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Study of the archaeological building materials on Farasan Islands, Kingdom of Saudi Arabia, and their relationship with the islands' local and climatic environment

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Abstract

The Farasan Islands are located in the Southern Region of Saudi Arabia. These islands comprise many archaeological buildings dating back to different historical eras. The present study reports some of the results that could be attained from the application of various analytical techniques to illustrate the structure of the used archaeological building materials. The study will be for the main building material (stone) and secondary building materials will be followed in a next study. The techniques also show what relationship relates the building materials to "the local environment", as well as their relationship to the climatic environment as factors of deterioration.

The case study of the building materials will be carried out by using proper scientific methods in the examination and analysis of the scrutinized building materials. The study will also implement a number of mechanical and natural properties' experimentation.
Keywords: Farasan Islands, building materials, lime stone, examination and analysis, local and climatic environment.

1 Introduction

The Farasan Islands are situated in the south central Red Sea at 16°20′–17°20′N, 41°24′–42°26′E, approximately 40 km from the coastal town of Jizan, Saudi Arabia. The Farasan Islands lie on the Arabian continental shelf, which is less than 200 m deep and about 120 km wide at Jizan. The archipelago contains

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approximately 176 islands. Most islands are low, and they are mostly composed of pavements and faulted blocks of uplifted fossil reef limestone.

The largest island in the region is Farasan Kabir. It is 66 km long and 2–8 km wide, with a total area of 381 sq. km and a 216 km coastline. It’s also connected to Saqid Island by a bridge; As-Saqid Island is 149 sq. km in area (Bruckner *et al.* [1]). The rest of the islands; however, can only be reached by sea.

One of the islands that contain heritage sites is Qummah (15.2 sq. km) lie south of Farasan Kabir. There are also 23 smaller islands (>0.2 sq. km area) and over a hundred other low islets and shoals. Nearly half of these are rocky; 20% have both rocky and sandy areas. Most of the islands are surrounded by narrow bands of reef habitats, generally with water depths of less than 11 m (Bruckner *et al*. [1]) (fig. 1).

Figure 1: Red sea topographic map, representing Farasan islands lying on the Arabian continental shelf (Wikimedia [2]) (a); detail of Farasan Islands (b); general map showing Farasan islands (c).

1.1 Studied buildings

These islands comprise many archaeological buildings dating back to different historical eras and are mainly located in the chief Farasan and Kommah islands. Eight of them have been selected in the study to represent the variety of main building materials (stone) used in the islands, while the rest of the islands comprise group of natural heritage sites and do not include any archaeological or historical buildings (fig. 2).

In order to defend this heritage, it should be studied to identify the components of its building materials and their properties to help determine the restoration and maintenance mechanisms.

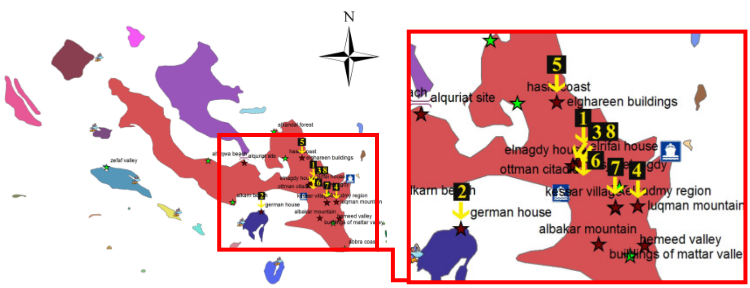

Figure 2: General view showing the distribution of studied heritage buildings.

Henceforth, the purpose of the research is to:

- Emphasize the significance of the Farasan Islands with their archaeological buildings dating back to different historical eras.
- Clarify the need to preserve these buildings and manage their sites to defend this heritage and achieve sustainable development.
- Study the archaeological building materials at Farasan islands as they have not been studied before.
- Identify the deterioration phenomena of building materials in Farasan islands and their relation to the surrounding environment.

