Characterization of Old Mortars from Historic Buildings in Muharraq, Bahrain

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[Abstract]

Muharraq Old City is one of the most emblematic areas of Bahrain and is classified by UNESCO as a World Heritage site (Pearling, Testimony of an island economy).

The city is rich with historic buildings which are in bad condition and need conservation interventions. Many monuments have suffered several conservation interventions in the last 30 years especially by using Portland cement, without, however, any type of previous knowledge about the type of mortars and materials used. This work was carried out to identify the mortar's composition in different buildings and to try to find the appropriate conservation mortars. XRD and petrography studies were carried out to find the results in addition to the physical and mechanical characterization. The results showed that the main composition of the bedding mortar and plasters are Gypsum.

1 Introduction

Muharraq is an old city located in Muharraq Island to the east of the main island (Bahrain). It is one of the most important historic areas in Bahrain. A trail of 3 km of Muharraq city is classified by UNESCO as a World Heritage site (Pearling, Testimony of an Island Economy).

The establishment of Muharraq City dates back to the beginning of the 19th century (AD 1810) by the Al Khalifa Family[(1)]. Muharraq was famous with pearling trade during 19th century until the early 1930s, when the pearl market in Bahrain crashed as a result of the introduction of cultured pearls from Japan[(2)].

The pearling trail in Muharraq includes 17 historic buildings embedded in the urban fabric of Muharraq city. The architectural testimony comprises residential and commercial structures that are tangible manifestations of the major social and economic roles and institutions associated with the pearling society. Most of the structures have survived relatively unaltered since the collapse of the pearl industry in the early 20th century and bear witness to distinctive building traditions that the industry fostered, and particularly their high standard of craftsmanship in timber and plaster[(3)].

The main goal of the present work is to identify and characterize the mortar's constituents by using different scientific methods and finding the appropriate conservation mortars to be used as bedding mortars and renders in repairing the historic of buildings of Muharraq.

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The study of physical and chemical characteristics of existing old mortars allows knowledge of the characteristics which must be expected to substitute mortars, as long as possible, and in that sense provides data for the formulation of new mortar mixes for repair.

2 Sampling Methodology

The sampling of mortars is a crucial step that can influence the success of the characterization methodology[4]. The studied samples were taken from 8 buildings in Muharraq. The selection of mortars was based on their location in the building, color, appearance and functions (Mortar and render or plaster). The size of each sample was the minimum that could guarantee the success of the analysis and the confirmation for future studies. All samples were given numbers and documented by photographs and text description.

3 Characterization Methodology

The characterization of such materials can be achieved by integrating properly the results of various methods of analysis[5], [6], [7]. Samples were mainly studied using XRD and petrography studies. Physical tests -water absorption, porosity, and compressive strength- were carried out.

Samples were subjected to X-ray diffraction (XRD) analysis to achieve the mineralogical composition. Samples were ground in an agate mortar to obtain homogenous powder. The powder diffraction pattern of the samples was obtained with Cu K α radiation, at a speed of $2\theta = 2$ deg. 1 min at constant voltage 40 kV and 25 mA using a PW 1840 X-ray diffractometer. The identification of the minerals was carried out using the data given in ASTM cards in comparison with the d-values of the different atomic phases and their relative intensities.

Thin sections and polished surfaces of the mortars were prepared by vacuum impregnation with an epoxy resin. These were observed with a Nikon petrographic microscope and the images were recorded digitally.

Physical and mechanical tests were conducted to assess the water absorption, porosity and compressive strength of the old mortars and new mix mortars.

4 Results and Discussion

4.1 XRD Analysis

Tables 1 and 2 present the mineralogical composition of the overall fraction of the mortars and render/plaster determined by XRD analysis.

The results of 8 bedding mortars show that the mortars are essentially composed of Gypsum followed by Anhydrite and minor Quartz.

The results of 3 plasters/renders samples indicate that (Sulfates) in form of Gypsum or Anhydrite are the main components of the different plaster layers, with a little amount of Quartz. Calcite was found in external layers of one sample as a second component. Halite was also found as a result of deterioration.

Presence of Anhydrite in those samples is either due to the dehydration of Gypsum into Anhydrite as a deterioration aspect or it occurred in nature with the Gypsum.

$$\text{Gypsum} \rightarrow \text{Anhydrite}$$
$$CaSO_4 \cdot 2\,H_2O \rightarrow CaSO_4$$

The presence of soluble salt, Halite, is normally an indicator of the occurrence of chemical degradation phenomena in the mortars.

