MINERALOGICAL AND TEXTURAL CHARACTERIZATION OF MORTARS AND PLASTERS FROM THE ARCHAEOLOGICAL SITE OF BARSINIA, NORTHERN JORDAN

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1. Introduction

Barsinia is located in the northwestern rural landscape of Jordan (Fig. 1), about 15 km west of the modern city of Irbid. The site is currently surrounded by agricultural fields, where cereals and olive trees are cultivated. The seasons of excavations, in 2006 and 2007, uncovered many architectural remains and artifacts, including pottery, glass vessels, stone grinding tools, and metal items, thus reflecting a flourishing settlement, particularly during the Hellenistic, Roman, Byzantine and Umayyad periods (ca. 2nd century BC - 8th century AD) [1-4].

The site includes three main parts: the domestic structures, the cemetery, and the agricultural fields. All the buildings were constructed for the most part using local limestone, some of which was interbedded with thin layers of flint. Marble was found in small quantities at the site, the most impressive pieces being a small cylindrical pillar and fragments of a decorated marble slab with geometrical and floral carvings, probably part of a chancel screen from a Byzantine church.

The walls were built using stones of different kinds and sizes. Both well-cut stones and rubble stones were used in constructing the same wall, indicating different phases of construction. Most of the walls were covered by plaster, as traces of it were still visible in some places (Fig. 2– plaster, Area A, Square B10).

During the two seasons of excavations at the site, in 2006 and 2007, twelve samples of plasters and mortars were collected; eleven samples were found in 2006 and only one sample (Br.07.B.A3.5) was found in 2007. The scarcity of the collected samples was due to the continued settlement, and disturbance and re-use of the residential facilities throughout a period of approximately one thousand years; from the late Hellenistic to early Islamic periods. The majority of the samples were found in the residential facilities, except sample Br.06.NecI.Tomb1.1, that was unearthed in a Roman-Byzantine tomb and samples (Br.06.NecI.Tomb1.1, Br.06.A.A9.7a and Br.06.A.A9.7b) that were originally parts of the plaster which covered the walls of a late Hellenistic/ early Roman cistern (1st century BC- 1st century AD) (Fig. 3).

