Lime-crusted rammed earth: materials study

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Abstract. This study analyses the durability of rammed-earth wall construction techniques. The analysis focuses on three medieval masonry types from the Castle of Villavieja (Castellón, Spain) using two variations of lime-reinforced rammed earth in its walls: lime-crusted rammed earth and brick-reinforced rammed earth. Materials analysis reveals the good properties of the materials used in the outer wall facing despite its age. It also clearly shows how deterioration depends more on the construction technique (construction of the wall with a base, cornice, facings, core; on-site installation, bonds, etc.) than on the material itself. These two types of lime-reinforced rammed earth (lime-crusted rammed earth and brick-reinforced rammed earth) are the most common kinds of fortified architecture in the Iberian Peninsula as well as in northern Africa and the Middle East. The case presented herein is therefore highly relevant as it advances our knowledge of the behaviour of the materials comprising these walls and lays the foundations for suitable future conservation works of a vast array of architectural heritage.

Introduction

This research centres on the construction techniques and materials of parts of the Castle of Villavieja (Castellón, Spain), which includes some of the construction techniques most commonly used in rammed-earth fortresses in the Iberian Peninsula [1]: lime-crusted rammed earth and brick-reinforced rammed earth. The methodology includes a historical and archaeological study of the castle. It then proceeds with an analysis of the diverse construction techniques used in it. For material characterization, samples have been taken and studied by XRF chemical analysis, carbonate content determination, XRD mineralogical analysis, determination of physical properties (real density, apparent density, and water-accessible porosity), and mechanical strength. These results provide a greater knowledge of the composition, structure, and strength properties of this type of walls. This in-depth knowledge of the materials, construction techniques, and possible pathologies can then be used as the basis for the correct definition of the criteria and techniques to be used in restoring historical walls [2]. This work is part of a broader research project “The Restoration of Rammed-Earth Architecture in the Iberian Peninsula. Criteria, Techniques, Results, and Perspectives” financed by the Spanish Ministry of Science and Innovation (ref. BIA 2010-18921) [3].

The Castle of Villavieja at Nules (Castellón, Spain) as a case study

The Castle of Villavieja is currently an imposing ruin on a hilltop with a commanding view inland and of the plain as far as the sea (fig. 1). The castle still preserves part of its walled enclosure, extending some 250 m long and 130 m wide at its maximum, following the hill's topography. Throughout the walled enclosure there is a series of towers of different types, shapes, and construction techniques that reflect the variety of constructive periods in which the complex was built.

Fig. 1. Top view of the castle and general view of the northern wall of the upper enclosure.

Due to the scarcity of archaeological work on the complex, the castle has become a centre of interest for researchers. The first explorations on the hill found surface material attesting to the successive occupation of this site by inhabitants of the Chalcolithic and Bell Beaker Period, the Bronze Age, the Iberian Period, the Roman Period, and the Medieval Christian Period [4]. The structures currently visible are mainly Medieval and comprise the following: a palace zone on the top of the hill delimited by two wall sections and the remains of a third; an upper enclosure following the contours of the hill's upper platform and encompassing the palace with four wall sections and nine towers all still plainly visible; a lower enclosure following the stretched-out contours of the hill's lower part created by the remains of walls and towers [5]. The upper enclosure has more remains and therefore a great variety of construction techniques due to various expansion and repair activities over the centuries.

Construction techniques at the castle

The castle walls mainly consist of masonry and rammed earth. But each of these techniques appears in a wide range of variations as to materials used and the type of execution (fig. 2). The types of masonry include: formwork masonry in a herringbone pattern with river rocks at the base of the north wall section in the upper enclosure (fig. 2a); masonry with courses of rough-hewn stone at the base of the central tower in the eastern wall of the upper enclosure (fig. 2b); formwork masonry in the palace zone walls (fig. 2c); masonry with rubble and river rocks in ten of the visible towers, six in the upper enclosure and four in the lower enclosure (fig. 2d). In addition, the rammed-earth technique has several variants in the castle: the lime-crusted rammed earth wall with more (fig. 2e) or less (fig. 2f) erosion of the outer lime layer in the eastern and southern wall sections of the upper enclosure and four towers therein; brick-reinforced rammed earth at the western end of the northern wall in the upper enclosure (fig. 2g) and in the eastern wall of the same enclosure (fig. 2h).

