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AN EVALUATION OF THE CONSERVATION STATE OF QASR EL-EMARA, AL-WAJH, SAUDI ARABIA

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Abstract

Qasr El-Emara, located in the center of the old city on Al-Wajh on the Red Sea coast, is an important historical coral building in the north of Saudi Arabia. This research aims to diagnose the current conservation state of Qasr El-Emara and to identify the building materials (stone, mortar, plaster and timber), the construction method and the deterioration and degradation effects on the Qasr El-Emara building. To achieve these objectives, we used a number of investigation and analysis methods, such as: field observations (visual examination), optical microscopy (OM), polarized microscopy (PM), X-Ray Diffraction (XRD) technique and image analysis (Sigma Scan Pro.5 of SPSS Inc.). The main building materials of Qasr El-Emara were identified as follow: limestone coral (three species), lime, gypsum mortar, two different plaster layers (external and internal lime plaster), and tamarisk wood, used for timbers and dormers. Random rubble (un-coursed) was the construction method. The most important aspects of damage we observed were the loss of mortar between the stone blocks, the loss of the external plaster layer, observed especially in the lower part of the building, spread cracks in the plaster layer and in the walls with partial collapses, and surface damage of the timber used for the construction of the main façade.

Keywords: *Qasr El-Emara; building materials; examination; Coral limestone; deterioration and degradation effects.*

Introduction

The old city of Qasr El-Emara is one of the most important sites at El-Wajh. It is located in the southwest corner of the northern plateau and contains the ruins of archaeological buildings, streets, and ancient mosques that age up to more than 200 years. Saudi Arabia's Red Sea coastline extends southwards approximately 1,840km from the Jordanian border, north of Haql (29° 30' N) to the border with Yemen at Oreste Point (16° 22' N). The continental shelf extends offshore for distances of less than 1km in the Gulf of Aqaba to more than 100km on the Farasan Bank. The northern Red Sea coast of Saudi Arabia is known for its distinct traditional buildings made from coral stones [1]. The Al-Wajh Bank supports the greatest range of reef types, as with the Tiran area, where reefs of the Al-Wajh Bank are endemic corals, un-described coral species and species with apparently restricted distributions. The size of the Bank, the diversity of reef habitats and their likely high level of ecological connection in terms of larval

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dispersal in ocean currents, both within the bank and in other parts of the Red Sea, afford it great conservation significance. Al-Wajh Bank includes Sharm Habban and Sharm Munaybirah, a protected area of 2,840km^2. It is home to the most extensive coral reef system in the entire Red Sea, diverse reef-associated fauna, seagrass beds and mangroves. It is inhabited by marine turtles and seabirds and is a key area for dugong (Fig. 1) [2].

El-Wajh city is located in the middle of El-Wajh coast, in the Saudi Red Sea north-western coast (latitude - 26° 13' North and longitude - 36° 27' East) [3]. El-Wajh is located 640km from Jeddah and 714km from Mecca, 190km from El-Ulla [4]. The El-Wajh site on this desert coast led to the emergence of the importance of El-Wajh as a commercial port, because of the presence of a hole in the Coral Coast that allowed ships to reach the coast, the existence of appropriate depths in the waters and the protection required for ships from the waves and the winds.

The building materials in old city of El-Wajh, like the most ancient buildings of other Saudi traditional cities, were mud and stone. El-Wajh city was completely deserted since 1980 AC (1400 AH). The mud and stone buildings are the original buildings of the old city of El-Wajh [1].

Qasr El-Emara is located in the center of the old city on the Red Sea coast; it is approximately 132 m away from the Red Sea coast. Qasr El-Emara was established by Prince Hazza El- Abdali at Muharram in 1340 AH. It consists of two floors [5] and is located on latitude 26° 13 ' 37.35 and longitude 36° 27' 30.02 (Fig. 2.)

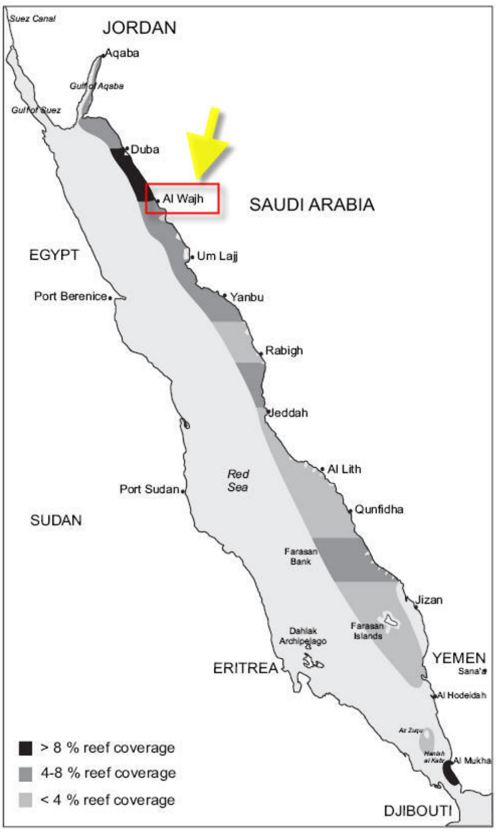

Fig. 1. Map of the Saudi Arabian Red Sea coast with the coral reef densities. Shading represents areas of 500m by 500m squares of reef, (MEPA/IUCN 1992b)