Figure 1. A map of Jordan showing the location of Barsinia

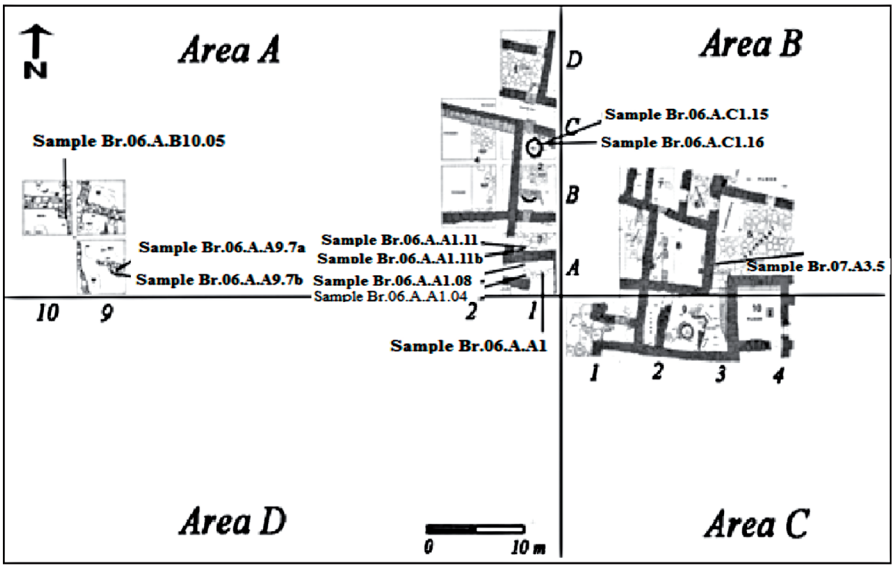

Figure 2. The residential area at Barsinia, and the sampling sites

Historical lime mortar and plaster in Jordan have been the subject of a very limited number of studies. Al-Saad and Abdel-Haim (2001) evaluated 3 types of mortars to be used as a restoration mortar for the Qasr Al-Bint monuments in Petra. The selection criteria was based on the mechanical and physical properties of the tested mortars compared with that of the building stone [5]. Dunn and Rapp (2004) studied Roman and Byzantine mortars and pozzolanic materials from the archaeological site of Umm al-Jimal; the studied samples were petrographically and mineralogically characterized [6]. Abde Hadi and Abdel Hadi (2012) studied lime mortar and plaster in the historic castle of Al-Shawbak in Southern Jordan. The physical, mechanical and chemical properties of the collected samples were determined; accordingly, restoration mortar and plaster were prepared from bituminous limestone designed to rehabilitate the castle [7]. Bani Yaseen et al. (2013), analyzed Roman mortar from the archaeological site of Jerash by using petrographical, mineralogical and chemical techniques. Two types of Roman mortars were differentiated according to this study; one contained pozzolana and the other did not contain pozzolana [8].

This study was aimed, firstly, at analyzing the plasters and mortars used at the archaeological site of Barsinia, dating back to different periods, to understand the development of the construction techniques used, chronologically. Secondly, characterizing the compositional and textural features of the mortar and plaster, substantially provides information on potential mortars that can be employed for conservation purposes at the site.

Mortar is a diachronic building material, used for bonding solid pieces of stone or brick for protective or decorative coverings in floors and substrates. Mortar is produced by mixing a binder with sand aggregates or an inorganic additive. Different types of binders can be distinguished; these include mud, gypsum, lime, pozzolan, hydraulic lime, cement or a mixture of them [9, 10].

However, lime binder has been the most frequently used traditional material in the building industry for more than three thousand years. Early civilizations, such as the Incas, Mayas, Chinese, Egyptians, ancient Greeks and Romans, used lime as a binder in brick or stone masonry structures and for rendering masonry surfaces [11].

In Jordan, lime plasters and mortars were used even earlier; examples of such materials have been found at Ain Ghazal archaeological site and have been dated to the Neolithic Period (ca. 7000 BCE). The people of Ain Ghazal used lime mortar and plaster as materials for both construction and decoration. The famous statues of Ain Ghazal were made using this type of material [12, 13].

Figure 3. A piece of plaster in Area A, Square B10 (sample Br.06.A.B10.05)

2. Materials and Methods

2.1. Samples

The study sampled 12 plaster and mortar pieces dating from early Hellenistic to Umayyad periods and come from 12 different structures at Barsinia. The studied samples represent the only samples that were collected from the site during two seasons of excavations. The first was conducted in 2006, when 11 samples out of the total number of samples were excavated, while during the last excavation season in 2007, only sample number Br.07.B.A3 was uncovered. The volume of the excavated samples ranges from about 15 cm3 (ca. 5cm x 3cm x 1cm) to about 1300 cm3 (20 cm x13cm x 5 cm). The samples were dated according to the associated archaeological objects and the chronological sequence at the site (Table 1).

2.2. Petrographic Investigations

Because some of the studied samples were fragile, preparation of the thin sections for petrographic examination required pre-consolidation; therefore, the samples were impregnated with Epoxy resin under vacuum. Thin sections were prepared as suggested by Lewis and McConchie (1994) [14], but instead of using water as a lubricant, oil was used to avoid damaging the water soluble minerals [15]. To differentiate between the carbonate minerals in the samples, the thin sections were dyed with a solution containing alizarin red-S in 2% hydrochloric acid (HCl) [14,16]. This solution is normally used by sedimentologists to differentiate between calcite and dolomite. In this study, it was used to distinguish between lime binder and calcite aggregate, based on the fact that lime binder has fine-grained crystals - and consequently a large surface area

- that etch more rapidly and show a more intense colour than coarser crystals (calcite aggregates). As a result, the contrast between the binder and the aggregate can be enhanced [17], making determination of the binder/aggregate ratio more accurate.

