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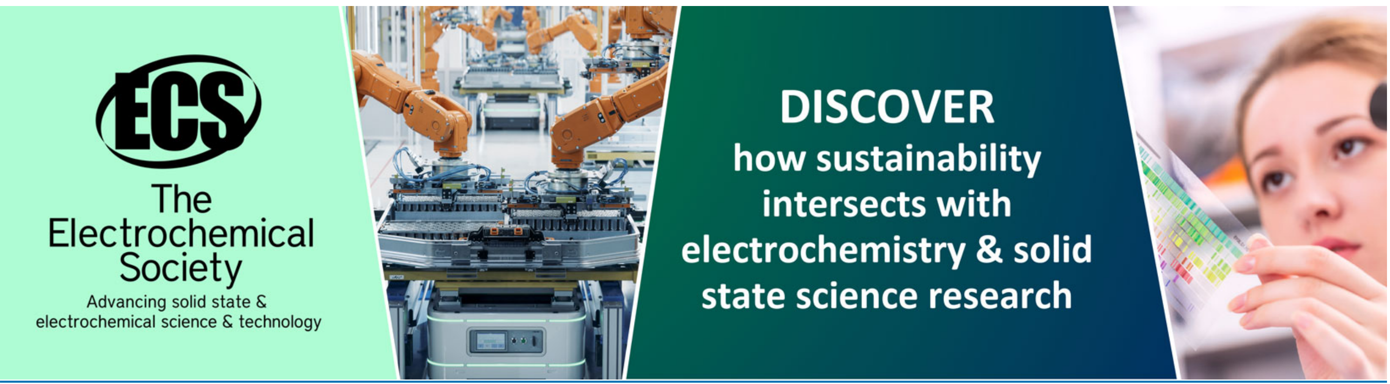

Characterization of historic mortars and earthen building materials in Abu Dhabi Emirate, UAE

Benjamin L. Marcus[1]

[1]Building Conservator, Abu Dhabi Authority for Culture and Heritage (ADACH)

Email: benjamin.marcus@adach.ae; blmarcus@gmail.com

Abstract. The Abu Dhabi Authority for Culture and Heritage (ADACH) is responsible for the conservation and management of historic buildings and archaeological sites in the Emirate. Laboratory analysis has been critical for understanding the composition of historic materials and establishing appropriate conservation treatments across a wide variety of building types, ranging from Iron Age earthen archaeological sites to late-Islamic stone buildings. Analysis was carried out on historic sites in Al Ain, Delma Island and Liwa Oasis using techniques such as micro-x-ray fluorescence (MXRF), scanning electron microscopy/energy dispersive x-ray spectroscopy (SEM-EDX), polarized light microscopy (PLM), and x-ray diffraction (XRD). Testing was conducted through consultant laboratories and in collaboration with local universities. The initial aim of the analysis was to understand historic earthen materials and to confirm the suitability of locally sourced clays for the production of mud bricks and plasters. Another important goal was to characterize materials used in historic stone buildings in order to develop repair mortars, renders and grouts.

1. Introduction

Since its establishment in 2005, the Abu Dhabi Authority for Culture and Heritage (ADACH) has been working to protect and conserve Abu Dhabi's built heritage. With over 90 listed historic buildings and hundreds of major and minor archaeological sites spread across a large territory, the scope of ADACH's work is large and continues to grow as new sites are added through survey and excavation. Traditional materials used in the construction of Abu Dhabi's historic buildings include earthen bricks and plasters, stone masonry with lime and gypsum mortars and renders, and wooden elements made from palm and hardwoods such as mangrove.

Figure 1: Map of the UAE showing site locations.