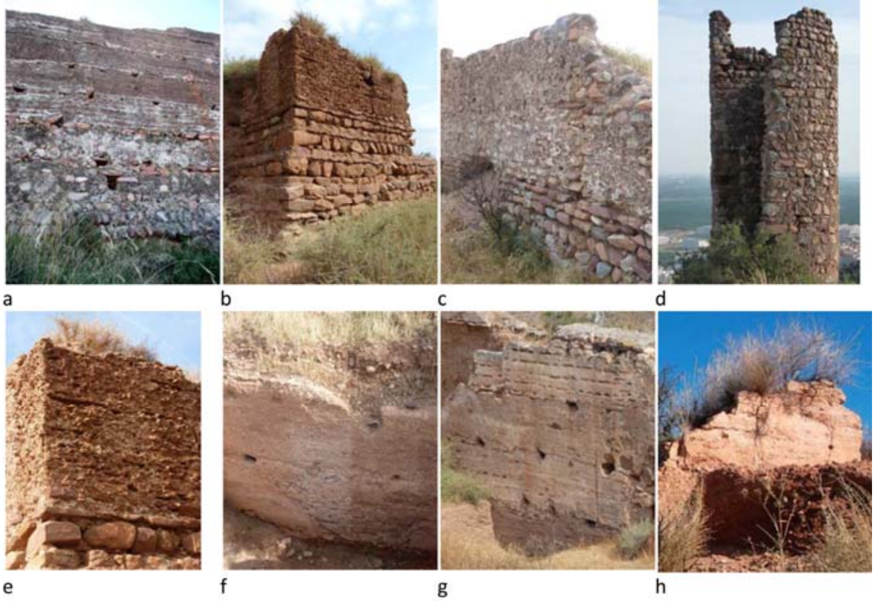

Fig. 2. Construction techniques at the Castle of Villavieja: masonry base and rammed-earth wall (a and b), masonry wall (c and d), lime-crusted rammed-earth wall (e and f), and brick-reinforced rammed-earth wall (g and h). Photographs: C. Mileto

Lime-crusted rammed earth

This article characterizes the materials used in two variants of the rammed-earth construction technique to reinforce the outer face: a lime crust and a brick-reinforced wall. A rammed-earth wall is built primarily using formworks and tamped or rammed earth. The difference in these two variants lies simply in the type of outer facing used to protect the earthen core [1]. In the lime-crusted rammed earth wall (from the Islamic period and radiocarbon dated by the authors as being from the start of the 12th century to the first third of the 13th century), the wall was built by the dumping in and tamping down of successive batches of lime mortar wedged against the formwork structure and earth in the middle. Once formwork removed, the outer lime surface was smoothened to create a soft protective layer. In the brick-reinforced rammed earth type (from the Christian period), these lime wedges also included bricks, which resulted in a protective facing of lime and brick (of the desired bond pattern).

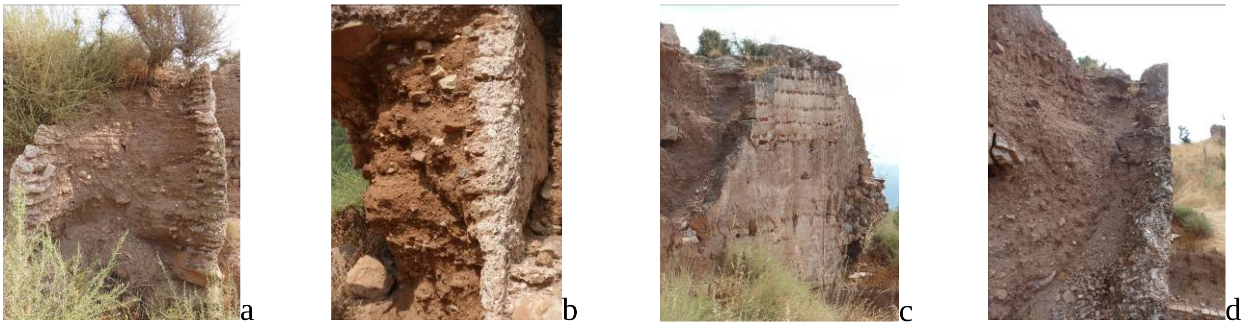

Fig. 3. Section of lime-crusted rammed earth (a), detail of outer lime crust (b), overview of brick-reinforced rammed earth (c), and close-up of same (d).

Characterization of rammed-earth wall

We have studied four samples from the outer facings of the defence and tower walls: CV1 is the brick-reinforced rammed-earth type, and CV2, CV3, and CV4 are lime-crusted types (fig. 4).

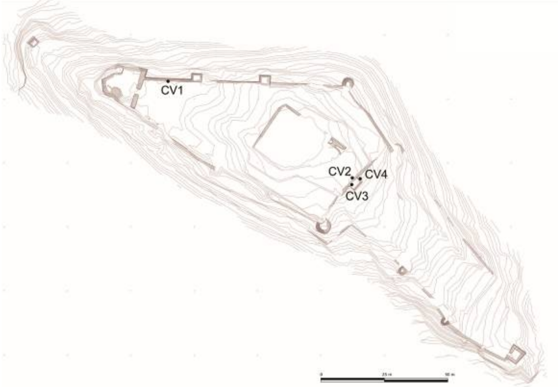

Fig. 4. Location of samples taken from defence walls and tower wall.