A Leica polarizing microscope was used to petrographically examine the prepared thin sections. One of the most important properties that determine the durability and specifications of a lime mortar is the weight proportion of aggregate/binder; therefore, lime mortar analysis for conservation purposes commonly involves the quantification of binder/aggregate ratio by weight. The mix proportion of the studied mortar was calculated by using a Prior J0415G point-counter; at least 300 counts were made for each sample according to procedures described by the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) TC-COM C2. Referring to this procedure, the weight proportion of aggregate/binder (F) is calculated using the equation:

$$F = \alpha \frac{\text{volume of aggregate}}{\text{volume of paste}}$$

where

$$\alpha = \frac{\text{density of aggregate X mole weight } CaCO_3}{\text{density of paste X mole weight } Ca(OH)_2}$$

Density of aggregate is approximately 2.67 g/cm^3, density of the lime paste is about 1.2 g/cm^3, mole weight of $CaCO_3$ is 100, and mole weight of $Ca(OH)_2$ is 74.

$$\alpha = \frac{2.67 \text{ X } 100}{1.2 \text{ X } 74} = 3$$

The portion coarser than 63 μm, which represents aggregate, was extracted by gentle crushing and wet sieving after treatment with diluted HCl to get rid of any remains of calcium carbonate binder.

2.3. X-Ray diffraction

Mineralogical characterization of the mortar was obtained by XRD analyses, using a Shimadzu Lab X, XRD-6000 X- Ray Diffractometer. Powder diffraction patterns were obtained by applying the following conditions: CuK∝ (Copper K Alpha) radiation (1.5418 Å) with 30 kV, 30 mA energy and Graphite Monochromator. The characterization of historical mortars by XRD was performed on the whole sample, and on the finer fraction (<63 μm).

2.4. Carbonate content

Carbonate content in the studied samples was determined using the "Dietrich-Fruhling gas volumetric method" calcimeter that meets standards DIN 19684. The method is based on measurement of the CO_2 volume developed by the HCl reacting with the powdered rock. The total carbonate is obtained using a formula that takes into account the pressure, temperature, amount of the previously weighed sample, and the volume of CO_2 developed by the sample. In this study 300 mg of powdered bulk sample was dissolved using 1 N HCl and the amount of CO_2 released from the sample was measured using a Dietrich-Frühling™ calcimeter. The amount of CO_2 released from the samples was then compared with that released from the same mass of a standard pure calcium carbonate sample.

Table 1. Description of the studied mortar and plaster samples

Registration No.	Source of sample	Date	Sample description
Br.06.A.A1.11	Plaster	Late Byzantine (5th century AD).	Soft, yellowish, made of one layer, unpainted, fine-grained, less than 7 mm thick, contains organic remains.
Br.06.A.A1.08	Bedding mortar	Late Roman (3rd – 4th century AD).	Hard, yellowish, made of two layers, the outer layer is light brown with chert and organic remains, medium-grained, with a thickness of about 8-11 mm. The inner part contains chert and organic remains, softer than the outer zone, coarse-grained, with a thickness of more than 15mm.
Br.06.A.B10.05	Plaster	Late Byzantine - Umayyad (6th – 8th century)	Soft, made of two layers, the outer layer is painted with a light brown color and has a thickness ranging between 1 and 3 mm. The inner zone is light colored, charcoal was detected in both layers, the sample has a total thickness of about 3 cm.
Br.06.Necl.Tomb1.1	Bedding mortar	Late Roman – Byzantine (3rd – 5th century AD).	Soft, made of two layers, the outer zone is fine-grained and light brown in color, it contains organic remains, with a thickness of about 5 mm. The inner zone is white colored and coarse-grained with a thickness of about 8 mm.
Br.06.A.C1.16	Floor mortar	Hellenistic (2nd century BC).	A compact floor, hard, white to yellow, more than 5 cm thick, made of one layer. Very coarse-grained, some grains are about 1 cm in size.