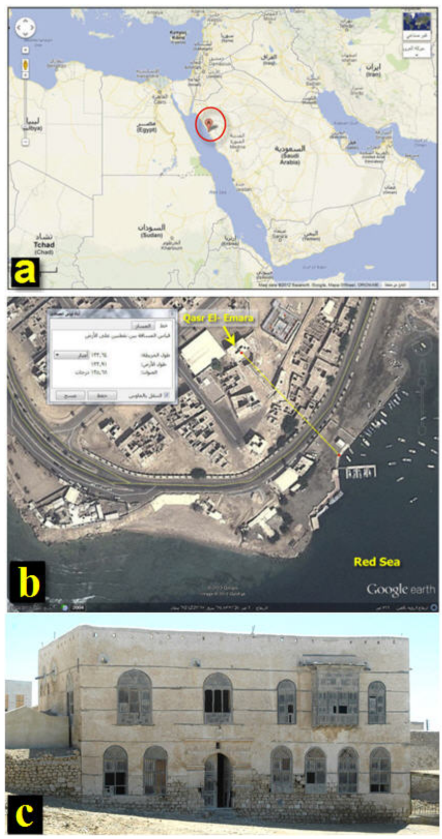

Fig. 2. General map of El-Wajh location (a), with details of the Qasr El-Emara on the Saudi Arabian Red Sea coast (b) and the general view of Qasr El-Emara coral buildings (c)

Materials and Methods

This paper sheds light on the results of field observations (descriptive study – documentation damage appearances) made in Qasr El-Emara, the old city of Al-Wajh. To achieve our objectives, Qasr El-Emara building materials samples were collected and analyzed by the following methods:

- optical microscopy (OM), by using a Smart-Eye USB Digital Microscope at various magnifications, up to a maximum of 170x fixed magnification, in order to characterize the morphological features [6], superficial shape and the grain size of the stone samples.
- polarized microscopy (PM), by using a MT 9000 Series MEJI Co. LTD Japan instrument. It was used to determine the mineralogical composition and the grain features, by using many cross sections and thin sections samples [7, 8]. Mineralogical composition, structure and percentage of pores were characterized.
- the total void areas were determined (as plane area %) in the different thin sections, by planimetery, using the computer program Sigma Scan Pro.5 of SPSS Inc., for image analysis [10].
- X-ray diffraction method (XRD) performed with an Ultima IV, multipurpose X-ray diffraction system, equipped with a copper anticathode. The measuring conditions were set as follows: Cu target 40 kV, accelerating voltage 40 mA current, the scanning range of 2θ was from 4 to 70° and the scanning speed was 2°/min. It was used to identify the chemical composition [9] of the Qasr El-Emara building materials.

Results and discussion

Field observations

- The field observations of the Qasr El-Emara buildings revealed that the main construction material was coral limestone.
- The double face walls technique was used to build the walls (Fig. 3).
- Three kinds of building stones (coral limestone) were used.
- Decoration stone was used in the main entrance (Fig. 4).
- The walls were rendered, laid with horizontal timbers.
- The interlock half to half method was used to connect timbers.
- Doors and windows openings were covered with rendered cut-stone arches (semicircular) [11], (Fig. 5, 6).
- The building method of Qasr El-Emara was random rubble, "un-coursed".
- The main façade was rendered with white to yellow wall plaster (Fig. 7).
- Complete loss of wall plaster layer was observed from ground level up to 2 m high.
- The main façade has a number of wooden artifacts: main entrance door, two oriels, ten wooden windows and four wood gutters to drain rain water. Most of those timbers were damaged (Fig. 8).
- There are moisture patches in the upper part of the façade.
- Stone deterioration can be noticed clearly in the lower course and the main entrance (Fig. 9).
- The lower parts of the building façade have partial collapses and penetrative cracks (Fig. 10).

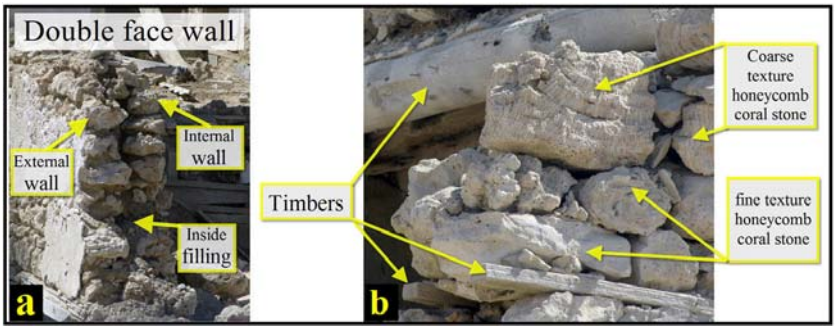

Fig. 3. The double face wall technique (a) and some of the Qasr El-Emara building materials (b)

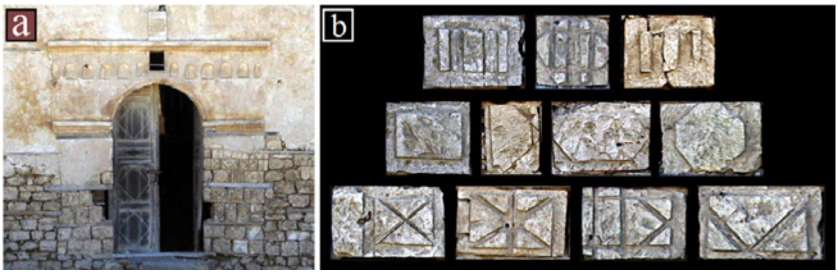

Fig. 4. The main entrance of Qasr El-Emara (a) and examples of the decoration stone of the main entrance of Qasr El-Emara (b)

