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Characterization of Architectural Mortars from Buildings at Umm Qais (Gadara), Northwest Jordan: Provenance Input

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Abstract

This paper aims at characterizing architectural mortars taken from structures at Umm Qais (Gadara) in northwest Jordan. The study intends to shed light on the mortar production technology, and to determine the provenance of the raw materials used in the mortar production. The Mortar samples were collected from the Western Theater and the Roman Market built during the Roman Period. The samples were analyzed by Optical Lenses, X-Ray Diffractometer, Optical and Scanning Electron Microscopes. The collected data was compared with some published literature on the geology of the Gadara area. The results show that the mortars are lime-based mixed with different local aggregates mainly fossiliferous micritic limestone, quartz, tuff, ceramic and basalt. The hydraulicity of the mortars was obtained through the addition of natural and artificial pozzalinic materials. Most likely, the high reactivity of the lime binder originated from the soft burning of the raw limestone. The results shed light on the Roman mortar production technology and the technology of ancient mortar production at other archaeological sites in Jordan.

Keywords: Lime mortar, Hydraulicity, Provenance, Fossiliferous limestone, Mineralogy, Petrography, West Theater, Roman Market, Gadara, Jordan

1. Introduction

The Greco-Roman and the Decapolis city of Gadara (Umm Qais) is considered one of the important archaeological sites in Jordan (Daher, 1999). It is located on a plateau that overlooks the Jordan Valley, Tiberius Lake, and the Yarmouk River in the northeastern part of Jordan, about 115 km from the Amman (Fig. 1). In antiquity, it connected several trade routes between Palestine and Syria, and the seashores and lowlands with the central and eastern uplands (Weber, 1990). Gadara was inhabited by Greeks, Romans, Byzantines, and Muslims. Its poets, fortunes, theaters, hippodrome, gates, nymphaeum, shops, churches, Ottoman village, and many other archaeological structures and remains attest for the wealth and prosperity of the city during this period. Unfortunately, the city was leveled and most of these buildings were destroyed by the devastating earthquake of 747 AD (Tsafrir and Foertser, 1992). The city was mainly constructed out of basalt, limestone, and caliche rocks bound and lined with mortar and plaster cement materials (Al-Bashaireh, 2003).

Unlike other sites and despite the great significance of Gadara, its cement materials have not been studied, however, other materials were analyzed. Al-Bashaireh (2003) and Al-Bashaireh (2011) characterized and provenanced the marble used in the construction of several structures at Gadara. El-Gohary and Al-Naddaf (2009) characterized the bricks used in building the walls of the Gadara's Roman Baths. El-Khouri (2014) investigated the early Byzantine glass production

Figure 1. Location map

excavated from the area at Gadara in 2011. Al-Bashaireh (2013) and Al-Bashaireh and Hodgins (2012) investigated the production technology of mortar and plaster samples from different structures at Petra and Udruh to radiocarbon

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date them. Al-Bashaireh (2014) investigated and produced a radiocarbon date of the plaster samples from House XVII-XVIII at Umm el-Jimal. Dunn and Rapp (2004) investigated the mortar and plaster of different structures at Umm el-Jimal. Al-Bashaireh (2016) characterized the lightweight mortar of the fallen dome of the West Church at Umm el-Jimal. Yaseen et al. (2013) investigated mortar samples from different structures at Gerasa.

This research is an archaeometric study of mortar samples collected from two of the Gadara structures (the West Theater and Roman Market) to describe their production technology and identify the material sources used during their production.

2. Geological Setting

Umm Qais is located in the southwestern part of Harrat Al-Jabban which belongs to Harrat Al-Shaam. It is mainly composed of basalt (El-Akhal, 2004) and flows of basic volcanic tuff (Kwatli et al., 2015). Gadara is built on the northwestern end of the Jordanian Highlands,which include the carbonate rock sequences of the Belqa Group, namely Muwaqqar Chalky Marl Formation (MCM) and Umm Rijam Chert-Limestone Formation (URC) (Bassam, 2000), Fig.2.