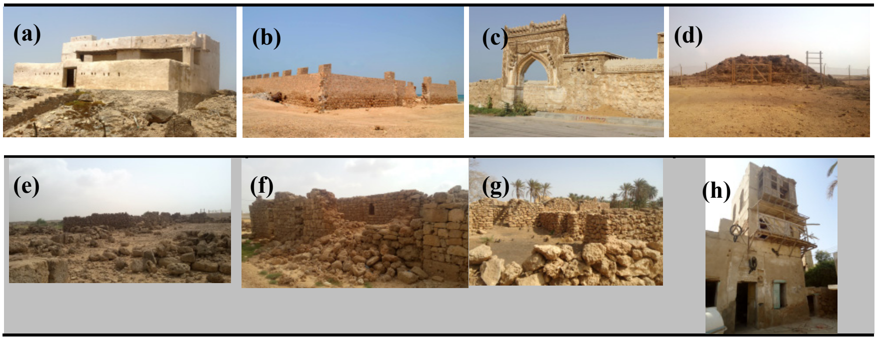

Figure 3: General view of the Ottoman citadel (a), the Germans house (b), Hussein Rifai House (c), Luqman Mountain (d), El-Ghareen buildings (e), Al-Arady buildings (f), Kessar houses (g) and Abdullah Ibrahim Rifai House (h).

1.2 Farasan environments

1.2.1 Local environment

About 60% of the surface of the Farasan Islands is a subtropical desert of fossil limestone. The remainder is divided approximately equally among silty sand and Sabkha, and rocky outcrops between 10 to 70 m high (Bruckner *et al.* [1]). "Sabkha" is a term used to describe the coastal flats and salt marches deposited in lagoonal areas under arid conditions (Banat *et al.* [3]).

The Farasan Islands are composed of cemented coral platforms that have been variously uplifted and deformed by salt tectonics (Bailey *et al.* [4]). Borehole data indicates that the Farasan reef lime stones are underlain by layers of gypsum and anhydrite, which in turn are underlain by a thick halite sequence. The oldest lime stone in the centre of the islands are reef floating stones that accumulated in the early Pleistocene, whilst younger grain stones (late Pleistocene age) occur at lower topographic levels around the coastline indicating that the Farasan Islands have been formed from progressive uplift and relative sea-level fall. Analysis indicates that the uplift may still be continuing today (Bantan [5]).

1.2.2 Climatic environment

Climate can be defined as the whole atmospheric events such as rainfall, temperature, wind, and humidity that cause certain damages on the monumental buildings for years (Gupta [6]).

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Regarding rainfall, Jazan rainfall rate is one of the highest in the Kingdom of Saudi Arabia as it reaches 131.8 mm annually (Almazroui *et al.* [7]); almost all precipitation events occur during November and April. However, due to the desert climate in Saudi Arabia, A large percentage of the rain (~20.0%) evaporates. The regions in the kingdom from which the rainwater originates are not highly industrialized; therefore acid rain is not expected. The important sources of mineralization of precipitated water are coal combustion, dust, car exhaust, and cement production (Alabdula'aly [8]).

But Farasan Islands don't suffer from any traffic density and don't have any industries, so we can exclude the impact of acid rain. The physical and mechanical influence of acid rain isn't taken into account, either. In such influence, rain can dissolve some building materials' components, and it can take some weak or corroded parts on its way.

If the harmful effects of wind exist – especially its continuality over Farasan with high humidity – together with sea salt and sand, serious surface weathering will be inevitable on the monumental buildings (Gupta [6]).

As for temperature, a 2–5°C rise in it and a rise in sea-level are predicted over the next 50 years. For example, weather phenomena are likely to increase such as extreme wind speed along with storms as well as an increase of the penetration of rainwater into buildings. Likewise, increased penetration of moisture may activate salt to be passively accumulated and stored in the building material. Once activated, the salt cause harm by migrating, in solution, to the point where moisture evaporates. Here they accumulate and crystallize. If the crystallization takes place within the pores of the masonry, crystal growth can exert enormous pressure on the walls of the pores, causing the stone to crumble (Inkpen [9]).

