Chapter 2
Technology of Rammed-Earth Constructions ("Tapial") in Andalusia (Spain): Their Restoration and Conservation

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2.1 Introduction

We should begin our study of this type of construction by analysing the various definitions of *tapial*. Some authors have used the term *tapial* to describe almost all large-scale primitive constructions with earth, whilst others associate the expression with the use of earth as a building material, and consider it similar to adobe (Sánchez Hernández et al. 2000).

Originally, however, *tapial* was the mould or formwork used in the building of *tapias* or walls, so it would seem wrong to use the term to define a building material (Algorri García and Vázquez Espi 1991).

2.1.1 Previous Research into Rammed-Earth Constructions

In Spain research into ancient and historical buildings made out of earth is still in an initial phase. There has been a long tradition of research into historical, artistic, and documentary aspects of this type of construction (Torres Balbás 1981); but until recently there has been no scientific or technical research with regard to the conservation and restoration of the cultural heritage constructed with this material (de la Torre López et al. 1991; Ontiveros Ortega 1995; Parra Saldivar and Batty 2006; Hall 2007).

In Spain and in Andalusia in particular there is still a wealth of important historical buildings that were constructed out of earth (Cañas Guerrero et al. 2005;

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Jiménez Delgado and Cañas Guerrero 2006). Large sums must be spent on the conservation and maintenance of these buildings and prior scientific characterization studies are also required.

2.1.2 Historical and Artistic Importance

The Alhambra of Granada (Andalusia, Spain) is perhaps the best-known and most striking example of rammed-earth construction (Fig. 2.1), but it is obviously not the only one. There are magnificent rammed-earth constructions in different parts of America, Africa, and Asia (The Great Wall of China is an excellent example). There are also more recent, smaller-scale buildings in different parts of Spain (in Aragon and Castile for example), with perhaps the best examples being found in Andalusia (and especially in Granada which has an important architectural tradition in rammed-earth construction) where a large number of historical buildings made out of earth survive today. From the 11th century onwards earth was used very frequently in the construction of forts, city walls, and towers. This technique was also used in churches built after the conquest of the city by the Christians in 1492. The Church of San Juan de los Reyes in the Albaicín quarter of Granada, thought to be the first Christian church built in the city, is an excellent example. This year the European Community awarded a prize for the restoration work done on this building.

2.1.3 Practical Use in Building

As indicated above, the term rammed-earth refers to a building technique in which the precise materials used may vary (Bazzana and Guichard 1987). These walls were built by placing a fluid mass (in layers known as "tongadas" about 10–15 cm thick) into a formwork structure made up of two parallel boards joined together by wooden pins known as *mechinales*. The mass was then trodden down. The dimensions of the boards, or "tapiales" (about 3 m wide and 0.90 m high and varying thickness) ensured that these frames were light, manoeuvrable and easy to use (Cuchí i Burgos 1996).

The composition of the materials placed in the formwork varied greatly and is normally classified into three groups "*earth tapial*", "*stone tapial*", "*lime tapial*". In most cases it was a mixture of lutitic materials and sand, with a varying amount of thick aggregate. The mass contained clay which acted as a binder, but in other cases the mass was held together with lime, especially in Spanish Muslim buildings (Valverde Espinosa et al. 1997; Sebastián Pardo et al. 2000).

The outer surfaces of the walls are not very resistant and erode easily if not protected with some sort of surface coating. This coating has other functions such as hiding any imperfections, protecting the structure from bangs or scratches, improv-

Fig. 2.1 General view of rammed-earth construction in the Alhambra (Spain)

ing the heat insulation, and enhancing the appearance of the building by providing a uniform colour (de la Torre López 1995).

A number of different techniques were used in the rammed-earth buildings built by the Arabs. In some extreme cases, the fine fraction (clay and silt) was discarded and a mixture of lime with sand and thick aggregate was used, creating a form of lime concrete, which when pressed down, became extremely hard and resistant. This was normally used for the foundations of large defensive buildings (Alcazaba Cadima of Granada, from the 11th century or the Alcazaba of the Alhambra). The other types used were:

A) The *Tapia Real* which itself appears in two forms: (1) the first is based on a series of layers or "*tongadas*" about 2–5 cm thick of 100% lime (fat lime) and other layers of earth to which lime has not been added (Puerta de las Pesas in the Albaicín, Granada); (2) the other method involves layers of earth about 60–80 cm thick, and layers of pure lime about 8–12 cm thick at the ceiling and at the base (example the Arch of the Puerta Elvira in Granada). These constructions date from the 12th and part of the 13th century. The facing on the walls was applied once the formwork frame had been taken down.

