provided invaluable information on the sea-level change in Sri Lanka. It has been suggested by Katupotha (2003) and Katupotha (1988) that beachrocks along the current coastline have been formed as a result of coastal progradation after the Holocene whereas those found inland from the present coastline are associated with the still-stand of high sea level in the mid-Holocene and some embedded corals in Sri Lankan beachrocks are as old as 6000 years. Further, these reef-like beachrocks are significant because of their ability to act as a natural barrier to sediment transport across the beach and make them extremely resistant to coastal erosion (Katupotha 2003).

Furthermore, recent findings have discovered a double-bedded beachrock complex in Bundala historic site in southern part of Sri Lanka. This unusual beachrock existence was exposed at Bundala lagoon mouth after Tsunami in 2004. As per the findings of Jayasingha (2014), the beachrock complex is composed of two beds lying one on another, with Holocene sea-level-change-triggered episodic origin. This has been revealed by the presence of two different events of lithification of beach sand under two different beach environments (Jayasingha 2014). Apart from these findings, the

information on Sri Lankan beachrocks is very limited in quantity.

1.2 Study area

The coastal belt of Sri Lanka is about 1600 km in length. The study area for this research work was the southern, southwestern and western coastline extending from Tangalle to Uswatekeiyawa, Colombo. Beachrock samples were collected from 11 selected localities having beachrock shoals along this section of the coastal belt (Fig. 1). The morphology of the area is typically characterized by a low-land with a flat ground. There are two major rivers and few small streams flowing across the study area, no sampling locations been close to any of them. Further, southwestern and southern coastlines are said to be more regressive and the majority of the sediments are quaternary to recent in age (Katupotha 1994). The climate of the study area is typically tropical with mean annual temperature of 27 °C and the average tidal range around Sri Lanka generally been micro-tidal ranging from – 37 cm to + 40 cm from mean sea level (Katupotha 1989). However, due to the geographic location of Sri Lanka in the Indian Ocean, the coastal hydrodynamics around the island are heavily influenced by monsoon seasons. Among the two major monsoons, the highly energetic southwest monsoonal winds and waves (May to September) create severe dynamics in the southern, southwestern and western areas. As a result, this strip of the coastline is highly vulnerable to coastal erosion and the width of the beach becomes extremely narrow at certain locations.

In geological terms, southern, southwestern and western regions of the island are predominantly underlain by the Highland complex rocks of Precambrian age composed of metasediments and granulitic orthogneisses (Katupotha 1995). Furthermore, Sri Lanka is located in a region with no tectonic activities.

2 Materials and methods

2.1 Sample collection and preparation

Beachrock samples from 11 sampling locations were randomly collected from coastal belt stretching from Tangalle to Uswatekeiyawa, Colombo. The geographic coordinates of the sampling sites shown in Fig. 1 were recorded using a global positioning system receiver (GPS; GARMIN eTrex Venture HC) and are given in Table 1. Rock samples of approximately 500 g were collected into plastic bags, transported out of the sites and air-dried under normal room temperature. Samples were cleaned to remove the weathered surfaces and algae covering the rock. All the samples were then exported to Laboratory of Biotechnology for Resources

Engineering, Hokkaido University for further analysis. The samples were exported from Sri Lanka to Japan following the Japanese Minister Permission System. In the laboratory, whole rock samples were broken down into rock chips of about 4–5 cm, selecting representative portions of the specimen and subsequently ground into 1 mm particle size manually. The size-reduced rock specimens were then pulverized into a powder using multi-beads crusher and sieved to obtain the portion with particle size not greater than 75 µm mesh size. Powdered samples were stored in plastic containers until they were analysed.

2.2 XRD analysis

X-ray diffractometer patterns of the powdered beachrock samples were analysed using X-Ray diffractometer (MultiFlex, Rigaku Corporation, Tokyo, Japan) in Division of Sustainable Resources Engineering, Hokkaido University, Japan. The analysis was carried out in room temperature using the XRD machine with CuKα radiation at a scanning rate of 1°2θ/min and a step size of 0.02°2θ ranging from 10 to 80°2θ. Qualitative mineralogy of the beach rock samples was determined with the standard interpretation procedures of XRD using Match 3.6.0.111 software for phase identification from powder diffraction.

2.3 XRF analysis

The quantitative elemental analysis of the powdered samples was determined using X-Ray Fluorescence spectrometer at Material Analysis and Structural Analysis Open Unit of Hokkaido University, Japan. The instrument consists of 5–50 kV, 1 mA, 50 W X-ray generator and Rh being the target. Samples were observed by a colourful CCD camera.

2.4 Scanning Electron Microscopy analysis

The cemented components were closely examined using Scanning Electron Microscope (SuperScan SS-550, Shimadzu Corporation, Kyoto, Japan) on dried beachrock specimens.

