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Similar appearance of mortar and brick masses in Algiers Casbah houses during the Ottoman period (16th- early 18th centuries)

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Abstract

The mixture of traditional mortars used in the houses of the Algiers Casbah during the Ottoman period (16th-early 18th centuries) has a similar appearance to the bricks mass. Grains of fired crushed ceramics of 5 mm or more, pebbles from sedimentary stones, shale, remains of nummulite limestone from the Algerian Atlas, and ashes from the lime calcination can be found in the mixture. The mortar joints were applied to the mixed masonry walls in layers that were thicker than or equally thick to the rows of bricks, whereas in the floors they are layered in thick beds interspersed with bricks until reaching 30-40 cm. Unhydrated lime lumps are encountered due to the artisanal mixing with limited water amounts to maintain a compact mortar. The Reddish colour of these earth-based mortars stems from the use of quartz, sand with illite, hematite and other components detected by XRD, EDXRF and DTA tests carried out on material samples. In light of this study, it is concluded that the Roman tradition of using lime and fired crushed ceramics is maintained in the earth-based mortars of the Ottoman period; knowing that their appearance is similar to the bricks one can argue that the bricks look like a baked mortar.

1. Introduction

The Casbah of Algiers is located within the current capital's bay at 120 m above sea level. Endowed with a Permanent Safeguarding and Presentation Plan that occupies a surface of 105 ha, it is divided administratively in six residential neighbourhoods, where great mosques, markets, public baths, historical houses and a citadel are amongst its most important buildings (Figure 1). The urban growth of the Medina was based on hydrographic units; each one was autonomous in terms of rainwater drainage system, which indicates its size by the end of the Arab-Berber period (950-1516). The Ottoman occupation took advantage of this urban layout (1516-1830) and strengthened the fortifications system upgrading thus Algiers, from a medieval marginal city to a Mediterranean capital [1].

Subsequently during the French colonization, the historic centre Casbah suffered a transformation process through the enlargement of its main streets, which led to the demolition and replacement of the traditional facades lining the roads [2]. Considering that building materials used in the conservation of the Casbah must be compatible with the existing ones [3], this study provides information about the construction techniques and materials implied during the Ottoman period. It consists of analysing the traditional mortars and bricks used in the houses that did not undergone transformations and are therefore considered original and authentic.

2. Constructive systems of the traditional Casbah house

The traditional house is usually introverted according to the Muslim culture principles, with a chicane entrance to the patio where the water-well is located [4, 5]. The rooms are organized around a central courtyard on two floors, with lattice windows and doors opening to a gallery of arcades supported by stone columns and a terrace overlooking the Mediterranean Sea (Figure 3). However, this stepped design adjusting to the site topography was altered by the French vertical densification (1830-1962).

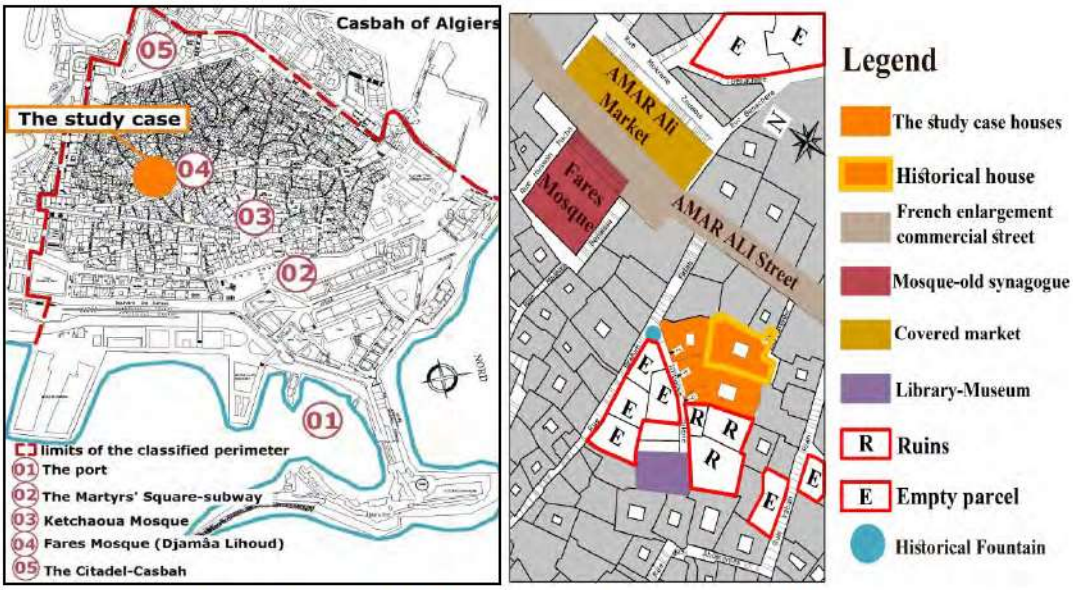


Figure 1. Left, the Casbah of Algiers. Right, location of the study case houses.

2.1 Masonry walls, ceilings and floors

The materials used in the construction of the Casbah houses came from the nearby environment notably the quarries of Bâb el Oued Faubourg later known as Jaubert extraction site during the French period (Figure 2), except for the ceramic wall tiles that were imported from Tunis, Italy, Spain and Netherlands [6]. The thickness of the walls varies 40-90 cm; they were made of bricks or mixed masonries (*opus mixtum*), adding rubbles or blue stones, with the bricks arranged horizontally or to 45º (*opus spicatum*) and the mortars applied in broad layers like to the brick's thickness.