B) *Tapial Calicostrado.* This technique appeared as a solution to the damage caused by erosion when the rammed earth was exposed to the elements. Using this method, a crust or finish was formed on the surface of the wall at the same time as the building was being constructed. This was a significant advance on the road to perfecting the rammed-earth technique, as it provided both protection against erosion and an aesthetically attractive finish. The building process followed was similar to that used in other rammed-earth structures, except that a strip of mortar with a higher proportion of lime was applied to the outside and the earth was then trodden down so that the lime mortar became indented in the wall, forming one single structure with the rest of the building (Ontiveros Ortega et al. 1999; Sebastián Pardo 2001).

This form of *tapial* first appeared at the end of the 13th century and reached its peak in the 14th century (e.g., the Arrabal in the Albayzin and other buildings from the Nasrid period in Granada).

Different construction techniques were used at different times in history and as time went by less and less lime was used, something which was perhaps related to the economic decline of the Kingdom of Granada as the Christians conquered more and more of its territories. Less lime meant poorer quality construction as explained below.

2.2 Research into Rammed-Earth Constructions and the Conservation Thereof

Rammed-earth constructions show serious durability problems, caused basically by the nature of their constituent materials (normally considered "poor" building materials), and by the types (mainly clays or lime) and the small amounts of binder used.

Damage to these constructions is normally caused by a variety of different factors and mechanisms, including rainwater, soluble salts from the material itself and/or contained in the water that enters the structure through capillary ascent, oscillations in temperature and, in desert regions, by the particles carried by the wind (Sebastián Pardo and Rodríguez Navarro 1996; Hall and Djerbib 2004, 2006a, b). The restoration of rammed-earth walls is almost always viewed as a question of replacing the damaged parts and there are few reports as to the use of consolidation or water-repellent products (Sowden 1990; Warren 1999; Jayasinghe and Kamaladasa 2007; Pineda Piñon et al. 2007). Chips and erosion dips are normally repaired by creating a support for the cement preferably with mesh (chicken-wire), or moistened pieces of ceramic that are pushed into the wall and act as pivots that stick out from the surface and help the mix used to repair the damage to adhere properly to the wall (ICCET 1987; Naval Mas 1990).

On the basis of these ideas, the objective proposed for this work was to discover a new way of conserving rammed-earth buildings of historical interest by treating them with chemical products, i.e., by impregnating them with consolidants and water-repellents. With this in mind we decided to characterize the constituents of the materials used in two historical buildings, the *Palacio de los Abencerrajes* (Palace of the Abencerrajes) and *Silla del Moro* (Seat of the Moor) otherwise known as Castillo de Santa Elena, situated inside the Alhambra complex.

According to studies by various different authors (Malpica 1992; Salmerón 1999), the *Palacio de los Abencerrajes* probably dates from the 13th century, the first Nasrid period, and is essentially a group of rooms situated at different levels.

There are few references in the specialist literature as to the characteristics and functions of the tower known as *La Silla del Moro*; but it seems likely that it was used as a look-out point, given its excellent position overlooking the valley of the River Darro. The walls of the tower are made from *tapial calicostrado* and the foundations are laid on the rock formation known as the Alhambra Formation that outcrops in the area. This formation is composed of conglomerates with intercalated sands and clays and dates back to the period between Pliocene and Lower Pleistocene. The tower has undergone several restoration attempts that are easy to identify: the first series by the architect Torres Balbas over the first third of the 20th century with masonry; and the subsequent work done by Prieto Moreno, several years later with stones linked together with vertical pilasters and horizontal lines of brick.

2.3 Materials and Scientific Methodology

Samples were taken from the original rammed-earth wall from the Nasrid period in the area of the *Palacio de los Abencerrajes.* It is important to highlight the fact that sampling in archaeological sites such as this one is a problem, as few original pieces remain and those that do are of enormous historical and artistic importance. This means that we were only able to take a few cubic centimetres of samples.

Sampling at the *Silla del Moro* did not pose such a problem as the tower was blown up by the French in September 1812 and large chunks of the original wall are to be found nearby, which enabled us to take more, larger samples.

