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An Analytical Study of Building Materials and Deterioration Factors of Farasan Heritage Houses, and the Recommendations of Conservation and Rehabilitation (German House Case Study)

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Abstract

Heritage Houses in Farasan Islands are facing several threats that may cause their destruction. The houses have been affected by both the richness and poorness of their building materials. This study is concerned with the deterioration factors which affect the heritage houses in Farasan Islands. Modern techniques will be used in investigating, analyzing and documenting the cultural heritage. The study will propose an integral and applicable plan for the restoration, conservation and rehabilitation of heritage houses in Farasan Islands.

Keywords: Farasan Islands; Factors of Deterioration; XRD; Conservation; Rehabilitation.

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1. Introduction

The Farasan Bank is in the southeast Red Sea, 40 km off the southwestern coast of Saudi Arabia. The Farasan Islands arise from the Farasan Bank and they are separated from the coast by the Al-Banat Sea. Muslim geographers and historians referred to the importance of the Farasan islands. Wadi Matar is the biggest archaeological site on the island, large numbers of foundations of circular and rectangular buildings were found. Some of the buildings were 30 x 15 m long and were probably used for official purposes. There are also some rock art sites which were discovered on the island and some foundations of Ottoman buildings such as a big watch tower called Hisn Al-Awadi. The antiquities of Farasan Islands vary in date between the first millennium BC and the Ottoman period. Various sites included The German house, Al-Rifai house, and Al-Najedi mosque, reveal the flourishing periods of Farasan islands.

Farasan Islands consist of six major sedimentary/environmental units. Three of these are recent sediments; bio clastic sand, wet sabkha and rocks, and vegetated areas, and three are units of shallow marine reefal limestone comprising bio clastic grain stone, bio clastic rudstone and bio clastic float stone. Present-day shallow sedimentary environments (e.g. coral reefs, sabkhas and sand dunes) have also been mapped and their distribution is related to prevailing environmental conditions. Previous borehole data indicates that the Farasan reef limestones are underlain by layers of gypsum and anhydrite, which in turn are underlain by a thick halite sequence. The Farasan Limestone has been deformed by salt diapirism into a variety of mapped structures including salt domes, anticlinal salt ridges, solution holes and surface breccias. Bathymetric mapping down to 30m identifies seafloor salt domes and solution holes. Al Banat Sea is considered to be a salt withdrawal basin between Farasan Bank and the Saudi Arabian coast (Bantan, 1999).

Kammah Island is in the south west of Farasan islands. About 6km off the coast there is a place known as the German house, built in 1319 AH-1901 AD during the German-Turkish alliance. The house was built to store coal fuel for ships crossing the Red Sea from the Suez Canal in the North to Bab Al-Mandeb in the South-East, because of the strategic island location (Shawati, 2011).

The German house is a rectangular building of one hundred and seven meters long, thirty-four meters wide, and four meters in height. The house has three entrances of 3.2 m wide, and a fourth entrance in the middle of the eastern facade is 8 m wide. Inside the building there are two rows of parallel columns in each row 20 square column (Al-Rashid, 2003), see Fig. 1.

The deterioration of stone is an international problem in the historic buildings. Problems related to the weathering and decay of natural stone monuments are of considerable interest and increasing concern to the building industry and the research community.

Natural stones are affected by weathering. The interaction between stone materials and natural or anthropogenic weathering factors controls the type and extent of stone damage. Utilization of the monuments, insufficient maintenance or inappropriate restoration activities may have contributed to the alarming rate of stone deterioration. Due to the increasing awareness and respect for our built heritage, preservation of stone monuments has become an important public and political concern. Today, all experts agree that precise damage diagnosis is the prerequisite for understanding causes, processes and characteristics of stone damage and for sustainable monument preservation. During the last few decades, interdisciplinary research and new technologies have been introduced in damage diagnosis and monument preservation activities.

![Diagram of German house](image)
2. Materials and Methods

X-Ray diffraction (XRD) was used to analyze the inorganic materials used in the construction of the building. Samples of weathered mortars, plasters, and stones were taken from the German house remains and analyzed by XRD analysis. A Philips X-Ray diffraction unit, model PW/1710 with Co radiation, Fe filter at 40 KV, 30 MA and scanning speed 0.02/s was used. From the diffraction charts, the dA and the relative intensities were obtained and compared with (JCPDS) files (Smith et al., 1967).

