Pergamon

Cement and Concrete Research, Vol. 26, No. 6, pp. 825-839, 1996

0008-8846/96 $15.00 + .00

PII S0008-8846(96)00075-0

A STUDY OF THE WALL MATERIAL IN THE ALHAMBRA (GRANADA, SPAIN)

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(Refereed)
(Received December 12, 1995; in final form April 17, 1996)

ABSTRACT

In this paper, we present a chemical, mineralogical, petrographical and textural study of the wall material in the Muslim Alhambra (XITH to XVTH centuries). Different types of concretes represent this material. The binder has been charaterized as very pure lime, and the aggregate is mostly composed of metamorphics rock fragments whit erosive morphology. The porosimetric nature of the wall material was charaterized by SEM and the Hg intrusion porosimetry. XRD data and Image Analysis studies have shown the differents proportions of binder, fine aggregate and coarse aggregate in the concretes. The construction technique consisted in putting material to form the wall (clay, aggregate, and lime) between two parallel, vertical planks attached to each other by bars of wood. Each layer of material was packed in. One particular type of wall is the "calicostrado", which is made of two materials: one rich in lime, in the outer part of he wall, and a more clayey material in the middle. The schematic cross-section of a "calicostrado" wall and its weathering patterns is presented. The state of preservation of the material in the walls of the study areas is acceptable, despite some zones being macroscopically more eroded.

Introduction

Packed earthen walls comprise the traditional method of construction for most of the outer walls in Spanish-Muslim Grenadine architecture,the Monumental Complex of the Alhambra being a prime example. The Alhambra complex was erected on Sabika hill, which overlooks the city of Granada. Although some parts can be attributed to the XITH Century (Zirí Period), most of the buildings were put up during the XIIITH and XIVTH Centuries (Nazarí Period), and some even in the XVTH Century. After the Christian Conquest (1492), the Alhambra underwent a series of changes and new construction was carried out, the most important of which were the Palace of Charles V (Renaissance) and the Church of Santa María. The Muslim Alhambra consisted of a military area (the Alcazaba), various palaces (the most famous and best-preserved being Comares and Leones), as well as several buildings such as the Rauda, or royal cemetery, the Albercones, associated with the water supply, and others. All this comprised a true city surrounded by a rampart fortified by numerous towers.

Most of the ramparts, towers, and palaces were constructed using the packed-earth technique, which can be traced back to the Roman tradition of limestone cement and packed earth, appropiately combined.

Types and Construction of Packed-Earth Walls

The term packed earth is used to refer to the method of construction, regardless of the materials employed (1). These types of walls have widely varying strengths and appearance, yet what they do have in common is that they are raised by putting a more or less malleable mass packed into a formwork comprising two parallel planks joined together by crossbeams. The mass in most cases comprises a mixture of clay and sand, with varying amounts of coarse aggregates. The clay may act as the sole binder, but frequently the mass is stabilized with lime, particularly in important buildings such as the Alhambra. In extreme cases, the fine fraction (clay and silt) is non-existent and instead one finds a mass of lime putty with sand and coarse aggregate, thus forming a true lime concrete which, when packed and thus loosing part of its natural tendency to crack due to shrinkage, acquires excellent strength and hardness.

Three basic typologies can be distinguished in the Alhambra: a) the gray concretes, which are very hard and almost entirely lacking in clay; b) the so-called "calicostrado" walls, with a higher lime content in the outer part of the material and a more clayey center, resulting in a reddish interior due to the source of the clay used; and c) the reddish walls, rich in clay, with a very low lime content, and a very similar composition in both the inner and outer parts of the wall.

Materials and Methods

A series of clear examples of each type were chosen: ten samples of gray lime concrete, nine examples of the "calicostrado" rammed-earth wall, and nine samples of the clay packed-earth wall that was stabilised with a small amount of lime. All the samples were taken from areas in the Monumental Complex where we have a certain assurance that the material is original and not from restorations.

The grey lime concrete samples were taken from the base of the Alquiza Tower (ALC1, ALC2, ALC3), from the remains of a water storeroom and walls that were uncovered by excavations under the Palace of Charles V (PV1, PV2, PV3, PV4, PV5), and from the perimeter wall of the Abencerrajes Palace, which is in ruins (PAB2). The fallen merlon from the Vela Tower (ALC13) can also be included in this category, even though it is light-rose colored. The examples of "calicostrado" earthen walls were taken from zones where part of the original outer surface is still preserved, though somewhat eroded away, thus allowing easy access to the inner material of the wall. The examples chosen were: the Revellín Water Storeroom (ALC15-ALC16), the Homenaje Tower (ALC41B-ALC41J), the N rampart of the Alcazaba (ALC42B-ALC42J), the Waterwheel Tower of the Albercones (ALB6-ALB7), the Leones Water Storeroom (PLE7-PLE8, PLE17-PLE18), and the basements of the Comares Tower (PCO39-PCO40, PCO45-PCO46). These latter samples are actually from the remains of the tower that existed there prior to the Comares one. Each of the "calicostrado" wall samples comprises two parts: one from the inner red concrete and another from the outer light-colored material. The more clayey walls occur in the more "distinguished" buildings in the Alhambra Complex: The Comares and The Leones Palaces. The samples comprise: (PCO1) from a storeroom in the

Ambassadors Salon, (PCO5) from the high part of the Comares Tower and (PCO3) from the lower part (basement), (PCO20) from the high Arrayanes Gallery, (PLE11, PLE12 and PLE13) from the Dos Hermanas basement, (PLE2) from the Harem Patio area, and (PLE9) from the Abencerrajes hall.