2 Materials and methods

2.1 Sampling

Eight (8) small samples were carefully collected and chosen for analysis (see Table 1).

Table 1: The codes, sites and site descriptions of the studied samples.

Code	Site	Site description	Latitude	Longitude
S. 1	The Ottoman citadel	existing building	16°42′44.40″N	42°7′20.80″E
S. 2	The Germans house	dilapidated building	16°39′17.86″N	42°1′51.36″E
S. 3	Hussein Rifai House	existing building	16°42′18.42″N	42°7′20.49″E
S. 4	Luqman Mountain	ruins	16°40′19.86″N	42°9′59.16″E
S. 5	El-Ghareen buildings	ruins	16°45′4.18″N	42°6′16.02″E
S. 6	Al-Arady buildings	ruins	16°41′58.65″N	42°7′19.81″E
S. 7	Kessar houses	existing building	16°40′14.68″N	42°8′56.70″E
S. 8	Abdullah Ibrahim Rifai House	existing building	16°42′19.27″N	42°7′21.47″E

2.2 Analytical methodology

Analysis of building materials by chemical and physical analytical methods reveals much information about its components, its state from deterioration side and its need for restoration. To achieve these objectives, Samples of Farasan building materials were collected, examined and analyzed by the following methods.

2.2.1 Examination methods

2.2.1.1 Scanning electron microscopy (SEM) The microstructure of the studied samples was investigated via SEM to assess morphological features, by a Quanta FEG 250 scanning electron microscope (FEI, Netherlands). The magnification on the studied samples ranges from 250 to 16000x. The accelerating voltage was 20 kV.

2.2.2 Analysis methods

The collected samples were investigated by mineralogical, physical and mechanical analyses.

2.2.2.1 X-ray diffraction method (XRD) It was used to characterize the mineralogical composition of samples by using XRD PHILIPS 1730 diffractometer with Ni filter at a scan speed 0.5/ min, Cu K alpha radiation.

2.2.2.2 X-ray fluorescence spectrometry (XRF) To determine the chemical composition, by using Axios advanced, sequential WD_XRF spectrometer, PANalytical 2005.

2.2.2.3 Water absorption (WA) (%) At atmospheric pressure: C97 2009.

2.2.2.4 Bulk specific gravity (BSG) Determination of BSG: ASTM C97 2009.

2.2.2.5 Bulk density (BD) (g/cm3) Determination of BD: ASTM C97 2009.

2.2.2.6 Apparent porosity (AP) (%) Determination of AP: ASTM C127 2001.

2.2.2.7 Compressive strength (CS) Determination of CS: ASTM C170 2009 by using 3000 KN soil test universal testing machine model OT-b200-8.

3 Results and discussion

3.1 Examination and analysis results

3.1.1 The Ottoman citadel sample (S.1)

Examination with SEM in fig. 4 shows the sample contains a large proportion of fiber due to the nature of the stone formation and illustrated the high porosity of the stone as it also shown within physical properties (as shown in table 2). Also, high water absorption due to high porosity is noticed.

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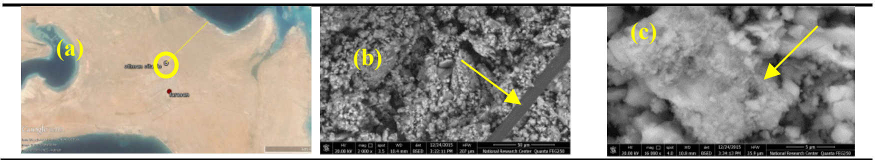
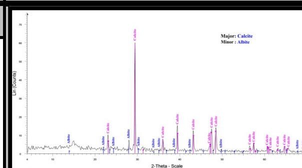


Figure 4: The site is 3.22 km from the sea (a) scanning electron micrograph of sample (S.1), shows fibre scattered in (b), and degradation in crystals (c).

