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SPECIAL ISSUE

Mineralogical and chemical characterization of historical mortars from military fortifications in Lisbon harbour (Portugal)

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Abstract Historical mortars from sixteenth to seventeenth century military forts located at the mouth of the Tagus River in Lisbon have been characterized by polarized light microscopy (PLM), thermal analysis (TG/DTA), X-ray diffractometry (XRD) and scanning electron microscopy + energy dispersive spectroscopy (SEM + EDS). The results indicate that the mortars used were all hydraulic lime-based. The presence of well-rounded lime lumps indicates a limited use of water during the lime hydration process. The detection of hydrated calcium chloroaluminate and carboaluminate compounds mostly at binder-aggregate interfaces provides evidence for the onset of pozzolanic reactions during mortar production as further confirmed by the presence of ceramic fragments in the aggregate fractions intentionally added by the fort builders to increase the hydraulic properties of the mortars. The higher mechanical strength and greater resistance to degradation processes imparted by these pozzolanic compounds could explain why, despite the extreme proximity of the investigated sites to the sea, salt weathering processes do not appear to have significantly affected the studied mortars.

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Keywords Historical mortars · Lisbon fortifications · PLM · TG/DTA · SEM + EDS · XRD

Introduction

The study and characterization of historical mortars has received remarkable attention in recent years from conservators, restorers and other professionals involved in the safeguard of European architectural heritage (Baronio et al. 1997; Riccardi et al. 1998; Sabbioni et al. 2001, 2002; Maravelaki-Kalaitzaki et al. 2003; Elsen et al. 2004; Moropoulou et al. 2000, 2002, 2005; Veiga et al. 2001; Candeias et al. 2005; Elsen 2006; Schiavon and Mazzocchin 2009; Silva et al. 2010). Historical mortars are composite materials consisting of an aerial (air hardening) or an hydraulic (water-hardening) binder (gypsum or lime based and, in the oldest cases, also mud) combined with an aggregate fraction commonly made up of sand-to-gravel sized mineral grains, rock and/or fossil fragments (Sabbioni et al. 2001; Elsen 2006). Aggregate material is usually derived from local beach or fluvial sand deposits available nearby the building/site under consideration (Schiavon and Mazzocchin 2009; Silva et al. 2010), although more unusual materials such as, for example, finely crushed pottery, tiles or bricks (the "cocciopesto" mortar for instance, widely produced during Roman times) have also been used. Hydraulic binders are characterized by two main properties: (a) they harden in the presence of water and (b) they produce a mortar with water-resistant properties (Baronio and Binda 1997).

The textural, mineralogical and chemical characterization of historical mortars provides useful information regarding the history of buildings, particularly as far as age, social context, construction techniques, past restoration

interventions, and decay processes are concerned. Moreover, the acquisition of data on mortars textural, chemical and mineralogical features is essential to assist restorers in the correct choice and production of replacement and/or repair mortars that are compatible from a physical as well as chemical point of view with the original ones (Veiga et al. 2001; Candeias et al. 2005). As a matter of fact, several historic monuments have been damaged by decay processes caused by the incorrect application of unsuitable mortar replacement/repair materials. In this respect, the use of cement (in particular the ordinary portland cement variety, referred to in engineering terms as OPC) is a typical example: OPC, introduced in the mid-nineteenth century, has been widely used both as the hydraulic binder of choice and as a restoration material despite mounting evidence of it being too hard, rigid and impermeable to be successfully used in mortar repair works (Callebaut et al. 2001). OPC also contains high amount of soluble salts, that are known to be responsible for crystallization stresses strong enough to induce fracturing in the original historical mortars (Callebaut et al. 2001).

This study focuses on the characterization of mortars from a 16th to 19th century Lisbon seaside military complex, made up by a system of fortresses built for the protection of the Lisbon harbour and located at the mouth of the Tagus River. The complex is now completely deactivated and its buildings have acquired a strong cultural and historic importance in Portugal. A multiple analytical approach has been adopted combining polarized light microscopy (PLM), thermal analysis (TG-DTA), X-ray diffractometry (XRD) and scanning electron microscopy + energy dispersive spectroscopy (SEM + EDS) to fully characterize the Lisbon forts mortars. In particular, the analytical routine was used to investigate the mineralogy/morphology of aggregate grains (single mineral, rock and/or ceramic fragments) and to provide data on the extent of crystallization, mortar homogeneity and microporosity, presence of microfractures (often caused by to the hardening process), presence of lime lumps and/or of neoformation phases (Baronio et al. 1997; Sabbioni et al. 2001; Callebaut et al. 2001; Elsen 2006) and assessment of marine-derived salt weathering processes and products (Sabbioni et al. 2002).

