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Characterization of the rammed-earth structure of the Moon Castle in Mairena del Alcor (Seville, Spain)

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ABSTRACT: In February 2008, in the laboratories of Vorsevi S.A., a series of analyses and tests were conducted on the rammed-earth walls, towers, and sections of barbican walls of the Moon Castle in Mairena del Alcor (Seville, Spain) in order to characterize the constituent material and to collect data that would enable the valuation and quantification of the future actions to consolidate the walls. Data related to the particle size and the physical, mechanical and chemical characteristics were provided, and information was obtained pertaining to the composition, conservation, and behavior of the wall when faced with consolidation and waterproofing treatments. These treatments form the basis of the consolidation and reinforcement techniques which, in these pages, are referred to as the most appropriate for these walls.

1 INTRODUCCIÓN

The Moon Castle in Mairena del Alcor, Seville (Spain), whose first stages were built in the mid-fourteenth century and later completed and refurbished in the second half of the fifteenth, is not only one of the most important castles of the province, but also constitutes one of its civil buildings of greatest magnitude constructed in rammed earth (Fig. 1).

In both stages, walls were constructed with rammed earth (Fig. 2) of diverse typology, which nowadays can be observed as having been greatly altered by successive consolidation work throughout its history, but especially by those interventions carried out in the early twentieth century by the English archaeologist George Bonsor (1822–1930) who bought the castle and set up his residence there.

The building is located on a steep slope in the eastern quarter of the town, organized around a rectangular courtyard (Fig. 3), which is delimited by four towers linked together by stretches of wall, oriented to the cardinal points.

Figure 1. View of the castle.

Figure 2. Bell tower.

Access is via two entrances: one from an urban street in the north sector, and the other to the south. Bonsor's house-museum is located in the eastern zone.

This Castle is situated in a very special geological region, defined by its alcoriza stone, that gives its name to the town (Mairena del Alcor) and by the "albero" sandstone traditionally used in mortar;

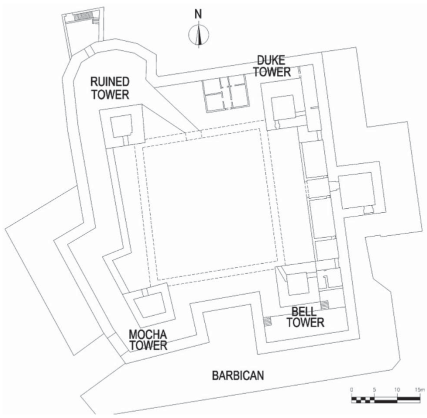

Figure 3. Plan of the castle.

this circumstance, together with the historical continuity of the construction, where it is assumed that there must have previously been an Islamic building, make this castle an extraordinary example to address the evolution of the Christian rammed-earth wall in the different phases of this period and also with respect to preceding Almohads.

Consequently, within the frame of the Project I+D+I BIA2004–1092 (Graciani 2005) we perform a study into the constructive solutions and types of these rammed-earth walls, as published by Graciani, A. Barrios, J. Barrios, and L.A. Núñez (2008).

In this context, in 2008, a series of analyses were carried out in order to first characterize the constituent material for a comparison with the conclusions obtained in the aforementioned study, and secondly to collect enough data to quantify future consolidation work on the walls.

2 DESCRIPTION OF THE RAMMED-EARTH WALLS

As explained earlier, in the Moon Castle, two different types of rammed earth are observed, corresponding to the simple and chained types, as established by Graciani and Tabales (2008).

Two of the four towers, which flank the southern front, that is, the SE tower (the Bell or Chapel tower) and the SW tower (Mocha Tower), were constructed in simple rammed earth, that is to say, the courses of the rammed-earth boxes were placed directly upon each other, thereby generating monolithic structures which lack both intermediate elements and vertical links.

The towers that delimit the northern front are of a mixed type of rammed-earth wall; in its chained variant, since it presents stone reinforcement at its edges. The chained rammed-earth walls were an Almohad contribution to the History of Construction, and constitute one of the many advances they brought to the *tapia* technique; while in the Almohad period, very few examples of stone chained *tapia* can be found (exemplified in the Torre del Oro, 1221) in relation to the proliferation of latericio chains. However, in the Mudejar era, there were some contemporary examples at the Moon Castle, such as the Mocha Tower in Albaida del Aljarafe (in the middle of the thirteenth century) and some other towers of castles in the Banda Morisca, such as those of Alcala de Guadaira and Los Molares.