While there is a rich oral tradition of construction techniques and materials that has been passed through generations, few scientific studies of historic buildings were made in Abu Dhabi before the establishment of ADACH. Laboratory analysis of architectural materials has complemented the oral tradition and played a key role in understanding historic buildings and developing appropriate conservation treatments. This paper presents scientific analysis of building materials carried out by consultants and ADACH staff over a period of five years beginning in 2007. Each site has been the focus of comprehensive assessment and planning, though this paper will focus mainly on materials and how analysis results informed conservation. The studies include two stone towers in Liwa Oasis: Hayla Tower and Qalat Umm Hisn; two earthen sites in Al Ain: the Hamad bin Hadi al Darmaki House in Hili Oasis and Hili 17, an Iron Age archaeological site located in Hili Archaeological Park; and a group of stone buildings located on Delma island that includes three mosques and a house museum (see map, Fig. 1).

2. Stone buildings and mortars

2.1. Bait al Muraykhi and the Al Muraykhi, Al Muhannadi, and Al Dawasari mosques, Delma Island

In 2009 ADACH began a conservation management plan (CMP) for four historic stone buildings located in the Old Town of Delma Island: the Bait al Muraykhi, or Pearl Merchants House, and the mosques of Al Muraykhi, Al Dawasari and Al Muhannadi (Fig. 2). Built around 1930, the decorated coral stone and plaster buildings reflect the wealth of the pearl trade, the main economic livelihood of Delma Island in the 19th and early 20th centuries. Pearling on Delma Island declined following World War Two and by the late 1980s the buildings had fallen into disrepair, with only one of the mosques still in active use. In 1993-94 all four buildings were restored and the Pearl Merchants House turned into a museum. However, the local coral stone and gypsum-based mortars used in the original construction and subsequent restoration contain salts that have caused significant damage to the buildings and their foundations. Structural problems, termites and the humid marine environment have also contributed to the deterioration of the exteriors and wooden elements such as doors and roof beams.

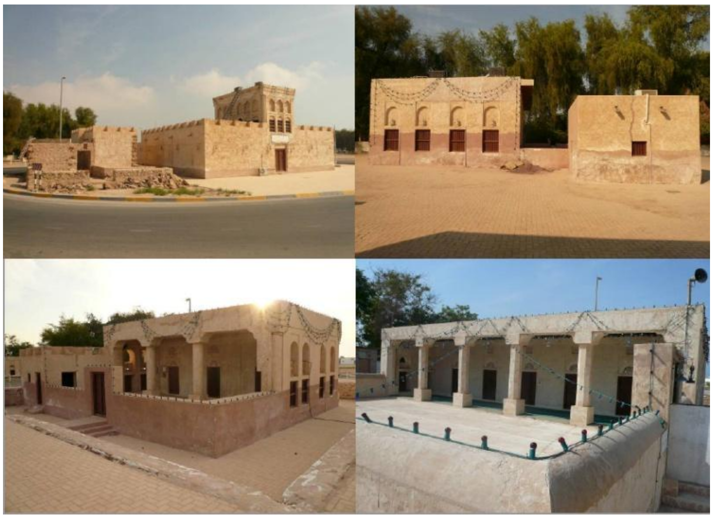

Figure 2: Clockwise from top left: Bait al Muraykhi and the Al Muraykhi, Al Muhannadi, and Al Dawasari mosques. Source: Donald Insall Associates (DIA).

CHEMICAL ANALYSIS	RS06	RS08	RS10	RS11
Insoluble Residue	0.25	0.25	4.80	8.45
Soluble Silica, SiO_2	3.69	3.28	3.79	3.94
Acid soluble Alumina, Al_2O_3	0.77	0.67	0.80	0.83
Acid soluble Iron, Fe_2O_3	0.05	0.07	0.09	0.11
Acid soluble Calcium, CaO	28.95	31.84	36.31	32.80
Acid soluble Magnesium, MgO	1.17	1.05	1.72	1.62
Acid soluble Sulphate, SO_3	49.92	40.37	30.20	31.91
Loss on Ignition	15.11	22.37	21.51	20.13
Total	99.91	99.90	99.22	99.79

Table 1: Chemical analysis results of four render samples showing predominance of gypsum ($CaSO_4{\cdot}2H_2O$). Source: DIA.