Historical military installations are increasingly recognised as an important part of our common European Cultural Heritage. It is expected that the characterization of the Tagus fortifications mortars will contribute towards a better understanding of the technology available during the construction of these military buildings and towards determining the geological sources or extraction region of the materials used in mortar production (Candeias et al. 2005; Silva and Veiga 2008; Schiavon and Mazzocchin 2009; Silva et al. 2010). At the same time results stemming from this study should provide the scientific platform needed for planning future conservation and restoration strategies aimed at protecting this particular type of built heritage under threat from attack by environmental agents as well as by urban developments.

Location/history/architecture

The Bugio Fortress (Figs. 1, 2) is located on a sandy islet called Cabeça Seca at the mouth of the Tagus River. It is a unique example of Portuguese Renaissance circular plant military fort, and is classified as a national monument since 1957. Construction began in 1590 under the direction of Italian military engineer Vincenzo Casale, during the reign of Filipe I and was completed around 1657, under the guidance of João Turriano. During the late eighteenth century, it was used as a prison. In 1775, the fort became a lighthouse which is still in use to support navigation at the entrance of Lisbon harbour.

The St. Bruno Fort (Figs. 1, 2) is a strong star-shaped fortress; it was built in 1647 during the ruling of king João IV. Dismissed in the nineteenth century, it witnessed several occupations and adaptations for government services. Since 1978 is classified as a building of national interest in Portugal.

The St. Juliao da Barra Fort (Figs. 1, 2) is located on the right bank of the Tagus River mouth very close to the seafront. It is an example of military Baroque architecture. It was operational in 1580 but its construction took nearly a century to complete. Throughout Spanish dominion (1580–1640), it was used as a state prison. By order of D. Joao IV in 1650, works were undertaken to increase the power of the defensive landside. In the early nineteenth century, during the French occupation, Napoleon military forces were installed in S. Juliao da Barra to defend Lisbon from the English fleet that blocked the

Fig. 1 Satellite map of Lisbon Harbour with the location of the three fortification monuments under study

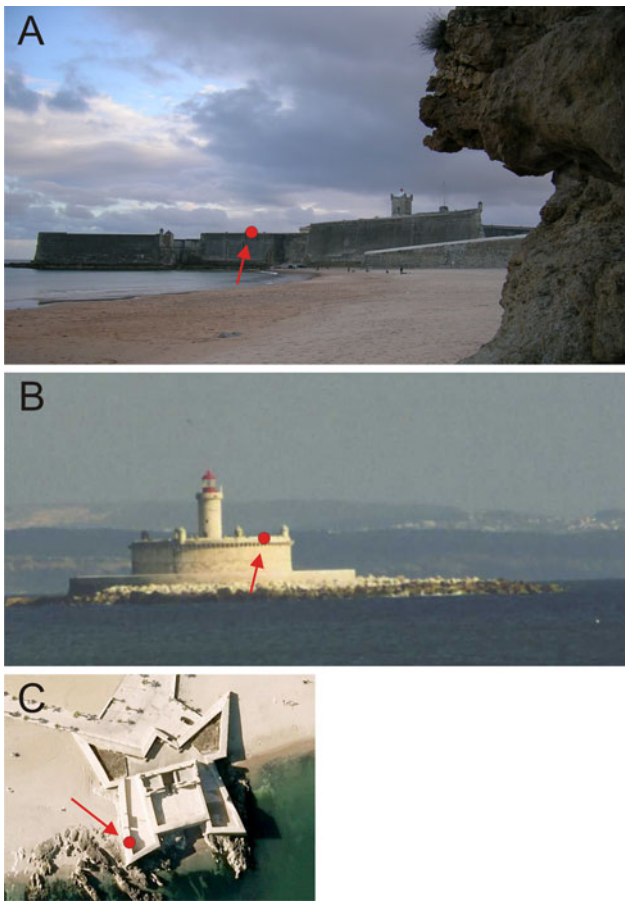

Fig. 2 Military Fortifications in Lisbon harbour. *Arrows* indicate sampling sites. **a** St. Juliao da Barra Fort, **b** Bugio Fort, **c** St. Bruno Fort

entrance of the Tagus. The latest military action involving the fortress took place in the context of the 1831 Portuguese civil wars.

Materials and methods

All samples were collected during the conservation works carried out by the Portuguese authorities (DGEMN—Direcção Geral de Edifícios e Monumentos Nacionais). In the Bugio Fortress, two samples mortar joints were taken, one on the top of the wall (FB 1) and the other from the lower wall (FB 2), close to the seawater. The sample of the St. Bruno Fort (FBR) was removed from the plaster mortar of the north facing second floor terrace wall. Samples from St. Juliao da Barra Fort were taken by DGEMN services. One sample comes from the filling mortar (FJB1) while the other comes from the plaster mortar (FJB2).