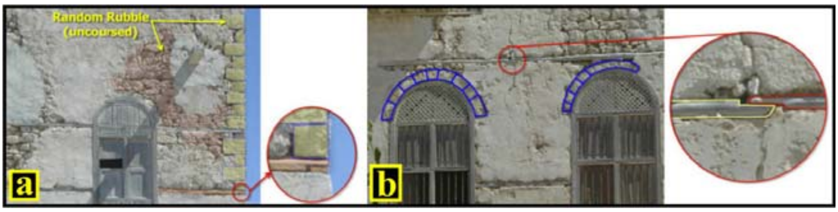

Fig. 5. Random rubble "un-coursed" method (a) and windows openings with rendered cut-stone arches (semicircular) (b)

Fig. 6. Main façade of the Qasr El-Emara building (a) and its deterioration map (b).

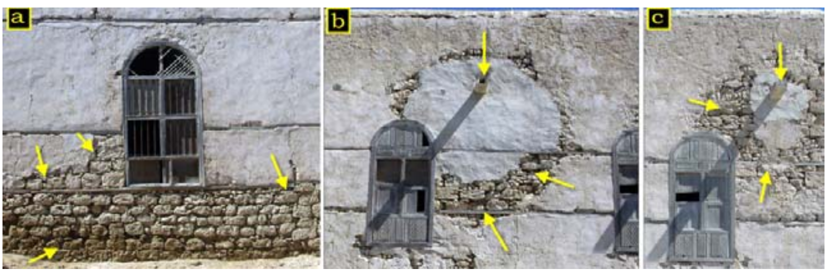

Fig. 7. Loss of wall plaster layer from ground level up to 2 m high (a) and deterioration of the wall plaster layer (b,c)

Fig. 8. The main façade has a number of wooden artifacts

Fig. 9. Deterioration aspects were determined on the main entrance of Qasr El-Emara.

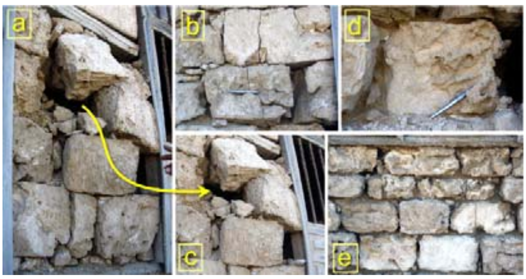

Fig. 10. Partial collapses and penetrative cracks

Qasr El-Emara building materials

Stones and mud were widely used in the old city of El-Wajh. Our field observation of Qasr El-Emara identified the main building materials as stone, mortar, timbers and two kinds of plaster. Stones were used as essential building materials in the construction of Qasr El-Emara; coral limestone was used where it was available, along the coast of El-Wajh. Limestone is a sedimentary rock composed mainly of calcium carbonate ($CaCO_3$), usually calcite, sometimes aragonite. Limestone is formed by the deposition and consolidation of the skeletons of marine invertebrates. If limestone is built up from corals and coral fragments, they are called coral limestone, which has a beautiful appearance and is often used as a building stone [12, 13]. According to Folk's limestone classification, coral limestone is biolithites, based on the type of particles and biosparite, based on the nature and proportion of the matrix and/or cement present, while Dunham (1962 and 1972) classifies coral limestone as a bound-stone [14]. This latter classification is a way to describe the composition of calcareous rock samples by eye observation. For description details of the textural components of sediments and sedimentary rocks [15], such as thin sections, the Folk classification is generally preferred. Both classifications are equally valid methods of classification with a different emphasis [16-18].

Optical & Polarized Microscope Results

Qasr El-Emara Coral limestone

Many kinds of marine invertebrates precipitate calcium carbonate to form their skeletons. There is an enormous range in size, shape, internal structure and composition. Crystal size within the skeletal material ranges from microscopic to large single crystals. Grain shape depends on the skeletal geometry of the particular species and, in the case of colonial organisms, on the style of colonial development, as well. Three kinds of coral limestone were identified in Qasr El-Emara.

The first kind is *Favites chinensis,* as shown in Figures 11, 12, 13 and 14. This species is mainly encrusting, or low massive and colonies very rarely attain much vertical height. Calices are about 10–13 mm in diameter, their walls are relatively thin. They may be round or fairly angled [19, 20]. The *Favites chinensis*, commonly known as honeycomb coral limestone, has fine and coarse textures, and its common name is given to the fossils, due to their resemblance to a honeycomb. By examination under optical microscope (OM) and polarized microscope (PM) of the honeycomb coral limestone cross sections, we found that the main component is aragonite and calcite, where the skeletal aragonite transformed to calcite. As a result of dissolution, calcite rims were formed. Dissolution is most obvious along the centers of calcification, under crossed polarized light (CN) [21-23]. The porosity of the samples was determined as 18.60% of fine texture and 26.41% of coarse texture. The honeycomb fine texture coral limestone was used to build the main entrance of Qasr El-Emara, but the coarse one was used to build the double face walls in Qasr El-Emara.