Following completion of the CMP this year, work began at the site on sourcing and testing mortars and renders for stabilizing the lower walls of the Bait al Muraykhi, which are undermined by rising damp and salts. Conservation of this delicate area involves removing failed gypsum render and replacing it with a new, more stable render that allows the walls to transmit moisture without damage. Careful scientific analysis and study were carried out on the original masonry including bedding mortars potentially dating from before the 1990s restoration, exterior and interior renders, and flooring material. 26 mortar and plaster samples, and one bedding sand sample, were submitted to a consultant laboratory for analysis. Mortar analysis was carried out according to BS4551: Part 2: 1998, whereby binder and insoluble aggregate proportions are determined through titration and acid digestion [1]. In addition, six of these samples were submitted for further petrographic analysis according to ASTM

C856 – 04, whereby thin sections are prepared in fluorescent epoxy resin and examined microscopically under fluorescent light [2].

The initial chemical analysis showed mainly gypsum : sand mixes (Table 1). However, chemical analysis alone is not able to distinguish between Portland cement and lime binders or between hydraulic and non-hydraulic limes. Petrographic analysis, however, revealed the presence of lime, which in some samples was in higher proportion than gypsum. There is very little insoluble residue remaining in most of the Delma samples following chemical analysis. This suggests that the aggregate is comprised primarily of ground soluble material such as carbonates and sulphates of calcium such as limestone, gypsum or shells, rather than silicate based sand. This is to be expected of sand sourced locally to the shore. Due to the use of soluble aggregates, the exact proportions of binder to aggregate were difficult to identify but the binder is in much higher proportion. The conclusion was that typical mortars contain gypsum, lime, and an aggregate of gypsum rock and/or limestone [3].

Because much damage to the buildings was caused by gypsum, which expands with moisture, lime was favored as a more stable conservation material. Both hydrated and natural hydraulic lime was sourced within the UAE. To determine the right mix for the new render, over 20 different samples were installed on site employing various mixes of lime (*noura*), sand and *sarooj,* a traditional waterproofing material produced in the UAE and Oman. S*arooj*, which is a mixture of fired clay and organic materials, is added to the mortar as a pozzolan to improve strength and decrease setting time. Multiple render samples were installed which allow conservators to test factors such as strength, porosity and bond with the wall, and thus be able to select the best mix for conservation works. The selected render will be used for conserving the damaged lower walls, repairing cracks, and potentially re-rendering the building exteriors. In addition, new drainage systems, termite treatment, and repair of exterior facades and roofs will ensure the long-term stability of the buildings.

2.2.Qalat Umm Hisn

Figure 3: Qalat Umm Hisn in undated historic photograph (circa mid-20th century). Source: Center for Documentation and Research (CDR), Abu Dhabi.

Figure 4: The site in 2011 during laser scanning. Source: photograph by author.

Qalat Umm Hisn is a ruined stone tower at the western end of Liwa oasis, near the mahdar of Arada. The UK and Saudi Memorials of 1955, drawn up at the time of the Buraimi dispute, state that the tower was built by the Manasir tribe in the early years of the Qatar-Abu Dhabi war (1883 – 1890) [4]. Originally consisting of a round tower between two low stone enclosures, today, the structure is largely collapsed with only one section of the tower wall standing (Figs. 3 & 4). Structural assessment carried out in 2010 on the standing wall highlighted the urgent need for stabilization through crack stitching, wall capping and repointing of eroded mortar joints.