Br.06.A.A9.7a	Plaster	Late Hellenistic - early Roman (1st century BC - 1st century AD).	Plaster on a cistern wall, hard to soft, consists of two parts, the outer layer has a thickness of about 7 mm, dark brown to black in color and contains coarse aggregates, the inner part is the underlying soil, it has a black color and contains charcoal. The sample contains chert grains.
Br.06.A.A1.04	Plaster	Late Byzantine – Umayyad (6th – 8th century AD).	Soft, grey, made of one layer, contains organic remains, it has a thickness of more than 9 mm.
Br.07.B.A3.5	Plaster	Late Byzantine – Umayyad (6th – 8th century)	Soft, yellowish, made of one layer, medium-grained, contains organic remains.
Br.06.A.A1.11b	Plaster	Byzantine (5th century AD).	Soft, yellowish, made of one layer, unpainted, fine- grained, less than 7mm thick, contains organic remains.
Br.06.A.A1.c	Plaster	Late Byzantine – Umayyad (6th - 8th century)	Soft to medium, made of 2 layers, the outer zone is white to yellow and has a thickness of less than 1 mm, the inner part is darker and thicker, and is more than 8 mm thick. The sample contains organic remains.
Br.06.A.C1.15	Bedding mortar	Roman (3rd – 4th century AD).	Mosaic mortar, soft, white colored, very fine-grained, more than 6 mm thick.
Br.06.A.A9.7b	Plaster	Late Hellenistic – Early Roman (1st century BC.– 1st century AD).	Plaster on a cistern wall, hard to soft, made of 2 layers. The outer layer is tough and is light brown with dark spots, contains chert, 5-6 mm thick. The inner zone is black and contains chert and organic remains.

Carbonate content was then calculated by applying the following equation:

$$\text{Carbonate Content \%} = \frac{CO_2 \text{ in the sample}}{CO_2 \text{ in the standard}} \text{ X } 100\%$$

Three measurements were conducted for each sample and the average was calculated.

2.5. Physical properties

The porosity and density of the study samples were measured according to procedures recommended by RILEM (1980); tests No. I.1 and I.2 as follows:

After drying to a constant mass, the samples were put in an evacuation vessel and the pressure was gradually lowered. A constant low pressure was maintained for 24 hours. Distilled water was then slowly introduced into the vessel until the samples were completely immersed. The samples were left for 24 hours underwater at atmospheric pressure. They were then weighed separately in water (hydrostatic weight). The samples were quickly wiped with a dampened cloth and weighed in the air. The following

$$\sigma_{abs} = \frac{M1}{M1 - M2} \text{ x } 1000$$

$$\sigma_{app} = \frac{M1}{M3 - M2} \text{ x } 1000$$

$$\boldsymbol{\rho} = \frac{M3 - M1}{M3 - M2} \text{ x } 100$$

formulas were applied to calculate the density and porosity:

σabs: absolute density in g/cm^3
σapp: apparent density in g/cm^3
ρ: porosity
M1: dry mass
M2: mass taken under water (hydrostatic weight)
M3: wet mass in air [18].

3. Results and discussion

According to the calcimetry results (Table 2), the carbonate content in all of the samples, except sample Br.06.A.C1.16, was high. It ranged between 4% and 89%. The average carbonate content was 65.6%. The portions finer than 63 μm contained more carbonate compared to the whole sample. The carbonate content in this portion ranged between 9.0 - 91.1% averaging 74.7%.