XRD was used to determine the mineralogy of the samples. The diffractometer was a Philips PW 1710 with automatic slit from the Departamento de Mineralogía y Petrología, Universidad de Granada. Since obtaining the complete mineralogical composition of the concrete would have required large samples (difficult to get in a complex like the Alhambra), we opted instead for separating out aggregates larger than 0.5cm and determining the mineralogical composition from the fine aggregate + binder fraction. Image Analysis was used to compare the proportions of coarse aggregate to the rest of the samples. As a first step, we took photographs of the uncovered walls of interest. The images were scanned and then read and improved with the Adobe Photoshop program, to be transformed into a format of rows of columns for transmission to the Sun station at the Centro de Instrumentación Científica, Universidad de Granada. At this station, the image in gray tones is segmented and converted to binary, the aim being to differentiate the matrix from the aggregate. Once we have the binary image, we measure the area of one of the portions and determine the percentage with respect to the total image area, thus obtaining an approximation of the binder/aggregate proportion. In fact, what we obtained is the proportion of coarse aggregate with respect to the fine-aggregate + binder portion, since it has been demonstrated that the photographs did not discriminate the aggregate under 0.5 cm. To obtain the total percentage, we had to combine the XRD mineralogical data with the data from the Image Analysis technique. Polarising light microscopy (Leitz microscope with transmitted light and reflected light devices) was used to determine the function of each of the minerals in the concrete and their degree of preservation. The samples were also analyzed by SEM, using a Zeiss DMS 950 microscope with a QX 2000 Microanalysis Link (from the Centro de Instrumentación Científica, Universidad de Granada). The percentage and distribution of the porous volume were measured via Mercury Intrusion Porosimetry using an Autoscan-60 Quantachrome (Universidad de Granada).

Results

X-Ray Diffraction. The mineralogical composition of the concretes is qualitatively quite homogeneous, while the differences between them are almost always quantitative. Results are

TABLE 1

Mineralogical Composition of the Gray Concretes, Expressed as %

Sample	Cal	Qtz	Phy	Fds	Dol	Gp	Ett	Tor
ALC1	58	29	6	≤ 5	≤ 5	-	-	-
ALC2	66	20	10	≤ 5	-	-	-	-
ALC3	38	43	13	≤ 5	≤ 5	-	-	-
ALC13	54	25	11	≤ 5	8	-	-	-
PV1	53	25	19	≤ 5	-	-	≤ 5	-
PV2	44	33	16	7	-	-	-	-
PV3	28	32	28	7	-	≤ 5	≤ 5	-
PV4	39	22	12	≤ 5	22	-	≤ 5	-
PV5	30	42	11	≤ 5	13	-	-	-
PAB2	60	23	12	≤ 5	-	≤ 5	-	≤ 5

TABLE 2
Mineralogical Composition of the Red Concretes

Sample	Cal	Qtz	Phy	Fds	Dol	Gp
PCO1	12	40	42	6	-	-
PCO3	12	31	46	8	≤ 5	-
PCO5	12	58	24	≤ 5	≤ 5	-
PCO20	18	42	29	5	-	-
PLe2	10	54	28	5	-	≤ 5
PLe9	26	42	25	≤ 5	≤ 5	-
PLe11	13	58	23	≤ 5	≤ 5	-
PLe12	12	50	31	5	-	≤ 5
PLe13	31	44	18	≤ 5	-	≤ 5

given in Tables 1, 2, and 3 (the abbreviations are based in (2), except Ett = Ettringite; Tor = Tobermorite; Phy = Phyllosilicates; Fds = Feldspars).

As may be seen from the tables, all of the concretes studied have calcite, leading us to suppose they contained greater or lesser amounts of lime. The red concretes plainly reveal to the naked eye the existence of a certain amount of clay that can be categorised as a fine aggregate, although it has some binding properties. Not all of the phyllosilicates in the mineralogical composition tables are fine aggregates. Rather, a considerable number of them correspond to sand- or gravel-sized aggregate, in which micaschist fragments are a common constituent (as commented below). Some of these concretes have traces of ettringite, a mineral usually present in Portland cement paste (3), and tobermorite, which also occurs from hydration of calcium silicates.