In the masonry construction work, besides the discharge arcs, round logs of Barbary Thuja (*tetraclinis articulata*) are inserted every 0.80-1.20m to reinforce the bearing walls against seismic solicitations [7], also acting like wall ties. Usually, the roofing systems of 30-100 cm in section, consists of large earthen and lime-based mortar layers inserted with brick beds, arranged on top of wooden sheathing supported by Thuja logs. Sometimes, calcareous stones of less density were used instead of the bricks, the same constructive system can be found in the terraces. In Turkey, the use of pumice stone in earthen mortars to lighten and mitigate the heat flow in the covering systems of the 13^{th} century is a known masonry practice [8].

Figure 2. Left: Plan of Algiers and its surroundings in 1808 by BOUTIN. Right: Lime Kiln of the Faubourg Bab el Oued in 1838 by Adolphe OTTH (BNF-Gallica archives).

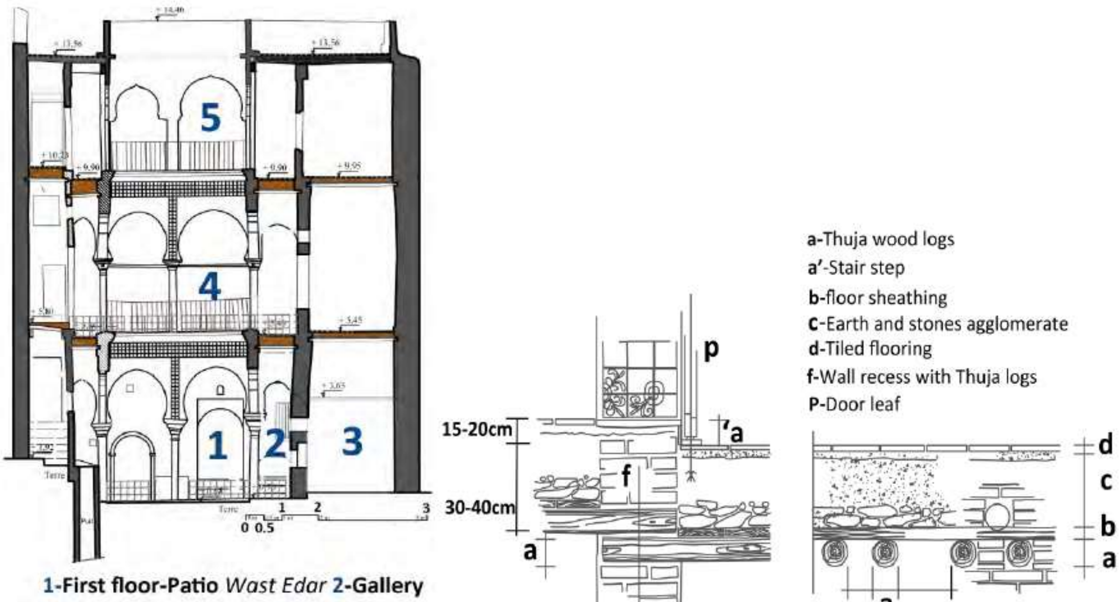


Figure 3. Left: Cross-section of a traditional house (Ali PACHA Agency). Right: Constructive system of ceilings/floors [9].

2.2 Mortars and bricks

The masonry mortars are generally of reddish or earth tones, with big rubbles of fired crushed ceramics (size 2mm-1.5 cm) in and sedimentary detritus from the Algerian Atlas, nummulite limestones remains, shale and ash. The mortars containing lime nodules and brick dust, or grains are known as *Khorasan* mortar in Turkey, *Surkhi* in India and are called *Cocciopesto* in ancient Rome [10, 11]. Fragments of recycled waste pottery and sometimes bones are found in the bedding mortar masses (Figure 4). The granulometry is variable, thin sand has a maximum size of 4 mm and pebbles of 5 mm or more. The presence of non-hydrated lime lumps is due to the artisanal mixing of the mortars, but especially to mixing a reduced amount of water maintaining an almost dry consistency and possibly using formwork panels during the mass application and hardening.

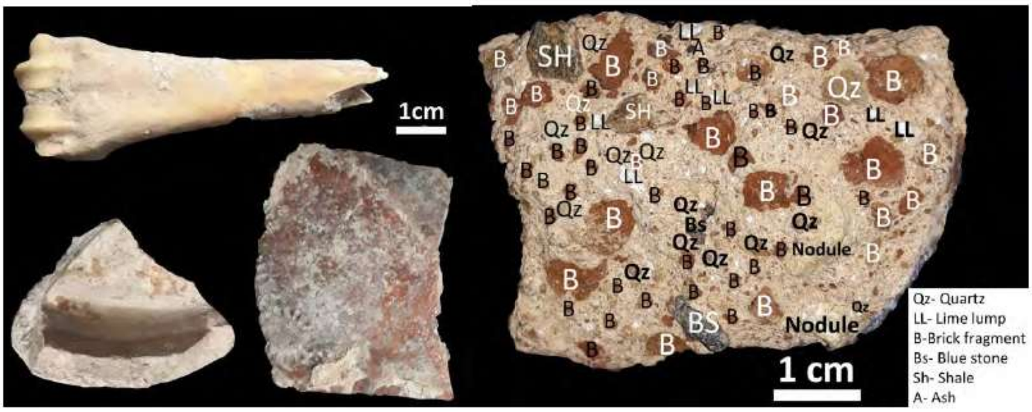


Figure 4. Left: Fragments of waste pottery, ceramic and bones added to the bedding mortar masses. Right: Microscopic characterization of sample M4.6.E1b, an elevation mortar.