2.5 Petrographic thin-section analysis

Petrographic thin sections were prepared from selected beachrock specimens to further analyze the microfabrics and composition of the connective cements. Polished thin sections were first investigated under Olympus BX60 optical microscope fitted with a Canon DS126431 camera to confirm the texture and fabric of beachrock cements inferred from SEM images and the mineralogical composition of the beachrocks. Further, Energy-dispersive X-ray spectrometer analysis in conjunction with Scanning Electron Microscopy

Fig. 1 **a** Location map of Sri Lanka, and **b** Beachrock sampling locations

Table 1 Coordinates of sampling locations

Location ID	Location name	Latitude	Longitude	Error
M1	Palikkuda	N05° 57' 04.2"	E80° 40' 23.8"	± 3 m
M2	Thalaramba	N05° 56' 13.7"	E80° 28' 40.8"	± 3 m
M3	Midigama	N05° 57' 37.9"	E80° 23' 54.3"	± 3 m
M4	Ahangama I	N05° 58' 03.2"	E80° 22' 26.5"	± 4 m
M5	Ahangama II	N05° 58' 29.3"	E80° 21' 22.9"	± 4 m
M6	Dalawella	N06° 00' 09.7"	E80° 15' 28.8"	± 3 m
M7	Dadalla	N06° 02' 59.1"	E80° 10' 59.3"	± 3 m
M8	Akurala	N06° 11' 30.1"	E80° 03' 46.2"	± 4 m
M9	Galkanda	N06° 19' 34.0"	E80° 01' 46.5"	± 3 m
M10	Induruwa	N06° 22' 13.9"	E80° 00' 40.3"	± 4 m
M11	Uswatekeiyyawa	N07° 01' 42.8"	E79° 51' 40.4"	± 4 m

(SEM–EDX) operated at an accelerating voltage of 20 kV and beam diameter of ~5 µm was performed at Centre for Environmental Nano and Bioengineering, Hokkaido University, Japan to investigate the elemental composition of the beachrock cement in quantitative terms.

3 Results and discussion

3.1 Morphology and surface nature of beachrocks

Occurrence of beachrocks in intertidal zone of the sandy beaches is a common feature along the southern, southwestern and western coastal belt of Sri Lanka. However, the studied beds were randomly selected for the current work. The beds are dipping towards the sea at angles smaller than 10° while running parallel to the present beach in almost all cases (Fig. 2a). However, at location M10 (Induruwa) (Fig. 2b), small beds were present with significantly deviated strike directions. In all locations except Uswatekeiyawa, the exposed beachrock thickness of the exposed beds does not exceed 50 cm. Beachrock site M11 (Uswatekeiyawa) is a special case where massive beachrock beds are prevalent (Fig. 2c). Having a visible thickness varying from 10 to 100 cm, it stretches over a length of approximately 500 m. Determining the width of the beds is difficult as seaward margin of the submerged beachrocks is not clearly visible in all cases.

Overall, the beds composed of either well-cemented sandstone or conglomerates (According to Folk's (1974) classification) of varying thickness and composition and in most cases with a high porosity. However, sandstone type is the most abundant while conglomerates are also present in few locations. In location M1 (Palikkuda), both types coexist in the two opposite ends of the same bed. In cases where

conglomerates are present, they form the uppermost surface of the beds with rounded or subangular blocks where fine particles have been eroded away (Fig. 2d). This is similar to beachrocks of conglomerates in Cyprus as reported by Ozturk et al. (2016). According to Psomiadis et al. (2014), the presence of pebbles in beachrocks can be attributed to either one of the following reasons: (i) a high-energy period (ii) the beachrock sediments been lithified in a different location than current sampling location, (iii) an early stage of coastal maturity. However, in-depth studies are necessary to determine the exact reason in this case study.

The sandstone-type beachrocks are composed of poorly graded sub-angular grains. The conglomerates are made of moderately to well-graded, well-rounded pebbles and coarse sand as analyzed by visual observations and SEM images. Poorly developed roundness of grains in most of Sri Lankan beachrocks indicates either littoral drift over a short distance or closeness to the source of sediments (Ertek et al. 2014).

Observations on composition of the rock specimens showed that beachrock composition is similar to that of the present beach in all sites, being generally composed of fine-to-coarse sand grains and in Palikkuda, Induruwa and Uswatekeiyawa (Fig. 2e) beachrocks, with heavy minerals in well-marked layers. In site M1 (Palikkuda), apart from the dark coloured distinctive layers of heavy minerals like ilmenite, magnetite and rutile, the presence of red coloured garnet is notably visible.

The studied beachrocks are extremely variable in strength and induration. For example, the beachrocks at Midigama and Uswatekeiyawa are well cemented and extremely hard whereas those in Galkanda, Induruwa are poorly cemented and friable. In many sites, the surface of the beachrocks is covered by a film of marine algae or kinds of red and/or green sea weeds (Fig. 2f, g). A remarkable feature observed in small beachrock outcrop in location M4 (Ahangama I) is the existence of bivalve shells loosely cemented to the rock surface (Fig. 2h). Figure 3 separately shows the distinctive features of sandstone type and conglomeratic beachrocks.