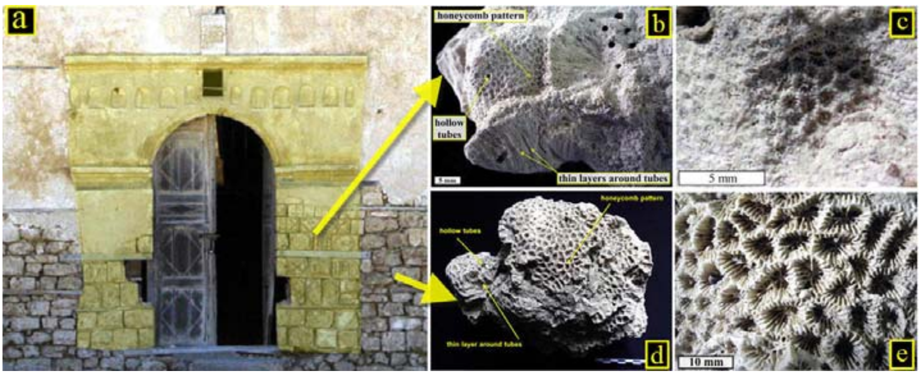

Fig. 11. Main façade having two kinds of honeycomb coral limestone (a), fine texture honeycomb coral limestone (b and c), coarse texture honeycomb coral limestone (d and e)

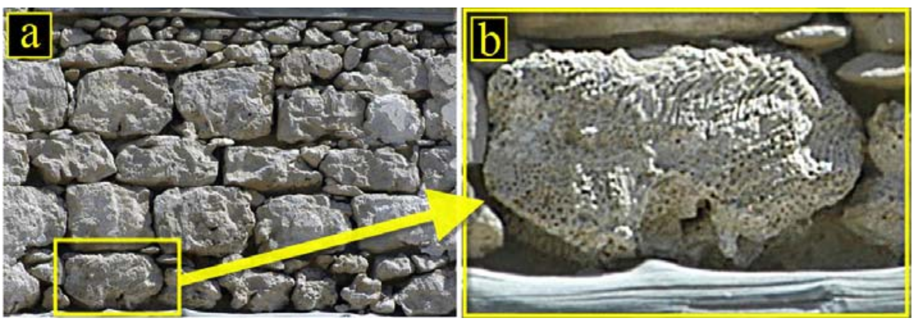

Fig. 12. Honeycomb coral limestone in the wall (a), detail of a coarse texture honeycomb coral limestone (b)

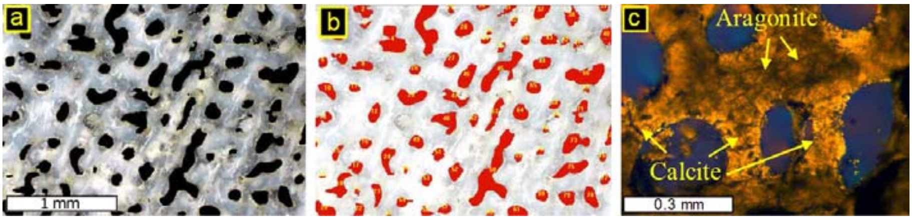

Fig. 13. Cross section of fine texture honeycomb coral limestone showing stone porosity (OM image) (a and b), The arrows indicate calcite rims and the darker color of the coralline aragonite (CN) (c)

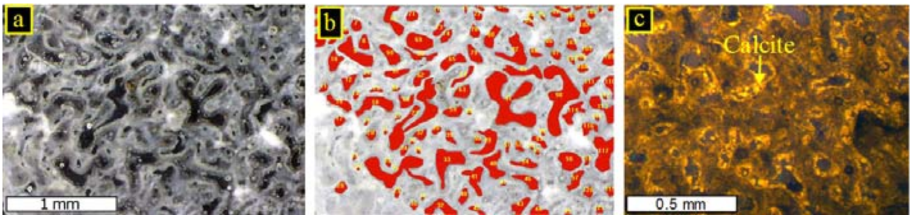

Fig. 14. Cross section of fine texture honeycomb coral limestone showing stone porosity (OM image) (a and b), The arrows indicate calcite rims and the darker color of the coralline aragonite (CN) (c)

The second kind of limestone is *Blastomussa merleti.* The colonies are *cerioid phaceloid*, or with both conditions occurring in the same colony. The illustration shows the range in which it occurs. Under an optical microscope (OM) and polarized microscope (PM) a *Blastomussa merleti* cross section showed that its main component was aragonite [24]. The porosity of the samples was determined as 27.22%, (Figs. 15 and 16). *Blastomussa merleti*, commonly known as star coral limestone, was used to build the foundation of Qasr El-Emara.

Fig. 15. *Blastomussa merleti* sample (a), *Blastomussa merleti*, morphology details (b and c).

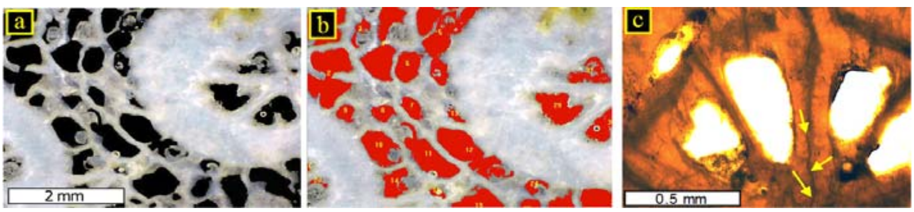

Fig. 16. Cross section of *Blastomussa merleti*, sample shows stone porosity (OM image) (a and b), arrows show the darker color of the coralline aragonite, (CN) (c).

The third kind of limestone is *Leptoria phrygia*, a species which is largely restricted to shallow waters in the Red Sea. It occurs mainly on exposed and moderate reef crests and on seaward facing slopes [19, 20]. *Leptoria phrygia* is commonly known as brain coral limestone and it was used in filling the double face walls of Qasr El-Emara. Brain coral is named so because of this coral's spheroid shape and grooved surface, which resembles an animal brain.