In the composition of the walls, abundant use of "albero" is observed; the typical ochre sedimentary rock of this zone, rich in calcite, poor in quartz and with a variable content of iron oxides in the form of goethite (Fig. 4). This material has been widely used in construction in Seville, since it gives mortars the good qualities of high mechanical strength and a low reduction in volume.

Many reconstructions in the walls related to different stages can be observed, and these have very varied construction type, ranging from reconstructions with stone and brickwork to modern *tapia* wall, but generally lacking protection from water, such as that provided by coatings or by consolidation and reinforcement of the lower part or top section of a wall.

In some areas, there are examples of paving and gardening elements, carried out in recent years.

In the less sun exposed walls, facing to prevailing winds, and next to streets, we can find zones with moisture concentration and partial loss of volume.

The state of walls is good, although it would be recommendable to undertake some works for protection and consolidation, in order to reduce cleaning and repair works, which continuously carries out the maintenance staff and to ensure the durability of the walls.

Figure 4. South barbican.

3 CHARACTERIZATION TESTS

In February 2008, under the I+D+I BIA 2004-C1092 project entitled "Proposals for maintenance, assessment and restoration for the rehabilitation of buildings and urban infrastructure with historic *tapia* wall in Seville's province", we carried out a study in the castle to analyze the types of walls and characterize the *tapia* in order to evaluate and quantify the future consolidation works.

Samples were taken from the walls, towers and from the Barbican (Fig. 5), and conducted the tests listed below.

3.1 *Granulometry*

Classification by grain size, to determine proportions of gravel, ceramic pieces, sand and clay. In this type of test, sample is prepared with previous manual shredded and dispersion in water, and sieved, separating grain size fractions bigger than 4 mm, between 4 and 0.06 mm, and of smaller size, related to, silts and clays.

3.2 *Physical properties*

Density and porosity, were tested, which are properties that evaluate compactness of the material and give us an idea of the permeability of the wall to water, and to waterproofing and consolidation treatments.

Results from testing compressive strength, gives us an idea of the components used, the dosage of binder and water addition, etc.

3.3 *Chemical properties*

We determined the content of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), lime (CaO),

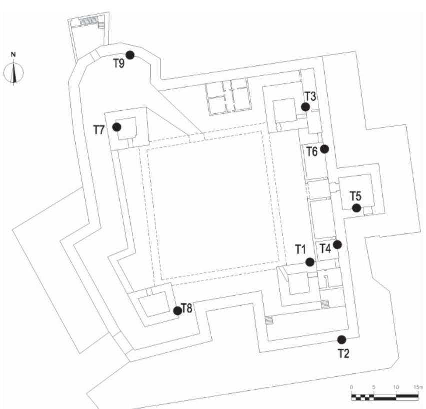

Figure 5. Location of samples.

Table 1. Samples location.

nº		
1	Bell tower. North wall	Outside
2	Barbican southeast	Outside
3	Duque tower east	Outside
4	Barbican east	Inside
5	Office	Inside
6	Dining room	Inside
7	Torre Southeast	Inside
8	Mocha Tower	Outside
9	Barbican Northeast	Outside
10	Barbican south.	Outside

Figure 6. Samples.

Figure 7. Sample 7.

magnesia (MgO), loss on calcinations (%), and sulfate (SO_3), and also aggressive compounds such as nitrates (NO_3) and chloride (Cl), to consider in consolidation works of the walls, to improve the effectiveness.

In order to obtain its composition, ten samples (Figure 6) were taken in the four towers and the barbican, in the more representative walls, numbered and located as following:

The samples extracted were mostly of *tapia* with different aggregate: sand and gravel, pieces of ceramic material, clay, silt and lime, and abundant "albero", easily found on site.

Most of the samples extracted show a high density and homogeneity in composition, not detecting disrupted areas.

In the case of samples number 7 (ruined tower, Fig. 7) and 10 (south barbican) sandstone samples were extracted.