Table 2. Composition of the studied samples

Registration No.	CaCO3 content (%)		XRD results					
			Complete sample			Grain size < 0.063 mm		
	In the complete sample	In the portion < 63 μm	Calcite	Quarzo	Apatite	Calcite	Quarzo	Apatite
Br.06.A.A1.11	70.1	80.6	***	**	*	***	**	-
Br.06.A.A1.08	63.3	77.0	***	**	*	***	**	-
Br.06.A.B10.05	70.9	73.5	***	**	-	***	**	-
Br.06.Necl. Tomb1.1	68.3	69.7	***	**	*	***	**	-
Br.06.A.C1.16	4.1	9.0	*	***	-	*	***	-
Br.06.A.A9.7a	61.1	79.1	***	**	-	***	**	-
Br.06.A.A1.04	70.1	86.0	***	**	*	***	**	-
Br.07.B.A3.5	81.9	83.9	***	**	*	***	**	-
Br.06.A.A1.11b	75.4	85.6	***	**	*	***	**	-
Br.06.A.A1.c	66.6	81.3	***	**	*	***	**	-
Br.06.A.C1.15	89.0	91.1	***	**	*	***	**	-
Br.06.A.A9.7b	62.2	78.7	***	**	-	***	**	-

The qualitative results of the XRD analysis are presented in Table 2 and Figure 4. Excluding sample Br.06.A.C1.16, calcite showed no significant quantitative differences in its content, in the mortars examined. All of the samples, except for sample Br.06.A.C1.16, were made of calcite (CaCO3) which was the main constituent and quartz (SiO2) in a lower proportion. Sample Br.06.A.C1.16 is mainly made of quartz and contains a smaller amount of calcite. Traces of the mineral, Apatite, were detected in most of the samples; its presence can be attributed to the addition of animal bones to the mortars and plasters of Barsinia. The addition of bone ash to the plaster facilitates the process of plastering by increasing the plasticity of the mortar. Furthermore, the presence of bone in mortar and plaster decreases the possibility of cracking and consequently increases their durability [19].

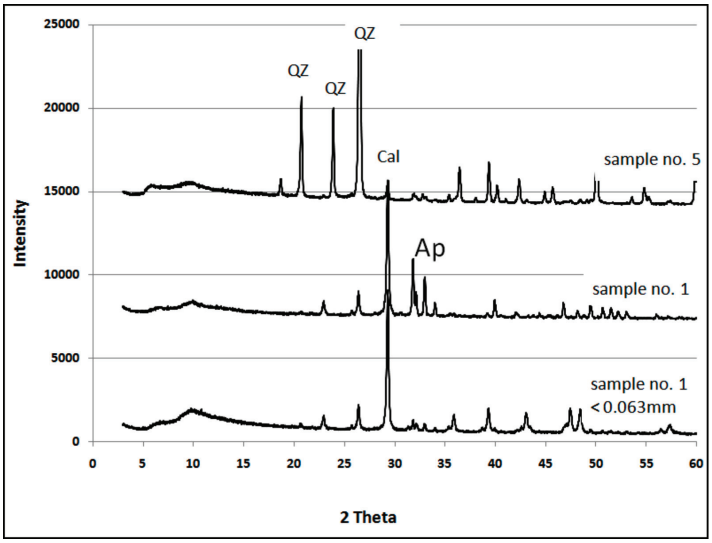

Figure 4. Powder X-ray diffraction pattern for 3 representative mortar samples. Qz. is quartz, Ca. is calcite and Ap. is apatite

For the grain size finer than 63µm, which is mainly made of a binding material, XRD results showed that the relative abundance of calcite and quartz in this portion is the same as in the whole sample. The only difference between the mineralogical compositions of this portion with that of the whole sample is the absence of apatite in the grain size finer than 63µm in the samples. No calcium silicate mineral could be detected in any of the studied mortars; a result which indicates a non-hydraulic mortar or which may be attributed to the fact that the structures of calcium silicate produced by pozzolanic reactions are somewhat difficult to analyze, because calcium silicates are very fine and are not easily distinguished with XRD or by microscope [6].