On the other hand, brick dimensions are 25x12 cm; usually their thickness is less than 4cm. According to a previous research about mortars in the Citadel of Algiers and a Casbah house, the ratio between the lime binder and aggregates in mortar joints is one volume of lime per two of sand (1: 1.5 - 2), and one volume of crushed bricks, adding organic additives like olive oil and eggs in the walls rendering mixtures [12]. Generally, waste bricks and tiles are used to increase the mixture volume and to get a pozzolanic mortar with the finest grains [13].

3. Materials and methods

3.1 Sampling materials

Four attached houses under current restoration works define our study area. They form an interlocked cluster located in the lower Casbah (Figure 1), on a commercial street resulting from a French enlargement of the medina's organic fabric, near an old synagogue converted into a mosque, a market hall and a historical fountain, their entrance is on a dead-end street. The corpus presents different states of conservation: a well-preserved martyr house (related to the Algerian revolution against the French occupation) and three partially collapse ones, due to the 2003 earthquake and a bombing incident during the colonization. Nine samples were collected composed of five bricks and four mortar fragments from various parts and levels of the houses. They were located on the data sheet below (Figure 5).

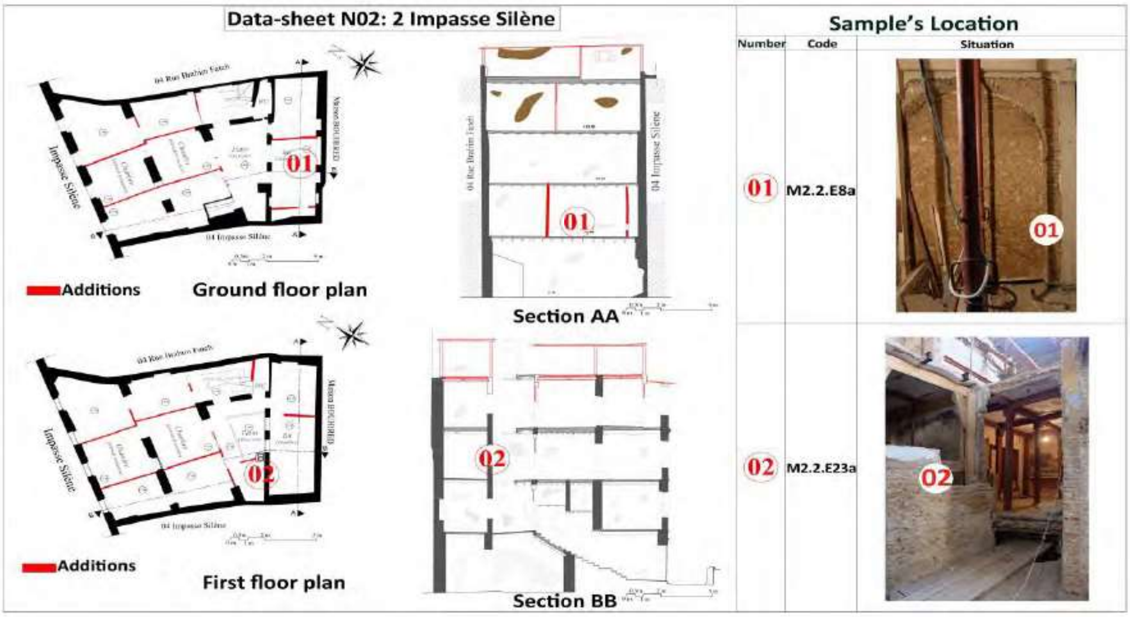
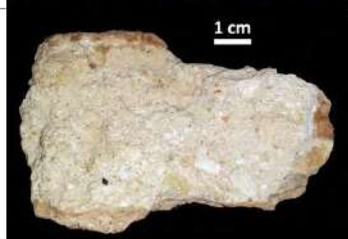
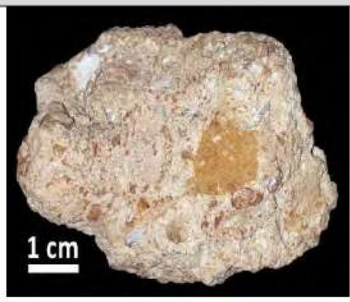
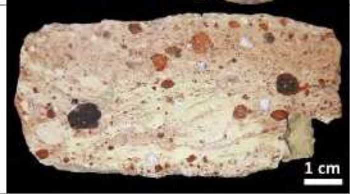
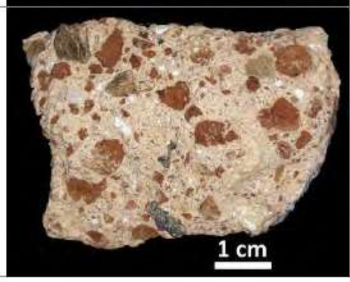


Figure 5. Data sheet of the house layout and the collected samples position

Non-destructive sampling protocol was carefully applied on bearing walls (main facade, inner partitions) and floors [14] from seriously damaged areas. Due to the lack of historical documentation and archives access, it is difficult to determine the construction date of the houses and the possible transformation phases they went through with accuracy, but the period is generally between the middle of 16th to early 18th centuries.