The analytical methodology employed was tested elsewhere (Silva et al. 2006, 2010) and is an adaptation of the standard analytical procedures used in historical mortars studies (RILEM Technical Committee 2004, 2009; Middendorf et al. 2005a, b; Elsen 2006). After epoxy resin vacuum impregnation, textural and mineralogical characterization of polished thin sections (thickness 30 μm) of mortar samples were carried out by polarised light microscopy (PLM: Olympus BX51). To gain additional data on the mineralogy and elemental composition of the mortars and on the presence of decay products, mortar fragments and selected thin sections were also analysed after coating by carbon evaporation by scanning electron microscopy (SEM, JEOL-6400) coupled with an energy dispersive spectrometer (EDS, OXFORD-INCA X-Sight Si(Li) X-ray detector). Complementary phase identification was performed by thermogravimetric-differential thermal analysis (TG/DTA: SETARAM TG-DTA Analyser) under Argon atmosphere, heating rate of 10°C/min and by X-ray diffraction (XRD: Philips Diffractometer), the latter using Fe-filtered CoKα radiation, speed of 0.05°/s and 2θ values ranging from 3 to 74°.

Prior to XRD and TG-DTA analyses, samples were disaggregated and grounded to a fine powder. A fraction was treated with warm diluted HCl (1:3) to separate the soluble fraction from the siliceous aggregate grains. The HCl digestion procedure is the method normally applied to dissolve the siliceous fraction present in the mortar. Depending on aggregate's type, other solvents can be applied. The residue obtained can be treated with sodium carbonate solution for the determination of the soluble silica content. In our methodology we only use the HCl attack since the carbonate fraction present in the aggregates is obtained by the point-counting microscopic method. The Jedrzejewska (1960) method was used to obtain values for the relative proportion between siliceous aggregates, carbonate binder and soluble fraction by combining the percent calcium carbonate estimated by TG-DTA with the residue analysis.

The relative proportion of the identified constituents and the ratio aggregate/binder was also assessed by PLM point counting (Schouenborg et al. 1993; Elsen et al. 2004). PLM analysis is particularly useful when carbonate grains are present in the aggregate fraction as, in this case, estimated aggregate content values, calculated after HCl treatment, can be significantly underestimated.

Results and discussion

Macroscopic observations

The FB1 sample is composed of a yellowish binder containing lime lumps. They show reduced mechanical resistance when hit by a rubber hammer during sampling.

Mineralogically, the aggregates are composed mainly of well-rounded quartz grains but darker mafic grains are also visible. Grain sizes range from coarse sand (0.5–2 mm) to (occasionally) gravel. FB2 samples present a slightly lighter binder with whitish lime lumps. The aggregates exhibit characteristics similar to FB1.

The Fort St. Bruno sample (FBR) is composed by a very hard light-coloured mortar, with some brown areas containing a small number of rounded to sub-rounded aggregate grains. The binder contains readily visible lime lumps.

In St Julião da Barra Fort, the sample FJB1 is composed of a light colour filling mortar with lime lumps. The aggregate grains range from fine sand to gravel in size and are mafic and felsic with roundness values in the rounded to sub rounded classes. In one sample of a plaster mortar (FJB2), a stratification can be seen with, from the interior to the exterior, three light coloured layers followed by two external dark grey layers. No lime lumps were observed. The two external grey layers appear to be the result of a recent cement-based restoration and therefore they were excluded from further tests by mechanical separation. All samples exhibit predominantly sub-angular aggregate grains.

Optical microscopy

Petrographic microscope observations of all mortar samples identified the presence of a microcrystalline carbonate binder. Anisotropic neoformation compounds (Table 1; Figs. 3, 4) were observed not only at the interface aggregate grains/binder, forming reaction rims, but occasionally also within the binder and sometimes filling cracks within aggregate grains.

All mortars from the St. Juliao da Barra Fort (FJB1—filling mortar and FJB2—plaster mortar) are characterized by a binder with a similar carbonate-rich composition although the aggregates grains are quite distinct (Table 1). Carbonate aggregates are abundant in FJB2 and almost absent in FJB1. Well-rounded lime lumps are most abundant in FJB2 where the distribution of aggregates is less homogeneous. The aggregate grains display very high roundness values. In sample FJB2, ceramic fragments (Fig. 4a) and aragonitic shell fragments (Fig. 4d) are widespread. In the FJB samples, neoformation pozzolanic products are more abundant than in mortars from other forts (Fig. 4b).