In addition to the minerals detected by XRD, other components were identified by using stereo and polarizing microscopes. Table 3 shows the modal analysis results obtained by using a stereo microscope for grain size coarser than 63μm, which is made of aggregate and contains no binding material. The results showed that the composition of the grains coarser than 63μm varies considerably in the studied mortars; calcite and/or quartz are the major components in many of the studied samples. The aggregate in some samples is mainly made of pottery fragments. Four of the samples revealed a considerable amount of chert, and volcanic ash was found in 3 others. Occasional fragments of charcoal were identified in 2 samples; their sporadic presence suggests that they are accidental, probably due to contamination from the kiln fuel. Most of the samples contained remains of organic materials (Fig. 5, Table 3). Although the studied samples are dated to different historical periods, the petrographic investigation showed that they have homogenous, cohesive binders displaying a strong aggregate-binder bond, in all of them the lime binders are fine-grained, rarely displaying shrinkage cracks (Fig. 5).

Some of the studied samples contained underburned lime particles (Fig. 5a). Evidence of binder-aggregate reaction was found in several mortars and the presence of ceramic fragments, chert, volcanic ash and /or fuel remains, acting as pozzolans, was also recorded in some samples (Figs 5b and 5c).

According to Pavìa (2005), the absence of binder cracks indicates a low shrinkage of the mortar binding materials. The high specific surface of the lime and low shrinkage suggest that the raw limestone was soft-burned [15].

Table 3. Modal analysis results of the aggregate as shown by the stereo microscope

Registration No.	Quartz	Calcite	Pottery fragment	Chert	Volcanic ash	Organic material remains
Br.06.A.A1.11	60	25	10	5	0	2
Br.06.A.A1.08	7	15	0	60	10	8*
Br.06.A.B10.05	35	5	25	35	0	0
Br.06.Necl. Tomb1.1	15	30	50	0	0	5*
Br.06.A.C1.16	6	4	0	90	0	0
Br.06.A.A9.7a	15	6	5	74	0	0
Br.06.A.A1.04	20	10	60	5	5	1
Br.07.B.A3.5	15	30	55	0	0	2
Br.06.A.A1.11b	55	40	5	0	0	1
Br.06.A.A1.c	54	40	5	0	<1	1
Br.06.A.C1.15	35	65	0	0	0	2
Br.06.A.A9.7b	20	5	10	65	0	0

**: mainly charcoal.*

Boynton (1966) and Cowper (2000) reported that low burning temperatures and/or shorter burning duration produce a desirable soft-burned quicklime, which is highly reactive and of low shrinkage and density and high porosity, whereas a high burning temperature and long calcining periods result in a hard-burned quicklime that has high shrinkage, high density, low porosity and low chemical reactivity [20, 21]. The higher reactivity of the binder in some of the studied mortars is evidenced by the occurrence of the reaction rims around grains having pozzolanic effects, such as chert (Fig. 5b).

Excluding sample Br.06.A.C1.15, which is a mosaic mortar, all of the studied mortars are more or less hydraulic; they contain one or more type of pozzolanic material, i.e. pottery fragment, chert, volcanic ash and/or charcoal. However, according to petrographic analysis, most of the mortars were made with non-hydraulic lime and their hydraulicity is due to the addition of materials acting as pozzolans. This agrees with the findings of Vicat (1997), who reported that the first production of calcined hydraulic lime was around the second half of the 18th century, i. e. much later than the studied mortar [22].

The weight proportion of aggregate/binder (F) in the archaeological mortars of Barsinia is shown in Table 4. Only 4 samples had an (F) higher than 1; these are samples (Br.06.A.C1.16, Br.06.A.A1.08, Br.06.A.A9.7a and Br.06.A.A9.7b). Three of these samples were dated to the Hellenistic period, with a high content of pozzolanic materials. The other samples had a value of less than 1, indicating that most of the mortars in Barsinia contain a relatively higher binder content.