By examining a *Leptoria phrygia* cross section we found that the main component was Aragonite. The porosity of the sample was determined as 51.37%, (Figs. 17 and 18).

Fig. 17. *Leptoria phrygia* (brain coral limestone) sample (b), *Leptoria phrygia* morphological details (b), *Leptoria phrygia* in sea water (c).

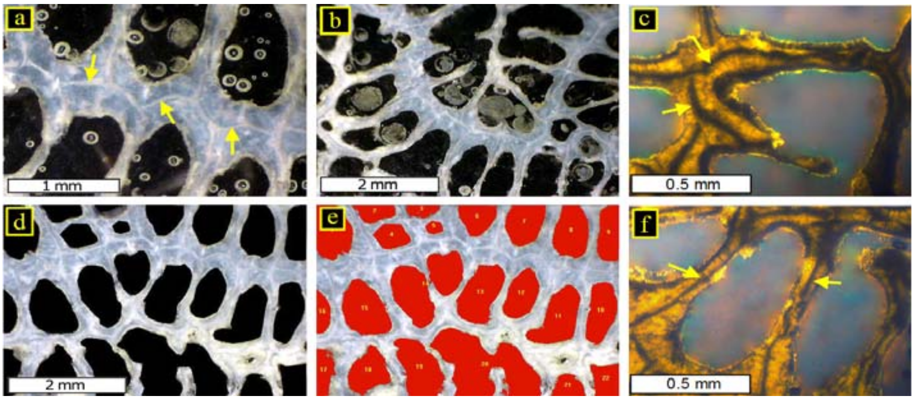

Fig. 18. Cross section of *Leptoria phrygia,* sample showing stone porosity (OM image) (a, b, d and e), The arrows indicate the darker color of the coralline aragonite (CN) (c and f).

Qasr El-Emara mortar

Visual examination of the Qasr El-Emara mortar revealed that it's texture was solid, cohesive, white-colored and homogeneous. The mortar was highly reactive to HCl 10%. The mortar of the lower part of the building was lost. Under optical and polarized microscopy examinations a background of calcite was observed, which contains clusters of gypsum, a little amount of quartz and different rock fragments [25-27], (Figs. 19 and 20).

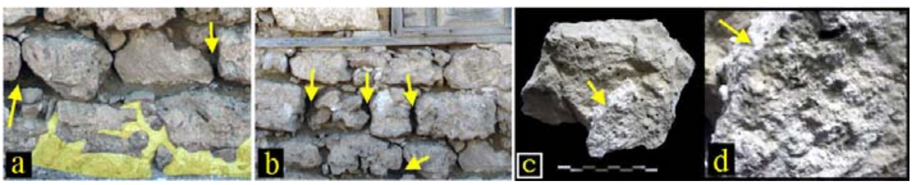

Fig. 19. Lack of mortar between stones (a and b), adhered mortar to the building stone (c and d).

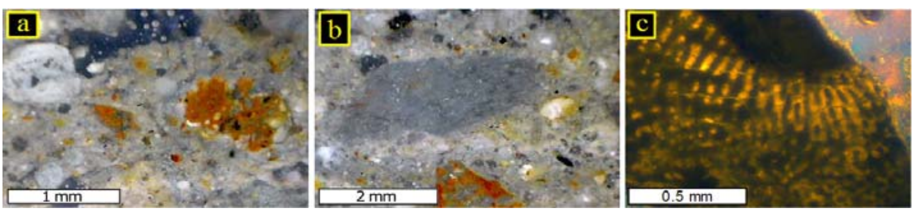

Fig. 20. Thin section of the mortar showing a rich background of calcite, gypsum clusters and stones fragments (OM image) (a and b), coral limestone fragment, aragonite (C.N.) (c)

Qasr El-Emara external plaster

Visual examination of the Qasr El-Emara external plaster revealed that it's texture was solid, cohesive and white to yellow in color. It was highly reactive to HCl 10%. It displayed the effects of wind erosion, except for the lower parts of the building, where the plaster layer was lost. Through optical and polarized microscopic examination, we observed a background rich in calcite, gypsum clusters, sand and stone fragments, as well as the existence of some spherical objects (fossils) [28] (Figs. 21 and 22).

Fig. 21. External collapsed wall plaster of green color (a and b),
The texture of the Qasr El-Emara wall plaster (c and d).

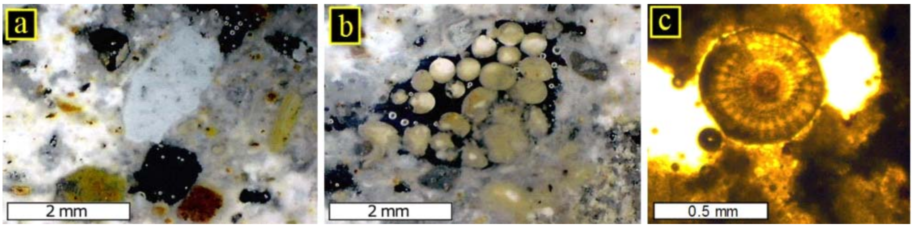

Fig. 22. Thin section of the external wall plaster showing a rich background of calcite, gypsum clusters, stone fragments and spherical objects (fossils) (OM image) (a and b). Spherical objects (fossils) in calcite background (CN) (c).