The samples from Bugio Fort (FB1—mortars from the top of the wall and FB2—mortars the bottom of the wall) are similar but two differences can be noticed: the proportion of aggregate grain is higher and neoformation compounds are less abundant in FB1. The aggregate distribution in the binder is nearly homogeneous. In both samples the aggregate grains are well rounded. The aggregate fraction consists predominantly of quartz; carbonate grains are not present in percentage high enough to require supplementary methods of aggregate/binder calculations. In FB2 micro-fractures were detected within the binder groundmass. These fractures resemble shrinkage cracks caused by dehydration-driven contraction after drying and in some cases are filled by secondary recrystallized calcite (Fig. 4c).

The aggregates of the St. Bruno Fort sample are predominantly quartz and carbonates. Well-rounded lime lumps are also frequent. The grains are mostly in the sub-rounded class but grains displaying higher roundness values can occasionally be found. Some quartz grains display

Table 1 Optical petrography of the mortar samples from the Tagus River fortifications

	Bugio Fort		St. Bruno Fort	St. Julião da Barra. Fort	
	FB1	FB2	FBR	FJB1	FJB2
Quartz	X	X	X	X	X
K-Feldspars	X				X
Plagioclases					X
Muscovite		X		X	X
Biotite				X	X
Rutile			X		
Carbonate aggregates	X		X		X
Shells	X		X		X
Quartzite	X	X		X	X
Sandstone	X	X			
Neoformation compounds	X	X	X	X	X
Ceramics	X				X
Lime lumps	X	X	X		X

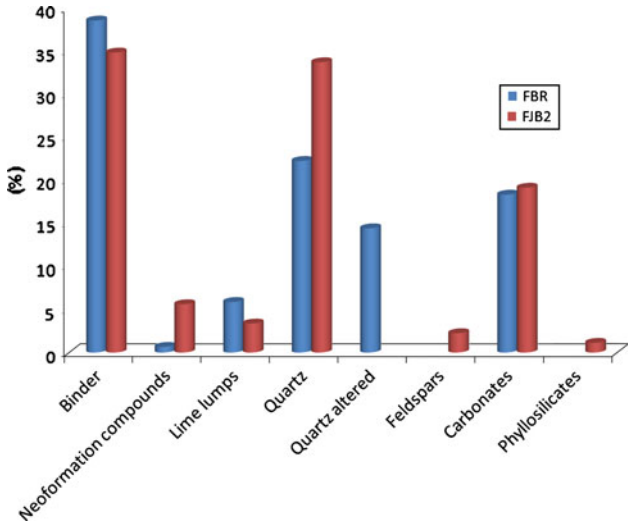

Fig. 3 Quantitative mineralogical composition of the mortars from St. Bruno Fort (FBR) and St Julião da Barra Fort (FJB2) by PLM point counting analysis

evidence of dissolution phenomena, possibly caused by the highly alkaline micro environment due to the presence of the lime binder. Neoformation compounds are less common than in the Bugio Fort and tend to be located only at binder/aggregate interfaces.

A significant presence of carbonate grains within the aggregate fraction can become a strong source of error when the ratio between aggregates and binder is calculated by acid digestion and thermo-gravimetric analysis. Therefore, point counting was applied to the FBR e FJB2 samples. The results are shown in Fig. 3; the abundance of carbonate aggregates is indeed significant (approximately 18% volume) and must be taken into consideration in carbonate binder corrections after the calculations performed according to the Jedrzejewska method (Lindqvist and Sandström 2000; (RILEM 2009). Once this correction is applied, it becomes clear that all mortars have quite similar binder relative percentages.

Thermal analysis (TG/DTA)

Thermogravimetric analysis is a powerful tool in mortar studies inasmuch as it allows to estimate the nature and weight of the binder and its hydraulic character (Moropoulou et al. 1995; Bakolas et al. 1995, 1998). Thermograms (Fig. 5) from the historic forts of Lisbon harbour are quite similar for all samples. Important weight loss occurs at more than 600°C, corresponding to Ca-carbonate decomposition processes and suggesting a high calcite content in the mortars (Table 2). No peaks ascribable to the presence of Mg-rich carbonates (hydromagnesite, magnesite or dolomite) are present. Weight losses occurring at low temperatures (<120°C) are due to adsorbed water dehydration processes. Furthermore, weight losses between 120 and 200°C can be ascribed to hydrated salts that seem