3.2 Petrographic composition and cementation characteristics

Depending on the diagenetic environment, the beachrock cement may contain varying CaCO₃ polymorphs; predominantly calcite or aragonite, but not limited to them. Silicified cements may also be found in very rare instances (Brian et al. 1997; Avcioglu et al. 2016). The mineral and elemental compositions of the cementing agent can provide insights about the origin of the cementation as calcite is generally precipitated from freshwater and aragonite from seawater (Vousdoukas et al. 2007). Examining the amount of Mg in total mass helps to determine whether cement is low magnesium calcite (LMC—less than 5 mol% of MgCO₃) or

Fig. 2 Images of Sri Lankan beachrock formations (a) General view of beachrock formations (M5) (b) Beachrock outcrops at different strike directions (M10) (c) Large beachrock beds at site (M11) (d) Surface view of conglomeratic type beachrock (M1) (e) Heavy mineral presence (M11) (f, g) Sea weeds and algae colonies on the uppermost surface of the rock bed (M3 and M6 respectively), and (h) Bivalve shells loosely cemented to the top surface (M4)

high magnesium calcite (HMC—5 to 20 mol% of MgCO_3) (Burton and Walter 1987) and, hence, detailed information revealing marine, meteoric, vadose or phreatic origin. Furthermore, the fabrics and textural features of the beachrock cement can provide valuable information about sources of cementation (Avcioglu et al. 2016). For example, micritic or stubby blade coatings are more preferred in HMC cements whereas coarse, fibrous acicular crystals are observed in aragonite cement (Voudoukas et al. 2007). However, examining beachrock cement becomes complex as cements of varying origins coexist or when beachrock cements that have

undergone several diagenetic phases show cements of different mineralogy and habitats in the same occurrence (Whittle et al. 1993).

Characterization of both chemical nature of the beachrock cement and crystal structure/micromorphology of the connective cements is necessary for proper identification of cementation characteristics. Numerous previous studies on beachrocks have effectively applied microanalysis methods, such as SEM/EDX, XRD and XRF, to achieve this. The interpretation of the data from these analyses was used to

discuss the chemical composition of beachrocks and micro-morphological characteristics of cements here.

The spectroscopic analysis of samples by XRD and XRF revealed the mineralogical and elemental compositions of the Sri Lankan beachrocks (Table 2). A typical XRF spectrum of a Sri Lankan beachrock sample is shown in Fig. 4. The elemental content is dominated by Si and Ca for all the samples suggesting the typical beachrock formation in silica-rich beaches (Chandrasekaran et al. 2015), however quantitative values for each sample varying over a wide range (Si: 1.42–79.16% and Ca: 1.58–92.29%). This variation may be due to the heterogeneous distribution of fragments of bivalve shells and coral fragments in the bulk samples that were directly powdered and used for spectroscopic analysis which adds up to the Ca% in the tested sample. Further, the variations in percentages of Ca, Mg, Na and K among the samples can also be attributed to the differences in clay minerals present in the samples (Ravisankar et al. 2012). Feldspars are another important group of minerals in all kinds of rock types. They are aluminium silicates with K, Na, Ca and rarely with Ba (Chandrasekaran et al. 2015). The presence of such elements is, therefore, partly derived from the feldspars in the beachrock samples. Thin-section analysis confirmed that beachrocks are made up of rock fragments with monocrySTALLINE quartz, feldspar, biotite, hypersthene, opaque minerals and in some cases, garnet minerals. In addition, bioclasts were observed in tested specimens at varying degrees. Beachrock specimens from M8 are predominantly composed of shell fragments than quartz grains which are an exception to other cases.

The beachrocks at M1 (Palikkuda), M10 (Induruwa) and M11 (Uswatekeiyawa) show distinctly higher percentages of Ti and Fe and abundant opaque minerals in thin sections under the polarizing microscope confirming the presence of heavy minerals in beachrocks as well as the study area. XRD spectra revealed the presence of ilmenite (FeTiO_3), magnetite (Fe_3O_4) and rutile (TiO_2) which are responsible for higher Ti% and Fe% and the reason for the presence of distinctive dark coloured minerals cemented in thin lamina form. Further, srilankite (Sri), rutile—ilmenite composite grain was also observed in XRD spectra of the samples from M11 location. The peaks in XRD spectra of Palikkuda beachrock samples corresponding to pyrope and almandine, two reddish coloured garnet minerals confirm what is visually observed in beachrock specimens as well as in the parent beach sediments. Figure 5 illustrates a typical XRD spectrum of a Sri Lankan beachrock sample showing the presence of heavy minerals. Overall, most common heavy mineral present in the Sri Lankan beachrocks in the studied area is ilmenite along with few others including magnetite, spinel, rutile, zircon, monazite and garnet which is in good agreement with the details documented by previous researchers (Cooray 1968; Katupotha 2003; Ratnayake et al. 2018).