Addressing the building's conservation, ADACH conducted materials analysis to understand the type of mortar used in the building and to plan appropriate repairs. Analysis sought to answer basic questions regarding traditional materials used in a remote area with few natural resources. Would the mortar be based on lime or gypsum, and what is the material source and method of production? Three mortar samples were taken from different areas of the remaining tower wall and surrounding low walls. Analysis techniques included optical microscopy to examine resin-embedded cross sections, and scanning electron microscope/energy dispersive X-ray spectroscopy (SEM-EDX) and X-ray diffraction (XRD) to determine elemental composition as well as mineral phases and crystalline compounds (Figs. 5 & 6). SEM investigation was performed on a Quanta 200 (FEI Company), equipped with a Wolfram-cathode with a Quantax microanalytical EDX add-on (Bruker AXS). X-ray diffractograms were recorded by a Philips PW 1729 equipped with a copper tube (30KV, 30 mA) on silicon single-crystal sample carriers [5].

Figure 5: Resin-embedded mortar cross section under microscope. Source: Stefan Simon.

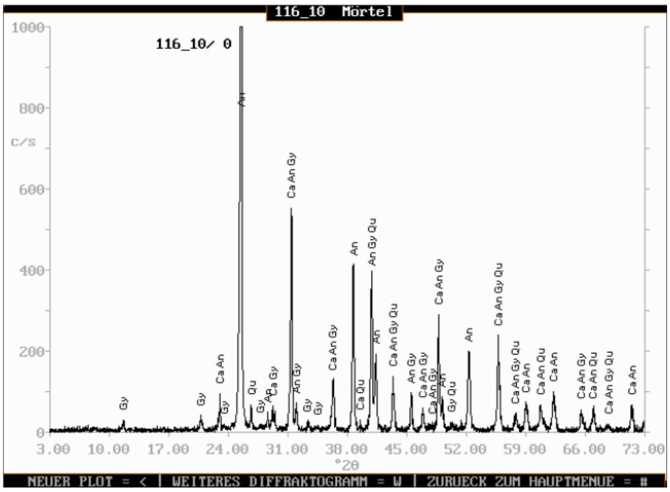

Figure 6: XRD results showing predominance of Anhydrite. Source: Stefan Simon.

Analysis revealed a composition of mainly Anhydrite ($CaSO_4$), which is the thermodynamically stable phase of gypsum ($CaSO_4 \cdot 2H_2O$) when it is heated above 42 degrees Celsius. The mortar is homogenous with small percentages of fine quartz, feldspar and calcite aggregate [5]. Anecdotal evidence provided by restoration craftsmen working in Liwa further clarified the source and method of mortar production. They state that the mortar is based on local gypsum stone which is mined from the valley floors between the dunes, burned using palm-wood fuel, then crushed to a powder and mixed with sand and brackish well-water to form a mortar [6]. The analysis provided information critical for developing compatible repair mortars such as the composition of the binder and the volume, size and type of aggregate. It also confirmed the use of gypsum stone suggested by the oral tradition, and will help conservators to select appropriate local materials for future testing of mortars and renders during conservation treatment.

2.3. Al Hayla Tower

Al Hayla tower is an unrestored stone building located on the western side of Liwa Oasis near the village of Marya al Gharbiya (Figs. 7 & 8). The tower is thought to have been built in the 19th century during the wars between Liwa and Ajman [7]. Constructed of local stone and traditional gypsum-based mortar, the tower may have served defensive purposes, been a mark of land ownership, or protected a local water source. As the only intact stone building in Liwa Oasis, Hayla Tower is an important record of stone building techniques in Liwa and a significant part of Abu Dhabi's heritage.

Figure 7: Hayla Tower in undated historic photograph (circa mid-20th century). Source: CDR.

Figure 8: Hayla Tower in 2011 during installation of retaining straps. Source: photograph by author.

When first surveyed by ADACH, the tower was in extremely dangerous condition. With its roof and floors gone, the walls were left vulnerable and large cracks in the masonry had developed that threatened to cause total collapse of the structure. In 2009, support scaffolding was installed and the largest cracks were stitched with stone and mortar (Fig. 8). This was followed by additional structural stabilization including the installation of retaining straps around the tower exterior. A conservation management plan was initiated which guides conservation decisions and included documentation through 3D laser scanning and laboratory analysis of mortars.