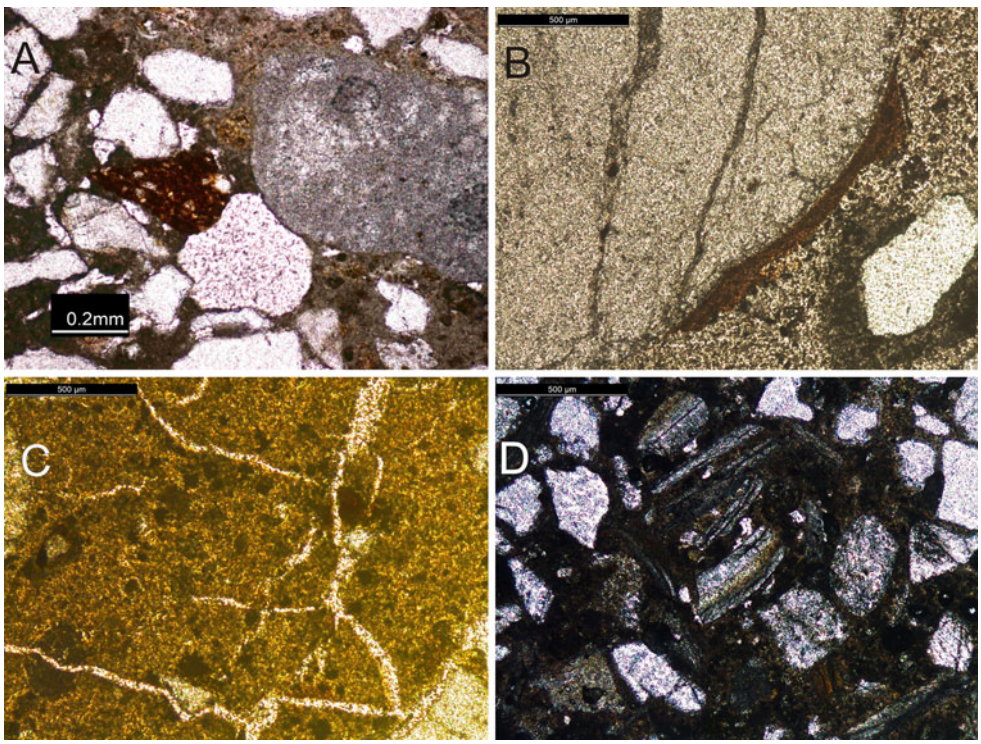

Fig. 4 PLM micrographs. **a** Quartz aggregates and a ceramic fragment, **b** neoformation pozzolanic material at a quartz grain/binder interface, **c** dehydration "shrinkage" cracks within the binder groundmass, **d** shell material as constituent of the aggregate grain fraction

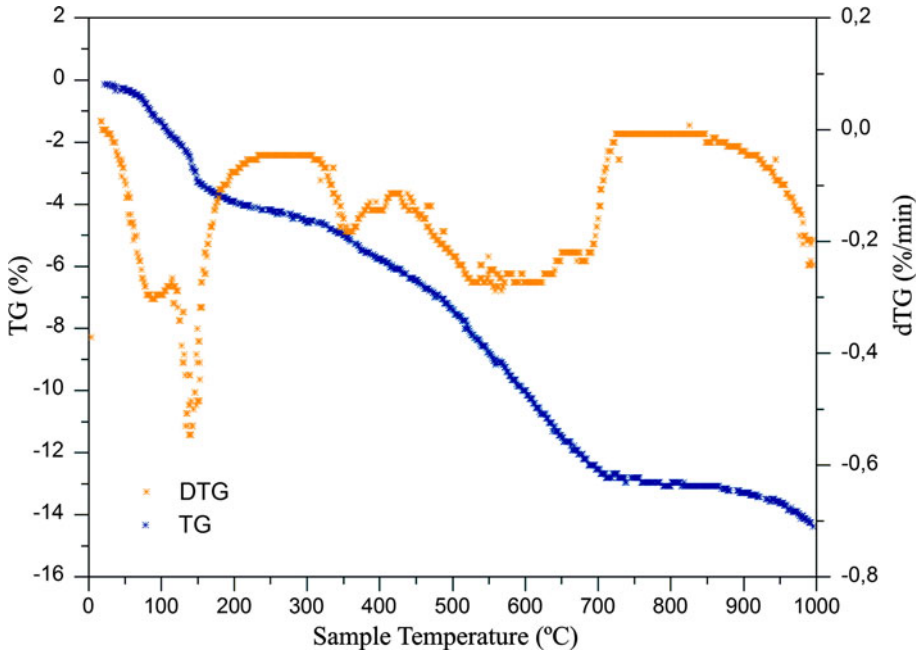

Fig. 5 Thermal analysis curves of sample FB2 (*TG* thermogravimetric curve, *DTG* derivative thermogravimetric curve)

to be relatively more important in Bugio Fort. This result is compatible with the location of this building at the river mouth, very close to the open sea.