Scanning Electron Microscopic imagery and thin-section images were used to examine the microfabrics of connective elements which indicated the presence of different cement fabrics. The cement mineralogy and fabric for beachrocks at each location as determined from XRD, XRF, SEM and thin-section analysis are briefly summarized in Table 3. Overall, EDX analysis reveals that

Table 2 Elemental composition of the studied Sri Lankan beachrock samples after XRF analysis

Location ID	Elements ($\mu\text{g/g}$)													
	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Fe	Cu	Ni	Sr	Br
M1-1	*	45.8	645.4	5.6	6.5	*	12.8	147.9	48.0	88.1	*	*	*	*
M1-2	*	39.6	791.6	4.4	3.7	*	12.6	81.2	16.1	50.0	0.9	*	*	*
M2-1	*	*	14.2	*	5.4	4.58	*	922.9	1.7	5.0	*	*	5.0	*
M2-2	*	*	74.1	*	7.0	*	*	874.2	15.6	14.8	*	*	3.6	10.7
M3-1	*	*	62.7	*	8.8	*	*	879.5	10.3	35.1	*	1.6	2.0	*
M4-1	*	*	178.9	4.3	8.8	*	*	780.1	9.0	14.5	2.3	*	1.5	*
M5-1	*	*	49.5	*	7.0	*	*	921.3	9.6	10.0	*	*	2.6	*
M6-1	50.9	*	128.1	2.7	7.4	*	*	792.3	4.0	13.3	*	*	1.3	*
M7-1	86.6	*	54.7	*	8.2	*	*	819.1	11.4	18.2	*	*	1.8	*
M8-1	48.6	*	152.8	1.8	6.9	*	*	777.4	3.8	7.1	*	*	1.7	*
M9-1	*	*	137.3	2.6	4.9	*	*	834.0	2.4	15.8	1.6	*	1.3	*
M10-1	*	*	338.6	5.9	5.5	*	*	496.3	94.8	56.8	1.0	*	1.1	*
M10-2	*	*	405.7	1.5	8.3	*	12.2	548.9	7.6	15.8	*	*	*	*
M11-2	37.3	30.6	690.8	2.9	7.3	*	7.9	205.6	7.3	10.2	*	*	*	*
M11-3	146.2	118.5	651.2	2.5	7.6	*	12.6	15.8	24.0	21.7	*	*	*	*

*Refers that corresponding elemental percentage is considerably lower than the others that have been quantified and tabulated and not that completely deprived of the particular element

Fig. 3 Images of beachrock samples **a**, **b** Conglomeratic beachrock samples (M1-2) **c** Sandstone type beachrock sample (M4-1), and **d** Occurrence of heavy mineral lamina (M1-1)

Fig. 4 A typical XRF spectrum of a Sri Lankan beachrock sample (M10-1)

connective cement is mainly composed of O, C, Ca, Mg and Si in the decreasing order of predominance. However, trace amounts of Al, Na and Fe are also present at varying degrees in few samples (Table 4).

Figures 6 and 7 show the scanning electron microscopic images and microphotographs of thin sections of Sri Lankan beachrock samples respectively. Apparently in location M1, sparry calcite and low magnesium calcite crystals were observed along with bridge cement. The anhedral-to-subhedral spar cement lines the grains or completely fills the pores (Fig. 7a, b). Moreover, the sparitic calcite/magnesium calcite crystals have a fibrous nature. The crystals also show signs of dissolution probably during a subaerial exposure

period. The cement surfaces consist of abundant of shells of gastropods along with organic matter and show traces of presence of fungal filaments. The dominant sparry calcite crystals found here are representative of saturated environments, with hydrochemistry that prefers magnesium calcite over aragonite. The carbonate cements of M4 samples show an initial cement generation of aragonite needles and second generation of pore-filling in which crystals cannot be clearly distinguished. The pore-filling cement is also composed of lots of organic matter, fungal filaments and shell fragments. Images of samples from M2 show micritic development with meniscus cements linking the amalgamated components preferably indicating a cementation in vadose zone.

Fig. 5 A typical XRD spectrum of a Sri Lankan beachrock sample (M10-1)

Fig. 6 SEM images of beachrock cements **a, b** Bridge cement and its closer view (M1-2) **c** Micritic coating (M2-1) **d** Pore filling cement (M4-1) **e, f** Radial aggregates of aragonite needles and closer view

(M8-1) **g, h** High magnesium calcite crystals with scalenohedral terminations and its closer view (M9-2), and **i** Presence of gastropod shells

Table 3 Characteristics of beachrocks and their connective cement

Location ID	Mineralogical composition and fabric/texture of cement	Accessory heavy/garnet minerals present	Other observations
M1-1	Ca, LMC (sparry pf, bc)	Pyrope, almandine	High void ratio, layers of dark coloured minerals and high proportion of red coloured minerals Sub rounded, maximum 1.5 mm size grains, gastropod shells are abundant on the surface of grains
M1-2	Ca, MC (sparry pf, some bc)	Zircon	Conglomeritic, gravel/pebble size grains on surface, algae on surface
M2-1	Ar, Ca, MC (micr, mc)	–	Shells embedded in the matrix are clearly visible
M2-2	Ar, Ca, MC (micr, mc)	–	Similar to M2-1, coral fragments are visible
M3-1	Ar, Ca (micr, pf)	Spinel	Large shell fragments are clearly visible
M3-2	Ar, Ca, MC (aragonite needles, pf)	–	Very hard and highly cemented, small shell fragments are visible
M4-1	Ar, Ca, MC (aragonite needles, pf)	–	Sandstone type, Maximum 2 mm sized subangular grains
M5-1	Ar, Ca, MC (aragonite needles, pf)	–	Sandstone type, Maximum 1 mm sized grains
M6-1	Ar, Ca, MC (micr pf)	–	Hard, well cemented
M7-1	Ar, Ca (micr, pf)	–	
M8-1	Ar, Ca, MC (aragonite needles, bc)	–	Maximum 0.75 mm sized subangular grains
M9-1	Ar, Ca, HMC (scalenohedral, mc)	–	Sandstone type, Maximum 0.5 mm sized grains
M9-2	Ar, Ca, HMC (scalenohedral, mc)	–	Similar to M9-1 with comparatively larger grains
M10-1	Ar, Ca, HMC (scalenohedral, bc)	Ilmenite, magnetite	Sandstone type, heavy mineral layering is clearly visible. Sub angular, well graded sand
M10-2	Ar, Ca, HMC (scalenohedral, bc)	–	Fine to coarse sand, sub angular grains
M11-1	HMC, Ar, (micr, needles, pf)	Srilankite, rutile	Angular, very fine to medium sand grains
M11-2	HMC, Ar (micr, needles, pf)	Ilmenite, magnetite, spinel	Angular, very fine to fine sand grains