Many studies of historic mortars have generated results suggesting compositions with an (F) of 1, i.e. 1 part lime binder: 1 part aggregate, in contrast to the 1: 3 (F = 3) ratio commonly specified in current building work [23]. Sample Br.06.A.C1.16 has a very high (F); this sample, which is a compact floor, contains a high content of coarse aggregates. Three other samples have an (F) close to 3; they resemble the mix proportion in present-day mortar. The high binder content in the other samples, samples with a low (F), could be attributed to the presence of unmixed binder, fragments of lime lumps that have not been fully mixed with the aggregate, and consequently have physical and chemical properties that differ from the matrix paste. As they do not play the role of a binder during the hardening process, the studied mortars (even those with high binder content) do not show any notable cracking, in spite of the fact that a high binder content in mortars tends to cause cracking.

The aggregate/binder ratio per weight in flooring mortars is much higher than that in lining mortars and plasters. The plasters taken from cisterns (samples Br.06.A.A9.7a and Br.06.A.A9.7b) contained relatively higher aggregate content in which a considerable concentration of pozzolanic components could be detected. The presence of such components in the plaster gives the mortar and plaster their hydraulicity, less solubility in water and more stability. The relatively high content of pozzolanic materials in these samples is consistent with the historical fact that pozzolanic components were preferred during Hellenistic and early Byzantine times for use in mortars related to water-bearing constructions such as cisterns [24, 25]. The porosity of this type of plaster is relatively less than that of other plasters and mortars.

Table 4. Weight proportion of aggregate/binder for the studied mortars

Registration No.	*Points*		*Weight proportion of aggregate/binder (F)*	
	Paste	*Aggregate*		
Br.06.A.A1.11	314		72	0.68
Br.06.A.A1.08	146		181	3.54
Br.06.A.B10.05	247		63	0.31
Br.06.Necl.Tomb1.1	345		28	0.24
Br.06.A.C1.16	8		312	150.7
Br.06.A.A9.7a	189		173	2.73
Br.06.A.A1.04	242		61	0.28
Br.07.B.A3.5	321		47	0.43
Br.06.A.A1.11b	356		43	0.31
Br.06.A.A1.c	367		58	0.45
Br.06.A.C1.15	517		46	0.22
Br.06.A.A9.7b	183		175	2.86

Table 5 shows the physical properties of the studied samples. The relatively low difference between the water uptake under atmospheric pressure and the water uptake under vacuum in all of the studied mortars is attributed to the low portion of micropores; in fact, most of the studied mortars have a saturation degree above 0.85. The results from the porosity tests showed that the porosities of the samples are higher than those in the typical range of historical lime mortars [15]. The porosity of the samples varied between 32.78 and 68.35%. Based on these results the samples can be classified into 2 groups. The first group comprising samples with porosities of less than 45% (samples Br.06.A.C1.16, Br.06.A.A1.08, Br.06.A.A9.7a and Br.06.A.A9.7b) are the samples with the highest apparent densities (1.46 and 1.78 g/cm³). The second group represents the samples with porosities higher than 50% and low densities (0.81-1.30 g/cm³); these samples have low weight proportions of aggregate/binder (F) ranging between 0.22 - 0.68. Porosity of mortars and plasters plays two different roles as regards their durability. On the one hand, a good porosity allows an extra interchange surface assimilating carbon dioxide, which will enhance the carbonation process of the slaked lime to produce calcium carbonate [26]. On the other hand, mortars and stones with a high porosity are more susceptible to deterioration under the effect of frost, salt crystallization and chemical deterioration factors. According to Sanchez-Moral et al. (2005) the high porosity of mortars and plaster can be attributed to cracking after drying linked to the high binder content [26]. However, most of the samples did not show such cracking. Instead, most of the samples contain remains of organic materials, such as straw and bones; the decomposition of these materials leaves cavities which increases the porosity of the mortars and plasters.