Table 1. Samples visual aspect and their location inside the construction.

House	Sample code	Material	Situation	Visual aspect
3 Imp Lavoisier	M1.3.E4a	Brick	 Terrace Ceiling	
3 Imp Lavoisier	M1.3.E4b	Mortar		
2 Imp Silène	M2.2.E8a	Brick	 Bearing wall	

House	Sample code	Material	Situation	Visual aspect
2 Imp Silène	M2.2.E23a	Mortar	 Inner Partition wall	
4 Imp Silène	M3.4.E19a	Brick	 Bearing neibouring wall	
4 Imp Silène	M3.4.E20b	Mortar		
6 Imp Silène	M4.6.E1a	Brick	 Elevation wall	
6 Imp Silène	M4.6.E1b	Mortar		
6 Imp Silène	M4.6.E20a	Brick	 Bearing wall	

3.2 Experimental methods

All samples were analysed and examined to determine the components, their dimensions, physical and chemical properties. For this purpose, different analytical techniques were applied in the characterisation the Casbah houses materials, among which X-ray diffraction (XRD) to identify the mineralogical composition, using a Siemens/Bruker D5000 instrument (40 kV, 40 mA), with a step of 0.03° and 4 s/step, from 10° to 80° in 2θ for the bricks. In the mortars, the X-Ray analysis was taken for the 2θ range of 4° to 100° to detect possible clay minerals. The chemical composition of the bricks and mortars was determined by Energy-dispersive X-ray fluorescence spectrometry (EDXRF) using the S2 PUMA device on pressed pellets. Differential thermal (DTA) and Thermogravimetric analysis (TG) were realized in order to assess the samples hydraulic properties by examining the weight loss at certain temperatures using SDT-Q600 TA Instrument (RT to 900°C, at heating rate of 20°C/min, in air flow: 100 mL/min). Chromaticity analysis was conducted on both mortars and bricks by means of an 8 mm Portable Digital Colorimeter and the Munsell rock and soil colour chart. Preliminarily, the initial step of these procedures consisted of a visual assessment of the samples with the naked eye and via Dino light Edge digital microscope 1.3-5 MP resolution, observing their texture and shape, aggregates consistency and size, especially the organic particles that can sustain damage or crumble before and during the tests.

4. Results and discussion

4.1 Visual analysis and chromaticity of the samples

In order to obtain prior qualitative information about the properties of the mortar and brick samples, macroscopic analysis was performed to determine the bonding agent and aggregates type. According to the visual aspect, texture and colour of the bricks under study, three main groups are distinguished (Table 2): yellow, red and pale olive.

Table 2. Chromaticity analysis results.

Sample code	Material	Colorimeter measures			Munsell chart
-	-	L	a	b	-
M1.3.E4a	Brick	65.542	4.283	14.714	2.5Y 8/2 pale yellow
M1.3.E4b	Mortar	59.432	6.056	14.183	2.5Y 9/2 very pale yellow
M2.2.E8a	Brick	53.192 52.152	14.106 5.508	19.141 12.084	5YR 6/4 light reddish brown- interior 2.5Y 8/3 pale Brown- brick's exterior
M2.2.E23a	Mortar	54.181	10.031	16.409	10YR 7/3 very pale brown-Mortar
M3.4.E19a	Brick	52.071 43.994	14.670 13.642	19.782 17.669	7.5yr 7/4 pink-brick's interior 5YR 5/4 reddish brown-clay spreads
M3.4.E20b	Mortar	46.371	10.334	17.846	7.5 YR 6/4 light brown
M4.6.E1a	Brick	54.740	10.853	17.039	5yr 6/4 light reddish brown
M4.6.E1b	Mortar	51.110 40.353	9.724 11.787	16.267 16.579	10YR 7/4 very pale brown 5YR 4/4 reddish Brown-Clay nodule
M4.6.E20a	Brick	34.844 65.151	2.921 3.730	13.731 20.041	5Y 6/3 pale olive-brick's interior 10YR 6/4 light yellowish brown-exterior

The first group comprises sample M1.3.E4a made with a yellowish *impasto*, homogeneous and rich in medium to fine grains of quartz (size <1mm) and very occasionally crushed brick ballasts. The second group contains three heterogeneous samples (M2.2.E8a, M3.4.E19a and M4.6.E1a), varying from pale to reddish brown (Figure 6). Generally, the red coloured bricks have a high iron contents while white or yellow colours are due to the high lime contents [15], which suggests a higher firing temperature. A white outer layer covers the brown-red matrix of the brick sample M2.2.E8a that contains medium to coarse quartz (size 1-3mm), shale and fired brick grains, while wavy yellow layers of clay spreads are packed in the paste matrix of sample M4.6.E1a, including an abundant quantity of crushed ceramic fragments (size 1-5mm). On the contrary, the presence of angular and rounded crystals of quartz in translucent pink or grey color is observed in large amounts compared to the crushed brick, in sample M3.4.E19a.