Ar aragonite, Ca calcite, MC magnesium calcite, micr micritic development, bc bridge cement, mc meniscus cement, pf pore filling

Table 4 SEM–EDX analysis results of Sri Lankan beachrock cements

Location ID	Cement surface observed (**)	Average elemental composition (µg/g)												
		C	O	F	Na	Mg	Al	Si	P	S	Cl	K	Ca	Fe
M1	Pore filling (20)	442.2	458.5	20.1	–	8.2	38.3	38.1	2.7	2.1	1.6	0.09	27.1	10.1
	Bridge cement (8)	542.7	399.4	23.1	0.4	11.7	3.1	15.9	–	–	0.9	–	12.8	5.5
M8	Grain coating (8)	490.8	480.1	–	–	14.2	–	1.0	–	–	–	–	23.6	–
	Pore filling (3)	495.0	474.8	–	1.8	10.1	–	–	–	–	–	–	19.5	–
	Bridge cement (2)	287.7	633.4	–	4.9	22.5	–	–	–	–	–	–	53.1	–
M10	Grain coating (10)	358.4	561.8	–	16.6	16.7	–	–	–	–	–	–	52.7	–
	Bridge cement (2)	553.5	412.5	–	–	7.8	–	0.8	–	–	–	–	25.9	–
M11	Grain coating (8)	249.3	664.2	–	12.0	27.8	–	–	–	–	–	–	47.7	–
	Pore filling (8)	254.0	659.5	–	9.0	26.8	–	2.5	–	–	–	–	42.0	–
	Radial aggregates (4)	303.9	612.5	–	19.8	23.2	2.2	1.8	–	–	–	–	43.7	–

**Number of cement surfaces analyzed to obtain the average elemental composition

The most common fabric/texture of Sri Lankan beachrock cements is the radial aggregates of acicular aragonite or scalenohedral/stubby blade HMC (cement generation 1). In all cases, this is isopachous suggesting a marine-phreatic precipitation where pores were constantly filled with water (Guerra et al. 2005; Erginal et al. 2008; Petropoulos et al. 2016; Vieira et al. 2017). Acicular aragonite rims and needles protruding from grain surfaces towards pore spaces

were clearly observed in samples collected from locations M3, M5 and M8 (Fig. 7c, d). Such protruding bladed crystals of size range 10–20 µm are suggestive of precipitation under marine-phreatic conditions (Moore 1973). Pore fills that occupy voids among grains are quite common within beachrock cements. In M3 and M5 samples, such pore-filling (cement generation 2) was also noted. The bridge and pore-filling cements between grains in M8 specimens possibly

Fig. 7 Microphotographs showing petrographic characteristics of selected beachrock samples under crossed polarizers **a**, **b** Sparry calcite/magnesium calcite crystals lining the grains and filling the pores and its closer view (M1) **c**, **d** Acicular aragonite rims and needles protruding from grain surfaces and its closer view (M8) **e**, **f** High magnesium calcite crystals with scalenohedral terminations and its closer view (M10) **g** Isopachous prismatic growths of magnesium calcite crystals (M11), and **h** Radial aggregates of magnesium calcite crystals (M11). *Qt* Quartz, *Hm* Heavy minerals, *Sf* Shell fragments, *Bt* Biotite

indicate a secondary cementation stage as mentioned in Avcioğlu et al. (2016). The grain surfaces of beachrock specimens collected from locations M9 and M10 are wholly encrusted with scalenohedral HMC crystals with isopachous disposition (Fig. 7e, f) which is a strong indication of the precipitation from marine water in phreatic zone (Holail and Rashed 1992; Longman 1980). However, crystals show a similar fibrous nature as in M1. In M9, this is followed by second-generation cements of meniscus bridges and pore fills which occlude the intergranular porosity. The second-generation cementation in M10 is characterized by pore fills and bridge cements. M11 specimens also display development of prismatic growths of magnesium calcite along with

subsequent dense pore-filling. Fibrous radial aggregates are also a significant feature here. These aggregates occur individually isolated or in groups directly on the grain surfaces or on the micritic envelopes (Fig. 7g, h).