Table 5. Physical properties of the studied samples

Sample No	Water uptake under atmospheric pressure	Water uptake under vacuum	Porosity	Saturation degree	Absolute density	Apparent density
	Mass %	Mass%	Vol.%	/	g/cm³	g/cm³
Br.06.A.A1.11	41.38	46.27	55.27	0.89	2.67	1.19
Br.06.A.A1.08	18.81	22.20	37.25	0.86	2.67	1.68
Br.06.A.B10.05	59.04	64.14	62.15	0.92	2.56	0.97
Br.06.Necl. Tomb1.1	76.57	84.06	68.35	0.91	2.57	0.81
Br.06.A.C1.16	16.03	18.40	32.78	0.87	2.65	1.78
Br.06.A.A9.7a	18.83	20.43	34.61	0.92	2.59	1.69
Br.06.A.A1.04	46.96	50.72	56.79	0.93	2.59	1.12
Br.07.B.A3.5	40.03	47.24	55.95	0.85	2.69	1.18
Br.06.A.A1.11b	40.11	45.32	54.86	0.88	2.68	1.21
Br.06.A.A1.c	43.08	47.36	55.27	0.91	2.61	1.17
Br.06.A.C1.15	28.00	30.02	43.91	0.93	2.61	1.46
Br.06.A.A9.7b	34.30	39.49	51.40	0.87	2.68	1.30

4. Conclusions

Although only a limited number of samples was available for this study, the physicochemical characterization of the samples from the archaeological site of Barsinia revealed significant compositional and textural differences. Consequently, no general restoration mortar or plaster can be adopted for the whole site to replace the original deteriorated one.

The high porosity of the mortars and plasters seems to be the most important intrinsic deterioration factor causing their deterioration. The saturation degree of the studied samples is higher than 0.85; stones and mortars having such a value are highly susceptible to frost damage [27, 28]. Therefore, to protect them, mortars and particularly plasters, should be consolidated with an appropriate consolidant immediately after being excavated.

The compositional and textural differences among the samples seem to be linked to the function of the mortars rather than their time of production, i. e. no evolution on the techniques to produce the mortar at the site could be traced. The XRD results showed that no important differences in the mineralogical composition could be detected among the studied mortar and plaster, except in sample Br.06.A.C1.16; all the samples were mainly made of calcite and quartz, minerals which are locally available in the limestone rocks and sediments at the site. However, the petrographic investiga-

tions revealed considerable compositional differences among the samples in terms of intentionally added components such as bone ash, pozzolanic materials, etc.

The high porosity, strong binder cohesion and perfect aggregate-binder bond of most of the analyzed mortars, together with the presence of aggregate-binder reaction denotes a high reactivity for the lime, that also agrees with soft burning which produces the best lime mortar. Accordingly, the people of Barsinia had the necessary knowledge and experience to manufacture mortars and plasters of a good quality.

Thanks to the physicochemical characterization conducted in this study, it is possible to prepare a restoration mixture having characteristics compatible with the original mortars and stone in the masonry structure to be used for the restoration of the structures in Barsinia and other similar archaeological sites.

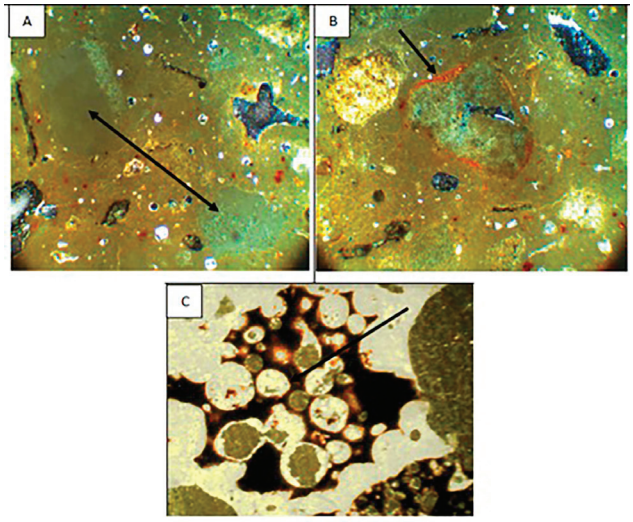

Figure 5. Photomicrograph (X100): a. XPL showing underburned lime, b. XPL showing reaction rim around chert grain and c. PPL charcoal

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