Brick masonry identification in complex historic buildings

Gonzalo Barluenga[a]*, Fernando Estirado[a], Raimundo Undurraga[a], Juan Felix Conde[b], Fernando Agua[b], María Ángeles Villegas[b], Manuel García-Heras[b]

[a] University of Alcalá, Department of Architecture, 28801 Alcalá de Henares, Spain.

[b] Instituto de Historia, Centro de Ciencias Humanas y Sociales, CCHS-CSIC, 28037 Madrid, Spain.

*Corresponding author. Tel.: +34 918839239; fax: +34 918839246

E-mail address: gonzalo.barluenga@uah.es (G. Barluenga), fernando.estirado@uah.es (F. Estirado), raimundo.undurraga@edu.uah.es (R. Undurraga), juanfelix.conde@cchs.csic.es (J F Conde), fernando.agua@cchs.csic.es (F Água), mariangeles.villegas@cchs.csic.es (M A Villegas), manuel.gheras@cchs.csic.es (M García-Heras)

Abstract

The aim of the study is to define a reliable interdisciplinary procedure for brick masonry identification in complex historic buildings, in order to enhance documentation, conservation and restoration issues, thereby putting into value the architectural heritage. The methodology integrates experimental data obtained through on site measuring and sampling with historical information. Direct measurements were obtained through photogrammetry and brick and mortar characterization tests and were used to relate stratigraphic units, fabric morphology and materials. The differences identified through morphological analysis and experimental results are double-checked with historical data, allowing a scientific interpretation, supported by experimental results and contrasted to historical information.

This approach was used for the study of the brick masonry walls of the first College of the University of Alcalá (Madrid, Spain), founded in 1495 and declared World Heritage Site by the UNESCO in 1998. Different brick masonry typologies with the same morphology but different constitutive materials and vice versa were found. An integrated constructive analysis based upon available historical data allowed to identify six brick masonry types based on their period of construction, fabric morphology and building materials.

Keywords: Historic masonry; Morphology; Brick; Mortar; Integrated analysis.

1. Introduction

The identification of building materials and constructive techniques is essential for conservation and restoration of historic buildings and helps putting into value their heritage importance. As a general rule, the walls of complex historic buildings are characterized by the overlapping of different masonry types, due to the addition of constructive elements and refurbishment works along time. As a consequence, their current appearance is the result of multiple interventions which are often difficult to identify. It is therefore necessary to develop strategies for the study of these buildings.

The investigation of historic buildings must combine on site observations and measurements, along with laboratory tests. The main aspects to consider may also include the history of the building, its chronology and the history of constructive techniques [1].

Some information concerning historical constructive issues could be obtained from documentary sources, such as ancient drawings and descriptions or historical studies [1]. In the case of buildings with a high historic or artistic value, there are usually many historical studies, although the constructive information is scarce and usually concerns to very specific decorative elements. While some assumptions can be made, mainly based on analogy to nearby buildings, actually the existing materials are often unknown. Therefore, studies on the actual building materials must be conducted as a first step before performing any conservation or restoration decision [1].

The study of masonry walls in complex historic buildings can be conducted considering two different issues: the masonry morphology [2] and the materials characterization [3,4].

Morphological analyses are based upon stratigraphic studies and are essential for architectural archaeology [5]. The aim is to find out the constructive units existing in a building considering the shape and size of bricks and the brickwork. This approach does not take into account the constitutive materials themselves, further than their external appearance, which limits the extent of this type of analysis.

Materials characterization of masonry walls involves the study of both the binder material and the pieces. The binder material is usually a mortar and the pieces are mainly bricks, as in the case of the present study. Mortars can be characterized by the physical-chemical composition of the binder and the physical-chemical and mineralogical composition of the aggregates. Bricks can be characterized through the physical-chemical composition of the raw materials and the production issues, as the firing temperature.

However, the usefulness of these tests alone is sometimes questioned [1]. The study of the materials, without considering other aspects as the masonry morphology or historic period, also has limitations [1]. Depending on the historic and geographical context, concerning raw materials and manufacturing techniques availability, the characterization results can be unable to identify significant dissimilarities. This can be the case of the composition and firing temperature of bricks and the composition and mineralogical aspects of the binder and aggregates used for mortar manufacturing.

2. Researching aims and significance

This paper presents an integrated methodology for the study of complex historic buildings which combines stratigraphic analysis of the walls and materials characterization along with historical information. The combination of the results obtained from different approaches produces more precise information and allows the identification of materials and masonry typologies existing in the building. This information is essential for conservation and restoration of historic buildings, highlighting their heritage value.

The novelty of the methodology is the inclusion of a double-check procedure: the differences identified by morphology and materials characterization are crossed and the discrepancies are double-checked with historical information. Therefore, the differences identified are supported at least by two different approaches, on site measurements or laboratory tests and historical data, and allow proposing a reliable scientific interpretation.