Mortars analysis was conducted using the same techniques as at Delma Island - a combination of wet chemical analysis and petrography. Analysis of 6 mortar samples showed that the binder is gypsum, while insoluble residue content is high which confirms that the aggregate is predominantly silicate based, which is to be expected given the tower's location in the sandy desert far from the coast (Table 2). Petrographic examination identified some limestone particles in the samples as aggregate, but from the chemical analysis it can be inferred that the percentage of limestone is low, ranging from 5.5% to 13.5%. The ratio of sand : gypsum is consistent across the samples at around 1:0.5 [8].

CHEMICAL ANALYSIS	H1	H2	H3	H4
Insoluble Residue	33.65	34.82	34.13	33.07
Soluble Silica, SiO_2	2.63	1.10	0.92	0.96
Acid soluble Alumina, Al_2O_3	0.17	0.13	0.07	0.09
Acid soluble Iron, Fe_2O_3	0.05	0.02	0.02	0.02
Acid soluble Calcium, CaO	24.41	23.92	25.74	25.62
Acid soluble Magnesium, MgO	1.86	0.51	1.11	0.81
Acid soluble Sulphate, SO_3	29.27	28.87	26.45	32.02
Loss on Ignition	7.92	10.11	10.89	7.28
Total	99.96	99.48	99.33	99.87

Table 2: Chemical analysis results of four mortar samples showing gypsum ($CaSO_4 \cdot 2H_2O$) and insoluble residue (sand). Source: DIA.

While gypsum was identified as the main component of the building's mortar, conservators have chosen lime as a repair material over gypsum for its stability against moisture and salts. Trials of lime-based repointing mortars, injection grout, and a shelter coating were carried out in June 2011. As at Delma, various mixes of lime, coarse sand and the pozzolanic *sarooj* were tested on a small area of the tower. After evaluation of the trial mortars, taking into consideration factors such as strength, adhesion, color and porosity relative to adjacent materials, full conservation treatment will be implemented followed by fencing, signage, and interpretive features to make the site accessible to visitors.

3. Earthen building materials

3.1. Hamad bin Hadi al Darmaki House, Al Ain

The Hamad bin Hadi al Darmaki House is an earthen structure located in Hili Oasis in northern Al Ain. Comprising several rooms and a tower situated around a courtyard, the site is enclosed with high earthen walls that rise several meters above the surrounding oasis (Fig. 9). Materials analysis including X-ray Diffraction (XRD), X Ray Fluorescence (XRF), and soil mechanics was carried out in 2007 to characterize the mud bricks and understand different phases of construction. Material sampling was carried out in two stages: first, 9 samples were taken for various tests, including 5 mud-brick samples, 2 plaster samples, 1 mortar sample, and 1 stone sample; the second stage was a continual study of the mud-bricks during which two more samples were taken. Since a number of different sizes of mud bricks were found, this study helped to identify the right size of mud bricks to be used in conservation.

Figure 9: Hamad Bin Hadi al Darmaki House, 2011. Source: Salman Muhammad Ali.

A sample of local clay-bearing soil from the Al Saad area was tested as well, so that it could be compared to the mud-brick samples for use in restoration. Based on the poor condition and cracking seen in the historic material, it is evident that the soil originally used to make the mud-bricks of Bin Hadi House is not of good quality. As indicated in the XRD analysis (Table 3, left), the mud-brick samples BH-01, BH-05, and BH-12 contain large percentages of the clay mineral montmorillonite. Montmorillonite is highly absorptive and increases greatly in volume with water. The large amount of montmorillionite in the mud-bricks would result in expansion and contraction of the clay surface causing cracks to form. In addition, montmorillonite loses viscosity over time, which results in the clay surface breaking down and powdering.