The weight losses between 200 and 400°C are due to the loss of chemically bound water and a strong indicative of the presence of hydraulic components. This factor and the ratio CO_2/hydraulic water (Table 2; Fig. 6) are compatible with the interpretation of the samples as lime mortars with hydraulic properties probably due to the presence of crushed bricks (Maravelaki-Kalaitzaki et al. 2003), confirming the petrographic results.

The difference between the total percent calcium carbonate, measured by TG/DTA, and the insoluble residue by warm HCl digestion constitutes the soluble fraction. This method (Jedrzejewska 1960) allows the subdivision of the mortar composition into three separate fractions: carbonate fraction, insoluble silicate fraction and soluble fraction (Table 2).

In the Bugio and St Julião da Barra Forts, the siliceous aggregate fraction constitutes between 67 and 75% of the total, quite similar to values found in other historical lime mortars in Portugal (Silva et al. 2010). On the other hand, the Ca-carbonate fraction in the binder, as determined by TG/DTA, appears rather low when compared with other Portuguese aerial lime mortars (Silva et al. 2010). Conversely, the soluble fraction is quite high. This could be due to the presence of hydraulic compounds (insoluble in diluted HCl) formed by pozzolanic reactions in the mortars (Sabbioni et al. 2001; Elsen et al. 2004).

X-ray diffraction

Bulk XRD spectra show calcite and quartz as the main mineralogical constituents in the Tagus fortifications mortars (Table 3). Feldspars represent also a very important crystalline phase. Mica minerals, aragonite and halite are occasionally present. Brucite, gypsum and ettringite salts have been detected in minor amounts only in Bugio Fort mortar samples while crystalline hydrated calcium chloroaluminate and carboaluminate compounds are much more conspicuous.

The silicates phases identified by X-ray diffraction (i.e. quartz, feldspars and micas) constitute the main minerals in the aggregate fraction suggesting a sedimentary source for the aggregate raw materials (fluvial sands) close to the original siliceous rock (Schiavon and Mazzocchin 2009). The sporadic presence of aragonite could be due to the presence of mollusc shell fragments or due to recrystallization processes. The abundance of calcite results from the use of lime as the binder. The significant presence of hydrated calcium chloroaluminates ($3CaO{\cdot}Al_2O_3{\cdot}CaCO_3{\cdot}11H_2O$) and/or carboaluminates ($3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O$) should be due to the onset of pozzolanic reactions in the presence of seawater. This demonstrates a much awarded use of the materials in order to obtain a hydraulic binder. The same kind of materials is known in Roman mortars used in buildings in direct contact in water (Silva 2002, 2003).

The minor amounts of halite, brucite and gypsum detected exclusively in the Bugio Fort samples can be

Table 2 TG/DTA weight losses, CO_2/H_2O ratio (weight loss percent >600°C/weight loss percent between 200 and 600°C) and composition of the mortar samples using the Jedrzejewska method

Sample	Weight loss (%)				CO_2/hydraulic water	Carbonates[a]	Insoluble residue or siliceous aggregate[c]	Soluble fraction[d]
	<120	120–200	200–600	>600		Binder/aggregate (vol%)[b]		
FB1	1.37	1.62	5.34	6.41	5.3	14.6	71.4	14.0
FB2	1.83	2.03	6.21	4.44	6.2	10.1	67.1	22.8
FJB1	1.68	1.06	3.63	6.32	3.6	14.4	75.0	10.6
FJB2	0.82	0.40	2.35	11.35	2.4	25.8	67.0	7.2
						65%/35%		
FBR	0.91	0.76	5.42	18.99	5.4	43.2	38.5	18.3
						68%/32%		

[a] As $CaCO_3$, calculated from CO_2 loss by TG

[b] Calculated by petrography

[c] Insoluble residue (IR) after warm hydrochloric acid (1:3)

[d] Soluble fraction = 100 − (IR + carbonates)