3. Results and Discussion

3.1. Stone samples

The XRD analysis of stone samples reveal that calcium carbonate is the main component of stone, the result of first sample of stone is calcite (61.6%), gypsum (16.3%), halite (13.7%), quartz (4.7%), hematite (3.7%), the result of second sample is calcite (25.6%), gypsum (31.5%), halite (16.8%), quartz (13.2%), hematite (12.9%), see Fig. 2.

3.2. Mortar samples

Mortars are composed of an inorganic or organic binder and sand or gravel aggregate with or without pigments. Inorganic binders may be lime, cement or gypsum, while organic binders can be animal glue. The kind of binder depends on the area where it is to be applied (Snethlage and Sterflinger, 2011). It acts as a link between other materials, such as stones, bricks and so on, in mortars; gypsum usually includes small percentages of sand and limestone powder (Moussa et al., 2009). Two samples were collected from the building, in the first sample the analysis detected, calcite (56.3%), gypsum (23.1%), quartz (11.4%), halite (9.3%), in the second sample the analysis detected, calcite (63.1%), gypsum (20.6%), quartz (9.2%), halite (7.1%), see Fig. 3.
3.3. Plaster samples

Plaster (the skin of the building) covers the walls, columns and façades of the building, preserving them from external weathering conditions and providing a paintable surface (Moussa et al., 2009). Two samples were collected from the building, the first sample consists of calcite (77.6%), quartz (15.5%), halite (6.9%), the second sample consists of calcite (78.2%), quartz (12.9%), halite (8.9%), see Fig. 4.

3.4. Salt sample

Samples of what appears to be salt efflorescence were collected, the XRD analysis of the sample reveals the presence of halite salt, the sample consists of halite (80.9%), and calcite (19.1%), see Fig. 5.
3.5. Factors of deterioration

Changes in temperature and moisture, salt, earthquakes, and human malpractice, are the main factors that accelerate stone decay processes of the German house, the building has suffered from many aspects of damage such as powdering of stone, efflorescence of salts, cracks, missing parts, and destroyed columns.

The building materials have deteriorated due to the action of natural factors, commonly found in Mediterranean cities near the sea, such is the presence of soluble salts in combination with environmental factors that control the movement and evaporation of the water – allowing salt to fluctuate between crystals and solution in the stone.

It is generally assumed that stone is one of the most durable materials when it is compared to weaker building materials, such as wood or mud. But stone can deteriorate and many factors will affect it. The nature of the stone is critical in determining its resistance to the various deterioration factors. The most important one is salt.

Salt weathering is one of the principal causes of deterioration of stonework and masonry used in architectural heritage all over the world. Physical stress resulting from salt crystallisation in pores is the most important deterioration mechanism causing breakage of carbonaceous building materials. Salts can be originated from incompatible building materials and inappropriate treatments, air pollution; meanwhile, at coastal sites marine aerosols are the main sources of deposited salts.

The growth of salt crystals within the pores of a stone can generate stresses that are sufficient to overcome the stone's tensile strength and turn the stone to a powder (Price, 1996). However, salt by itself is not necessarily damaging. It requires the presence of water for its aggressiveness to become evident, and water is needed for biocolonization to occur, for freeze-thaw phenomena and for wet-dry expansion. Control of this single factor can decrease significantly the deterioration potential of a stone and any structure built from it.

Deposition of acidity from the atmosphere is an important source of salt enrichment in building materials. The major anions associated with atmospheric acid forming species are sulphate and nitrate. Therefore, the processes described in the previous section lead to the enrichment of sulphates and nitrates of calcium, in the case of mortars and calcitic stones, as well as sodium, potassium and magnesium in the case of other stone materials. In addition to these salts formed through chemical reaction, there is also a direct input of salts from the atmosphere. For example, in a marine environment, sea salt has an important presence in the local atmosphere. On a global scale, emissions of sea salt droplets ejected from the oceans are considered as one of the most important primary sources of the atmospheric aerosol (Blanchard and Woodcock, 1980). Sea salt particles will undergo both wet and dry deposition, the major processes leading to their enrichment in building materials.