Sample No.	Major phase	Minor phase
BH-01	Calcite (29%), dolomite (25%), montmorillonite (20%)	Quartz (10), orthoclase (8%), albite (7%)
BH-03	Calcite (29%), dolomite (25%), montmorillonite (20%)	Quartz (10), orthoclase (8%), albite (7%)
BH-04	Gypsum (90%)	Quartz (8%)
BH-05	Calcite (31%), montmorillonite (23%), dolomite (14%), quartz (12%)	Chlorite (7%), orthoclase (6%), albite (5%)
BH-12	Calcite (30%), quartz (18%), dolomite (15%), montmorillonite (14%)	Albite (8%), chlorite (7%), orthoclase (5%)
Al Saad	Quartz (24%), montmorillonite (22%), calcite (14%), dolomite (11%)	Albite (10%), chlorite (10%), orthoclase (6%)

		BH-01	BH-03	BH-04	BH-05	BH-12	Alsaad
SiO_2	%	29.05	18.11	8.71	23.93	23.34	36.20
Al_2O_3	%	2.95	2.94	1.14	2.43	2.71	4.03
Fe_2O_3	%	3.34	3.42	1.58	2.83	4.02	5.99
CaO	%	29.17	29.24	25.04	32.80	27.01	17.94
Na_2O	%	0.63	0.28	0.09	0.36	0.43	0.30
K_2O	%	0.95	0.84	0.26	0.78	0.85	0.95
MgO	%	8.05	11.29	4.52	8.94	8.66	13.64
TiO_2	%	0.215	0.181	0.081	0.163	0.184	0.285
MnO	%	0.056	0.063	0.023	0.050	0.050	0.095
P_2O_5	%	0.043	0.060	0.075	0.056	0.049	0.065
LOI	%	24.62	32.32	20.09	26.88	22.86	19.66
SO_3	%	0.145	0.135	37.900	0.160	0.065	0.173

Table 3: Results of XRD (left) and XRF analysis (right). Source: Ali Malekabbasi / Zarazma Testing.

Based on the analysis results and the examination of area soils it is evident that sand-lime structures dominate in the Al Ain area, with only trace amounts of clay minerals. This has resulted in a quality varying from average to poor for the soil used in mud-bricks. The most significant information found through XRF analyses (Table 3, right) is the very low amount of aluminum oxide (Al_2O_3), which is limited to only 2 to 3 percent in the samples. The acceptable amount of aluminum oxide in mud-bricks that perform well in tests is around 8 percent. The size grading test, used to separate and quantify the contituents of soil, also confirmed these results. Thus no better condition could be expected of the historic mud-bricks of Bin Hadi House considering the relative percentage of these elements [9].

The materials analysis at Bin Hadi house also confirmed the suitability of the clay from the Al Saad area for conservation, as it contained comparable quantities of montmorillionite and other key minerals that indicate compatibility with the historic bricks. The clay was taken from the source and combined with straw and sand to make mud bricks and plasters for repairing damaged areas. Many of these repairs have been in place for over five years with little damage or alteration, demonstrating their compatibility and the success of the analysis in determining appropriate conservation materials.

3.2. Hili 17

Figure 10: House 1 in the early 1990s. Source: DAA n. 2

Figure 11: Detail of deterioration. Source: author.

Hili 17 is an Iron Age II period archaeological site located in Hili Archaeological Park, Al Ain. The site comprises three earthen houses and numerous hearths built over several centuries of occupation. It has been carbon dated to ca. 1000 BCE and is significant as a possible pottery production center [10, 11]. Excavated from 1991-94, Hili 17 has been exposed for over 20 years and has deteriorated significantly with many areas of collapse and general loss of definition from erosion (Figs. 10 & 11). The rapid rate of deterioration is thought to be related to cracks formed by swelling and shrinkage of the white clays used for mud bricks and plaster, and to salts in the walls and surrounding sand. ADACH's conservation approach for Hili 17 has been to document the site through laser scanning, analyze the clay materials to understand deterioration mechanisms, and in the short-term begin emergency conservation treatments while studying the implementation of a long-term protective shelter. Initial materials analysis included microscopy, XRF, XRD, and SEM.