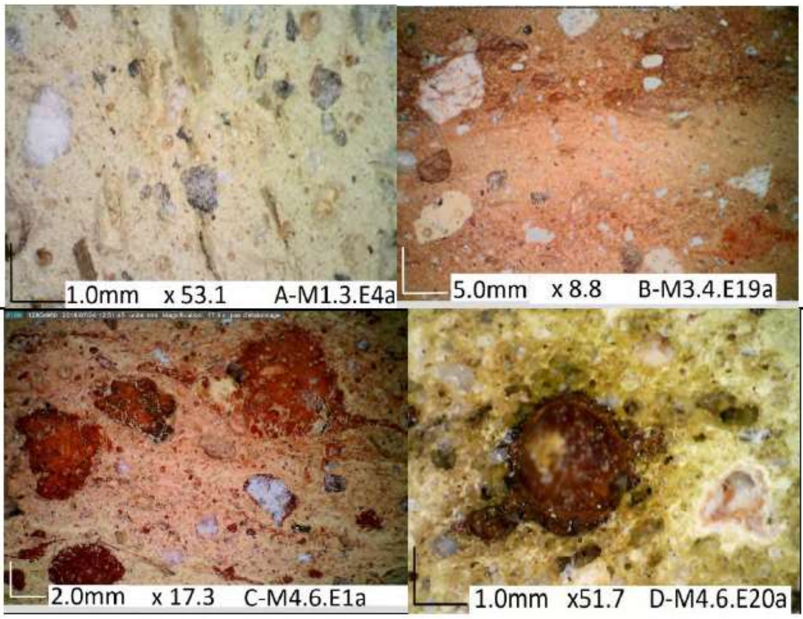


Figure 6. Macroscopic aspect of bricks. M1.3.E4a: yellow *impasto* with quartz grains. M3.4.E19a: yellow and red layers of clay with quartz, pebbles, shale and crushed ceramics. C-M4.6.E1a: Fired crushed ceramic fragments with dark reaction rings and quartz. D-M4.6.E20a: Fired crushed brick fragment in a pale olive paste showing dark reaction ring.

The last group includes sample M4.6.E20a, collected from one of the oldest parts of the house at the bottom of a neighbouring wall. This brick is pale olive with a yellow lump of the original clay matrix; this grain has dark reaction rings at the interface with the clayey matrix (Table 1), there are also quartz sand and dark fired crushed ceramics of medium to coarse size reaching 2 cm. On the other hand, the mortar specimens present similar aspects. Observed by the naked eye, they are all composed mainly of sand, lime, large visible crushed ceramic fragments used as coarse material additives and accessory minerals like quartz (Figure 7). Based on the colour of patina, the mortars are divided in two groups. Sample M1.3.E4b stands out from the other mixtures with its very pale yellow binder. The matrix has a very refined texture including rounded unhydrated lime lumps not exceeding 6mm in size, and small amounts of crushed ceramic fragments (size<0.5mm), while ash and fine-grained aggregates of quartz are found very occasionally, when compared to the other samples. It is noteworthy that another layer of brown reddish mortar was applied on top of this roof filling mixture to prepare the floor tiling (Figures 3, 7).

The second group contains samples M2.2.E23a, M3.4.E20b and M4.6.E1b, where the binders are reddish to pale brown and present different quantities and variation in the types of aggregates, their size and shapes. The occurrence of sand grains, quartz and pebbles particles, sub-rounded fired crushed ceramics (size 0.5-3mm), and unhydrated lime lamps (size 0.5-4mm) is found in sample M2.2.E23a. Evident ballast of brick of 1.2mm in length is observable with no reaction rings and a good cohesive aspect with the pale brown matrix. Sample M3.4.E20b shows crystals of quartz, shale (size 4-8mm) and crushed ceramic fragments engrossed in a reddish matrix ranging from clay to sand.

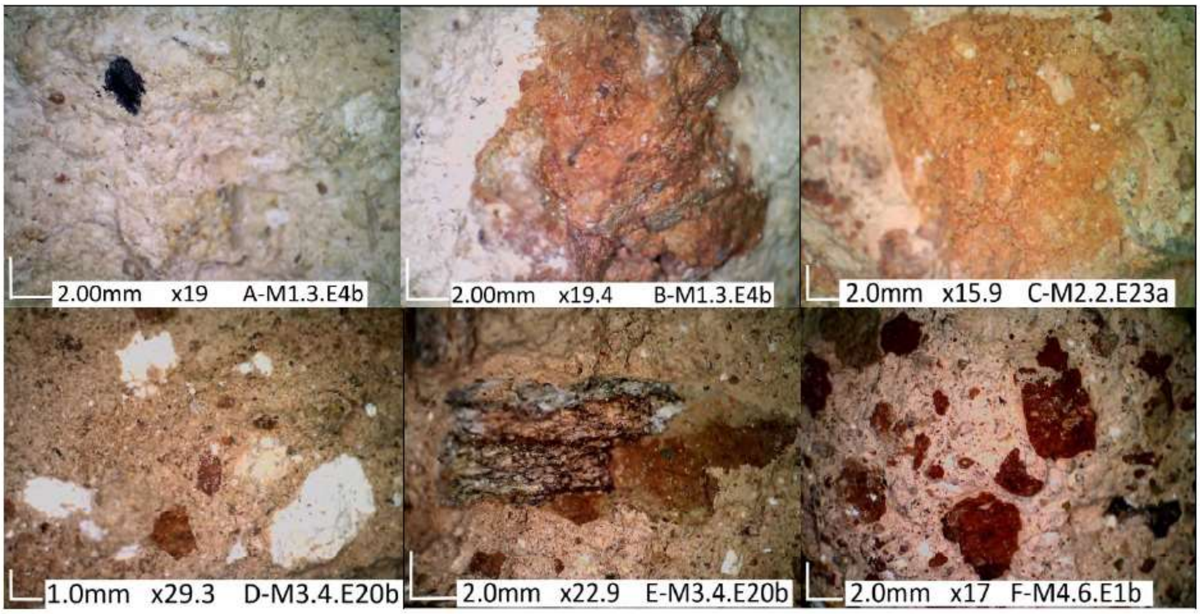


Figure 7. Visual aspects of the mortars. A-M1.3.E4b: yellow *patina* with quartz grains, lime lumps and ash. B-M1.3.E4b: layer of reddish bedding mortar covering the filling mixture. C-M2.2.e23a: coarse crushed brick fragment in a brown mortar matrix. D-M3.4.E20b: medium lime lumps and fine to coarse fired brick clasts, E-M3.4.E20b: shale and crushed brick fragment. F-M4.6.E1b: fine-grained quartz and lime nodules, subangular brick clasts.