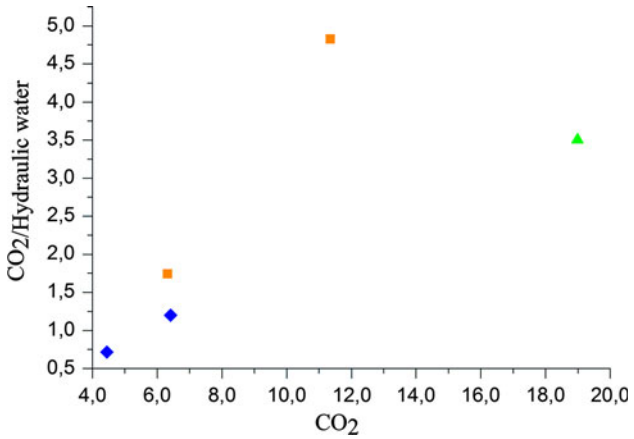

Fig. 6 CO_2/H_2O ratio (weight loss percent >600°C/weight loss percent between 200 and 600°C) versus CO_2 percent (weight loss percent >600°C) referred to the total mortar sample. *diamonds* FB, *squares* FJB, *triangles* FBR

related to the particular island location of this fort which makes it the most exposed to marine aerosol agents and to seawater salt crystallisation and weathering processes amongst the three fortifications under study:

Scanning electron microscopy and energy-dispersive X-ray micro-analyses

Neoformation compounds were found in all mortar samples. They exhibit a similar elemental composition but in three different textural configurations: (a) within the binder (Fig. 7), (b) at aggregate/binder interfaces (Fig. 8) and (c) within inter-granular fractures inside aggregate grains. EDS analysis confirms XRD results inasmuch as it reveals that these compounds are calcium aluminates and aluminosilicates with iron and/or titanium and magnesium as minor elements. It is known (Reis and Silva 1995; Sabbioni et al. 2001; Moropoulou et al. 2000, 2002) that the precipitation of calcium silicates and/or calcium aluminates is related to the development of pozzolanic reactions among the lime and the pozzolan materials (natural and/or artificial) used as mortar additives. In this respect, it is worth noting that the widespread presence of artificial pozzolan fragments, i.e., ceramic materials (Fig. 4a), has been in fact confirmed by PLM analysis.

Conclusions

Mortar characterization is a challenging task because no single analytical method is by itself sufficient in providing definitive results. For instance, while X-ray diffraction is adequate to identify crystalline phases, especially when grain size is very small, this technique cannot be used to identify amorphous compounds. Moreover, as already mentioned in the previous sections, neither XRD nor thermal analyses are able to correctly determine the binder/aggregate ratio when the aggregate fraction contains a significant number of carbonate grains. In addition, while optical microscopy is well suited for the identification of mortars textural features such as micro-fractures, aggregate grain-size distribution, aggregate homogeneity or heterogeneity, it is also useful in the petrographical identification of aggregate fraction constituents such a rock fragments and/or mineral grains, lime lumps and natural (volcanics) or artificial (ceramics) pozzolans, it cannot be used to identify fine-grained phases which can be detected only by SEM + EDS.

The carbonate mineralogical composition of the St. Bruno, Bugio and S. Julião mortars binder indicate that

Table 3 Mineralogical composition of the mortars by XRD analysis

	Bugio Fort		St. Bruno Fort	S. Julião da Barra Fort	
	FB1	FB2	FBR	FJB1	FJB2
Quartz	++/+++	+++	+++	+++	+++
Feldspars	+/++	+	+	+/++	+/++
Micas	–	+	–	?	tr
Aragonite	–	–	+	–	tr
Calcite	+/++	+/++	+++	++	++/+++
Brucite	tr	tr	–	–	–
Gypsum	+	+	–	?	–
Ettringite	tr	?	–	–	–
Hydrated calcium chloroaluminate	tr	tr	tr	+	–
Hydrated calcium carboaluminate	?	tr	–	+	–
Halite	tr	tr	–	tr	–

+++ abundant, ++ present, + small amount, *tr* traces, ? uncertain, – undetected

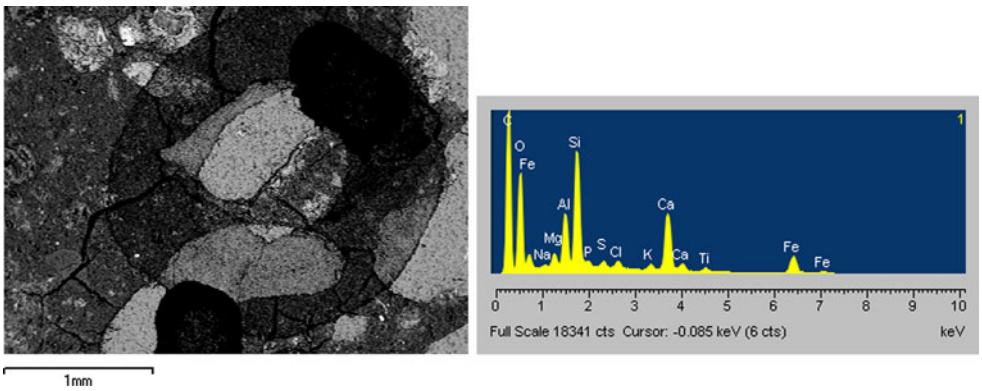

Fig. 7 SEM + EDS analysis. Neoformation pozzolanic compounds occurring within the binder. EDS spectrum (*right*) reveals that these compounds are calcium aluminates with iron, titanium potassium, magnesium and sodium as minor elements

