Petrological Study on the Roman Mortars from Kom El-Dikka Archaeological Site (Alexandria, Egypt)

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Abstract Two types of Roman mortars were collected from the buildings of the *Thermal Baths*, *Villa of birds* and *Cisterns* located at Kom el-Dikka archaeological site (Alexandria, Egypt). It is believed that these mortars date back to the first or second century A.D. Petrographical, and chemical characterization of these mortars were performed, to differentiate the various construction phases of Kom el-Dikka archaeological site. Results showed that the analysed samples are lime mortars, with different types of aggregates. The samples from the Cisterns, which showed a high superficial strength, also have a different isotopic ratio ($\delta^{13}C$ and $\delta^{18}O$) than the rest of the studied mortar samples. The analysis of soluble salts in the mortar samples was conducted. It reveals a main content on sulfates, nitrates and chlorides, of which provenance probably accounts for atmospheric pollution and marine aerosol, as well as possibly, previous restoration interventions.

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1 Introduction

Historic mortars are composite materials consisting of a combination of non/hydraulic binding materials, aggregates and additives (Moropoulou et al. 2000, 2005). The identification of their mineralogical and chemical composition is very useful in the recognition of the damage causes of the host building (Middendorf et al. 2005).

Non-hydraulic lime binder was used in most of the Roman buildings (Hamey and Hamey 1990; Siddall 2011). The lime mortar hydraulicity has been enhanced by highly reactive silica and alumina rich aggregates and/or additives leading to high bonding capacity and more pozzolanic reactions (Rodríguez-Navarro 2004; Mertens et al. 2009). The hydraulic and mechanical behaviour of lime mortars were improved by using these pozzolanic materials (Jonaitis et al. 2019). Roman masons widely used volcanic pyroclasts, ceramic bits and dust as pozzolanic admixtures when natural pozzolans were lacking (Stefanidou 2016). To make the mortar hydraulic, either hydraulic lime or non-hydraulic (pure) lime was used and the above-mentioned pozzolanic reactions were provided by aggregates or additives. Reactive clayey sands, chert, slates and silica rich additives could provide pozzolanicity (Ergenç and Fort 2019).

One of the threats facing most lime-based mortars is their susceptibility to salt damage (Rossi-Manaresi and Tucci 1991) because of the high water evaporation rate they have due to their porous structure (Stefanidou and Papayianni 2006). The random pore system and the pore interconnectivity of the lime-based mortars provide them a high open porosity (Papayianni et al. 2013). Thisresults in easy entrance of saline solutions penetrating into the masonryleading to seriously compromising the stability of the structure (Papayianni et al. 2013).

This study aimed to investigate and characterize the mortars employed in different buildings at Kom el-Dikka archaeological site focusing understanding the reasons of the growth of various soluble salts on the studied samples.

2 Study Area

Alexandria extends about 20 miles along the Mediterranean coast of Egypt. Alexander the Great founded it around 331 BC (Abdelhady 2014). Kom El-Dikka archaeological site seems like a whole city (Fig. 1), since it has an amphitheatre, a theatre auditorium, a school, some baths and cisterns (Theodore 2001; Hemeda 2013). The site is the only historic example allows researchers to study the urban fabric of the ancient Alexandria city in a wider urban context. Nowadays, the site

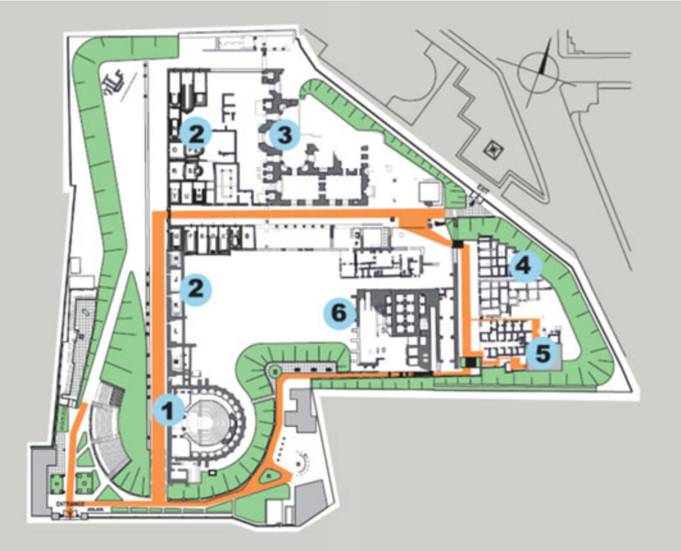

Fig. 1 Map of Kom el Dikka archaeological site (*source* Centrum Archeologii srodziemnomorskiej UW: Alexandria: Kom el-Dikka). 1. Theatre, 2. Auditoria 3. Baths 4. Domestic Quarter 5. Villa of the Birds 6. Cistern

embedded in the city, located nearby to Qaitbay citadel, towards the Southwest part of Alexandria.