Accordingly, the main aims of the study are:

1. To define an interdisciplinar methodology for the study and identification of different masonry typologies existing in complex historic buildings, integrating the constructive stages, morphology and constitutive materials.
2. To apply the methodology for the study of the Saint Ildephonse's College of the University of Alcalá (Madrid, Spain), founded in 1495 and declared World Heritage Site by the UNESCO in 1998, to identify the building materials of the constructive units recently discovered. The specific results of materials

characterization also allow knowing the state of conservation of the different types of bricks and mortars.

3. Materials and methods

The interdisciplinar study involves four main steps: preliminary historical and morphological studies, materials sampling, materials characterization and integrated analysis of the results.

The methodology was used for the study of the brick masonry walls of the first building of the University of Alcalá, Saint Ildephonse's College [6]. Fig. 1 shows the main plan of the building, characterized by a large central arcaded courtyard (Saint Thomas' Patio) surrounded by rooms for different uses.

Although the building has been the subject of many studies [7-9], there is a lack of architectural studies that are able to identify neither the materials nor the constructive techniques, further than the use of brick masonry and rammed earth.

3.1 Preliminary studies

Preliminary studies were necessary to identify the history and the actual state of the building and, consequently, involved historical and planimetric investigations.

Regarding the history of the College, the original two-story building was erected in the early 16th century using brick masonry and rammed earth. In 1537, the outstanding three-story stone façade, which can be seen nowadays, was built and the north side of the College was raised an additional floor [10]. During the 17th century, the original building completely changed its appearance. In 1599, a new clock tower was erected on the south side and, between 1656 and 1670, a granite cloister was built inside the Patio, raising one floor more to the east, west and south sides of the building [11]. The building underwent multiple minor interventions during the 19^{th} and 20^{th} centuries that provided its current appearance. Table 1 summarises the main chronological stages which were identified according to the history of the building and the key periods of the construction [12].

Once the historical data were processed, a planimetric survey was performed taking advantage of the rehabilitation works that were performed in 2011 [13]. It must be highlighted that, during these works, all the walls' coatings of the central patio were removed and the constitutive materials could be seen together for the first time. It was found that the inner dimensions of the central patio had remained constant during time, as far as the historical works were overlapped on the same plane of the walls.

A morphological analysis was performed based upon the planimetric survey (Fig. 2) and four different masonry morphologies were identified (Fig. 3 and Table 2) [14].

3.2 Sampling

A set of 11 bricks and their associated mortars were taken from the freshly discovered walls. Fig. 2 shows the location of the samples on the four walls of the central patio. Sampling was performed according to the planimetric survey and the morphological analysis described in 3.1.

3.3 Characterization techniques

The samples extracted from the building were studied in the laboratory to identify their constitutive materials [15]. Material samples were characterized according to procedures that can be found in the literature [4,16,17]. The following observation and analytical techniques were used: Scanning electron microscopy (SEM) coupled with Energy dispersive X-ray spectrometry (EDS), thin section polarized light microscopy (petrographic microscope), X-ray diffraction (XRD), thermogravimetry (TG) and Differential Thermal Analysis (DTA).

SEM images were taken using a Philips XL30 microscope and a DX4i spectrometer attached to it, with acceleration voltages of 20 kV. Polarized light microscopy was undertaken through examinations of thin sections by means of a Kyowa Bio-Pol 2 microscope. Micrographs from thin sections were recorded with a Moticam 2500 digital camera. Powder XRD analyses were carried out with a PANalytical X'Pert-MPD unit using Kα of copper radiation (1.54056 Å), under set conditions of 45 kV and 40 mA. Diffractograms were obtained between $2\theta = 5\text{-}60°$. Powder samples for XRD analyses were prepared by grinding the samples of bricks and mortars.

Observation techniques provide qualitative information about orientation and size of particles, pores and cracks. Aggregates can be identified using a petrographic microscope, although this technique is hardly useful for binder identification [16]. This limitation can be overcome when using SEM, as it can visualize the microstructural components of the binder and analyzed its structure. SEM coupled with EDS allows a qualitative determination of the chemical elements of the sample.

X-ray diffraction (XRD) analysis characterized crystalline or semi crystalline phases of the materials composition and can identify the binder (lime, gypsum, cement, etc.), the aggregate (siliceous, calcareous, etc.) and other additions.

TG-DTA recordings were undertaken by a SDT Q600 equipment using a platinum cell holder under air atmosphere, at a heating rate of 10°C/min ranging from room temperature up to 1200°C. TG measures the weight loss of the sample as it is heated. Weight loss during heating can be related to specific physical decompositions in the materials produced by temperature increase [16]. DTA produces a graph comparing the temperature difference between the sample and an inert reference, during the thermal cycle. When the sample does not increase its temperature and the standard does, endothermic peaks are noted. The endothermic or exothermic transitions are characteristic of particular minerals, which can be identified and quantified [16].

4. Materials characterization

Through the characterization of the constitutive materials of the samples, several classifications can be obtained. Mortars were sorted considering the chemical and mineralogical composition of the binder and aggregates. Bricks were classified considering mineralogical and chemical issues, taking into account manufacturing parameters as grinding and firing temperature.