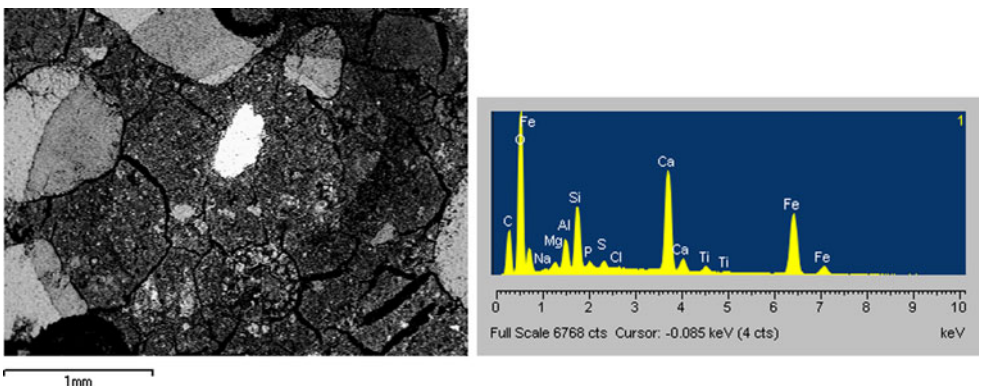

Fig. 8 SEM + EDS analysis. Neoformation pozzolanic compounds at the aggregate grain/binder interface. EDS spectrum (*right*). The composition is similar to the same material in Fig. 7

they all are lime-based mortars. The presence of lime lumps indicates a limited use of water during the lime hydration process [from CaO into $Ca(OH)_2$] in order to obtain a dry-slaked lime (Elsen 2006). The lime/aggregates (siliceous) ratio is peculiarly low whereas the soluble compounds proportion is very high. This can be explained by the strong hydraulic nature of the mortars as confirmed by TG/DTA analyses. The evidence for the onset of pozzolanic reactions in the mortars under investigation can also be inferred from the detection of hydrated calcium chloroaluminate and carboaluminate crystalline compounds by X-ray diffraction, and from the presence of ceramic fragments and of neoformation compounds with calcium, aluminium and silicon as detected by optical and

electron microscopy. When natural and/or artificial pozzolans are added, the most reactive constituents become a source of silica and alumina that can be introduced in the system and be involved over time in pozzolanic reactions activated by the high alkaline environment, provided by the presence of lime in the binder (Baronio et al. 1997; Moropoulou et al. 2000; Reis and Silva 1995; Silva and Reis 1999; Moral et al. 2004; Silva and Veiga 2008). Owing to their small size, the majority of these compounds is not visible by optical microscopy and hardly detected even by electron microscopy, except when they occupy empty pore spaces or when they occur at binder/aggregate interfaces.

Since ancient times, the addition of natural pozzolans (volcanic rocks) or artificial pozzolans (ceramics) during mortar production have been known to confer to the final mortar not only the above mentioned hydraulic properties, but also high mechanical strength and greater resistance to degradation caused by marine environmental agents (Baronio et al. 1997; Moropoulou et al. 2000; Reis and Silva 1995; Silva and Reis 1999). The intentional addition of hydraulic compounds to lime mortars used in the construction of Lisbon military fortifications demonstrates, therefore, the effort made by the Portuguese builders to adapt the technology of mortar production to the local harsh coastal environmental conditions. In fact, salt phases such as ettringite, halite and gypsum have been detected in Bugio Fort although in amounts not sufficient to lead to appreciable salt weathering effects on the mortars as it has been found in historical mortars (and bricks) from other marine locations such as the Venice lagoon (Sabbioni et al. 2002; Schiavon et al. 2008).

As far as the sedimentary sources for the sand used as aggregate raw material in the mortars under investigation are concerned, the mineralogical composition together with the high roundness values of the inert grains suggest the use of local Tagus fluvial deposits. The widespread use of local sandy fluvial deposits as building materials for the production of historical mortars is indeed well documented both in Portugal and elsewhere (Candeias et al. 2005; Schiavon and Mazzocchin 2009; Silva et al. 2010).

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