Table 2: Composition, some physical and mechanical properties of S.1.

No	Minerals	Formula	Content %	Index no.	Chart
S. 1	Calcite	$Ca(CO_3)$	71.50	88-1808	
	Albite	$NaAlSi_3O_8$	28.50	01-0739	

Constituents %	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	SO_3	Cl	SrO	L.O.I
S. 1	0.73	0.22	0.13	0.44	52.69	0.30	1.32	0.19	0.59	43.24

Sample no.	WA (%)	BSG	BD (g/cm^3)	AP (%)	CS (Mpa)
S. 1	8.62	1.87	1.82	16.15	15.95

Limestone is a sedimentary stone with at least 50% by weight calcite or calcium carbonate ($CaCO_3$) content; the other 50% can be one of various clasts or minerals of other kinds of stone (Marble Institute [10]). XRD analysis illustrated minerals as (major calcite + minor albite).

As for mechanical properties, the low compressive strength is noticed (which is 12–55 Mpa by ASTM standards).

3.1.2 The Germans house sample (S.2)

Fig. 5 shows the small distance between the Germans house and the sea which is affected negatively by the chemical action of seawater rather than physical breakdown caused by wave action.

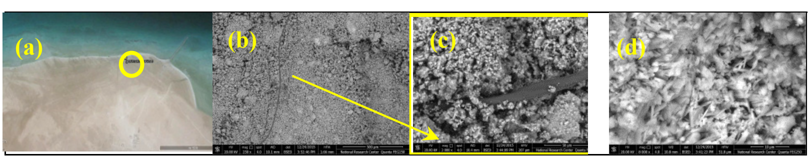
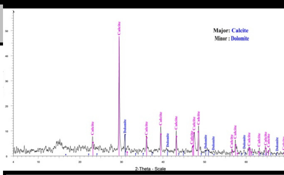


Figure 5: The site is 0.05 km from the sea (a), SEM micrograph of sample (S.2), shows some fibres (b), (c), appearance of salts and corroded crystals (d).

Table 3: Composition, some physical and mechanical properties of S.2.

No	Minerals	Formula	Content %	Index no.	Chart
S. 2	Calcite	$Ca(CO_3)$	84.30	88-1808	
	Dolomite	$CaMg(CO_3)_2$	15.70	74-1687	

Constituents %	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	SO_3	Cl	SrO	L.O.I
S. 2	2.36	0.59	0.39	8.29	41.76	0.98	0.31	1.09	0.20	43.69

Sample no.	WA (%)	BSG	BD (g/cm^3)	AP (%)	CS (Mpa)
S. 2	4.62	2.15	2.16	9.86	21.47

XRD analysis illustrated minerals as (major calcite + minor dolomite); The origin of dolomite is post depositional; it is chemically transformed from a pure calcium limestone after deposition and burial, (Marble Institute [10]), XRF assured that the sample contains percentage of halite (appeared with SEM).

3.1.3 Hussein Rifai House's sample (S.3)

XRD illustrated Calcite as a major mineral; while the physical and mechanical tests showed the very weak properties of the stone, where the porosity and water absorption is very high and the stone's compressive strength is very low.

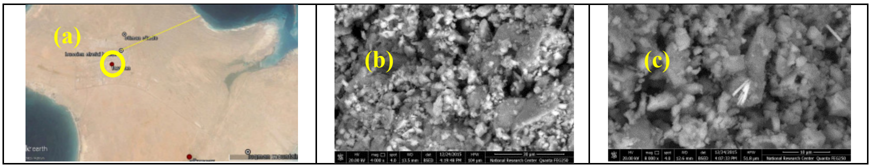
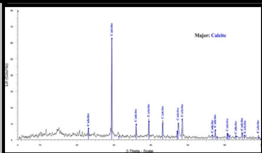


Figure 6: The site is 3.67 km from the sea (a); degradation in crystals (b), (c).