Muwaqqar Formation (MCM) contains massive, soft, white chalky marl rich in planktonic foraminifera. Umm Rijam Chert-Limestone Formation (URC) contains a variety of chalky, marly and kerogenous limestones in its lower part, while those of its upper part have chert beds and/or concretions (Moh'd, 2000).

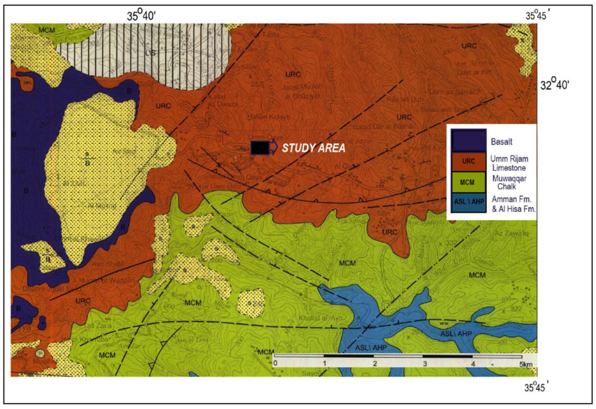

Figure 2. Geological map of the study area; after Bassam (2000).

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3. Sampled Structures

The mortar samples were collected from two structures of Gadara, namely, the West Theater, and the Roman Market (Fig. 3). Both structures face the west and are located on the east bank of Cardo Street facing the North-South. The two structures date back to the Roman period (they were most likely constructed during the 2nd century AD), but they were reused during later periods (Zayadine, 1973, Weber, 1990, Al-Dahash, 1993). They are mainly constructed of basalt blocks bonded with mortar.

The basalt seats of the West Theater are distributed into lower, middle, and upper sections. The upper part is supported by a vault in the form of an entrance facing east (Figure 3a). The Roman Market consists of twenty rows of shops adjacent to the north of the West Theater below the western extension of the basilica terrace (Guinée et al., 1996).

4. Materials and Methods

and from light to dark gray. They are moderately hard, compacted, and brittle. Small chips were taken by a sharp chisel and a hammer from the cement mortars filling the boundaries between stone courses. The samples were in their original position and did not show signs of reuse or refilling; therefore, their expected construction dates back to the Roman Period, (2nd Century AD). Small parts of the chips were ground into powder for the XRD analysis, and the rest were used for thin section preparation and analysis by the Scanning Electron Microscopy. The thin sections were prepared by a vacuum impregnation process using an epoxy resin to harden the mortar. The samples were then carefully polished until the resulting thin section was about 0.03 µm in thickness following standard procedures (see Al-bashaireh, 2013:10).

The XRD analyses were performed to determine the mineralogical composition (mineral crystalline phases) of the samples. The polarized light microscope was used to identify the types of the aggregates added to the binding material (binder), their distribution within the binder, and the ratio between the binder and aggregates. The polarized light microscope can also show the interaction of pozzalanic materials with the lime binder (Elsen, 2006).

The thin sections were prepared and examined using the Leitz 7062 Polarizing Microscope at the laboratories of the Faculty of Archaeology and Anthropology at Yarmouk University in Jordan. A Shimadzu Lab X, 6000 X- Ray Diffractometer was used for the XRD analysis. Powder diffraction patterns were obtained under the following conditions: CuKα radiation (λ = 1.5418 Å) with 30 kV, 30 mA energy and Graphite Monochromatic.

Scanning Electron Microscopy (SEM) analysis was used for further investigations of the components of the mortars, their morphology and textural interrelationships which cannot be observed by the optical microscope. The EDX spectra provide an elemental analysis of the mortar components. Initially, the samples were coated with a thin film of gold and then analyzed by an FEI Quanta 200 scanning electron microscope equipped with EDS (Energy Dispersive X-ray Microanalyzer) at the SEM laboratory in the Department of Earth and Environmental Sciences of the Faculty of Science at Yarmouk University. The analyses were performed under the following conditions: they were run at an accelerating voltage between 0.3 and 30 kV with the chamber's pressure being at about 50 Pa in a variable-pressure mode.