Qasr El-Emara internal plaster

The field and visual examination of Qasr El-Emara internal plaster indicated that it was solid, cohesive and white to yellow in color. It was highly reactive with HCl 10%. It contained small black rock fragments and sand grains, various in shape, size and color. The microscopic examination, under optical and polarized microscope, showed a background rich in calcite, gypsum clusters, stone fragments and different rock fragments, as well as coral limestone fragments [29, 30] (Figs. 23, 24 and 25)

Fig. 23. (a and b) Qasr El-Emara internal wall plaster containing black stone fragments.

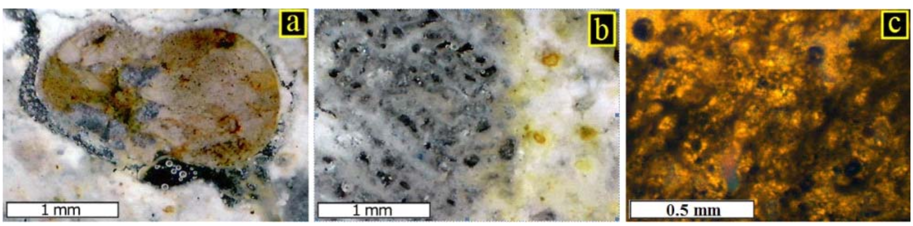

Fig. 24. (a and b) Thin section of the internal wall plaster showing calcite background, quartz grains, coral stone fragments (OM image), (c) Calcite and gypsum matrix, (CN)

Fig. 25. (a and b) Thin section of the internal wall plaster showing calcite background, quartz grains, stone fragments in different shapes and colors (OM image) (c) calcite and gypsum matrix, (CN)

Qasr El-Emara timbers

The timber used in Qasr El-Emara was horizontal timber (tamarisk trunks). It was used as a support for the coral wall. Timbers were connected with each other by the interlock method, half/half. The doors, windows and oriels were made of tamarisk wood. The visual and microscopic examinations of the timber samples revealed superficial damage, such as loss of surface fibers, fading in color, cracks, fissures, wrapping and rust stains (Figs. 26, 27 and 28).

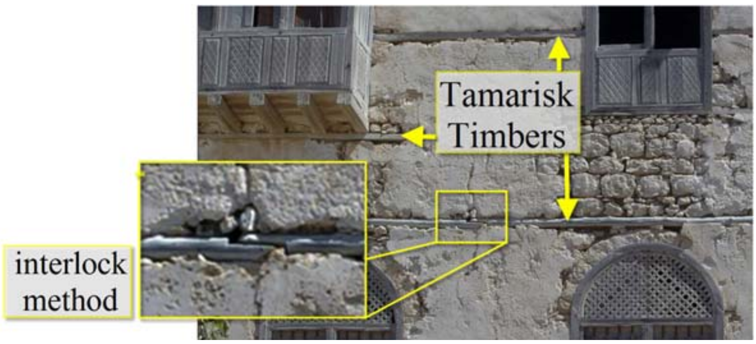

Fig. 26. Horizontal timber that supported the rendered coral wall and the half/half interlock method used to connect timbers

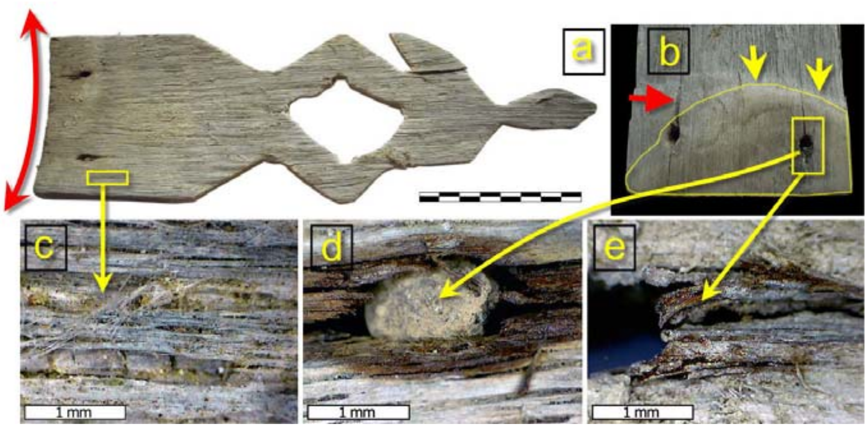

Fig. 27. Outer surface of oriel decorated wooden element, which was affected by warping, cracks and superficial damage (a); the internal surface has rust stains, due to use of iron nails (b); enlarged image of cracks (c); enlarged image of rust stains (d and e).

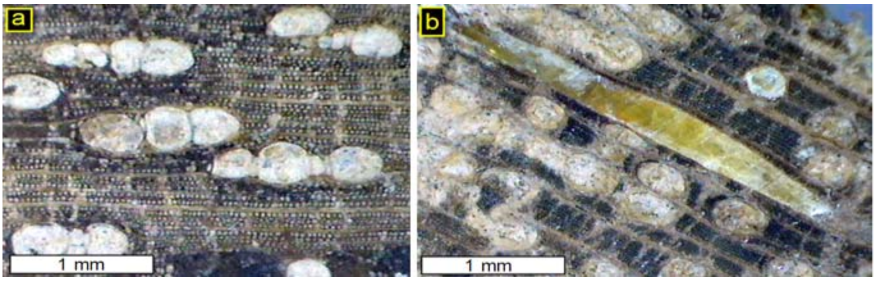

Fig. 28. Cross section of the timber sample which shows vessels (perforation plate) (a); longitudinal tangential section, which shows longitudinal tracheas filling with resin used to plug up the wood pores (b).