We also analysed different samples from the outcrops of the Alhambra Formation. These samples were taken from the Cerro del Sol, near the Alhambra.

The techniques and procedures used in this study were those normally used in the granulometric, petrographic (compositional and textural), physical and mechanical characterization of building rock. We also performed accelerated aging tests that enabled us to evaluate the effectiveness of the treatment products we applied. The techniques and procedures normally used in geology, and in particular in mineralogy and petrology, have also been shown to be useful tools for the characterization and study of rammed-earth constructions.

2.4 Results

2.4.1 Granulometric Analysis

We were only able to analyse samples of the *tapial* from the *Silla del Moro* and samples from different levels of the Alhambra Formation. When we analysed the values obtained from the different types of sample, we found that none of them came near the granulometric standards that should be followed in the preparation of concretes used nowadays. In Nasrid times, it would seem that there was no selection process for the materials used in rammed-earth constructions, and they used materials from the different levels of the Alhambra Formation almost as they found them, only discarding the thickest fraction and possibly a small proportion of the finest materials.

2.4.2 Compositional and Textural Study

For the compositional and textural characterization of the materials, we used X-ray Diffraction (XRD), optical microscope and scanning electron microscope (SEM).

The most significant results are those obtained for carbonates (Table 2.1). The values for calcite allow us to state that lime was used in the construction of the original walls, as the proportions of lime encountered are systematically higher than those obtained from the samples from the outcrops of the Alhambra Formation collected nearby. For various reasons it is difficult to establish the exact proportions of lime added. Firstly, because it is impossible to distinguish what proportion of the calcite was originally an aggregate and what was originally lime (after the mix sets and goes hard, the lime is converted into crystals of calcite). The amounts added seem to vary depending on the particular part of the wall analysed, with less lime

Table 2.1 Results of XRD analysis of samples collected in the *Palacio de los Abencerrajes* (ABEN) and *Silla del Moro* (SMO)

	Qtz	Cal	Dol	Phy	Fds	Gyp	Port
ABEN2	30	55	tr	10	tr		
ABEN3	35	40	tr	15	10		
ABEN4	45	35	tr	15	5		
ABEN5	10	90					
ABEN6	35	45		15	5		
ABEN7	45	40	tr	10	5		
SMO1	40	10	20	25	5	tr	x
SMO2	45	25	5	20	5		x
SMO3	30	30	5	10	5	20	x
SMO4	45	15	35	tr	tr	5	x
SMO5	35	15	10	35	tr	5	x
SMO7	50	25	15	10	tr		x
SMO8	25	20	5	45	5		x
SMO9	50	30		15	5		x
SMO10	50	40		10	tr		
SMO11	55	5	5	30	5		x
SMO12	55	40		tr	5		
SMO13	45	25	10	10	tr	10	
SMO14	30	30	10	25	5		
SMO16	50	30	5	10	5		x
SMO17	45	25	15	tr	5	10	
SMO18	30	15	35	15	5		
SMO19	65	25	tr	5	5		
SMO24	45	25	15	10	tr	5	
SMO1-1	60	25		5	10		
SMO1-2	60	25	tr	10	5		

Legend: Qtz = quartz; Cal = calcite; Dol = dolomite; Phy = phyllosilicates; Fds = feldspar; Gyp = gypsum; Port = Portland cement; "tr" means traces; "x" means that this phase has been detected

used for the inside of the wall than for the outside; they also vary according to the period in which they were constructed and the function of the building. The samples taken from the *Palacio de los Abencerrajes* contain higher quantities of calcite, which means that larger amounts of lime-binder were added, around 30%. While in the *Silla del Moro*, the walls were cemented with much lower amounts of lime (15–20%).

Another contrast was that there was almost no dolomite in the walls of the *Palacio de los Abencerrajes*, while traces were found in almost all of the samples from the *Silla del Moro* (Table 2.1). It is important to point out that in other parts of the Alhambra complex and in other pre-14th century Muslim buildings in Granada, no dolomite can be found in the aggregate (whereas in modern buildings in the city, it is almost the sole constituent of the aggregate).

Another important result was that we found traces of Portland cement in several samples (Table 2.1). As this product was not used in building until the end of the 18th century, it means that these samples must come from the restoration work carried out by Torres Balbas or Prieto Moreno. It was only identified in the samples from the *Silla del Moro*, and not in those from the *Palacio de los Abencerrajes*.