TABLE 3
Mineralogical Composition of the "Calicostrado" Concretes, Expresses as %

Sample	Cal	Qtz	Phy	Fds	Dol	Gp
ALC15	34	40	10	11	5	-
ALC16	23	30	34	7	6	-
ALC41B	31	48	15	≤ 5	≤ 5	-
ALC41J	26	47	17	≤ 5	7	-
ALC42B	28	41	13	≤ 5	14	-
ALC42J	24	40	26	7	≤ 5	-
ALB6B	33	49	11	≤ 5	≤ 5	-
ALB6J	7	66	18	≤ 5	≤ 5	-
ALB7B	32	41	11	8	≤ 5	≤ 5
ALB7J	17	55	19	≤ 5	≤ 5	-
PCO39H	47	31	9	≤ 5	10	-
PCO40	19	40	35	≤ 5	-	≤ 5
PCO46H	33	46	13	5	-	≤ 5
PCO45	16	52	23	5	-	≤ 5
PLe7	35	29	12	≤ 5	20	-
PLe8	26	48	15	≤ 5	7	-
PLe17H	38	35	13	≤ 5	11	-
PLe18	31	42	16	≤ 5	7	-

Light Microscopy. Light microscopy analysis of thin sections from the concrete samples was used to determine the petrographic composition of the aggregate. It comprises fragments of metamorphic rocks, primarily quartzites, various types of schists (with graphite, with granate, and micaschists), and lesser amounts of dolomitic marbles and amphibolites. The grain morphology is clearly erosive, with no one size predominating; instead, there is a gradation from the very fine sizes (<1mm) to the coarse ones (>10 cm). These characteristics are common for all the walls studied.

The greatest petrographic differences among the walls are in the texture of the binder. In general, the lime-rich walls have a microcrystalline to spathic texture. In samples ALC1, ALC2, and ALC3 the lime appears as a mosaic of well-formed calcite crystals (see photo 1), very crystallized in the fissures, a fact also confirmed by SEM. These samples are high in lime and very compact, with low porosity that is always fissural. The binding in the aggregate-lime contact is so strong that the calcite crystallizes in the schist-fragment fissures, which are the major component of the aggregate (see photo 2). The PVn concretes are among the best-quality lime concretes in the Alhambra. Hand samples are surprisingly hard and coherent, while the microscope reveals scarce porosity (always fissural) and an excellent binding in the aggregate-lime contacts. They naturally contain no clay. In the other samples, the lime tends to have a very fine grain size, appearing under the microscope as a more or less dark mass surrounding the fragments of metamorphic rocks that form the aggregate. In the red concretes (inner part of the "calicostrados" and clayey packed-earth walls) the texture of the lime is always micritic. Selective staining of the calcite demonstrated that this lime is not dolomitic. We have also observed that in most of the samples the calcite can be considered as a binder, since we have

PHOTO 1
Lime texture in a gray concrete (scale bar: 1 mm).

found no calcitic aggregate. Likewise, most of the dolomite can be considered aggregate, as it appears as rounded polycrystalline grains, around which there may be crystallization of the binder calcite, sometimes syntaxial.

In the gray concretes and outer parts of the "calicostrados", the aggregate mixture is relatively homogeneous, and the predominant porosities are the shrinkage fissures in areas poorer in aggregate. In contrast, the mixture is more uneven in the red concretes, with some zones being more consolidated than others and frequent powdery lumps of lime that were perhaps not properly heated. Porosity is either fissural (in areas rich in lime) or rounded (in intergranular spaces).

SEM. Samples have been analyzed in both fresh-cut sections and in polished sections. Particular attention was paid to the porosity, which is very different in the gray and in the red packed-earth walls. In the red walls, the porosity is much greater and intergranular, with empty spaces not completely filled in by binder between the grains. In the gray walls, the porosity is fissural and less abundant (see photo 3). In the gray walls, it is apparent that the lime recrystallizes in the fissures, with quite perfect crystals (4). Thread-like gypsum crystals can be seen in the pores of samples PV3 and PAB2. Nevertheless, these samples show no visible signs of weathering.

Another aspect we were interested in determining was the origin of the dolomite. We knew that, in part, it could be attributed to the aggregate, but wondered if it were also present in the binder. It is well known that dolomitic lime responds poorly to deterioration (5). Via EDAX and Mg mapping we were able to ascertain that the lime scarcely contained any dolomite at all, and in fact is a very pure calcium carbonate.

PHOTO 2

Calcite crystallization in aggregate fissures of a gray concrete (scale bar: 200 μm).

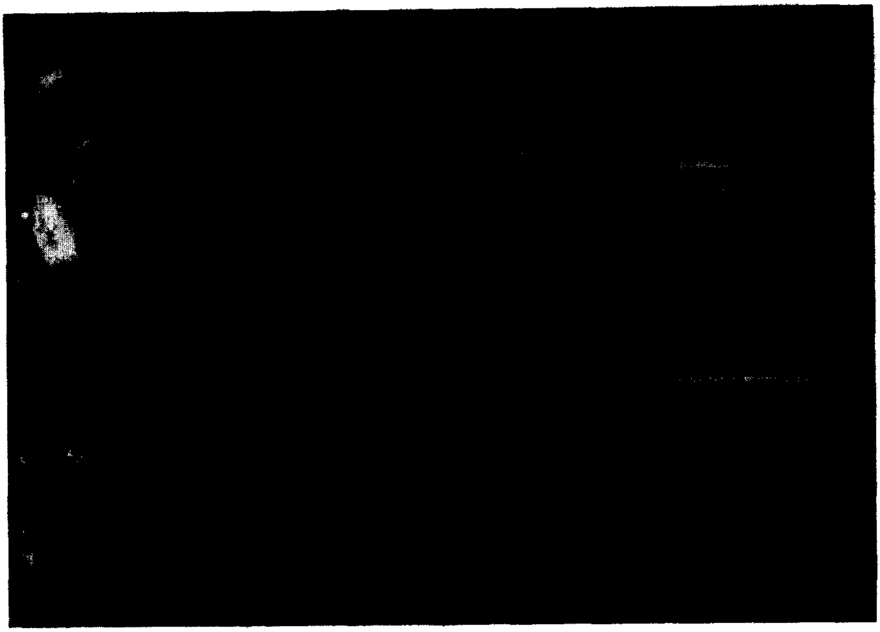

PHOTO 3
Appearance under SEM (secondary electrons) of a lime-rich concrete.