3 Material and Methods

Joint mortar samples were taken from the *Thermal baths*, *Villa of birds* and *Cistern* structures, while from this last one, a rendering mortar was also sampled. The collected samples dated back to the period from the 2nd to the sixth century CE (Fort et al. 2021). The *Cistern* and *Baths* mortars showed a dark color and they were used to bond red brick blocks, while the *Villa of birds* mortar was pale in color and used to bond limestone (see Table 1).

4 Analytical Methods

The following analytical techniques were used in this study:

- Polarizing optical microscope Olympus BX51 polarized optical microscope (POM) with an attached Olympus DP12 digital camera was used for examining the mineralogical and petrographical features of the thin sections.

Table 1 Description of samples

Sample code	Type	Location
1	Joint mortar	Thermal Baths
2	Joint mortar	Thermal Baths
3	Joint mortar	Villa Birds
4	Joint mortar	Villa Birds
5	Joint mortar	Cistern
6	Joint mortar	Cistern
7	Rendering mortar	Cistern

- Ion Chromatography for the analysis of soluble salts: the anion content in the mortar samples were determined by a Metrohm 761 Compact ion chromatograph. The anions analysed were: fluoride, chloride, nitrite, nitrate, phosphate, sulfate and oxalate.
- Isotope analysis: δ18O and δ13C. Isotopic analyses of mortars were carried out with a MAT-252 Mass spectrometer. The results of the isotopic composition of carbon and oxygen were performed with the notation with respect to the Vienna Belemnite Standard Pee Dee (VPDB). The standard deviations were $\delta 13C = 0.03$ ‰; $\delta 18O = 0.06$ ‰.

For ion chromatography and isotope analyses, whole samples were ground for the analyses and binder-rich fragments of the samples were tested where applicable.

5 Results

5.1 Petrographic Characterization

The petrographic investigation of the studied mortars displayed different characteristics according to their hosting buildings, which correspond more likely to the different construction phases of the site. Samples collected from the Thermal Baths are lime mortars with a microcrystalline appearance (< crystal size 4 μm) with intercrystalline *vug* type porosity, and occasionally fissures in the binder (a petrographic estimation of porosity >15%). Two types of aggregates were identified, irregular ceramic fragments of ~1 to 0.1 mm size, in which quartz and quartzite could be identified (Fig. 2a). The second type of aggregates is limestone (mainly fossiliferous and oolitic) fragments seen larger than 4 mm (Fig. 2b). Other less frequently observed aggregates are poly-crystalline quartz (<1 mm), and some feldspars (potassium feldspar and plagioclase).

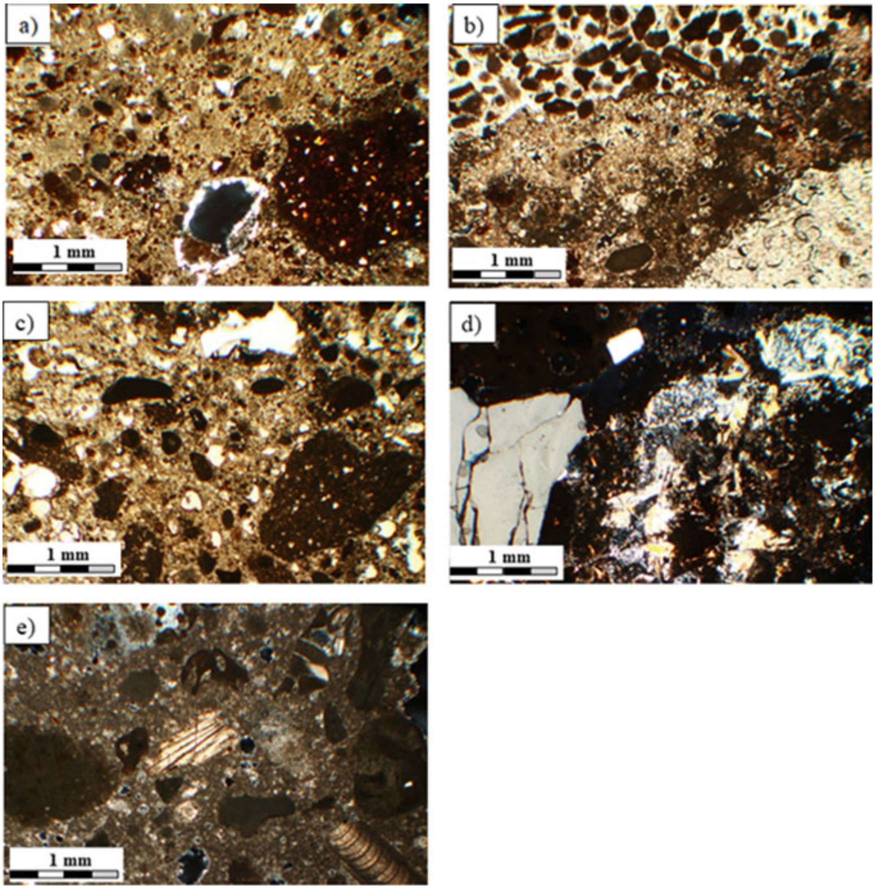

Fig. 2 Photomicrographs **a**, **b** *Thermal baths* joint mortar, **c** *Villa Birds* joint mortar, **d** *Cistern* joint mortar, **e** *Cistern* rendering mortar

In mortars of Thermal Baths, the binder: aggregate ratios ranged from 1:2 to 1:4. Both dissolution processes, resulting in an increase of the porosity, andrecrystallization processes leading to an increase of crystals size in the binder and therefore a reduction in the porosity were observed.