The results from spectroscopic and thin-section analysis suggest that first generation of cementation is of marine-phreatic origin and possibly followed by meteoric-vadose cementation which could be indicative of either uplift or relative sea-level fall (Kelletat 2006; Erginal 2012; Ertek et al. 2014).

Overall, the widespread occurrence of HMC and aragonite at various morphologies in specimens elucidate that the significant formation mechanism of majority of Sri Lankan

beachrocks in studied area is precipitation in marine-phreatic environment. The diagenetic history of these beachrocks can be confirmed as commencement of precipitation on grain surfaces suggesting a rapid supersaturation of pore waters (Erginal et al. 2008). The growth of radial aggregates and/or scalenohedral crystals confirms the continuation of accumulation of cement under supersaturation of CaCO_3 by seawater evaporation (Erginal et al. 2008). The occurrence of meniscal cement (in two locations) is a characteristic of a vadose cementation (Kneale and Viles 2000). Albeit in limited amounts, the presence of traces of fungal filaments and similar evidences suggests possible influence from biological aspects.

4 Conclusions

In this study, field and laboratory investigations were carried out to gather knowledge on distribution and cementation characteristics of beachrock occurrences along southern, southwestern and western coast of Sri Lanka. Based on the field work and laboratory spectroscopic analysis, following preliminary conclusions can be derived.

The intertidal beachrock formations are a remarkable coastal feature along the studied area which also acts as a natural barrier against coastal erosion. Petrographically, two types are identified: poorly sorted conglomerates and moderately to well-sorted sandstone type, latter been most abundant. The XRF analyses reveal the presence of varying percentages of major elements (Si, Ca, Mg, Al, Fe and Al) and trace elements in the samples with Si and Ca dominating overall composition, thus indicating typical beachrock formation.

Most of these sandstone-type beachrocks are composed of silica-rich grains cemented together by carbonate cement. In certain locations, various heavy minerals and garnet minerals are present in lamina form in various amounts and show similarity to the unconsolidated beach sediments.

Despite variety of fabrics and textures of carbonate cements rich in aragonite and calcite, the majority of the studied beachrocks suggests precipitation from marine water in phreatic zone. This includes intertidal beachrock cements of radial aggregates of scalenohedral magnesium calcite and needles of aragonite. Exceptions to this trend include samples with meniscus cement suggesting precipitation in vadose zone. Although not common, existence of traces of fungal filaments and organic matter suggests possible effects from microbial presence.

Nevertheless, beachrock-formation mechanism is a complex process which involves various physico-chemical factors along with biological influences. Hence, understanding precise formation process and cementing

materials require more detailed work, such as radiocarbon dating and stable isotope ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) values, of connecting cements which are out of the scope of this paper.

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References

- Arrieta, N., Goienaga, N., Martínez-Arkarazo, I., et al. (2011). Beachrock formation in temperate coastlines: examples in sand-gravel beaches adjacent to the Nerbioi-Ibaizabal Estuary (Bilbao, bay of Biscay, north of Spain) *Spectrochim Acta—Part A. Mol Biomol Spectrosc*, 80, 55–65. <https://doi.org/10.1016/j.saa.2011.01.031>
- Avcioglu, M., Yigitbas, E., & Erginal, A. E. (2016). Beachrock formation on the coast of Gökçeada Island and its relation to the active tectonics of the region, northern Aegean Sea, Turkey. *Quat Int*, 401, 141–152. <https://doi.org/10.1016/j.quaint.2015.10.108>
- Brian, J., Michael, R. R., & Robin, W. R. (1997). Silica-Cemented beachrock from Lake Taupo, North Island, New Zealand. *Journal of Sedimentary Research*, 67, 805–814. <https://doi.org/10.1306/d4268644-2b26-11d7-8648000102c1865d>
- Burton, E. A., & Walter, L. M. (1987). Relative precipitation rates of aragonite and Mg calcite from seawater: temperature or carbonate ion control? *Geology*, 15, 111–114. [https://doi.org/10.1130/0091-7613\(1987\)15%3c111:RPROAA%3e2.0.CO;2](https://doi.org/10.1130/0091-7613(1987)15%3c111:RPROAA%3e2.0.CO;2)
- Calvet, F., Cabrera, M. C., Carracedo, J. C., et al. (2003). Beachrocks from the island of La Palma (Canary Islands, Spain). *Marine Geology*, 197, 75–93. [https://doi.org/10.1016/S0025-3227\(03\)00090-2](https://doi.org/10.1016/S0025-3227(03)00090-2)
- Chandrasekaran, A., Rajalakshmi, A., Ravisankar, R., & Kalarasai, S. (2015). Analysis of beach rock samples of Andaman Island, India by spectroscopic techniques. *Egypt J Basic Appl Sci*, 2, 55–64. <https://doi.org/10.1016/j.ejbas.2014.12.004>
- Chowdhury, S. Q., Fazlul Haq, A. T. M., & Hasan, K. (1997). Beachrock in st. martin's island, bangladesh: Implications of sea level changes on beachrock cementation. *Mar Geod*, 20, 89–104. <https://doi.org/10.1080/01490419709388097>
- Cooper, J. A. G., Green, A. N., & Wiles, E. A. (2017). Beachrock morphology and genesis on a paraglacial beach. *Sediment Geol*, 360, 47–53. <https://doi.org/10.1016/j.sedgeo.2017.08.005>
- Cooray, P. G. (1968). A note on the occurrence of beachrock along the west coast of Ceylon. *Journal of Sedimentary Research*, 38, 650–654. <https://doi.org/10.1306/74d71a0f-2b21-11d7-864800102c1865d>