Timber is an organic material that can partially or totally decompose due to deterioration factors. Dryness is the main problem of the restorer, when dealing with outdoor timber in Saudi Arabia. The direct effect of temperature on the timber is slow, when compared with the effect of relative humidity. As a result of dryness, fragility and weakness of the timber surface and changes in the original dimensions, deformation, fissures, cracks different in length and depth and breadth, warping and loss of cellulose content occurs [31]. The outdoor timber is damaged slower than buried timber in moisture condition [32, 33].

Timber is a hygroscopic material affected by water, due to the hydroxyl groups (OH) of cellulose. Therefore, wood has a great ability to absorb moisture. By continuous shape shifts wood detaches its fibers, develops cracks and changes its dimensions [34].

XRD results

Results of the XRD analysis for the main building materials used in Qasr El-Emara at Al-Wajh are shown in Table 1 and in Figure 29 [35, 36].

Table 1. Minerals identified in the building materials samples by XRD analysis.

No.	Samples	Minerals	Formula	Index No.
1	**Honeycomb coral limestone (*Favites chinensis*)**	Calcite	$CaCO_3$	5-0586
		Aragonite	$CaCO_3$	5-0453
2	**Star coral limestone (*Blastomussa merleti*)**	Aragonite	$CaCO_3$	5-0453
		Halite	NaCl	5-0628
		Calcite	$CaCO_3$	5-0586
		Bassanite	$2CaSO_4{\bullet}H_2O$	14-453
3	**Brain coral limestone (*Leptoria phrygia*)**	Aragonite	$CaCO_3$	5-0453
		Halite	NaCl	5-0628
		Calcite	$CaCO_3$	5-0586
		Bassanite	$2CaSO_4{\bullet}H_2O$	14-453
4	**Mortar**	Calcite	$CaCO_3$	5-0586
		Bassanite	$2CaSO_4{\bullet}H_2O$	14-453
		Silicon Oxide	SiO_2	14-0260
		Gypsum	$CaSO_4{\bullet}2H_2O$	6-0046
		Halite	NaCl	5-0628
		Iron Oxide	Fe_2O_3	25-1402
		Hematite	α- Fe_2O_3	13-534
		Quartz	SiO_2	5-0490
5	**External wall plaster**	Calcite	$CaCO_3$	5-0586
		Silicon Oxide	SiO_2	14-0260
		Iron Oxide	Fe_2O_3	25-1402
		Halite	NaCl	5-0628
		Gypsum	$CaSO_4{\bullet}2H_2O$	6-0046
		Hematite	α- Fe_2O_3	13-534
6	**Internal wall plaster**	Calcite	$CaCO_3$	5-0586
		Gypsum	$CaSO_4{\bullet}2H_2O$	6-0046
		Albite	$(Na,Ca)(Si, Al)_4O_8$	09-0456
		Iron Oxide	Fe_2O_3	25-1402
		Halite	NaCl	5-0628