The data collected to determine the mineralogical composition of the binders and aggregates of the mortars and their content of fossils were compared to the available geology of the study area, including charts, maps and related literature; see for example Bender (1974), Abded (2000), (Bassam (2000), El-Akhal (2004), and Moh'd (2000), to identify the provenance of the original raw materials used in the production of the mortars.

5. Results and Discussion

5.1. X-Ray diffraction analysis

The XRD analyses of the samples show the presence of calcite as a major mineral, quartz as a minor mineral, and the absence of gypsum (Fig. 4a,b) in the composition of the mortars. Analyses show the presence of quartz in different quantities in all of the samples examined, and the presence of pyroxene (augite) and anorthite in sample 10 (Fig. 4c). The absence of gypsum and the high content of carbonates in the samples that came from the binder and/or the aggregates indicate that the studied samples are lime-based mortars.

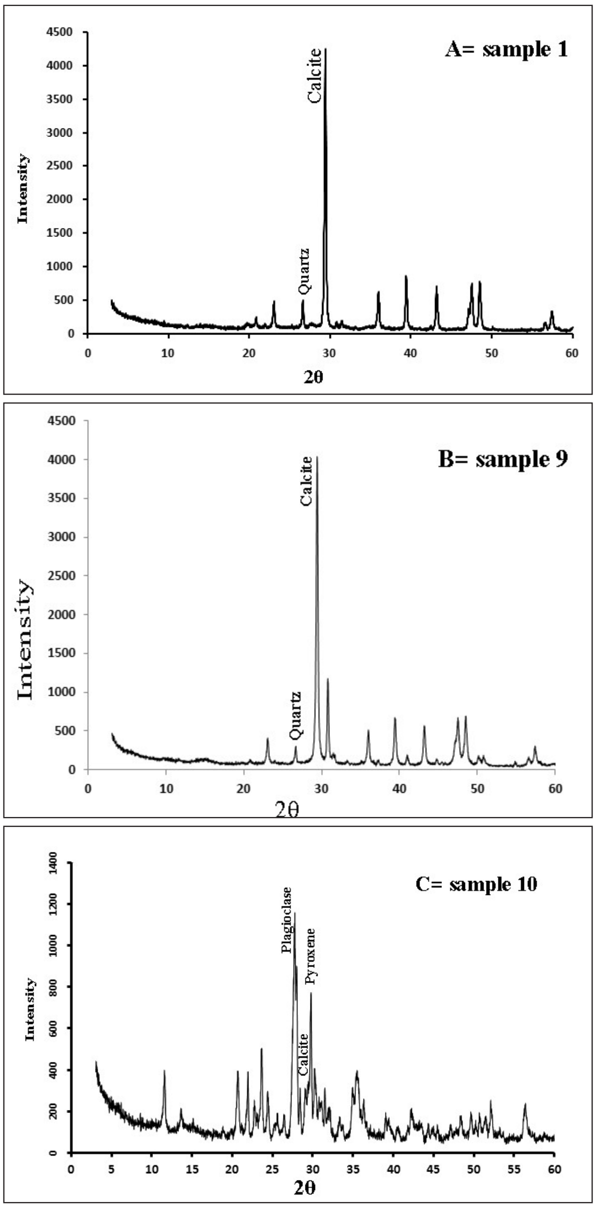

Figure 4. XRD patterns showing the mineralogical composition of samples 1 (A), 9 (B) and 10 (C).

5.2. Petrographic analyses

Ancient mortar is a composite material made of a binder and aggregates (fillers). Lime and gypsum were common binders and a variety of aggregates were also used. The colors of the binder samples vary from grey in samples 7, 8, 9, 10, and 11 to light brown in samples 2,4, and 6 and brown in samples 1,3, and 5. Petrographic analyses showed a strong cohesion between the binder and aggregates except for in sample 7 which showed a weak cohesion and some cracks (Fig. 5a). They showed that the studied mortars contain different types of aggregates, including micritic chalky and fossiliferous limestones, porphyritic basalt, reused mortars, ceramics, clays, quartz grains, and an organic matter of wood and charcoal.