The major elements analysis (Table 1) was performed with a Panalytical X-ray fluorescence spectrometer (model AXIOS). The chemical analysis results are within expected ranges, with high SiO_2 contents attributable to the aggregate quartz and silicates (micas, clays, feldspars), and high CaO and LOI contents attributable to the $CaCO_3$ from the lime or the limestone fraction of the sand. Carbonate determination with the Bernard calcimeter [6] is valid for approximating the original lime content since over time the lime carbonates and becomes calcium carbonate ($CaCO_3$). However, both the earth and the aggregates used in its manufacture may naturally contain carbonate fractions. Therefore, the entire carbonate content is not always attributable to the addition of lime. Table 2 gives the sample results and the composition of the reference lime mortars [7]. As can be seen, the mortars for the lime crust were manufactured at a ratio of lime to sand by weight of 1:2 to 1:3 for CV1, CV2, and CV3 and of about 1:1 for CV4.

Table 1. Chemical composition [%] of major elements in the lime crusts.

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	SO_3	Cl	LOI	TOTAL
CV1	44.54	6.80	2.29	5.76	18.25	0.10	2.02	0.29	0.08	0.05	0.02	19.62	99.80
CV2	48.27	7.51	2.68	1.80	19.54	0.09	2.24	0.33	0.12	0.04	0.01	18.76	101.41
CV3	45.73	7.81	2.68	1.28	21.25	0.09	2.22	0.34	0.08	0.04	0.01	18.94	100.48
CV4	34.98	4.77	1.88	1.05	29.90	0.16	1.47	0.19	0.05	0.08	0.17	26.04	100.57

Table 2. Carbonate contents of samples.

Sample	Carbonates [expressed as % $CaCO_3$]	Reference lime mortars [7] Proportions by weight of lime:sand versus % $CaCO_3$	
CV1	36.2	1:1	57.4%
CV2	33.0	1:2	40.3%
CV3	37.2	1:3	31.0%
CV4	54.9		

X-ray powder diffraction (XRD) has been proposed for determining overall mineralogy using a Bruker-AXS model D8 Advance diffractometer. Clay minerals were studied in orientated aggregates using standard methods involving drying at room temperature, solvation with ethylene glycol, and heating at 350 and 550ºC for 2 h [8]. Phase abundances were semi-quantitatively estimated according to mineral intensity factors [9] (Table 3).

Table 3. Semi-quantitative mineral composition of lime crusts.

Samples	Quartz	Calcite	Phyllosilicates	Haematites	K-feldspars	Dolomite
CV1	45	36	16 (muscovite)	2	1	--
CV2	43	33	17 (muscovite+illite+chlorite)	3	1	3
CV3	37	39	19 (muscovite+illite+chlorite)	3	1	1
CV4	24	62	11 (muscovite+illite+chlorite)	2	1	--

The quartz, phyllosilicates (muscovite and clay minerals), K-feldspars, dolomite, and haematites originate in the mortar aggregate for the outer facing of the wall. Calcite can derive from either the aggregate or the added lime, which becomes $CaCO_3$ once it has carbonated. However, in this case, the texture (lime nodules) and distribution indicate a majority origin from added lime. The physical and mechanical properties determined (Table 4) were real and apparent density and water-accessible porosity [10]. Compressive strength [11] was calculated with a TCCSL model PCI-30 Tn strength-testing machine on prepared cubic specimens (smoothness = 1) and edges ranging from 5–10 cm depending on the thickness of the sample taken. Sulphur was later used to cap those pieces.

Table 4. Physical and mechanical properties of the lime crusts.

Sample	Real density (g/cm^3)	Apparent density (g/cm^3)	Open porosity [%]	Compressive strength [Mpa]
CV1	2.65	1.88	29.2	5.96
CV2	2.67	1.83	31.8	-- (highly altered sample)
CV3	2.70	1.93	28.7	5.32
CV4	2.68	1.83	31.6	6.83

The real density values are as expected given the real density of the major elements comprising the samples: quartz at 2.62 g/cm^3 and calcite at 2.71 g/cm^3. All samples had a porosity of approximately 30%, thereby classifying the mortars as having medium–low porosity keeping in mind that these materials tend to have porosities of 30% to 50%. Low porosity can be due to a scant fine fraction in the aggregate as this fraction can absorb large amounts of batching water that leaves behind pores as it evaporates. It may also be due to low amounts of water during mortar batching, followed by good