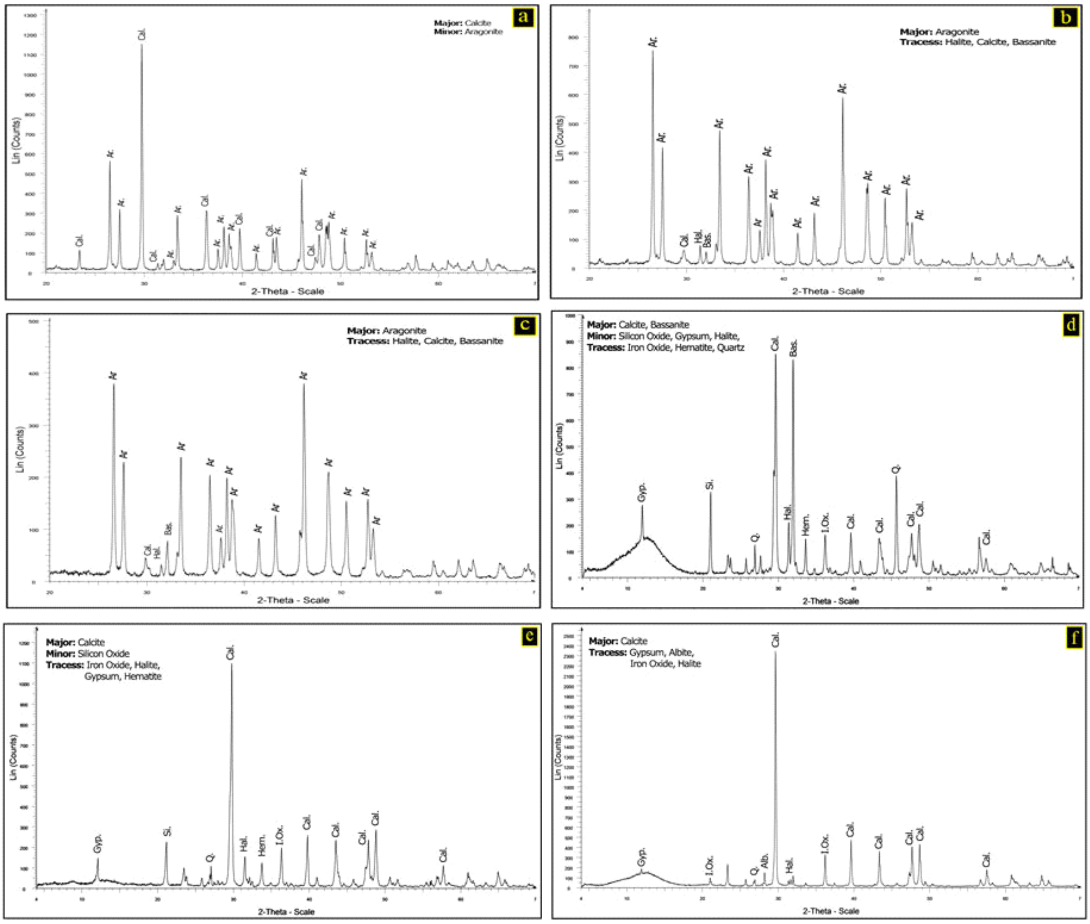

Fig. 29. X-ray patterns of the identified minerals in the studied building materials samples: (a) - Honeycomb coral limestone sample, (b) - Great star coral limestone sample, (c) - Brain coral limestone sample, (d) - Mortar sample, (e) - External wall plaster sample and (f) - Internal wall plaster sample.

The XRD results confirmed the investigations results obtained by optical microscopy and polarized microscopy. From those results, we deduced that the main building materials used in the Qasr El-Emara buildings at Al-Wajh were:

- Honeycomb coral limestone (major Calcite + minor Aragonite $CaCO_3$)
- Great star coral limestone (major Aragonite $CaCO_3$ + traces Halite NaCl, Calcite $CaCO_3$, Bassanite $2CaSO_4{\cdot}H_2O$)
- Brain coral limestone (major Aragonite $CaCO_3$ + traces Halite NaCl, Calcite $CaCO_3$, Bassanite $2CaSO_4{\cdot}H_2O$)
- Main components of mortar were *Lime* "Calcite"+ *Gypsum* "Bassanite and gypsum"+ *Sand* "Quartz") and traces of Halite, Iron Oxideand Hematite
- The main components of the external wall plaster were *Lime* "Calcite"+ *Sand* "Silicon Oxide"+ *Gypsum* "gypsum" and traces of Halite, Iron Oxide and Hematite.
- The main components of the internal wall plaster were *Lime* "Calcite"+ *Gypsum* "gypsum" + *Stone fragment* "Albite" and traces of Halite and Iron Oxide.

Aragonite is a carbonate mineral, one of the two common, naturally occurring, crystal forms of calcium carbonate, $CaCO_3$ (the other form being mineral calcite) [12 , 37].
Aragonite forms naturally in almost all mollusk shells and as the calcareous endoskeleton of warm- and cold-water corals (*Scleractinia*). Aragonite also forms in the ocean and in caves as inorganic precipitates, called marine cements and speleothems, respectively. Aragonite is thermodynamically unstable at standard temperature and pressure and it tends to alter to calcite. The mineral vaterite, also known as μ-$CaCO_3$, is another phase of calcium carbonate that is metastable at environmental conditions typical to the Earth's surface and decomposes even more readily than aragonite. The physical properties of aragonite are shown in Table 2.

Table 2. Physical properties of aragonite

Category	Chemical Formula	Crystal system	Mohs scale hardness	Streak	Specific gravity
Carbonate mineral	$CaCO_3$	Orthorhombic	3.5 – 4.0	White	2.95

Halite (NaCl) was detected in all samples, as traces of salt, rather than as a main component. Its existence is a result of its transferring from the saline underground water in the soil through water capillarity, especially as Qasr El-Emara at Al-Wajh is only 133 m away from Red Sea shore.

Calcite was detected in mortar and in the external and internal wall plaster samples. Lime was used as the main cementing material for mortar and plaster. Mortar and plaster take a long time to harden after drying and they turn into a coherent mass. The mechanism of the drying process varies according to the type of the lime used; non-hydraulic lime (air-lime) or hydraulic lime [35, 36]. The properties of the lime plaster are influenced by additional materials [38] that affect the solidification process and may improve its mechanical properties [39].

Gypsum was detected in mortar and in both the external and internal wall plaster samples. It was used to accelerate the mixture setting [40].

Conclusions

From our analyses and investigations we concluded that Qasr El-Emara at Al-Wajh comprises three kinds of stone. The first kind is *Favites chinensis*, commonly known as honeycomb coral limestone (Calcite $CaCO_3$ + Aragonite $CaCO_3$), which has fine and coarse textures. The fine texture stone was used to build the main entrance of the building and the coarse textured one was used to build the walls of Qasr El-Emara. The second kind is *Blastomussa merleti,* commonly known as star coral limestone (Aragonite $CaCO_3$), which was used to build the foundation of Qasr El-Emara. The third kind of building stone is *Leptoria phrygia,* commonly known as brain coral limestone, which was used to build the foundation and filling of the double face wall of Qasr El-Emara.

Qasr El-Emara mortar, consisting of *Lime* "Calcite"+ *Gypsum* "Bassanite" was used as cementing material, while sand "Quartz" was used as a filler.

There are two kinds of plasters used at Qasr El-Emara. The first kind is external plaster, consisting of lime, "Calcite", as a cementing material, sand, "Quartz", stone fragments as a filler, gypsum as mixture setting accelerator. The second kind is internal plaster, which consists of the same components, but different from the first one in that the filler material is black rock fragments, instead of quartz.

Tamarisk trunks were used as horizontal timbers in the Qasr El-Emara walls. Those timbers are suffering from many superficial damage aspects, such as loss of surface fibers, color fading, cracks, fissures, wrapping and rust stains.

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