The limestone fragments are micritic, chalky, fine, sometimes very coarse, and rich in planktonic foraminifera (Fig. 5b). The quartz grains are small in size and round to angular in shape (Fig. 5c). While the basalt fragments are porphyritic ranging from medium to large in size (Fig. 5d), the ceramics are small in size, sub-rounded and rich in fine quartz grains (Fig. 5e). The old, reused, mortar fragments are large and contain fossiliferous micritic limestone fragments, basalt particles, and fine quartz grains (Fig. 5f). The small clay particles were likely an accidental addition during the preparation and mixing of raw materials. The ratio of binder and aggregates ranges between 1.2 and 2.1, where their percentages ranging from 50-60: 30-35% to 65-70:25-30%. The sample contents of binders and aggregates are presented in percentages in Table 1. Eventhough limestone is a common aggregate, its abundance differs in the tested samples. Other present aggregates differed in type and abundance. They can be classified into three groups. The first group includes samples (1, 2, 5, and 7), the second group includes samples (4, 6, and 9), and the third group includes samples (6, 8, and 10).

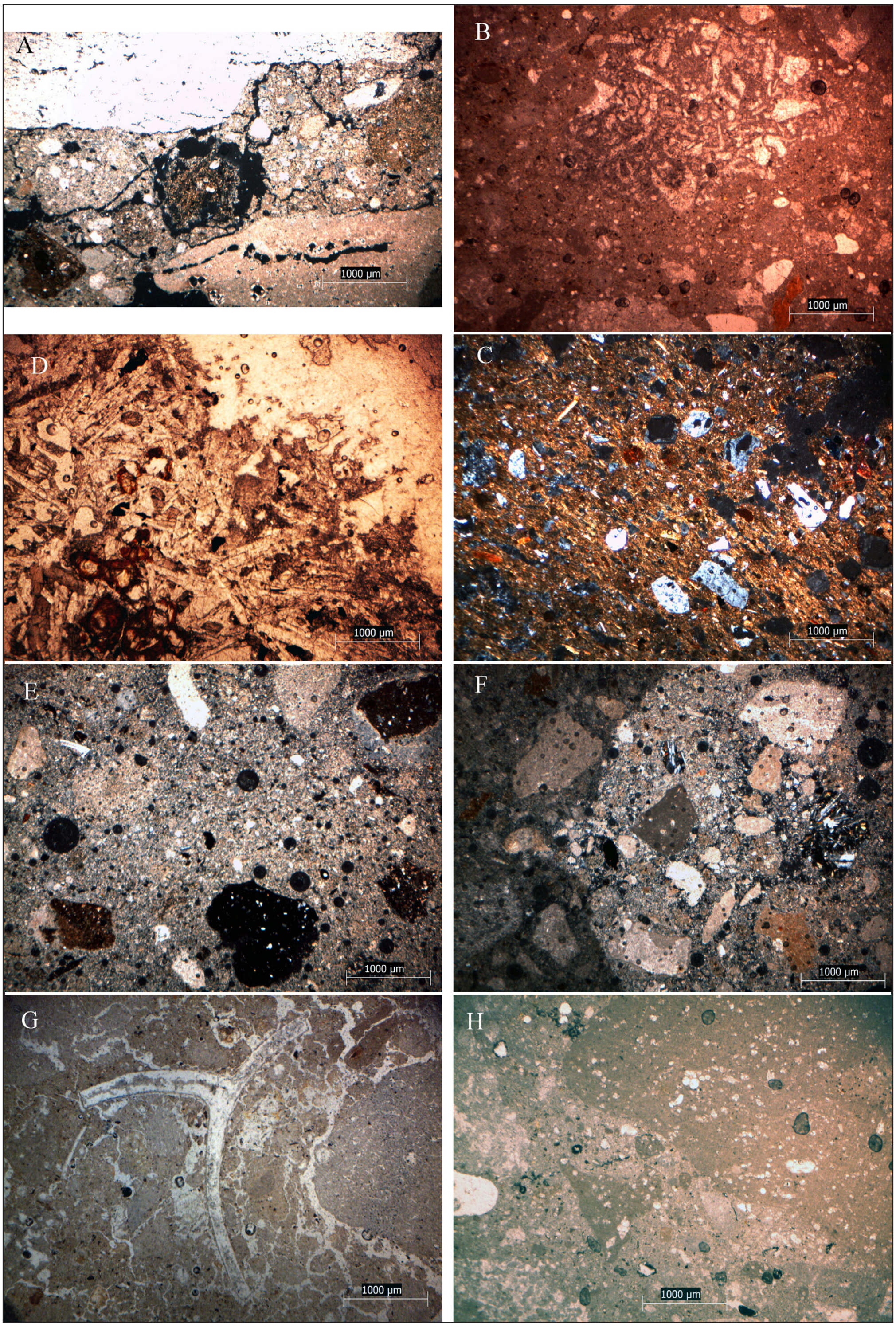

Figure 4. Microphotograph of Gadara mortars showing micritic lime binder and different kinds of aggregates. A. the weak cohesion, cracks and tuff (middle) of sample 7, B. fossiliferous limestone aggregate, C. quartz grains, D. porphyritic basalt fragment, E. ceramic grains, F. reused mortar, G. recrystallized calcite and shells, H. underburned angular fossiliferous micritic limestone.

The three groups differ mainly in the type and the amount of the available aggregate. The first group is comprised mainly of limestone rich in fossils, large shell fragments, and some tuffs. Small fragments are angular while large ones are sub-rounded. The second group is mainly comprised of limestone fragments rich in fossils, and has reused mortar rich in limestone, basalt, and quartz. These aggregates are angular and vary in size from fine to very coarse. The third group has limestone rich in fossils and high quantities of ceramic, porphyritic basalt, and quartz particles of angular to sub- angular shapes.