Sub-angular and Rounded lime masses appear in large amounts up to 4mm in length, indicating that the lime was dry-slaked using a small amount of water. The shale and blue stones are extracted in-situ according to their abundance during the earth and foundation works of the house. Differently from the other samples, M4.6.E1b has rather an important quantity of sub-angular crushed bricks in medium to coarse size (1-8mm), in addition to quartz, blue stone and ash. Boundary reactions are observed at the interface between these particles and the binder. In roman times, the coating lime mortars used in water related structures or buildings located in areas with high humidity contained pozzolanic material like crushed ceramics, tiles and pottery fragments [16]. This specimen was collected from the exterior façade, highly exposed to climate conditions.

4.2 Mineralogical and chemical composition of the samples

This visual examination was contrasted with data from X-ray diffraction analysis on both mortar and brick samples whose main components are indicated in Table 3.

The XRD patterns of the bricks indicate that quartz and calcite are the main dominant components of the matrix, with the presence of feldspars and plagioclase (Albite and Anorthite) in small amounts, phyllosilicates (muscovite) as accessory minerals. The yellow and red bricks are mineralogically different.

Table 3. Results of XRD analysis

Sample	Qz	Cal	Ms	He	S	Fs				Gh	Di	β-c	CM		Ah
						Ab	An	Mc	A				K	I	
M1.3.E4a	+++	++	-	±	-	±	±	-	-	+	+	-	-	-	-
M1.3.E4b	+	+++	-	-	-	-	-	-	-	-	-	-	-	±	-
M2.2.E8a	+++	++	±	+	-	±	-	±	-	+	+	-	-	-	-
M2.2.E23a	+++	+++	±	-	-	±	-	±	-	-	-	-	±	-	-
M3.4.E19a	+++	++	±	-	-	±	-	±	-	-	-	-	-	-	-
M3.4.E20b	+++	++	±	-	±	±	-	-	±	-	-	±	±	-	-
M4.6.E1a	+++	++	-	+	-	-	-	-	±	-	+	-	-	-	-
M4.6.E1b	+++	++	+	±	-	+	-	+	-	-	-	-	-	-	-
M4.6.E20a	+++	++	-	-	-	-	-	-	±	-	+	-	-	-	-

Qtz=Quartz, cal=Calcite, Ms=Muscovite, He=Hematite, Fs=Feldspar (Ab=Albite, An=Anorthoclase, Mc= Microcline, A=Anorthite), Gh=Gehlenite, Di=Diopside, β-c=Cristobalite beta, CM= Clay minerals (K=Kaolinite, I=Illite), S= Siderite, Ah= Anhydrite.
+++ Very abundant, ++ abundant, + present, ± scarce, - not detected.

The presence of calcium silicate diopside can explain the yellowish color of the first group (M1.3.E4a), suggesting the existence of carbonate, which inhibits the development of iron oxides, they were presumably made from calcareous kaolinitic or illitic clays. The second group (M2.2.E8a, M3.4.E19a and M4.6.E1a) has hematite providing the red color of the bricks (Figure 8). Indeed, the formation of iron oxides by recrystallization during the decomposition of the phyllosilicates demonstrates that these bricks were fired around 850°C. Calcite peaks are detected in all samples showing that the firing temperature of the bricks is between 700 and 900°C. The Gehlenite is usually formed from 800°C; it appears in samples M1.3.E4a and M2.2.E8a. The feldspar evolved into Anorthite in samples M4.6.E1a and M4.6.E20.

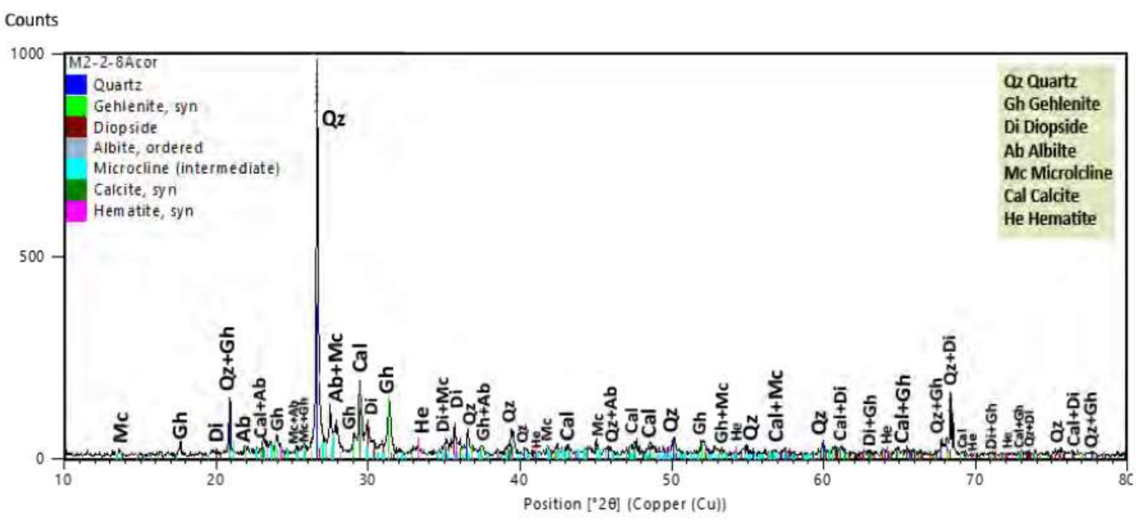


Figure 8. XRD pattern of brick sample M2.2.E8a.