Changes in temperature and moisture are supposed to be important factors in stone degradation. The expansion suffered during heating to high temperatures will result in the literal shattering of the external layers of the stone blocks leaving a typical rounded surface behind. Even if the temperature changes are not particularly large, the repeated heating and cooling of the stone will eventually lead to its deterioration over time (Abd El-Hady, 1986).

Changes in temperature, either increases or decreases, will result respectively in volume expansion or contraction of stone, and may be the cause of the cracks in structure, while catastrophic events such as earthquakes are responsible for heavy damage to buildings.

All porous materials will absorb water vapour from the atmosphere and expand. Although stone does not suffer this hygric expansion to the degree that wood does, it will still be affected by the inevitable cycling that it is subjected to by the normal changes in relative humidity in the air. Most affected by this process are the stones that contain clays, because their platy structure makes them particularly susceptible to retaining moisture.

Biodeterioration of stone monuments and buildings is a well-recognized problem in tropical regions, where environmental factors such as high temperatures, high relative humidity levels, and heavy rainfall favor the growth and sustenance of a wide variety of living organisms on stone surfaces (Kumar and Kumar, 1999). The most decisive factor for microbial growth is the availability of water. Therefore, porous stones that are able to retain high amounts of water are easily colonized by a wide variety of bacteria and fungi.

The deteriorating effects of microorganisms is based upon induced chemical and mechanical processes and are therefore relevant to the conservation of building stone (Lisci et al. 2003). The contraction and expansion of microorganisms following wet-dry cycles causes mechanical stress by the disruption of the grain or crystal structure of the stone. Loosened stone particles accumulate within the lower layer but get lost completely upon removal of the
microorganisms from the surface (Gadd, 2007).

The worst biodeterioration agent are humans ourselves, not considering catastrophic events such as wars; there are plenty of other examples that condemn us. To begin with, poor design in buildings, especially detailing, leads to water flowing over walls with the consequent biocolonization of surfaces. Then, there is the ubiquitous problem of poor maintenance (Salama, 2009). Faulty gutters and drainpipes allow water penetration into walls, with the resulting problem of hygric expansion of the material, and, if salts are present, to their solubilization, mobilization and eventual recrystallization, or to freeze-thaw damage. These problems are subsequently followed by the eventual restoration of the building. It is not the aim to criticize those restorations carried out in the past that used some conservation materials that would not now be used. Although in principle, the original methods of joining blocks were to be followed, i.e., metal pins or clamps embedded in lead, this was not correctly implemented, poor quality iron, rather than stainless steel was used, sometimes cement or similar materials were used for filling the holes. Since the condition of the joints between the blocks was not perfect, water penetrated and corroded the iron elements leading to their expansion with consequent mechanical damage to the stone blocks (Steiger and Charola, 2011).

Wind can cause enormous damage to buildings. Wind driven rain is important for impelling water into different elements of a building and as a relevant factor in the dry and wet deposition of atmospheric pollutants to facades. Wind not only drives rain, but sand can also be a problem in arid regions.

The previous sections discussed the different processes involved in the deterioration of stone through mechanical stresses. But in nature these seldom act alone and the observed damage is the result of their interaction. One of the difficulties faced when trying to find a remedy to a problem is the identification of the key deteriorating factor, or if there are several, as is more likely, then it is important to know if these act simultaneously or sequentially.

### 3.6. State of preservation

Farasan's climate is a desert one where there is virtually no rainfall all year long. According to Köppen and Geiger, this climate is classified as BWh. In Farasan, the average annual temperature is 29.8 °C. In a year, the average rainfall is 120 mm. Precipitation is the lowest in June, with an average of 1 mm. With an average of 18 mm, the most precipitation falls in August. With an average temperature of 33.2 °C, June is the hottest month of the year. January has the lowest average temperature of the year - it is 25.7 °C. Between the driest and wettest months, the difference in precipitation is 17 mm. During the year, the average temperatures vary by 7.5 °C (http://en.climate-data.org/location/53591/) see Fig. 6.