The binder of the mortars used in the *Villa of birds* presented a similar appearance to that of the mortar of the *Baths*. The aggregates of this mortar were mainly ceramic fragments, existing also lime lumps. Aggregates were smaller than those of the *Baths´*s mortars, together with quartz and some feldspar grains, smaller than 0.25 mm. They showed sub-rounded to angular shapes (Fig. 2c). The binder: aggregate ratio ranged from 1:3 to 1:4.

The samples from the *Cistern* were lime mortars, too. The carbonated binder consisted of microcrystalline calcite. It had an inter-crystalline porosity (>15%) in form of *vug*-type pores and fissures. The aggregates were fragments of fossiliferous

Table 2 Anion content in the mortar samples (ppm)

Sample	Fluoride	Chloride	Nitrate	Sulfate	Oxalate	Total
1 (Baths)	0.06	98.94	78.96	734.75	0.79	913.49
2 (Baths)	0.25	313.43	127.40	48.72	0.00	489.81
3 (Villa Birds)	0.31	90.47	60.61	1338.10	0.00	1489.49
4 (Villa Birds)	0.38	115.09	131.36	90.84	1.22	338.88
5 (Cistern)	0.21	727.03	924.85	577.64	0.00	2229.74
6 (Cistern)	0.27	725.09	475.64	39.40	0.00	1240.40

and oolitic limestone, and monocrystalline quartz (>2 mm). The presence of lime lumps was abundant. The binder: aggregate ratio ranged from 1:3 to 1:4. Drusy-type calcite crystals grew inside some pores. Filling of pores (secondary crystallization in the border) and shrinkage cracks in the binder were observed (Fig. 2d). The sample of the rendering mortar of the *Cistern* was composed of porous microcrystalline lime binder with aggregates consisting of fossil fragments and lime lumps (Fig. 2e). There was *vug*-type porosity within small drusy-type calcite crystal grown inside it.

Aggregate shapes, mainly quartz and feldspar, were irregular and surface textures were angular to sub-angular. This implies that the sands were transported by fluvial water currents.

5.2 Ion Chromatography

The results show that sulfates were abundant in some mortars such as Villa of Birds, which accounts for the inclusion of gypsum to the mortar (Table 2). Samples from the *Cisterns* showed higher amount of chlorides and nitrates than the others, which indicates a salt source related to rising damp. Neither nitrite nor phosphate was detected.

5.3 Isotope Analysis

The content of δ13C and δ18O in mortars showed values between −12.85 and −5.03 for δ13C and from −12.11 to 3.87 for δ18O (Table 3). The joint mortars from *Villa of birds* were those that have a lighter content of isotopes along with the rendering mortar of the *Cistern*. Mortars from the joints of the *Baths* and the *Cistern* showed a behaviour that moves away from those obtained in *Villa of birds*. The joint mortar of the *Cistern* had positive values of δ18O close to 3.8, and those of the *Thermal baths* between - 4 and 2. Both types had $\delta^{13}C$ values between −9,5 and −5,4.

The different isotopic composition of *Villa of bird* mortars with those of *Baths* and *Cistern* joints may be due to the presence of limestone aggregates, or to an

Table 3 Results of isotope analysis

	$\delta^{13}C$ (VPDB)	$\delta^{18}O$ (VPDB)
Baths joint mortar-1	−9,27	−3,96
Baths joint mortar-2	−5,36	1,96
Villa of birds-3	−5,04	−7,26
Villa of birds-4	−12,85	−12,11
Cistern joint-5	−8,7	3,82
Cistern joint-6	−9,45	3,87
Cistern rendering-7	−9,4	−11,67

uncompleted calcination of the limestone used to produce lime, which can increase the ratio of δ13C (Usdowski and Hoefs 1993; Dotsika et al. 2009). Another reason can be the presence of salt phases and ceramic dust, and even greater processes of dissolution and reprecipitation of calcium carbonate (Dotsika et al. 2018).

6 Conclusion

In this study petrographic and elemental description of Kom EL Dikka mortars are presented. Deterioration level of the mortar samples is discussed considering salt contents. Results showed that in the site, similar Roman construction technologies were used as those mentioned by Vitruvius.

Collected mortars confirmed to be lime mortars; fossiliferous limestone and ceramic were used as aggregates. This shows the selection among the available local raw materials.

Aggregate selection was based on where the mortars would be applied; humid or dry environment. Mortars from *Villa of Birds* have different characteristics, which implies different construction phase. Alternatively, this could be due to the weathering induced by salt presence.

The elaborate mason workmanship can be ruled out for the elaboration of mortars due to the high number of lime lumps due to the lack of a regular calcination temperature.

The high salt content has a high effect on dissolution–recrystallization processes. Therefore, classification based on the isotopic data according to the original composition is turned out to be complicated.

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