The mineralogical composition of the mortar samples includes multiple crystalline phases The most present minerals are calcite, quartz, feldspar, plagioclase and phyllosilicates such as kaolinite in samples M2.2.E23a and M3.4.E20b, while illite peaks characterize only sample M1.3.E4b. The latter portrayed a vitreous amorphous phase that is evident by the increasing slope observed at the range 2θ =10°–20° (Figure 9).

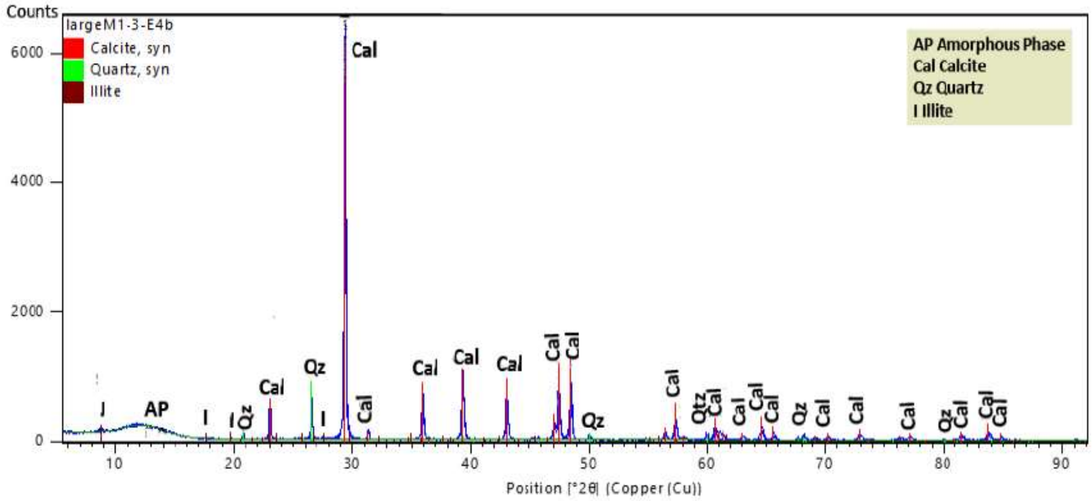


Figure 9. XRD pattern of mortar sample M1-3-E4b (ceiling).

Furthermore, the existence of Muscovite and Albite, likely due to the use of fired crushed ceramic fragments as pozzolanic additives, was found in almost all the samples apart from M1.3.E4b that was extracted from the ceiling of the last level in the house. Other components, such as Hematite was encountered in the reddish mixture of specimen M4.6.E1b, whereas the embedded anhydrite and siderite in M3.4.E20b stems probably from the clay minerals of the soil.

Meanwhile, oxide concentration has been obtained in the samples by XRF analysis and results are indicated in Table 4. Only the results of the M1.3.E4a and M4.6.E1a brick samples are reliable because magnesium oxide has not been detected in the others. In any case, these results would correspond to the use slacked hydrated air lime. The high amount of Fe_2O_3 in sample M4.6.E1a confirms the presence of hematite in red bricks.

Table 4. Oxide concentration in the samples (Wt. %) by XRF analysis

Sample	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	Fe_2O_3
M1.3.E4a	0.48	12.37	52.79	0.41	0.71	0.92	26.25	0.45	5.23
M1.3.E4b	-	1.79	13.79	0.59	0.2	0.21	79.52	0.17	2.67
M2.2.E8a	-	11.11	49.45	0.92	0.3	2.65	25.11	0.78	8.86
M2.2.E23a	-	10.02	46.87	0.65	0.52	2.2	28.73	0.68	9.04
M3.4.E19a	-	7.84	46.12	0.46	0.66	1.86	30.58	0.86	10.44
M3.4.E20b	-	13.9	48.22	0.55	0.15	2.53	21.36	0.97	11.46
M4.6.E1a	0.3	11.84	52.76	0.69	0.72	2.19	18.03	0.96	11.13
M4.6.E1b	-	11.63	48.16	0.65	0.19	2.53	24.71	0.96	10.03
M4.6.E20a	-	7.87	49.35	0.73	-	1.91	29.36	0.73	9.04

4.3 Differential thermal and Thermogravimetric tests (DTA-TG)

In order to evaluate the hydraulic properties of mortar samples, TG/DTA tests were carried out. For this purpose, percentages of weight loss between RT (Room Temperature) and 120ºC maybe due to humidity or to the dehydration of the sample. The weight losses between 650 and 800ºC can be attributed to the decarbonization of the limestone. It is observed that the (CO_2/H_2O) ratio of the samples is lower than 10 [17]. According to this ratio in Table 5, two groups were identified; the first one contains sample M1.3.E4b, while the second includes samples M2.2.E23a, M3.4.E20b and M4.6.E1b with a close (CO_2/H_2O) ratio and better hydraulic properties compared to the first group.