Image Analysis. Image Analysis was carried out on photographic images of walls areas lacking in a surface layer. The photographs were taken close enough to be able to distinguish aggregates as small as 0.5 cm in diameter. Image analysis results are in complete agreement with XRD results from samples lacking in coarse aggregate. Care was taken to avoid shadows and areas were chosen in which the aggregate is of one color, that is, either lighter than the matrix or darker. In the Alhambra, the best images came from the Alcazaba due to the fact that there are some barren walls exposed to the outdoors there (and therefore with sufficient natural light) that are most definitely original Nazarí.

We should note that, given the heterogeneity of the material, the data are widely dispersed and figures are therefore always approximate (data in the tables are an average of several values

TABLE 4
Percentages of Coarse Aggregate with Respect to Total Surface Area

Place	% coarse aggregate
Homenaje Tower, W (in)	49
Homenaje Tower, W (exterior)	26
Vela Tower, N (interior)	63
Vela Tower, N (exterior)	27
Revellín Water Storeroom (interior)	48
Revellín Water Storeroom (exterior)	27
Alcazaba Rampart (interior)	52
Alcazaba Rampart (exterior)	15

from the same area of wall). The proportion of coarse aggregate in the concretes is variable not just among different buildings, but in general between outer and inner parts of the wall. We have, for example, measured up to 50% coarse aggregate in the inner part of a very weathered wall while in the outer part of the walls the proportion does not tend to rise above 15-30%.

Hg Intrusion Porosimetry. Porosimetry analyses on ancient concretes have one great drawback compared to those carried out on natural rock. In the case of rock, original quarry material can be used to compare unweathered material with material from the monument, thereby allowing one to discern changes in the porous system that weathering agents may have caused. However, there is no original material available for concretes. In an attempt to solve this dilemma, we have analyzed concretes that seemed to be relatively unweathered, as we considered that they must have characteristics and properties close to those of the material in its original state.

The porosimetric distribution of the concretes is complex and, in fact, they tend to have several maximum pore-access radii. It is apparent that the porous system is very alike for materials whose function and preparation are similar. Thus, lime-rich concretes (both what we have named lime walls as well as the material from the outer zone of the "calicostrado" earthen walls) have a maximum pore-access radius of around 0.1 μm. Clay-rich materials (found in the inner part of the "calicostrado" walls and the so-called clay walls) are different from the ones described above, and have a very heterogeneous porous system with several access maximums. Note that the porosimetry measurements were carried out on the concrete matrix (binder + fine aggregate). The lime-rich concretes (PV3, PV4, and ALC2) have a very low maximum size (under 0.1 μm) and the porous-volume percentage is also low (15-22%). Other concretes with lower lime levels have higher maximum sizes (1-0.1 μm), as can be seen in Fig. 1. Samples from the inner and outer part of the same "calicostrado" wall tend to display a greater amount of micropores in the inner-wall sample. In general, lime-rich concretes are less porous than clay-rich ones. The concretes from the Leones Palace and from ALC42J (inside zone of an Alcazaba wall) have the highest percentage of porous volume, and are very rich in clay, with values of over 30%.

Discussion

Type of Binder. Mineralogical and petrographic data have revealed that the main binder in the ancient concretes is lime. We wondered, however, whether we were dealing with an aereous lime or with a lime with some degree of hydraulicity. The most common methods proposed in the bibliography to decide whether a mortar has hydraulic components are:

*Residue color: the sample is submitted to an acid attack and the color of the fine residue is then noted (not that of the aggregate). Gray colors indicate the lime has hydraulic components, while light or rose tones denote aereous components (6). Although this method is quick and easy, even for those with scarce knowledge of chemistry, it seems to be very little reliable.

*Presence of soluble silica (7). This method has several variations according to the intensity of the acid attack in the sample. It is based on determining whether or not a sample attacked by acid contains silica and aluminum in the resulting solution. In spite of being theoretically quite valid, it does have two drawbacks: a) the scarce stability of silica in an acid solution; and b) when the aggregate contains silica and particularly if there are somewhat degraded fine sizes (as is the case of the Alhambra concretes), it is impossible to be certain that the silica measured comes from the binder and not from the aggregate.

*Petrographic method (8). This method involves the recognition of the typical textures of the different concrete components in polished sections using reflected light microscopy. It is reliable and definitive but requires a sample with a large amount of hydraulic compounds.