Microscopic analysis revealed a number of factors important to understanding the site's decay process; microscopy showed an extremely fine-grained material with few large particles. The sand fraction is limited to a maximum grain size of ca. 0.3mm, and the majority of the material is silt or clay sized fractions. Such fine grained material is much more susceptible to cracking than earthen material made with graded aggregates. Microscopy also showed elongated voids, indicating that the mud-bricks and plaster may have originally been reinforced with vegetable fiber (a practice that continues today) but that the fibers have disintegrated over time (Fig. 12).

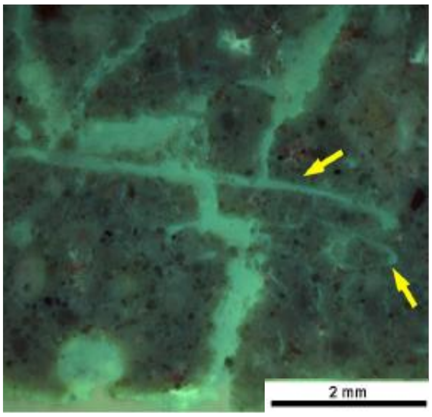

Figure 12: Microscopic image showing elongated voids under UV light. Source: Christof Ziegert, ZRS.

XRD results (Fig. 13) included minerals such as dolomite, kaolinite, calcite and albite. It also revealed the presence of swelling clays such as palygorskite, which is often associated with smectite [12]. Smectites are fibrous clays with small particle sizes and large internal surface areas. They have negative layer charges which allow them to absorb several times their weight in water. The presence of this type of clay, combined with precipitation and atmospheric moisture causes expansion and contraction of the clay surface and the subsequent cracks and deterioration seen at Hili 17. XRD also revealed a high concentration of halite (NaCl), or sodium chloride. Further testing using electrical conductivity showed nearly double the amount of soluble salts at the bases of the walls as at the tops. The high salt content may explain the deterioration of the lower walls, as wetting and drying causes cyclical salt dissolution and re-crystallization that erodes the wall.

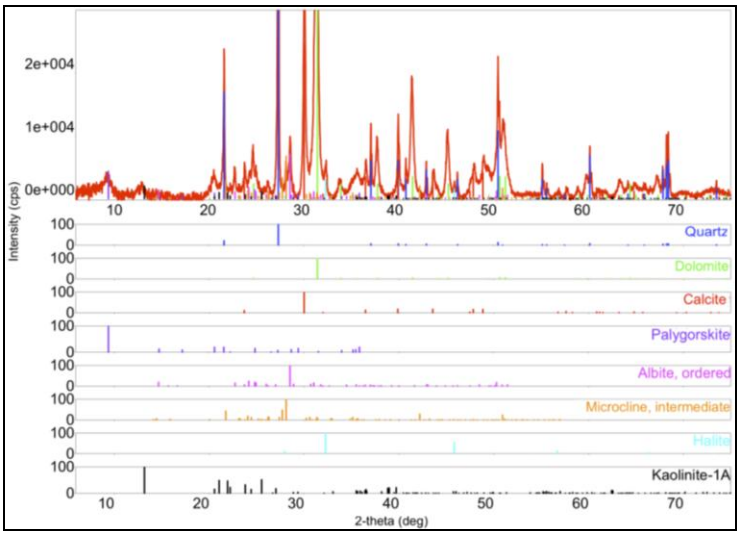

Figure 13: Results of XRD analysis showing presence of swelling clay (palygorskite) and salts (halite). Source: Cristof Ziegert, ZRS.