There are two further interesting aspects of the materials from the *Silla del Moro*: (1) gypsum was identified in several samples; and (2) phyllosilicates were discovered in higher percentages than in the other samples analysed. The gypsum could come from the cement itself, as it was added to the cement in the factory to delay the setting process, or it could be produced as a result of reactions with the other materials, with the gypsum being the product of the migration of ion-rich solutions inside the wall.

The high proportions of phyllosilicates suggest that either Torres Balbas or Prieto Moreno used the Alhambra Formation as an aggregate in the mortars used in the restoration work (as did the Arabs) to ensure among other things that replacement materials had a similar colour to that of the original structure. It would seem however that the process was carried out without selecting the material.

2.4.3 Polarization Optical Microscope Examination

We prepared thin layers from samples that showed sufficient consistence, as this type of material is very fragile and the samples often fall apart during the cutting process.

In terms of composition we were able to distinguish two basic types of aggregate: a carbonated aggregate formed by mainly rounded grains of calcite and/or dolomite; and a siliceous aggregate, made up of normally subangular fragments of different kinds of metamorphic rock: quartzites, schists, amphibolites.

The following points are worth noting with regard to textural aspects of the samples: petrographical observation showed that the binder was formed by fine-grain calcite, although in some areas it appeared in recrystallized form (Fig. 2.2a). There was a large amount of aggregate with subangular or rounded grains of all sizes from very fine to very thick (several centimetres). This was basically made up of quartzite and schists. The adherence between the aggregate and the binder was good (Fig. 2.2b). The matrix, composed of calcite and phyllosilicates, was not very well mixed in some areas. We also observed nodules of clays and other areas that were rich in lime. Porosity was normally very high with pores that were normally round and on occasions showed cracks.

The original plasterwork was a very pure uniform lime stucco that was made up almost exclusively of calcite. The pores were rounded and poorly communicated. Fissures could be observed running parallel to the outer surface; an ochre-coloured layer had formed on the outside.

2.4.4 Scanning Electron Microscope Analysis

The SEM showed how the aggregates were perfectly encased in the matrix formed by the calcite crystals which surrounded them completely. These crystals came

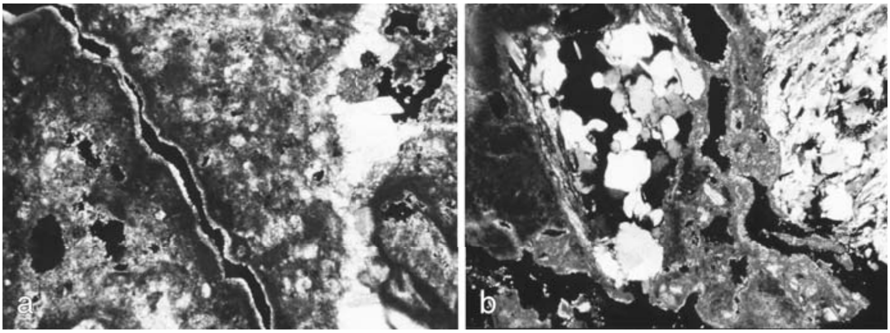

Fig. 2.2 Optical microscopy of some samples where binder and aggregate components can be seen

from the lime that had been transformed into calcium carbonate. In other cases, we observed that the calcite appeared as a mosaic of well-formed crystals, especially when it was located in pores and fissures. In this case the crystals were produced either by the dissolution and subsequent crystallization of the original calcite from the aggregate or by the carbonation of the lime.

In other areas, the lime looked powdery and had large cracks, which could be the cause of the damage that we observed at a macroscopic level. There were other areas that showed considerable damage. These sometimes contained gypsum (and other salts) that normally crystallizes in tabular form.

2.4.5 Physical and Mechanical Parameters

Table 2.2 shows the various physical and mechanical parameters we calculated for the samples of *tapial*. The results shown are the average values for several readings.