![Fig. 6. (a) climate graph all the year in Farasan Islands; (b) temperature graph all the year in Farasan Islands.](image)

The German house was exposed to severe deterioration factors, including salts, fluctuations in temperature and moisture, wind, and neglect; that caused several deterioration phenomena, i.e. separation between plaster layers which led to the loss of large parts, many cracks in plaster layers, crystallization and efflorescence of salt between plaster layer and stone, and between plaster layers which led to the degradation of plaster, the degradation and separation of the outer surface layers of the stone, many cracks in walls, loss of mortars between stones, and destruction of some columns and pillars, see Fig. 7.
3.7. Conservation and Rehabilitation

The main aim of all investigations presented above is to find the causes of deterioration to the Farasan buildings and to provide a scientific basis for decisions about appropriate restoration measures.

The results should provide information that can be used for the restoration practice. For instance the sources of damaging salts and their transport path through the object, and depth of weathering; type of weathering profile, assessment of changed material properties in the deteriorated zone (is there any chance for conservation or does the material need to be replaced?), assessment of climatic conditions with respect to salt activity and material behaviour (proposals for changes, if necessary), recommendations for replacement materials (stone, mortar) etc.

Complex restoration and conservation interventions very often require several procedures to be undertaken, the first step is the removal of harmful or undesirable deposits in order to reduce the deterioration rate of the substrate. In the case of the Farasan buildings, these may be easily removed by mechanical and chemical cleaning using water with a little detergent.

As previously established, salts, in combination with moisture, are the main factors for stone deterioration in Farasan. Before undertaking conservation measures such as consolidation, desalination should be carried out. This is a necessary component of preventive conservation. Desalination of masonry is usually attempted through the use of poultices, which may consist of a range of materials (e.g., clay, sand, and paper pulp). Additional materials may be added in order to increase solubility of the salts. The additives may include EDTA and sodium salts, sodium bicarbonate, ammonium bicarbonate, and ammonium carbonate (Doehne and Price, 2010).

Deterioration always causes a decrease in strength starting from the surface and progressing into the interior of stone. Consolidating stone therefore aims at equalizing this strength deficiency. To consolidate a deteriorated and poorly cohesive stone such as the heritage buildings on Farasan, it has to be impregnated with consolidant several times.

Repair and joint mortars should be used to fill open masonry joints or to repair smaller missing parts of dimension stones or filling of gaps. Heavily damaged stone that can no longer be repaired with a mortar should be replaced by new stone.

Filling of cracks with a fine-grained acrylic dispersion mortar should be carried out, also repairing, replacement and injection of plaster layers should be carried out. Rehabilitation and re-using of the building should be carried
out, to protect the building from neglect, see Fig. 8.

![Simulation of German house before and after conservation and rehabilitation (AutoCAD).](image)

Fig. 8. (a); (b); (c); (d) simulation of German house before and after conservation and rehabilitation (AutoCAD).

4. Conclusion

Precise damage diagnosis is required for the characterization, interpretation, rating and predication of weathering damage on stone monuments and is vital for sustainable monument preservation. According to the global diagnosis, performed by the integrated approach based on X-ray diffraction analysis, the main decaying product affecting the materials of the German house was Halite (NaCl). But changes in temperature and moisture, an earthquake, and human malpractice, have all contributed to accelerate the stone decay of the German house. However, there is no direct evidence for chemical biodeterioration in the stone decay. The building suffered a substantial on the materials of its walls like powdering of stone, efflorescence of salts, cracks, missing parts, and destroyed columns. A conservation project should always start with a thorough investigation of the archives with respect to previous conservation and renovation measures. This now has been done. A conservation policy for the building materials studied here, exposed to marine environment, can only be established by improving routine maintenance practices. This involves developing the most suitable desalination procedures followed by the right consolidation and protection interventions according to the stone types. Before continuing with the treatment, further chemical, physical and mechanical studies of the stones are required. In particular, the pore systems should be characterized since they control their process rates and have an influence on the different forms of deterioration.

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