None of these methods can be applied to the Alhambra, and therefore we have employed only mineralogical criteria, that is, detailed mineralogical study using XRD (9). In samples

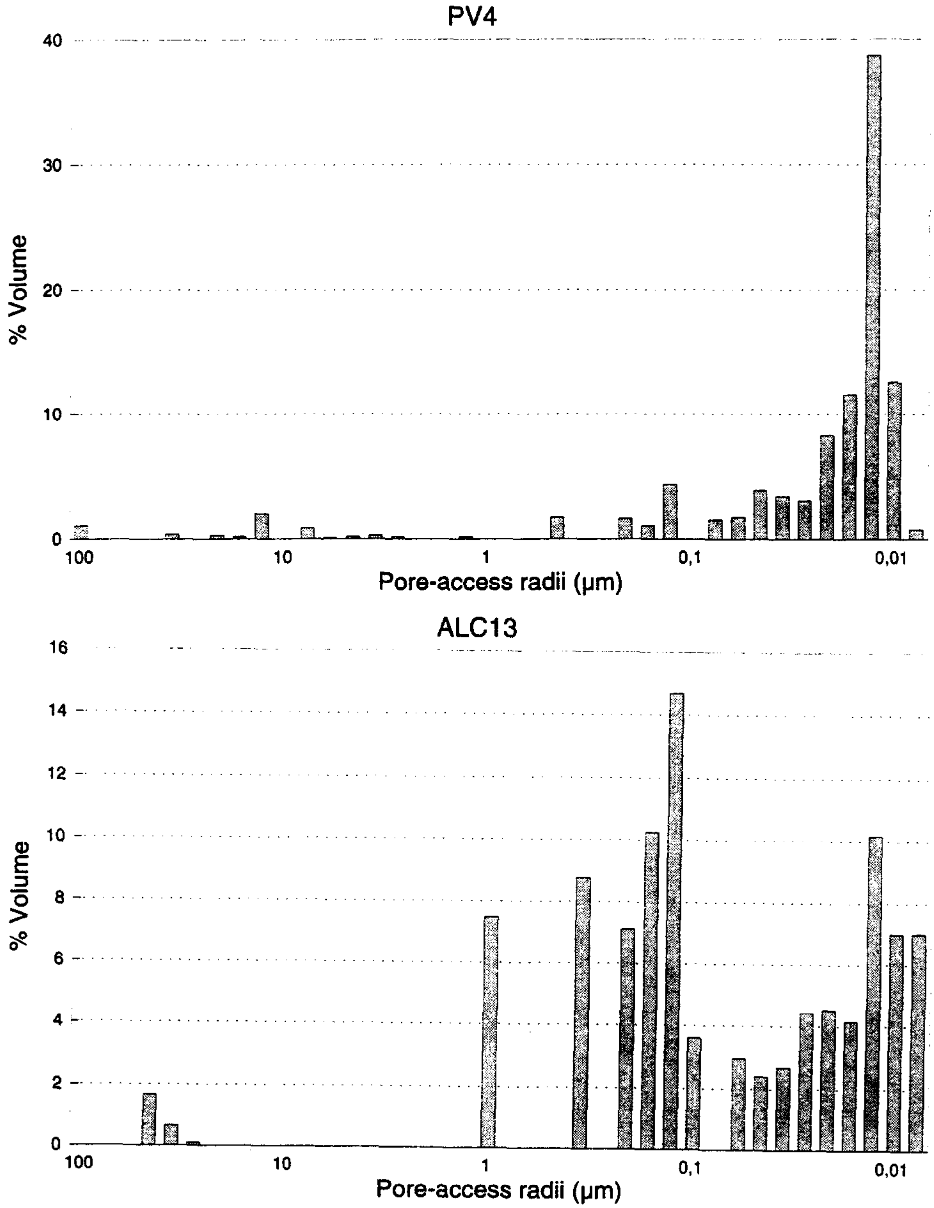

FIG. 1.

Histograms of the distribution of pore access radii in lime-rich concretes.

PAB2, PV1, PV3, and PV4, we found only traces of minerals that would indicate a certain hydraulic character (tobermorite or ettringite). These two minerals point to a certain degree of hydraulicity since they may be present in the original Portland-type cement (10) or, in the case of ettringite, be a product of the weathering of hydraulic compounds in sulfate-rich environments (11). These minerals could be considered as products of weathering in hydraulic compounds, even though they occur in very minor amounts. No other indications of hydraulicity, such as