We should emphasize that it is very difficult to establish the mechanical parameters of this kind of material, as the rules for the experiments (as there are no official standards for rammed-earth structures, we normally use the standards for cement mortars or concrete) require large volumes and a large number of samples (requirements which we have been unable to meet in this work for the reasons explained

Table 2.2 Physical mechanical parameters of rammed-earth and modern concrete/mortar samples

	ρ	P	∅	σ_C	σ_T
Rammed-earth	2.02	>35%	1–15	2.1	0.2–0.3
Concrete/mortars	2.15	<20%	<1	8.2	1.1

ρ = apparent density (g cm^{-3}); P = porosity (%); ∅ = pore range (μm); σ_C = resistance to compression (MPa); σ_T = resistance to traction (MPa) above). This means that the values set out in the table should be viewed with some degree of caution.

The highest density was in the *Palacio de los Abencerrajes*. The average pore access radius was between 0.7 and 5 μm; the open porosity values varied from 30 to 35% in the areas with low doses of lime (the innermost part of the wall); while in the case of the mortars used in the restoration work on the *Silla del Moro* (20th century), the values were less than 20% and microporosity was the dominant feature.

There are also marked differences between the mechanical resistance of the original samples (2.1 MPa) and the materials used in the restoration work, which is four times higher (8.2 MPa). This is another parameter that can help us to distinguish between the two materials when there are doubts as to whether the *tapial* is original or not. The traction values are very low (0.2–0.3 MPa), but this is only to be expected if we bear in mind that the union between the clasts was made with a binder (lime or clays) with relatively limited binding power.

2.5 Consolidation and Protection Procedures and Treatments

An essential objective of this work is to impregnate samples of *tapial* from historic buildings with chemical products and then evaluate how suitable and how effective they are. The products we applied were Tegovakon V (Tk) and Tegosivin HL100 (Tg), both manufactured by Goldschmidt Industrial Specialities. These treatment products were selected because of their composition. The first is an ethyl silicate (an organosilicic product of the alkoxysilane type) which polymerizes inside the material and is converted into silica. This cements the material together so consolidating the structure. It is therefore a product with considerable chemical affinities with the silicated materials that form the main constituents of these rammed-earth structures. Tegosivin HL100 is a silicone resin with a water-repellent effect. We carried out the treatment by immersing the samples completely in the product, which in the case of Tegosivin HL100 was dissolved in Toluene (Tg concentration of 10%).

The penetration of these products in the samples was calculated by measuring the increase in weight. Although the weight increase was never particularly notable it was slightly higher in the samples from the *Silla del Moro* (these figures must be viewed with a lot of caution, as pieces of material break off very easily in the liquids, leading to a loss of weight that offsets the weight increases caused by the successful penetration of the treatment product).

2.5.1 Techniques and Experiments to Evaluate the Effectiveness of the Treatments

We also noticed that the samples had undergone chromatic change during the treatment (Table 2.3). They went noticeably darker when the consolidant (Tk) was

Table 2.3 Lightness and chromatic coordinates (a* and b*) calculated for samples without treatments and treated with Tegovagon V and Tegosivin HL100, using illuminant C

	Without treatments			With Tegovakon V			With Tegosivin HL100		
	L*	a*	b*	L*	a*	b*	L*	a*	b*
ABEN2	66.96	0.06	3.69	59.78	0.36	5.06	67.20	0.08	4.04
ABEN3	66.27	0.33	8.13	63.29	0.25	8.10	68.71	0.13	6.11
ABEN4	74.67	0.14	4.83	67.24	0.55	8.08	71.74	0.38	5.77
ABEN7	70.43	0.26	4.59	63.15	0.65	7.46	67.43	0.23	4.76
SMO14	65.14	1.77	9.22	57.61	2.44	11.24	62.14	1.92	10.12
SMO19	65.15	3.14	8.56	53.46	5.51	12.09	59.82	3.87	11.25
SMO24	63.71	2.12	7.83	53.06	3.39	10.57	57.23	2.57	9.44
SMO1-1	58.93	3.85	12.18	50.87	4.40	12.77	54.12	3.64	11.58
SMO1-2	73.79	2.72	11.24	64.90	1.18	13.14	66.23	1.19	13.77

applied and the same thing happened albeit to a lesser degree when the water-repellent (Tg) was applied. In all cases however the samples began to recover their original colour after a few days of drying-out.

We calculated the numeric values for the chromatic parameters a* and b* and the lightness figure L* using a Minolta CR-210 colorimeter, which allowed us to describe the colour of the *tapials* in a quantitative way and so evaluate the effect of the treatment products on the samples.

Tk provides similar results to those for the wet samples, in terms of the variation in the primary stimuli a* and b*. Tg causes only very minor changes (Table 2.3).