4 LABORATORY TESTS RESULTS

Granulometry tests were done in order to detect fractions of sand, gravel and clay contained in the *tapia* samples, obtaining a maximum aggregate size exceeding 40 mm in sample 2, and lower in the rest, and detecting a 80–90% of sand, containing a higher quantity of silts and clays than 10% in all samples except for No. 1 (Fig. 8).

The physical properties tested, show high values of compressive strength in samples number 1, 4, 7 and 9 and medium porosity.

Chemical properties tested show that the fraction obtained of limestone is high, corresponding to the lime used for making the mortar, and the fraction of "albero" used as aggregate.

The fraction of sulfate ranges between 0.25 and 0.41%, equivalent to 0.38% and 0.50% of gypsum, concluding that the lime used as binder was contaminated with a small fraction of this material.

No presence of organic compounds, or aggressive substances (the fraction of nitrates and chlorides is very small), and no fractions of magnesia (dolomite) are detected:

We cannot define the dosage of lime and aggregates—clay used in the *tapia* wall, because of the "albero", which is a calcium carbonate in a 70–85%, with silica and iron oxide in an 15–30%, that distorts the result.

Table 2. Granulometry tests (% passing through sieves).

Size (mm)	Samples						
	1	2	3	4	6	8	9
50	100	100	100	100	100	100	100
40	100	80	100	100	100	100	100
25	100	75	100	88	86	79	100
20	93	72	92	87	83	75	95
10	68	69	85	80	75	69	82
5	49	66	77	69	70	63	69
2	34	60	67	52	62	56	58
0,4	20	36	40	30	32	37	35
0.08	9	16	12	17	14	18	13

Table 3. Physical properties.

Sample	Density (gr/cc)	Compressive strength (N/mm^2)	Porosity (%)
M1	1.60	4.70	34.80
M2	1.47	1.50	36.40
M3	1.51	1.30	35.10
M4	1.69	4.40	28.60
M5	–	–	–
M6	1.55	3.20	33.80
M7	1.79	6.00	8.60
M8	1.58	1.80	34.90
M9	1.70	5.20	27.40
M10	1.34	1.10	38.60
M10	1.55	5.30	10.80

Table 4. Chemical compound.

Compound	Content (%)					
	1	2	3	6	8	9
SiO_2	33.50	35.00	31.70	66.10	30.30	29.40
Al_2O_3	1.30	0.80	7.00	0.30	0.50	0.70
Fe_2O_3	2.30	1.50	1.30	0.60	1.20	1.30
CaO	34.70	33.60	35.60	13.90	33.20	37.10
MgO	0.00	0.00	0.00	0.00	0.00	0.00
Calcinations (%)	27.30	28.30	30.30	18.90	34.00	31.00
SO_3	0.25	0.30	0.41	0.31	0.32	0.35
NO_3	0.024	0.040	0.040	0.018	0.016	0.034
Cl	0.021	0.014	0.014	0.021	0.014	0.014

Figure 8. Sample 1.

5 CONCLUSIONS

The *tapia* walls of the Moon castle in Mairena del Alcor, Seville, are made with 15% clay, lime, and a variety of aggregate: sand, pieces of ceramic, and "albero", the ochre sedimentary rock rich in calcite, which was traditionally used in mortar and paving, mixed with lime, in order to improve the mechanical strength and compactness, limiting volume changes and cracking through shrinkage.

From the tests carried out, we can conclude that the *tapia* walls show medium-to-high resistance to compression, and yield similar values to the walls of brick or stone with lime mortar, and an average level of porosity, which, make it suitable to receive treatment and water repellent liquids.

The state of the walls is generally good, and only a few areas are detected as having partial loss of material, damp, and rooting of plant species.

We recommend protection of the walls from the action of water, both due to capillarity, or infiltration and splashing, through the provision of rigid discontinuous or continuous lime coatings, in upper and lower zones, and also in those walls exposed to prevailing winds, or by means of applying waterproofing and consolidant products, after cleaning and restoring.

The heterogeneity of the types of walls and the dispersion of the areas to repair lead us to suggest a reinforced coating of lime mortar and "albero".

ACKNOWLEDGEMENTS

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