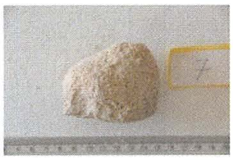
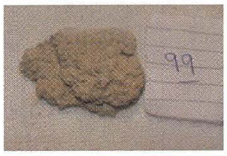
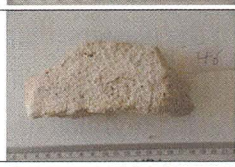
Sample No.	Composition			Illustration
	Mineral	Chemical Formula	Semi Q %	
M/Jalahma 711-7	Gypsum	$CaSO_4.2H_2O$	62	
	Anhydrite	$CaSO_4$	30	
	Quartz	SiO_2	8	
M/Salman 99	Gypsum	$CaSO_4.2H_2O$	58	
	Anhydrite	$CaSO_4$	29	
	Quartz	SiO_2	13	
M/Gous 710-6	Gypsum	$CaSO_4.2H_2O$	55	
	Anhydrite	$CaSO_4$	37	
	Quartz	SiO_2	8	
M/Nohkada 91	Gypsum	$CaSO_4.2H_2O$	40	
	Quartz	SiO_2	33	
	Anhydrite	$CaSO_4$	20	
	Halite	NaCl	7	
M/Syadi 724-49	Gypsum	$CaSO_4.2H_2O$	66	
	Quartz	SiO_2	20	
	Anhydrite	$CaSO_4$	14	
M/Fakh 717-22	Anhydrite	$CaSO_4$	52	
	Gypsum	$CaSO_4.2H_2O$	41	
	Quartz	SiO_2	7	
M/FakAm 752-46	Gypsum	$CaSO_4.2H_2O$	70	
	Anhydrite	$CaSO_4$	30	
M/Kaysr 104	Gypsum	$CaSO_4.2H_2O$	54	
	Anhydrite	$CaSO_4$	36	
	Quartz	SiO_2	5	
	Halite	NaCl	5	

Table 1 Mineralogical composition of the mortars assessed by XRD

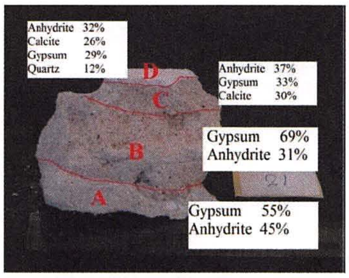
<table>
<tr><th>Sample No.</th><th colspan="4">Composition</th><th>Illustration</th></tr>
<tr><td rowspan="6">P/Jalahma 711-7 (2 layers A-B)</td><td colspan="2">Mineral</td><td>Chemical Formula</td><td>Semi Q %</td><td rowspan="6">
</td></tr>
<tr><td rowspan="3">A</td><td>Gypsum</td><td>$CaSO_4.2H_2O$</td><td>69</td></tr>
<tr><td>Anhydrite</td><td>$CaSO_4$</td><td>21</td></tr>
<tr><td>Quartz</td><td>SiO_2</td><td>10</td></tr>
<tr><td rowspan="2">B</td><td>Gypsum</td><td>$CaSO_4.2H_2O$</td><td>88</td></tr>
<tr><td>Anhydrite</td><td>$CaSO_4$</td><td>12</td></tr>
<tr><td rowspan="11">P/Fakro 21 (4 layers A-B-C-D)</td><td rowspan="2">A</td><td>Gypsum</td><td>$CaSO_4.2H_2O$</td><td>55</td><td rowspan="11">
</td></tr>
<tr><td>Anhydrite</td><td>$CaSO_4$</td><td>45</td></tr>
<tr><td rowspan="2">B</td><td>Gypsum</td><td>$CaSO_4.2H_2O$</td><td>69</td></tr>
<tr><td>Anhydrite</td><td>$CaSO_4$</td><td>31</td></tr>
<tr><td rowspan="3">C</td><td>Anhydrite</td><td>$CaSO_4$</td><td>37</td></tr>
<tr><td>Gypsum</td><td>$CaSO_4.2H_2O$</td><td>33</td></tr>
<tr><td>Calcite</td><td>$CaCO_3$</td><td>30</td></tr>
<tr><td rowspan="4">D</td><td>Anhydrite</td><td></td><td>32</td></tr>
<tr><td>Gypsum</td><td></td><td>29</td></tr>
<tr><td>Calcite</td><td></td><td>26</td></tr>
<tr><td>Quartz</td><td></td><td>12</td></tr>
<tr><td rowspan="4">P/Qayser 106 (1 layer)</td><td colspan="2">Anhydrite</td><td>$CaSO_4$</td><td>58</td><td rowspan="4"></td></tr>
<tr><td colspan="2">Gypsum</td><td>$CaSO_4.2H_2O$</td><td>35</td></tr>
<tr><td colspan="2">Quartz</td><td>SiO_2</td><td>4</td></tr>
<tr><td colspan="2">Halite</td><td>NaCl</td><td>3</td></tr>
</table>

Table 2 Mineralogical composition of the plasters/renders assessed by XRD

4.2 Petrographic Studies

Five petrographic studies were carried out for two plaster samples which consist of more than one layer. Observation of thin-sections under a petrographic microscope allowed further insight into the composition of the plasters/renders. Thin-sections from samples P/Jalahma 711-7 (A and B) and P/Fakro 21 (A-B-C) were analyzed (Table 3).