Table 4: Composition, some physical and mechanical properties of S.3.

No	Minerals	Formula	Content %	Index no.	Chart
S.3	Calcite	$Ca(CO_3)$	100.00	88-1808	

Constituents %	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	SO_3	Cl	SrO	L.O.I
S. 3	1.79	0.62	0.37	0.66	53.36	0.16	1.59	0.11	0.26	40.86

Sample no.	WA (%)	BSG	BD (g/cm^3)	AP (%)	CS (Mpa)
S. 3	15.80	1.70	1.59	26.90	5.98

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3.1.4 Luqman Mountain's sample (S.4)

XRD illustrated minerals as (major calcite + minor aragonite); most limestone is marine in origin, composed of micro-sized fossils of marine invertebrate organisms (Marble Institute [10]), as shown in fig. 7(b).

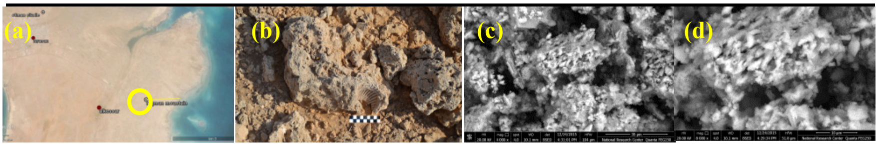
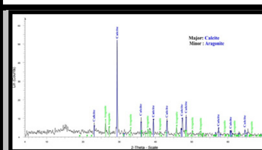


Figure 7: The site is 1.00 km from the sea (a), fossils or shell formations (b), SEM micrograph of the needle shape of aragonite crystallites (c), (d).

Table 5: Composition, some physical and mechanical properties of S.4.

No	Minerals	Formula	Content %	Index no.	Chart
S.4	Calcite	$Ca(CO_3)$	68.70	88-1808	
	Aragonite	$Ca(CO_3)$	31.30	75-2230	

Constituents %	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	SO_3	Cl	SrO	L.O.I
S.4	1.75	0.68	0.36	0.49	51.74	0.26	0.33	0.17	0.32	43.67

Sample no.	WA (%)	BSG	BD (g/cm^3)	AP (%)	CS (Mpa)
S.4	17.92	1.64	1.48	29.21	3.10

These include clay, silt, quartz or other sands, pebbles, and especially fossils – usually calcite or aragonite (a mineral with the same chemistry as calcite ($CaCO_3$), but with an unstable atomic geometry unlike calcite, which has a stable atomic geometry (Marble Institute [10]).

3.1.5 El-Ghareen buildings' sample (S.5)

XRD illustrated calcite as major and aragonite as minor minerals; while the physical and mechanical tests showed the very weak properties of the stone, where the percentage of porosity and water absorption is very high while the stone's compressive strength is very low.

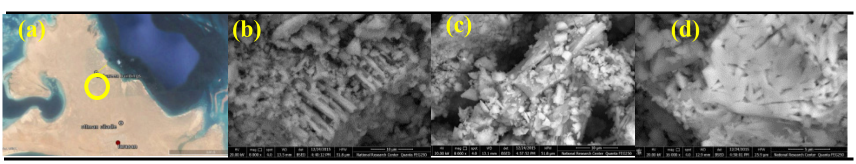
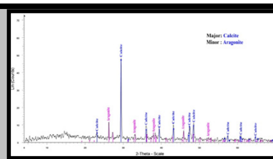


Figure 8: The site is 1.22 km from the sea (a), SEM micrograph showing kaolinite and quartz (b), and the presence of aragonite (c).

Table 6: Composition, some physical and mechanical properties of S.5.