Table 1. The colors of the binders and percentages of the samples components (S =sample, b/a binder/aggregate, Lst.= limestone, Q= quartz, Cer.= ceramic, Or. M. = organic materials).

S.	b/a ratio	Binder		Aggregates%							
		Color	%	Lst.	Q.	R.M.	Bas.	Tuff	Cer.	Or. M.	Clay
1	1.2	Brown	50-60	30	3	-	-	2	5	3	2
2	1.2	Light brown	50-60	28	3	-	2		5	3	-
3	1.9	Brown	65-70	12	14	-	3	-	3	2	-
4	1.6	Light brown	60-65	35	1	-	-	-	-	2	-
5	1.4	Brown	50-60	30	1	-	-		7	4	-
6	1.5	Light brown	60-65	35	1	-	-	-	-	2	2
7	1.4	Grey	50-60	30	1	-	-		7	4	-
8	2.1	Grey	65-70	10	13	-	4	-	2	3	-
9	1.6	Grey	60-65	35	1	-	-	-	-	2	-
10	1.9	Grey	65-70	10	15	-	3	-	2	2	2

Petrographic analyses confirmed the XRD results that calcite, quartz, and pyroxene are major minerals present in the samples resulting from the addition of limestone, silica, and basalt aggregates.

It is worth mentioning that both the natural (tuff) and the artificial (ceramics) pozzolanic materials gave the mortars their hydraulicity, durability, adhesion to the stones and resistance to the environmental conditions. The hydraulicity of the samples is confirmed by the reaction rim between the pozzalanic materials and the lime (Fig. 5a and 5e) (Pavia and Caro, 2008, Izzo et al., 2016). The presence of some charcoals and other few fine wooden fragments could be contaminants from kiln fuels and are therefore accidental. Their reaction with the lime-binder might have given the mortars the hydraulic properties, reinforcement, and reduced fracturing (Leslie et al., 2002, Pavia and Caro, 2008). The results indicate that the stone builders at Gadara used hydraulic materials not only in buildings exposed to humidity, but also to improve the performance of mortars that were exposed to aerial conditions (Baronio et al., 1997, Fichera et al., 2015).