The petrographic results proved and confirmed the results of XRD analysis which showed that the main composition of the plasters/renders is Gypsum and Anhydrite.

The 5 samples were composed of ill-defined anhedral grains of Gypsum mineral, while most of them were composed of defined grains of Anhydrite. However, 1 sample (P/Jalahma 711-7 A) consisted of ill-defined grains of Anhydrite minerals.

In addition, results showed that the binder in those plaster samples was mainly Gypsum and Anhydrite, while the aggregates were Quartz and Fossils and sometimes Dolomite or Calcite, which come naturally with the quartz in the soil.

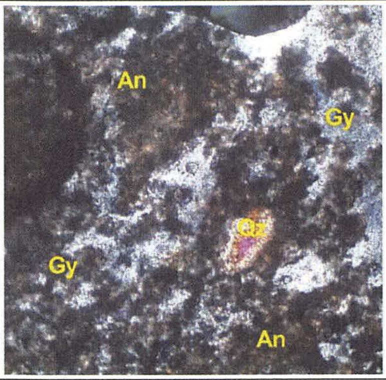
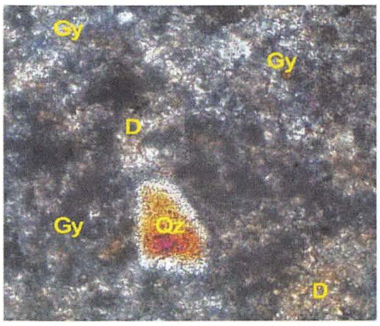
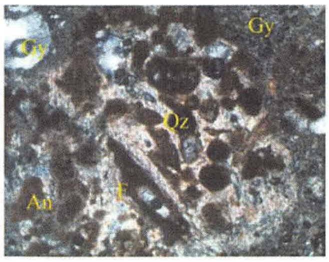
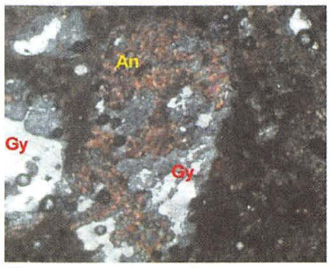
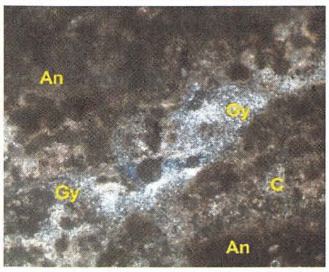
Sample No.		Petrography Results	Illustration
P/Jalahma 711-7	A	Sample is composed of ill-defined anhedral grains of gypsum minerals embedded in ill-defined grain boundaries of anhydrite forming an Alabastrine texture. In addition, sub-rounded coarse-to-medium grains of quartz crystals were detected.	 Qz : Quartz Gy : Gypsum An : Anhydrite
	B	Sample is composed of ill-defined anhedral grains of gypsum minerals. In addition, sub-angular coarse-to-medium grains of quartz crystals and anhedral grains of dolomite mineral were detected. A kind of reaction rim around a quartz grain was observed.	 Qz : Quartz Gy : Gypsum D : Dolomite
P/Fakro 21 (A-B-C)	A	Sample is composed of ill-defined anhedral grains of gypsum minerals embedded in well-defined grain boundaries of anhydrite forming an Alabastrine texture. In addition, sub-rounded coarse-to-medium grains of quartz crystals were detected.	 **Qz: Quartz** **Gy: Gypsum** **An: Anhydrite** **F : Fossils**
	B	Sample is composed mainly of ill-defined anhedral grains of gypsum minerals embedded in well-defined grain boundaries of anhydrite forming an Alabastrine texture.	 **An: anhydrite** **Gy: Gypsum**
	C	Sample is composed of ill-defined anhedral grains of gypsum minerals embedded in well-defined grain boundaries of anhydrite forming Alabastrine texture. In addition anhedral medium grains of calcite mineral were detected.	 **C : Calcite** **Gy: Gypsum** **An: Amhydrite**

Table 3 Petrography results

4.3 Mechanical and Physical Tests

These tests were conducted following test procedures that are close to those of the European standard EN 1925: 1999[8].