- Danjo, T., & Kawasaki, S. (2014). Characteristics of beachrocks: a review. *Geotechnical and Geological Engineering*, 32, 215–246. <https://doi.org/10.1007/s10706-013-9712-9>
- Erginal, A. E. (2012). Beachrock as evidence of sea-level lowstand during the classical period, Parion antique city, Marmara Sea, Turkey. *Geodinamica Acta*, 25, 96–103. <https://doi.org/10.1080/09853111.2013.842740>
- Erginal, A. E., Kiyak, N. G., Bozcu, M., et al. (2008). On the origin and age of the Ariburnu beachrock, Gelibolu Peninsula, Turkey. *Turk J Earth Sci*, 17, 803–819.
- Ertek, A., Kılıç, E., Erginal, A. E., et al. (2014). Preliminary assessment of submerged Beachrock and Tsunamiogenic deposit, Hasır Island, Marmara Archipelago, Turkey. *J Coast Res*, 31, 428–433. <https://doi.org/10.2112/jcoastres-d-12-00177.1>
- Folk, R. L. (1974). *Petrology of sedimentary rocks*. Austin: Hemphill.
- Friedman, G. M. (2011). Beachrocks record Holocene events, including natural disasters. *Carbonates and Evaporites*, 26, 97–109. <https://doi.org/10.1007/s13146-011-0056-3>
- Ginsburg, R. N. (1953). Beachrock in South Florida. *Journal of Sedimentary Petrology*, 23, 85–92. <https://doi.org/10.1306/D4269558-2B26-11D7-8648000102C1865D>
- Guerra, N. C., Kiang, C. H., & Sial, A. N. (2005). Carbonate cements in contemporaneous beachrocks, Jaguaribe beach, Itamaracá island, northeastern Brazil: petrographic, geochemical and isotopic aspects. *An Acad Bras Cienc*, 77, 343–352.
- Hanor, J. S. (1978). Precipitation of beachrock cements: mixing of marine and meteoric waters vs. CO₂-degassing. *Journal of Sedimentary Petrology*, 48, 489–501.
- Holail, H., & Rashed, M. (1992). Stable isotopic composition of carbonate-cemented recent beachrock along the Mediterranean and the Red Sea coasts of Egypt. *Marine Geology*, 106, 141–148. [https://doi.org/10.1016/0025-3227\(92\)90059-Q](https://doi.org/10.1016/0025-3227(92)90059-Q)
- Howie, F. M. P. (2009). Beachrock development along the north coast of Cornwall. *Geosci South-West Engl*, 12, 85–94.
- Jayasingha, P. (2014). Episodic beachrock complex at Bundala coast southern Sri Lanka—a preliminary study. *J Geol Soc Sri Lanka*, 16, 119–126.
- Katupotha, J. (1988). Hiroshima University radiocarbon dates 2, west coasts of Sri Lanka. *Radiocarbon*, 30(3), 341–346.
- Katupotha, J. (1989). Coastal landforms during the Holocene epoch in Sri Lanka: are they compatible to those in Brazil and Venezuela? International symposium on global changes in South America during the quaternary: past—present—future, Sao Paulo, Brazil. May 8–12, 1989
- Katupotha, J. (1994). Quaternary research in Sri Lanka. *J Geol Soc Sri Lanka*, 5, 141–152.
- Katupotha, J. (1995). *Evolution and the geological significance of late pleistocene fossil shell beds of the southern coastal zone of Sri Lanka*. Sri Lanka: Colombo.
- Katupotha, J. (2003). Beachrock in the west coast of Sri Lanka. International workshop on sea level changes in the Eastern Mediterranean during the holocene. Department of Geography, Horkopio University, Athens, Greece. October 16–18, 2003
- Kelletat, D. (2006). Beachrock as sea-level indicator? remarks from a geomorphological point of view. *J Coast Res*, 22, 1558–1564. <https://doi.org/10.2112/04-0328.1>
- Khadkikar, A. S., & Rajshekhar, C. (2003). Microbial cements in Holocene beachrocks of South Andaman Islands, Bay of Bengal. *Current Science*, 84, 933–936.
- Kneale, D., & Viles, H. A. (2000). Beach cement: incipient CaCO₃-cemented beachrock development in the upper intertidal zone, North Uist, Scotland. *Sediment Geol*, 132, 165–170.
- Krumbein, W. E. (1979). Photolithotrophic and chemoorganotrophic activity of bacteria and algae as related to beachrock formation and degradation (gulf of aqaba, sinai). *Geomicrobiology Journal*, 1, 139–203. <https://doi.org/10.1080/01490457909377729>
- Longman, M. W. (1980). Carbonate diagenetic textures from near surface diagenetic environments. *Am Assoc Petrol Geol Bull*, 64, 461–487.
- Mauz, B., Vacchi, M., Green, A., et al. (2015). Beachrock: a tool for reconstructing relative sea level in the far-field. *Marine Geology*, 362, 1–16. <https://doi.org/10.1016/j.margeo.2015.01.009>