The sample contents containing the rounded nodules of quicklime (CaO) (Fig. 5g), might be an indication of poor mixing or dry slaking (with the minimal amount of water) (Bakolas et al., 1995). Some samples showed secondary calcite partially filling the pores and the cracks which is a result of the shrinkage effects (Fig. 5g). Abundant areas of recrystallization of binders in the small pores and larger cracks were observed in several of these samples.

Angular limestone fragments within the lime-binder (Fig. 5h) indicate low firing temperatures of below 850^{o}C, which is the temperature needed to break up limestone. In accordance with Pavia and Caro (2008), Goffer (1980), and Boynton (1980), analytical results showed that the low firing temperature of the raw materials in the Gadara samples resulted in a lime binder with a large specific surface, low shrinkage, and high chemical reactivity.

5.3. Scanning Electron Microscopic Analysis (SEM)

The SEM analyses of the samples' microstructures are shown in Fig. 5. The analyses showed that all mortars have compact microstructures of aggregates embedded in the fine lime binder of calcite particles (Fig. 5a), organic inclusions, wood (Fig. 5B), and quartz grains (Fig. 5C). The SEM images reveal micro pores and cracks, particularly at the binder-aggregate interface (Fig. 5D). The pores presented in sample 9 are filled with new calcite crystals formed possibly by the recrystallization processes of the binder (Fig. 5F). The bond between the lime binders and the aggregate grains is mostly strong, especially those with the hydraulic properties, and shows good cohesion through the SEM observations. It is probable that the acicular (needle-like shape) crystals seen in figures 5E and 5F are formed of calcium silicate hydrates (C-S-H) and are obtained through the reaction between the pozzolanic materials rich in reactive silica and the lime binder.