After analysis of the historic clay, XRF was used to identify a suitable material for conservation interventions. Clay-bearing soil from six different areas within the park was sampled and compared with the original material for color and soil mechanics including rate of water absorption and percentage of sand, silt, and gravel. Samples from the most promising natural clay layer, located about 20 meters east of the site, were submitted for XRF analysis at the University of Sharjah and compared with samples of mud bricks from Hili 17. Four samples were powdered and analyzed using a Horiba XGT-7200 micro-XRF microscope.

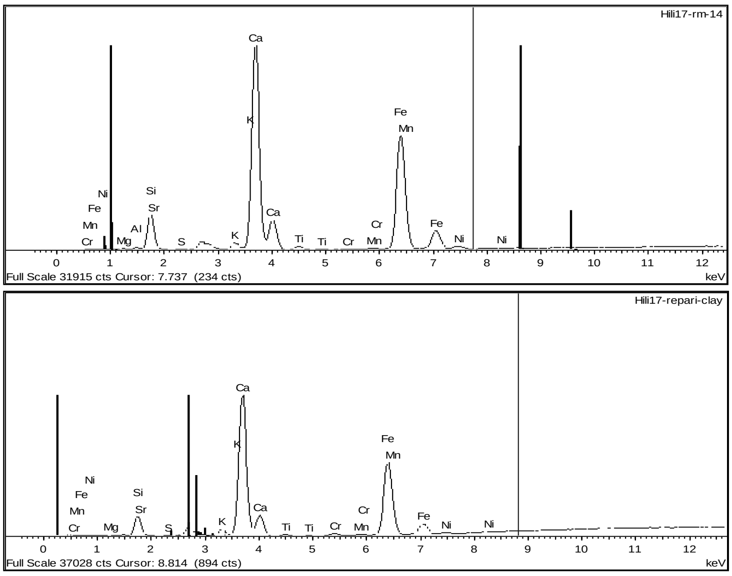

Figure 14: XRF results showing comparable composition of historic material (above) and repair clay (below). Source: Univ. of Sharjah.

XRF Analysis (Fig. 14) showed comparable amounts of key elements calcium, iron, magnesium, and silicon, and indicated that the new clay was indeed similar and compatible with the original. Based on the analysis results, the identified clay was mined from the source layer and brought to the ADACH workshop for further field testing. This white clay is used to make mud bricks, plasters and grouts for the repair of damaged areas.

4. Conclusion

The analyses presented in this paper have revealed important information regarding both the composition of traditional building materials in Abu Dhabi as well as their limitations. The studies of mortars have shown that in remote areas such as the Liwa Oasis, stone buildings were constructed using mortars based on readily available stone with desert sand aggregate. This evidence is corroborated by oral testimony, which points to the burning of local gypsum rock for the creation of mortars. At Delma Island, analysis results show that lime was used in mortars and that carbonate aggregates are more common on the coast than the sand aggregate of the desert interior. However, the results of the Delma island mortars are complicated by later restoration and further analysis of historic coastal buildings is needed to understand the sources and use of lime-based mortars on the coast.

The studies have also highlighted the limitations of local historic building materials, particularly in regards to earthen buildings, which are constructed with sandy clays and problematic minerals such as montmorillonite and smectite. In addition, analysis revealed concentrated soluble salts, a problem that affects most masonry materials in Abu Dhabi and causes rapid and significant damage. The combination of salts and poor materials leads to a high rate of deterioration that must be addressed through conservation with stable and compatible materials. While gypsum is common in the regions historic mortars, its poor performance in the presence of moisture and salts has led ADACH to use more stable materials in conservation such as lime and *sarooj*. Similarly, the weak and sandy clays used historically in earthen buildings are not suitable for conservation, and more suitable clays have been chosen for repairs. Through analysis, ADACH has been able to gain a more thorough understanding of Abu Dhabi's built heritage, diagnose decay mechanisms, and make informed decisions regarding conservation and management.

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