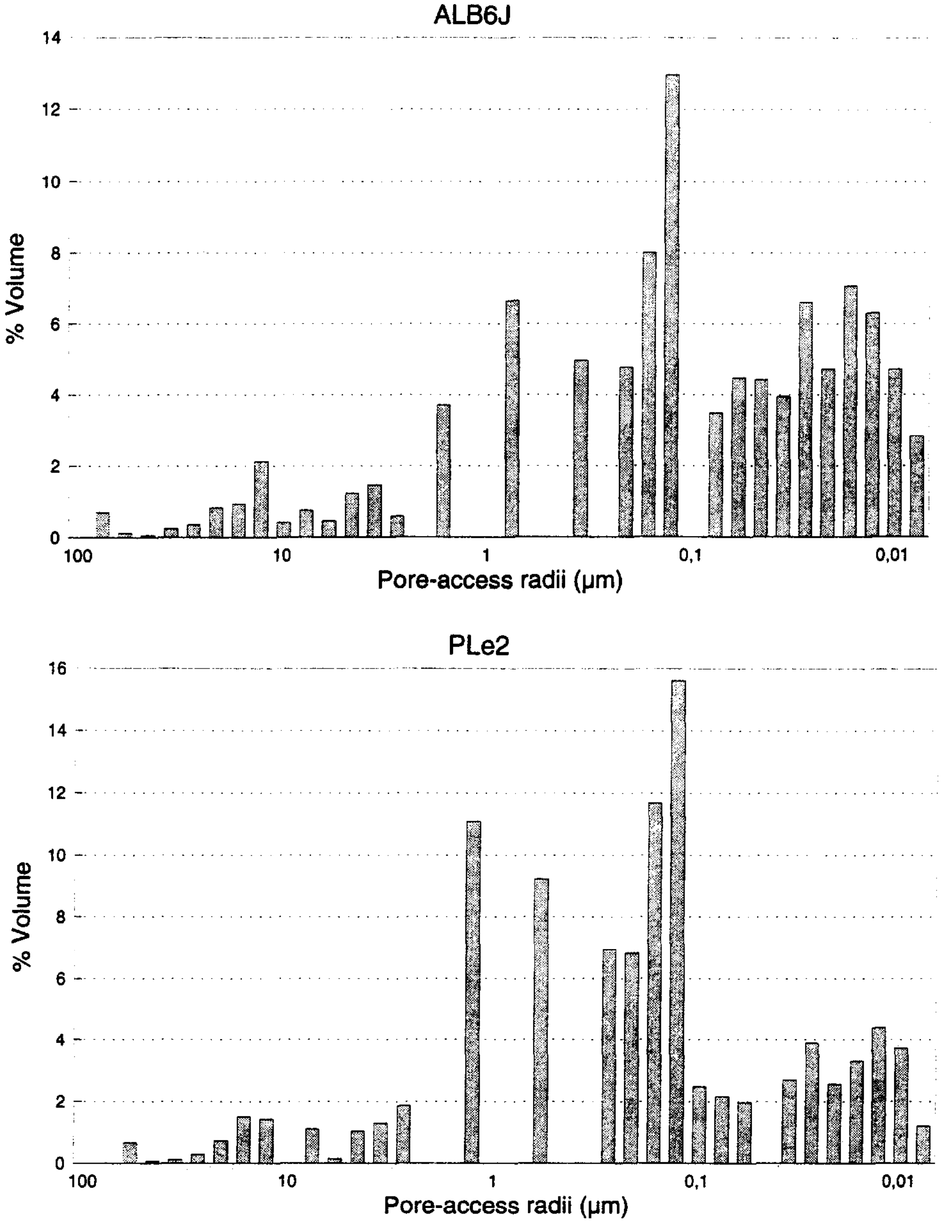

FIG. 2.
Histograms of the distribution of pore access radii in clay-rich concretes.

the addition of pozzolana (a volcanic sand that is vitreous and reactive) or ground brick, have been found. It is true that one finds the occasional piece of brick in the concretes, but they are large and isolated, more as a filler than an additive. The lime used in most of the concretes in the Alhambra was, in conclusion, fat and not hydraulic. The lime was also quite pure, with a low Mg content. SEM (12) and light microscopy were used to reach these conclusions. The thin sections were stained with alizarine, which stains calcite red, leaving the other minerals their original color. The carbonated lime is in the form of calcite, not vaterite or aragonite, which are types of calcium carbonate that also occur in lime mortars.

Aggregate Types and Proportions. All the samples studied are quite similar in the types and proportions of aggregates, comprising a great variety of metamorphic rocks: quartzites, schists, dolomitic marbles, and amphibolites. It seems likely that the aggregate belongs to the Alhambra Formation (13), as indicated by the great petrographic similarity between the formation pebbles and that of the mortar aggregate, chemical similarity, proximity and availability of the material, and even some written sources from the XII Century, which speak of the ancient Alcazaba being repaired with local red soils ("alpañata") (14). As we have mentioned, the aggregate is mainly composed of subrounded metamorphic rocks, with graded sizing from clay in some red concretes to large rocks of 10 cm in diameter or more. Spathic calcite crystals can sometimes be seen in the concretes, and although at first sight they may seem to be a calcite aggregate, closer inspection of their edges indicates a transition between the crystals and the binder, and never erosive morphologies. These fragments must therefore be counted as part of the binder that was either carbonated or recrystallized early. This certainty regarding the lack of a calcitic aggregate allows us to use a simple method for determining the aggregate/binder proportion (15) using only the XRD and image analysis results. Diffraction gives us the proportion of calcite to fine aggregate by weight, while the image analysis reveals the proportion of coarse aggregate versus the matrix (binder + fine aggregate).