In order to characterize the mechanical and physical properties of old mortars, samples -which have similar visual properties and are from one place- were extracted from a historic building in Muharraq. The samples were prepared in 3 cm cubes and studied using 3 tests; water absorption, porosity, and compressive strength.

The results of the mechanical and physical tests are shown in Table 4. The results obtained show high water absorption and porosity and a low compressive strength.

Water Absorption (%)	Porosity (Vol. of Permeable pore space voids) (%)	Compressive Strength (N/mm^2) 29 Days
26 %	36.7 %	2.5

Table 4 Mechanical and physical tests of old mortars

5 Studying New Mortars for Conservation

Choosing compatible mortars depends on multiple conditions and requires several characteristics that are not always easy to achieve and harmonize. Fundamentally these mortars should allow an efficient protection of the substrates on which they are applied, to avoid the development of processes that may lead to degradation. They should present good mechanical, physical and chemical compatibility with the masonries and simultaneously their characteristics should be enough to withstand their own degradation, particularly in the case of soluble salts[9].

In order to choose appropriate conservation mortars both for bedding or plastering purposes, 6 mortar mixes were prepared in 3 × 3 cubes. The compositions of the new mortar mixes were chosen based on the XRD and petrographic results of old mortars. Lime was added to some of the mixes to enhance their properties.

Water absorption, porosity, and compressive strength tests were carried outin the lab for the new mixes. The water absorption and porosity are both related to the permeability property of mortar.

The results indicate that Mix 10, Mix 7, Mix 5, and Mix 3 possess the highest water absorption and porosity values, while Mix 6 and Mix 9 possess the lowest values. The results of compressive strength indicate that Mix 7, Mix 10, and Mix 3 have the highest values, while Mix 5, Mix 6, and Mix 9 possess the lowest values.

The purpose of undertaking those mechanical and physical tests is to choose two kinds of mortar:

- Mortar for bedding and pointing with high values of water absorption and porosity to allow free movement of moisture and breathing of mortar easily, and on the other hand, possessing high compressive strength to be able to bond the stones in the walls.

- Mortar for plastering with high values of water absorption and porosity to allow free movement of moisture and breathing of plaster, so any damages will happen to the plaster as a sacrificial layer, and not to the stones themselves. In this case, compressive strength is not important, but low compressive strength is still better.

Based on the results that have been found and according to the required properties for both bedding and plastering mortars, we found that the most compatible bedding mortar mix is Mix 3 (2 Gypsum, 1 Lime, 1/2 Sand) and the most compatible plastering mortar mix is Mix 10 (2 Lime, 1 Gypsum).

Sample ID			Test		
Mix No.		Description	Water Absorption (%)	Porosity (Vol. of Permeable pore space voids) (%)	Compressive Strength (N/mm^2) 29 Days
1.	Mix 3	2 Gypsum, 1 Lime, 1/2 Sand	37.4 %	50.7 %	5.4
2.	Mix 5	1 Lime, 1 Gypsum, 1 Sand	41.7 %	55.6 %	1.5
3.	Mix 6	1 Lime, 2 Sand	14.4 %	33.6 %	1.3
4.	Mix 7	Gypsum	48.4 %	58.2 %	7.1
5.	Mix 9	2 Lime putty, 3 Sand	16 %	35.1 %	0.8
6.	Mix 10	2 Lime, 1 Gypsum	60.7 %	62.9 %	5.5

Table 5 Summary results of mechanical and physical tests

6 Conclusions

Information about chemical characteristics together with physical and mechanical characteristics is necessary both to adjust the formulation of repair mortars and to assess the state of conservation of old mortars.

According to the studies and experimental results, the following conclusions can be drawn:

- The main composition of both the bedding mortar and plaster is Calcium Sulfate either in form of Gypsum or Anhydrite as a binder, and minor Quartz (sand) as aggregates.
- Presence of Anhydrite in studied mortar samples is either due to the dehydration of Gypsum into Anhydrite as a deterioration aspect, or the presence occurred in nature with Gypsum.
- The presence of soluble salt, Halite, is normally an indicator of the occurrence of chemical degradation phenomena in the mortars.
- The results of the trail mortar mixes for conservation showed that the most compatible mortar mix for bedding is Mix 3 (2 Gypsum, 1 Lime, 1/2 Sand) and the most compatible plastering mortar mix is Mix 10 (2 Lime, 1 Gypsum).
- The plaster and render mortars that were used in the historic buildings in Muharraq are composed of 1 to 4 layers.

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