- May, S. M., Vött, A., Brückner, H., et al. (2012). The Lefkada barrier and beachrock system (NW Greece)—controls on coastal evolution and the significance of extreme wave events. *Geomorphology*, 139–140, 330–347. <https://doi.org/10.1016/j.geomorph.2011.10.038>
- Moore, C. H. (1973). Intertidal carbonate cementation Grand Cayman, West Indies. *Journal of Sedimentary Petrology*, 43, 591–602. <https://doi.org/10.1306/74D72810-2B21-11D7-8648000102C1865D>
- Neumeier, U. (1999). Experimental modelling of beachrock cementation under microbial influence. *Sediment Geol*, 126, 35–46.
- Ozturk, M. Z., Erginal, A. E., Kiyak, N. G., & Ozturk, T. (2016). Cement fabrics and optical luminescence ages of beachrock, North Cyprus: implications for Holocene sea-level changes. *Quat Int*, 401, 132–140. <https://doi.org/10.1016/j.quaint.2015.03.024>
- Petropoulos, A., Baziotis, I., Anagnostou, C., & Evelpidou, N. (2016). Beachrock cement characteristics and conditions of formation. Case study Platanias beach, Chania Greece. *Bull Geol Soc Greece*, 50, 458–467.
- Psomiadis, D., Albanakis, K., Zisi, N., et al. (2014). Clastic sedimentary features of beachrocks and their palaeo-environmental significance: comparison of past and modern coastal regimes. *Int J Sediment Res*, 29, 260–268. [https://doi.org/10.1016/S1001-6279\(14\)60041-X](https://doi.org/10.1016/S1001-6279(14)60041-X)
- Ratnayake, N. P., Ratnayake, A. S., Azoor, R. M., et al. (2018). Erosion processes driven by monsoon events after a beach nourishment and breakwater construction at Uswetakeiyawa beach, Sri Lanka. *SN Appl Sci*. <https://doi.org/10.1007/s42452-018-0050-7>
- Ravisankar, R., Eswaran, P., & Rajalakshmi, A. (2012). Beach rocks from the south east coast of Tamilnadu, India : a spectroscopic study. *Adv Appl Sci Res*, 3, 95–102.
- Russell, R. J., & McIntire, W. G. (1965). Southern hemisphere beach rock. *Geographical Review*, 55, 17–45.
- Scoffin, T. P. (1970). A conglomeratic beachrock in Bimini, Bahamas. *Journal of Sedimentary Petrology*, 40, 756–759. <https://doi.org/10.1306/74d72040-2b21-11d7-8648000102c1865d>
- Siesser, W. G. (1974). Relict and recent beachrock from southern Africa. *Bull Geol Soc Am*, 85, 1849–1854. [https://doi.org/10.1130/0016-7606\(1974\)85%3c1849:RARBFS%3e2.0.CO;2](https://doi.org/10.1130/0016-7606(1974)85%3c1849:RARBFS%3e2.0.CO;2)
- Vieira, M. M., & De Ros, L. F. (2006). Cementation patterns and genetic implications of Holocene beachrocks from northeastern Brazil. *Sediment Geol*, 192, 207–230. <https://doi.org/10.1016/j.sedgeo.2006.04.011>
- Vieira, M. M., Sial, A. N., De Ros, L. F., & Morad, S. (2017). Origin of holocene beachrock cements in northeastern Brazil: evidence from carbon and oxygen isotopes. *J South Am Earth Sci*, 79, 401–408. <https://doi.org/10.1016/j.jsames.2017.09.002>
- Vousdoukas, M. I., Velegrakis, A. F., Kontogianni, A., & Makrykosta, E. N. (2009). Implications of the cementation of beach sediments for the recreational use of the beach. *Tour Manag*, 30, 544–552. <https://doi.org/10.1016/j.tourman.2008.09.007>
- Vousdoukas, M. I., Velegrakis, A. F., & Plomaritis, T. A. (2007). Beachrock occurrence, characteristics, formation mechanisms and impacts. *Earth-Science Reviews*, 85, 23–46. <https://doi.org/10.1016/j.earscirev.2007.07.002>
- Wagle, B. G. (1990). Beach rocks of the Central West Coast of India. *Geo-Marine Letters*, 10, 111–115.
- Webb, G., Jell, J., & Baker, J. (1999). Cryptic intertidal microbialites in beachrock, Heron Island, Great Barrier Reef: implications for the origin of microcrystalline beachrock cement. *Sediment Geol*, 126, 317–334.

Whittle, G. L., Kendall, C. G. S. C., Dill, R. F., & Rouch, L. (1993). Carbonate cement fabrics displayed: a traverse across the margin of the Bahamas Platform near Lee Stocking Island in the Exuma Cays. *Marine Geology*, 110, 213–243. [https://doi.org/10.1016/0025-3227\(93\)90086-B](https://doi.org/10.1016/0025-3227(93)90086-B)

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