TABLE 5

Hg-Accessible Porous Volumes for Different Concretes, Expressed as % of Total Volume

Sample	Concrete tipe	Hg-accesible porous volume
ALC2	Gray	15
ALC13	Gray	21
ALC42B	"Calicostrado" (exterior)	28
ALC42J	"Calicostrado" (interior)	32
PV3	Gray	22
PV4	Gray	22
ALB6B	"Calicostrado" (exterior)	21
ALB6J	"Calicostrado" (interior)	24
PCO39H	"Calicostrado" (exterior)	27
PCO40	"Calicostrado" (interior)	24
PLc2	Clay rich	33
PLc8	"Calicostrado" (interior)	36
PLe9	Clay rich	37
PLe13	Clay rich	37

In the lime-rich walls, such as ALC3, combining both types of data leads to the following results:
Coarse aggregate = 27%; Matrix (ALC13) = 73%, of which Calcite = 54% and the Fine aggregate = 46%. Assimilating the weight and volume percentages (the densities are similar) and adjusting to 100, we obtain:
Binder = 39%; Total aggregate = 61%, of which 34% (of the total concrete) is fine aggregate and 27% has a diameter of over 0.5 cm.

The "calicostrado" wall in the area near the Aljibe del Revellín in the Alcazaba gave these figures:
Outer part of the wall: Coarse aggregate = 27%; Matrix (ALC15) = 73%, of which Calcite = 34% and fine aggregate = 66%.
Adjusting to 100 we obtain:
Binder = 27%; Total aggregate = 73%, of which 52% (of the total concrete) is fine aggregate and 21% is larger than 0.5 cm in diameter.
Inner part of the wall: Coarse aggregate = 48%; Matrix (ALC16) = 52%, of which Calcite = 23% and fine aggregate = 77%.
Adjusting to 100 we obtain:
Binder = 16%: Total aggregate = 84%, of which 52% (of total concrete) is fine aggregate and 32% coarse.

The Homenaje Tower provided the following data:
Outer part of wall: Coarse aggregate = 26%; Matrix (ALC41B) = 74%, of which Calcite = 31% and fine aggregate = 69%.
Adjusting to 100 we obtain:
Binder = 23%; Total aggregate = 77%, of which 51% (of total concrete) is fine aggregate and 26% is larger than 0.5 cm in diameter.
Inner part of wall: Coarse aggregate = 49%; Matrix (ALC41J) = 51%, of which Calcite = 26% and fine aggregate = 74%.
Adjusting to 100 we obtain:
Binder = 13%; Total aggregate = 87%, of which 38% (of total concrete) is fine aggregate and 49% coarse.

North Wall of the Alcazaba:
Outer part of wall: Coarse aggregate = 15%; Matrix (ALC42B) = 85%, of which Calcite = and fine aggregate = 72%.
Adjusting to 100 we obtain:
Binder = 24%; Total aggregate = 76%, of which 61% (of total concrete) is fine aggregate and 15% is larger than 0.5 cm in diameter.
Inner part of wall: Coarse aggregate = 52%; Matrix (ALC42J) = 48%, of which Calcite = 24% and fine aggregate = 76%.
Adjusting to 100 we obtain:
Binder = 12%; Total aggregate = 88%, of which 36% (of total concrete) is fine aggregate and 52% coarse.

State of Conservation. Since the main aim of this study was to characterize the wall materials, sampling was done in the best-preserved areas in order to examine materials in as close a state as possible to the original. Therefore, we are not dealing with representative samples to determine the true state of preservation. We have noted some dissolution of the binder lime, but have not seen any "floating" aggregate grains, which would signify a worrisome degree of weathering. Moreover, although both XRD and SEM have revealed gypsum crystals in the pores of some of the study samples (PV3, PAB2), no serious signs of deterioration can be seen