No	Minerals	Formula	Content %	Index no.	Chart
S. 5	Calcite	$Ca(CO_3)$	58.40	88-1808	
	Aragonite	$Ca(CO_3)$	41.60	75-2230	

Constituents %	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	SO_3	Cl	SrO	L.O.I
S. 5	0.59	0.21	0.06	0.37	53.51	0.19	0.31	0.11	0.77	43.74

Sample no.	WA (%)	BSG	BD (g/cm^3)	AP (%)	CS (Mpa)
S. 5	4.33	2.35	2.34	10.16	3.62

3.1.6 Al-Arady buildings' sample (S.6)

XRD illustrated calcite as major, albite and aragonite as minor and quartz as traces minerals, XRF assured the results except the presence of magnesium which its appearance may be due to dolomite. XRD and XRF also indicate the high percentage of quartz which assured the presence of kaolinite with SEM.

As for physical and mechanical properties, unfortunately, it was difficult to provide the required sample to conduct these tests but visual and microscopic examination illustrate the weakness of the structure of these stones.

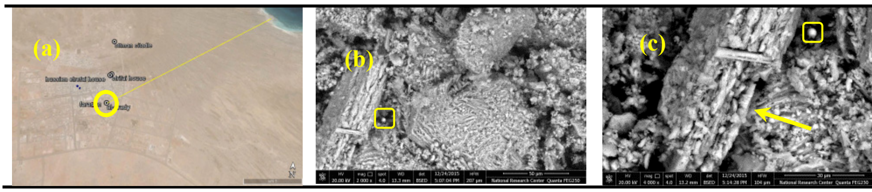
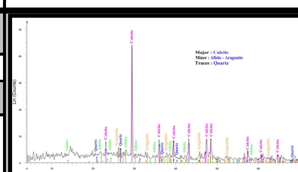


Figure 9: The site is 4.00 km from the sea (a), SEM micrographs (b) and (c) show iron in rounded shapes, also showing slight etching of well-crystallized kaolinite and growth of illite bridging kaolinite and quartz (Robinson *et al.* [11]).

Table 7: Composition, some physical and mechanical properties of S.6.

No	Minerals	Formula	Content %	Index no.	Chart
S. 6	Calcite	$Ca(CO_3)$	58.30	88-1808	
	Albite	$NaAlSi_3O_8$	19.70	01-0739	
	Aragonite	$Ca(CO_3)$	17.00	75-2230	
	Quartz	SiO_2	5.40	05-0490	

Constituents %	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	SO_3	Cl	SrO	L.O.I
S. 6	4.75	0.06	1.13	1.16	48.74	0.32	0.49	0.21	0.28	40.27

3.1.7 Kessar houses' sample (S.7)

XRD analysis illustrated minerals as (major Aragonite and Calcite + traces Quartz); physical and mechanical tests showed better compressive strength.

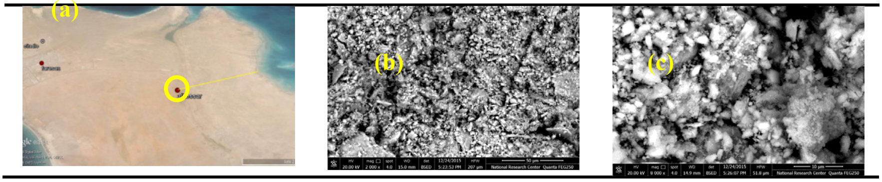
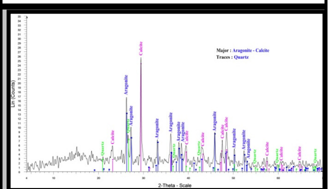


Figure 10: The site is 2.69 km from the sea (a); SEM micrographs show degradation of crystals (b) and aragonite (c).

Table 8: Composition, some physical and mechanical properties of S.7.