2.5.2 Scanning Electron Microscope (SEM)

Surprisingly, the SEM showed that the treatment products had penetrated the samples quite well. We identified pores that were covered in consolidant (Tk) at a depth of 2 cm (Fig. 2.3a). We observed that not only had the consolidant coated the pores, but it had also impregnated the whole sample, including the matrix of clays and lime, a sign that it had performed well.

The consolidant also significantly reduced the porosity level (as can be seen in Fig. 2.3b). This big fall in the porosity level could have a negative effect in terms of the success of the treatment, because if the consolidant sealed the surface completely, it would prevent the normal transpiration of the humidity in the wall, which in the medium term could cause serious damage.

The water-repellent produced numerous retraction fissures of different sizes on the surface, forming polygonal-shaped layers of about 100 µm (Fig. 2.3c), some of which adapted to the morphology of the crystal over which they ran. We also observed pores produced by the release of gas bubbles which would enable some evaporation of the humidity from the inside of the wall (Fig. 2.3d). The treatment achieves a noticeable reduction in surface porosity.

The water-repellent normally appears as a very fine film (approximately 0.5 µm) that covers the majority of the clasts and the binder without penetrating very far into the *tapial* sample.

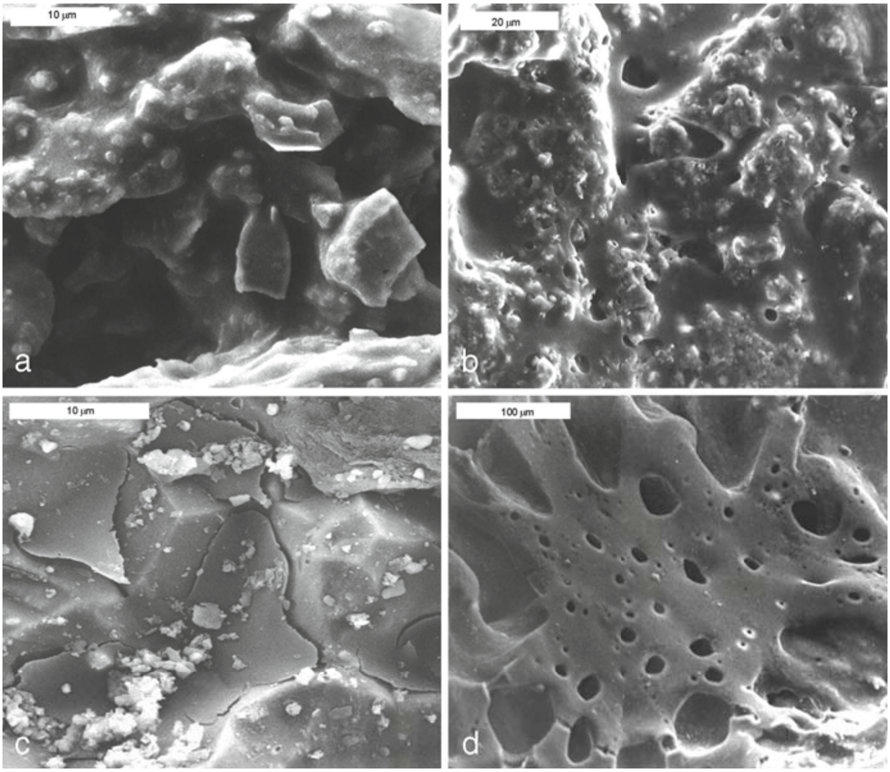

Fig. 2.3 SEM images of rammed-earth samples treated with Tegovakon V (**a** and **b**) and Tegosivin HL 100 (**c** and **d**)

2.5.3 Hydric Tests and Porosimetry

We also carried out hydric tests to evaluate the effectiveness of the treatments. The fact that these samples are very fragile and lack cohesion made it very difficult for us to perform these tests. The majority of the samples fell apart when placed in water for a short period of time, sometimes within just a few minutes. This even happened with the samples treated with consolidant or water-repellent products.

In the absorption test the untreated samples behaved very differently from the samples that had been treated with Tk or Tg. The untreated samples absorbed large amounts of water fast as shown by an increase in their weight. This process occurred over the first 5 min of the test, after which the weight of the sample stabilised and only minimal changes occurred. In some cases weight reductions occurred due to the fact that part of the material broke off when submerged in the water.