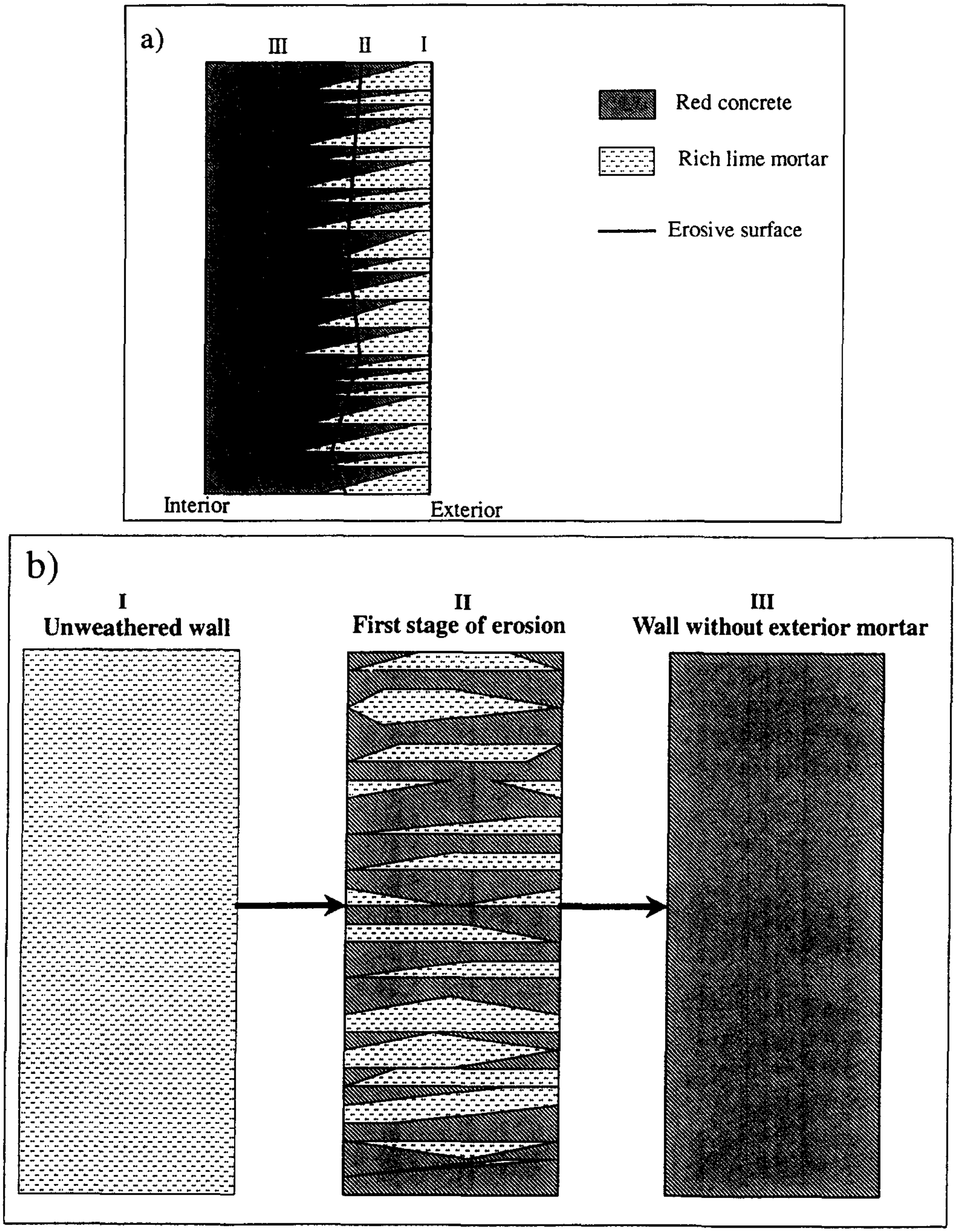

FIG. 3.
a) Cross-section of a calicostrado wall, showing the different materials; b) Front view of distinct stages of erosion.

in these concretes. We may therefore affirm that the state of preservation of the material in the walls of the study areas is acceptable, despite some zones being macroscopically more eroded.

Wall Construction. The construction technique consisted in putting material to form the wall (clay, aggregate, and lime) between two parallel, vertical planks attached to each other by bars of wood. Each layer of material (more or less clayey, with or without lime) was packed in. Once the wall was finished, the planks were removed, though not the crossbeams. One particular type of wall is the "calicostrado", which is made of two materials: one rich in lime, arranged in wedges with the wide part forming the outer part of the wall, and a more clayey material in the middle (16). It tends to have a "striped" look when somewhat eroded. The outward appearance and the intermixing of the two concretes (light-colored and reddish) seen under the microscope seem to indicate that the two were erected and packed simultaneously, in the following manner: the construction technique is similar to that of any earthen wall except that in the outer part is placed a strip of lime-enriched concrete; the whole is then pressed in and the result is that the lime mortar becomes embedded in the wall, forming one solid piece with the rest. The mineralogical-composition tables show that the materials in the outer part of the wall always contain a higher percentage of calcite and a lesser percentage of phyllosilicates. Nevertheless, it can be seen that there are no drastic differences between the materials in the same wall, and that the nucleii always contain lime, which gives them a certain degree of stability.

The schematic cross-section of a "calicostrado" wall (such as those studied in the Alhambra) and its weathering patterns can be seen in Fig. 3. The advantages of this type of wall are many and evident:

* Savings in costly lime with regard to walls made only of lime concrete, without an excessive loss of strength.
* The outer concrete, which is closely attached to the rest of the wall along a serrated-type surface, substitutes plastering, which always tends to lift off in the contact zone.
* It prevents many of the weathering processes that attack the susceptible earthen wall (17;18) without being much more costly or difficult to carry out. In addition, when weathering occurs it is progressive and not drastic.

Conclusions

The main conclusions to be drawn from the study of the materials forming the earthen walls in the Alhambra are:

a) All the wall were stabilized with lime, mostly non-hydraulic, although not dolomitic, well-carbonated, and of good quality.
b) The source for the aggregate was always the same during the Muslim period, the only difference being that for some uses (those requiring more strength) the smaller sizes were removed (clay and silt).
c) We have obtained the proportions of aggregate and lime, which range between 39% and 23% of binder in the strongest materials, and 16% and 12% in the most earthy materials.
d) In general, these materials are quite porous, and perhaps not very strong, which is compensated for by the thickness of the walls (always thicker than 1 m). However, this high porosity results in a lesser risk of humidity setting in, the presence of which is a major cause of deterioration in many other historical buildings.

e) The good durability these materials have demonstrated does not derive so much from the materials in themselves (they are, in fact, quite poor), but in the intelligence shown in the construction, in the packing of the earth, and in the good distribution of the different types of concrete in the wall.

Acknowledgments

This work was supported by Spanish Project PB-93-1090 (DGICYT) and Research Group 4065 of "Junta de Andalucía".

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