Table 5. TG/DTA analysis results in mortars

Sample code	H_2O (%)	CO_2 (%)	CO_2 / H_2O
M1.3.E4b	0.76	4.07	5.53
M2.2.E23a	2.82	6.16	2.18
M3.4.E20b	2.38	6.16	2.58
M4.6.E1b	2.78	6.76	2.43

Results of Differential thermal (DTA) and Thermogravimetric analysis (TG) show the decomposition of calcium carbonate $CaCO_3$ (calcite phase) at 650° and conversion of quartz alpha to quartz beta at 577.23°C in bricks (Figure 10), determining their firing temperature at approximately 800-900°C. On the other hand, it is known that the same kilns were used for lime slacking and baking the bricks.

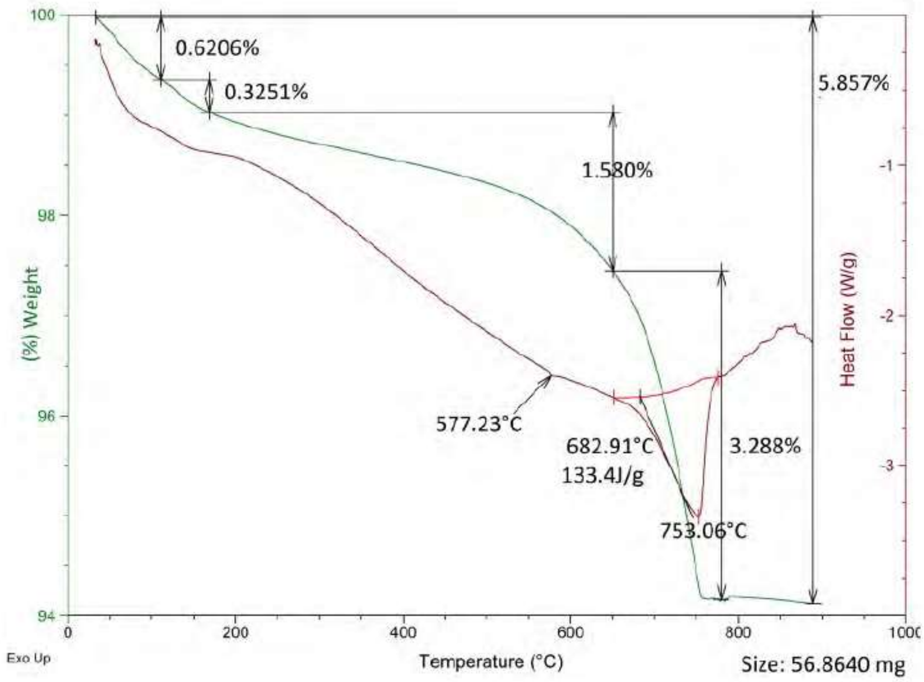


Figure 10. Thermal degradation curve of brick sample M2-2-8a

5. Conclusion

In this research, representative samples of mortars and bricks from the traditional houses of Algiers Casbah were investigated, allowing the following results:

a) The macro-scale analysis by microscopy and visual investigation of mortar and brick samples, has demonstrated its efficiency in observing the mass and particularly the heterogeneous granulometry of the crushed ceramics. Also, the size and distribution of the organic material, presenting overall a good compactness by the absence of interface cracks between the large clasts and matrix of fine grains, which is important for the constructive study.

b) The DRX results have shown that the mortars and bricks are composed mostly of calcite, quartz and other components from the soil in which the sand has been collected. Anhydrite was encountered in mortar M3-4-E20b extracted from an inner partition-bearing wall of a room that was not altered; while traces of illite were observed in floor mortar M1-3-E4b, which confirms the presence of unburned clay material.

c) This study classifies the mortar joint in the Casbah houses as “lime based mortar”, composed mainly by siliceous aggregates and calcitic slaked lime binder. The aggregate include quartz, pebbles, combined with shale or blue stone, occasionally ash and brick fragments as coarse additives (Muscovite). In addition to feldspars and phyllosilicates, three of the four mortar samples analyzed in this paper, present kaolinite, but it has not been detected in the bricks probably due to their firing treatment.

d) The fundamental difference in the mineralogical composition between bricks and mortars is that the former has diopside, anorthite or gehlenite, but the latter do not.

e) The brick samples M4-6-E1a (elevation) and M4-6-E20a (room) present the same major components except that the first one have hematite; they could have the same age, but their firing in oxidizing atmosphere may have produce the whitish appearance in the first sample and the unidentified amorphous materials in the second.

f) In some bricks, the outer white layer hypothetically may come from the lime beds used in the kilns used for baking and drying the bricks or may have formed during the firing process in the same kilns. However, the presence of calcite in all of them has been confirmed in the tests.

g) Artisanal kneading and mixing may have led to the disparity and heterogeneity in the clay matrix, forming layers or lumps of raw materials. In general, the firing temperatures of the bricks did not exceed 900 °C.

h) The use of lime and crushed ceramics as pozzolanic additives in the mortars and bricks, confirm their similar appearance and that the masons prepared similar mixtures for both of them.

i) Finally, the obtained data could be useful to produce compatible repair mortars in the restoration and consolidation works of the masonry in the Casbah of Algiers upon further investigation.

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