No	Minerals	Formula	Content %	Index no.	Chart
S.7	Aragonite	$Ca(CO_3)$	53.90	75-2230	
	Calcite	$Ca(CO_3)$	36.90	88-1808	
	Quartz	SiO_2	9.20	05-0490	

Constituents %	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	SO_3	Cl	SrO	L.O.I
S. 7	1.29	0.29	0.09	0.69	51.38	0.40	0.72	0.24	0.95	42.62

Sample no.	WA (%)	BSG	BD (g/cm^3)	AP (%)	CS (Mpa)
S. 7	2.61	2.53	2.41	6.60	45.13

3.1.8 Abdullah Ibrahim Rifai House's sample (S.8)

XRD illustrated minerals as (major calcite + traces quartz), while XRF shows the high percentage of magnesium may be due to the presence of Dolomite and it's noticed also the Reduction of L.O.I 'loss of ignition' in the sample and the height of sulfur and strontium content at it, SEM explained that by the presence of Gypsum and Celestine crystals in the gypsum matrix.

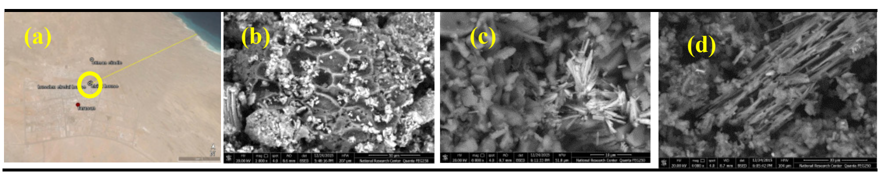
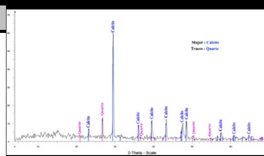


Figure 11: The site is 3.71 km from the sea (a), SEM micrographs shows honeycomb formations (b), gypsum and/ or anhydrite crystals (c), degradation and microbiological damage within clay minerals (d).

Celestine ($SrSO_4$) is mostly found in sedimentary rocks usually in small quantities , often associated with the minerals gypsum, anhydrite, and halite (Wikipedia [12]); Celestine is relatively rare mineral that is found in some limestones, sandstones, and evaporate deposits, the presence of Celestine in substantial quantities would indicate unusual chemical conditions after and possibly during deposition of the host sediment (McCartan *et al.* [13])

Table 9: Composition, some physical and mechanical properties of S.8.

No	Minerals	Formula	Content %	Index no.	Chart
S.8	Calcite	$Ca(CO_3)$	85.80	88-1808	
	Quartz	SiO_2	14.20	05-0490	

Constituents %	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	SO_3	Cl	SrO	L.O.I
S. 8	2.61	0.65	0.29	1.28	32.95	0.34	35.27	0.26	0.81	25.31

Sample no.	WA (%)	BSG	BD (g/cm^3)	AP (%)	CS (Mpa)
S. 8	2.69	2.43	2.37	6.52	36.57

4 Conclusions

All investigations and analysis results confirmed each other and from those results we deduced that the main building materials used in the Farasan Islands were:

- The same mineralogical composition but in different proportions: calcite, Aragonite, Albite and Dolomite; also present different rates of degradation.
- With high calcium content (The high percentage of Loss of Ignition “LOI” in the samples also ensure that) this could be correlated with its light colour, while iron content of sample (n. 6) could be responsible of the red tones.
- Local building stones cut from Farasan itself and carry all its characteristics and properties.
- Affected negatively with local and climatic environment, so we must defend Farasan heritage by quick intervention to improve the properties of building materials so that they become more resistant to surrounding conditions.
- Load fracture of limestone subjected on research is very low and that’s attributed to the presence of aragonite mineral with reasonable ratios (which demonstrates - with dolomite - the recent hardening process of the stone after deposition); noting the lack of density due to high porosity and also the high rate of water absorption at atmospheric pressure.

All these factors increase the rate of deterioration which adversely affect the mechanical and physical properties of the stone.

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