The absorption kinetics of the treated samples was very different, with water absorption occurring much more slowly, as manifested in a very slow increase in weight. At the end of the process the water absorption coefficient was less than 5% (in the untreated samples, this figure was around 12%). There was a clear difference between the group of samples treated with Tk and the samples treated with Tg. The latter showed considerably lower water absorption coefficients. It was impossible for us to observe any differences between the samples from the *Palacio de los Abencerrajes* and the *Silla del Moro*, as only one sample from the *Silla del Moro* survived the test.

We deduced that desorption of water was constant, as within a few hours the samples had returned to their original pre-experiment weight, and sometimes even fallen below it. This confirmed once more that the material lacked cohesion, even when treated with consolidant products.

A very important result is that desorption of water did not seem to be blocked by the treatment, as the desorption curves were very similar for the treated and untreated samples. In general, they shed water (dried out) very quickly. Although in the case of the curves for samples treated with one of the products the slope is less inclined, this could imply that the level of porosity has changed, possibly because of a reduction in the diameter of the capillaries that link the large pores. This is even clearer when the product applied is the consolidant.

2.5.4 Density and Porosity

The figures for effective porosity, and the figures for apparent density and surface area were calculated with a mercury intrusion porosimeter (Micromeritics Autopore III 9410).

In all cases the treatments provide a relatively limited reduction (between 10 and 20%) in the effective porosity of the samples, except in the sample from the *Palacio de los Abencerrajes* (porosity fell by 33% with Tg). The values for specific surface and apparent density vary greatly from one sample to another, and no clear tendency can be observed for the treatments. This is one more in a series of facts that confirm the obvious heterogeneity of these rammed-earth structures.

2.5.5 Accelerated Aging Tests in the Laboratory

We performed two different accelerated aging tests using salt crystallization cycles and freeze-thaw cycles. The destructive effects of these two tests are of a physical nature. The results obtained in these tests were mainly based on differences in weight before and after the successive cycles. They were complemented with macroscopic observations of the damage to the samples.

2.5.5.1 Salt Crystallization Tests

The test was carried out according to the UNI EN 12370 Standard (2001).

The samples treated with the consolidant Tk suffered sharp weight loss from the 4th cycle onwards, and one sample fell apart completely during this cycle. This was especially true in the case of the samples from the *Silla del Moro*. The damage began in the area where the clasts and the matrix joined, and they came apart very easily. Another important aspect is that most of the pieces that break off are parts of the matrix. As they fall off, the larger, more resistant clasts are laid bare, so creating the typical uneven appearance of the damaged rammed-earth structure.

Most of the samples from the *Palacio de los Abencerrajes* gained weight (slightly) during the first few cycles. This increase then waned and by the 5th and 6th cycle the samples fell below their initial weight. These samples passed through all the cycles without breaking up and no salts crystallized on their surface.

The samples treated with the water-repellent (Tg) behaved in a somewhat different way. Their weight increased at the beginning of the test, indicating that salts had crystallized inside them, possibly because the porous system had changed in such a way as to prevent the salt solution from coming out of the samples during the drying phase. In some cases there was a significant reduction in weight at the end of the test (around 10% after 10 cycles). The samples from the *Palacio de los Abencerrajes* also showed better results with this product (Tg).

2.5.5.2 Freeze-Thaw Tests

There are different standards laying down the procedure to be followed in this type of test (RILEM, ASTM, UNE,…) In this work we followed the UNI EN 12371 standard (2003).

We observed during this test that almost all the samples performed badly (irrespective of whether they had been treated with the consolidant or the water-repellent), as from the 6th or 7th cycle onwards (some samples even earlier) they began to lose weight; in most cases to a significant degree. Some samples (mostly from the *Silla del Moro*) fell apart completely before the 10th cycle, while others lasted for 20 or 25 cycles before finally breaking up. The only samples that managed to complete the whole test (30 cycles) were the two samples from the *Palacio de los Abencerrajes* treated with Tg, which at the end of the experiment had lost between 6 and 8% of their weight.

In this accelerated aging test, the samples from the *Silla del Moro* were once again shown to be less durable than the other samples. In short, we should stress the fact that the samples from the *Palacio de los Abencerrajes* were in general more durable than those from the *Silla del Moro*. This is because they have a higher proportion of binder (lime) and also to a lesser extent because the grain size of the materials from the *Palacio de los Abencerrajes* was more carefully selected (the *tapials* from this monument do not normally contain overly large stones for example).