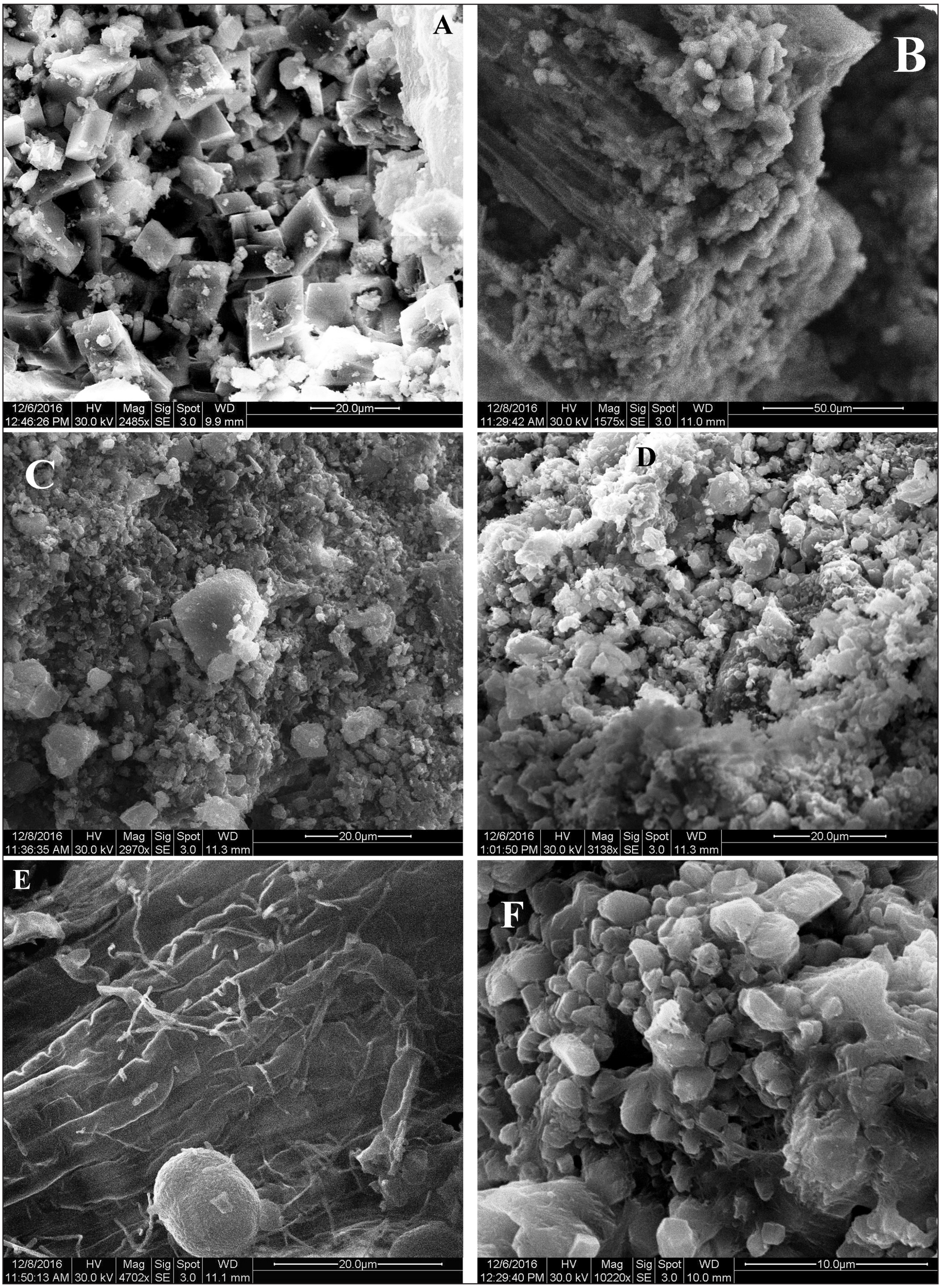

Figure 5. General microstructures of Gadara mortars. Aggregates represented are A) calcite particles, B) wood, C) quartz are embedded in lime binders, D) pores and cracks, needle-like shapes of hydraulic crystals (E and F).

6. Raw Materials Sources

Correlating the fossils and mineralogical composition of the underburned limestone fragments present in the lime-binder and the added aggregates to those of possible raw materials can determine their source within the surrounding area; see similar works of Elsen, (2006) and Ontiveros-Ortega et al. (2016). The planktonic foraminifera observed in the underburned limestone and the limestone aggregates were most likely sourced from the limestone layers of the Muwaqqar formation rich in foraminifera outcropping in the vicinity of Gadara. The most likely source of the quartz present are the sands from the valleys surrounding Gadara. The Mediterranean sands can still be their possible source because of their proximity to Gadara. Similarly, basalt and tuff that crop out in the area and its surroundings are the most likely source for the porphyritic basalt and tuff particles added to the mortars. The angularity of some limestone and quartz fragments might indicate a deliberate crushing of the source rocks. The basalt presence could be either a deliberate addition by the stone builders or was just an accidental addition resulting from the crushing processes of the rocks using basalt millstones. Some basalt fragments are inadvertently present in some of the studied mortars through the addition of reused mortar. These results indicate that local raw material sources were utilized in the production of the cementing materials used for the construction of the Gadara structures.

Conclusion

This multidisciplinary study of some archaeological mortars from Gadara provides information about their production techniques and the sources of raw materials used to produce them.

The micritic binder is lime mixed with aggregates of fossiliferous limestone fragments, quartz grains, basalt, clay, tuffs, ceramics, and organic materials. Because of the variation in the sample contents of their components, they are divided into three categories. The Hydraulicity of the lime binder was obtained by the addition of the pozzalinic materials to the mixture such as basalt, tuffs, and ceramics. Hydraulicity was observed through the reaction rims between the pozzolanic fragments and the lime binder. The samples showed good cohesion between the binder and aggregates.

The presence of lime lumps indicated that the lime was slaked with the minimum amount of water or poor mixing. Low firing temperatures (soft burning) were proven and verified by the presence of limestone fragments in the binder, the high chemical reactivity of the binder, and lack of cracks normally formed because of the shrinkage. The Raw materials used in the production of mortars were most likely local from the outcropping limestones, tuffs, basalts rock surrounding the archaeological site. The analytical results concerning the Gadara mortars are similar to the results of the examination of Gerasa mortars found by Yaseen et al. (2013) who observed that the cementing mortars were formed by a soft burning of the limestone which produced the high reactivity of the lime and the low shrinkage.

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