2.6 Conclusions

The *Tapiales* constructed in the Nasrid period did not conform to present-day building standards at least in terms of the ideal or correct granulometry of the aggregate. The available information suggests that the sedimentary stone from the Alhambra Formation was used more or less as it came, with only about a third being rejected (the thickest fraction and possibly a small proportion of fine aggregate).

The mineralogical and petrographic study of the samples shows that the *tapial* was made up of a mixture of detritic material (lutites, sand, and stones of varying sizes), and slaked lime. The proportion of lime varies depending on which part of the wall the sample is taken from, and on the importance of the building and the historical period in which it was built. On the basis of the results obtained in this work and in a previous study (de la Torre et al. 1996) the proportion of lime in the *Palacio de los Abencerrajes*, is around 25–30%, while in the *Silla del Moro* it is less than 20%.

In all cases, the lime used is very magnesium-poor (fat lime) which leads us to the conclusion that they carried out a pre-selection of the rock they were going to fire to obtain the lime. We can also conclude that the lime added to these *tapials* was good quality lime. The aggregates used were siliceous (especially pebbles from metamorphic rocks) and/or carbonated, and only rarely were dolomite pebbles used. It would therefore seem that they also made a careful selection of the aggregate they were going to use.

As these are building materials with a very heterogeneous internal structure, rich in clays, with a relatively low proportion of lime and which have lost their original protective coating, it is necessary to treat them with consolidant or water-repellent products that can prevent their progressive decay. This decay is caused by a wide variety of factors, the most important of which is water. Damage is caused both by rainwater and by the water that ascends by capillarity from the ground and which may contain high proportions of soluble salts. The damage is produced mainly by contact between matrixes and clasts, due to the fact that any interface between two different materials is a potential weak zone. If conservation treatment is not applied to these rammed-earth structures (especially those in the *Silla del Moro*) they will probably fall into a ruinous state in a relatively short time.

The heterogeneity of the samples taken from different points of the walls can influence the degree of damage they are likely to suffer in the accelerated aging tests in the laboratory. The samples in which the aggregate has a maximum size of just a few millimetres resist the accelerated aging tests relatively well, while the samples with aggregate containing larger pebbles of a centimetre or more in diameter break up quite quickly.

In spite of their heterogeneity and their lack of cohesion, the samples we studied absorbed all the treatment products quite well. SEM examination showed that the consolidant impregnated the *tapial* to a depth of 2 cm, a perfectly acceptable result.

The consolidation and protection products analysed in this study were both effective. All the treated samples performed much better in the hydric tests than the untreated samples, absorbing about 50% less water. In addition, the water absorbed was soon lost as the samples dried out. They also performed well in the accelerated aging test using salt crystallization. No external changes were observed in this test with just scattered salt crystallization in some of the samples.

We should also mention that the application of these products leads to chromatic changes in the samples, especially when the product contains ethyl silicate. In the samples treated only with the silicone resin, the change in the colour is much slighter and the original colour is recovered more quickly. In all cases however, the samples gradually recover their original colour. Samples treated with the consolidant acquired a sheen, which also disappeared gradually when in contact with water. This suggests that these undesirable aesthetic effects (unacceptable in a historic monument such as the Alhambra) would disappear upon exposure to the natural elements in our atmosphere, without this implying any loss of effectiveness.

We would like to finish by proposing possible future lines of research for this building material. More detailed analysis of the chemical, physical, and mechanical behaviour of earth as a building material is required and of its interaction with the environment, in order to be able to develop conservation techniques that are as non-invasive as possible and to devise more effective maintenance procedures.

Another question that must be analysed and evaluated is the damage that can be caused by the use of materials that are unsuitable for the conservation/restoration of rammed-earth buildings. Research into the most suitable products or materials for the conservation of these buildings must also be carried out.

Finally, we must bear in mind that most repair work on rammed-earth buildings must be classified as restoration work in which it is normally decided to substitute or replace the parts of the building suffering from serious damage. It is therefore necessary to study which quarries can supply the best aggregate for the work, so as to ensure that the aggregate selected has the best possible granulometry, composition, and chromatism and that it is compatible with the other materials used. The nature and the quality of the binder to be used in the work must also be studied beforehand. We recommend that fat lime should be the only binder used.

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