Material types were compared and the results combined with the masonry morphologies, identifying the brick masonry typologies existing in the building. Additionally, these integrated results were double checked considering the historical data available.

4.1 Mortars classification

Most of the samples correspond to lime mortars (reflections of calcite and gehlenite phases), except the cement based mortars of the 20th century. Apart from this exception, the different types of mortar show small differences probably due to the similar raw materials employed.

The results of SEM-EDS analyses are presented in Table 3. Four groups of mortar samples could be identified based on the qualitative determination of the chemical elements of the binder. Group 1 (samples A, B, D, G, H) is characterized by the presence of calcite in XRD analysis, and a proportion close to 95% of CaO according to

EDS determinations, which corresponds to a typical lime mortar [18]. Group 2 (sample C) presented SiO_2 percentages around 50 % and, according to the literature [18], this composition could correspond to a hydraulic lime mortar with low hydraulic binder content. Group 3 (samples E, F) can be differentiated considering the high presence of hydraulic compounds (50 % SiO_2 and 10 % Al_2O_3) regarding to CaO (30-50 %) and iron oxides (around 5 %). According to the literature, this composition could correspond to crushed brick-lime mortars with medium hydraulic binder content: lime mixed with small fragments or dust of ceramic materials [18,19]. Group 4 (samples I, J, K) incorporate the cement mortars, characterized by CaO and SiO_2 as major components (80 %) and other minor components as $Al_2O_{3,}$ Fe_2O_3, MgO and SO_3 in percentages above 3% [20].
The mortars were also sorted according to the aggregate composition. XRD data allowed the identification of three groups of mortars (Fig. 4). Feldspathic sands were used in all cases and the differences obtained were: Samples A, B, C, D, H (Fig. 4a): Na-K feldspar sand with traces of illite; Sample G (Fig. 4b): K-feldspar sand also with traces of illite; Samples E, F (Fig. 4c): Na-K feldspar sand without traces of illite.
Summarising, Table 4 presents the five types of mortars identified when considered the combined results of the binder and aggregate analyses.

4.2 Brick classification

According to the analyses, there are three types of brick which can be differentiated (Fig. 5). It must be said that the hollow bricks were not considered in the analyses, because they undoubtedly correspond to the 20th century. The first type of bricks (B1) is integrated by the samples: A, B, C, D and H. Thin sections of this group (Fig. 5a) show fine textured calcareous clay with a high degree of birefringence. Inclusions composed of quartz, feldspar, and mica appears disseminated throughout the clay matrix. Quartz and feldspar inclusions are rounded to sub-angular in shape and not higher than 500 µm in size, while mica is generally small needle-shape and between 500 and 600 µm in length. The most outstanding feature of this group is the presence of relatively abundant inclusions of grog or chamotte (crushed fragments of ceramic) which was deliberately added to the clay matrix to improve mechanical properties of these bricks [21]. The size of grog fragments reach up to 1 mm in length. XRD data (Fig. 5b) confirm the presence of quartz and two kinds of feldspars: plagioclase (Na-rich feldspar) and microcline (K-rich feldspar). In addition, they also determine reflections corresponding to illite, calcite, hematite, and gehlenite. Illite decomposes from 850 to 900°C and calcite from approximately 750°C, while hematite is usually neo-formed from 700-750°C and gehlenite from 800°C [22]. Based on the combined presence of these four phases, a low firing temperature of 800-850°C can be estimated, except for sample A, which has a lower temperature. A shrunken microstructure of non-vitrification is observed by SEM, while TG-DTA curves (Fig. 5c) agree with the firing temperature estimated by diffractograms.

Type 2 (B2) consists on sample G alone. The petrographic thin section (Fig. 5d) shows very sorted calcareous clay with low birefringence and signs of vitrification. Small mainly rounded inclusions not higher than 300 μm of quartz and feldspars appear disseminated throughout the clay matrix. Apart from quartz and two kinds of feldspars: plagioclase (Na-rich feldspar) and microcline (K-rich feldspar), the X-ray diffraction (Fig. 5e) determines reflections of hematite, gehlenite, and diopside. Due to the presence of both gehlenite and diopside, which approximately crystallize from 800°C; and the absence of illite, whose full dehydroxilation occurs near 900°C [21], it can be estimated a relatively high firing temperature, between 900 and nearly 950°C, for this brick sample. The starting of a vitrification microstructure is observed by SEM, while TG-DTA curves display neither endothermic nor exothermic effects as a result of the high firing temperature (Fig. 5f).

Type 3 (B3) included samples E and F. Thin sections of this group (Fig. 5g) show a poor sorted and birefringent non-calcareous clay in which a feldspathic sand, characterized by highly angular and sub-angular grains of quartz and feldspars, was added. X-ray diffractograms (Fig. 5h) confirm the presence of quartz and both feldspars. They also display reflections assigned to hematite. However, those reflections corresponding to illite and calcite are not present, which indicate an intermediate firing temperature that can be estimated roughly from 850 to 900°C.

5. Discussion of results and brick masonry identification

5.1 Combined analysis of masonry morphologies and constitutive materials

The characterization of the samples' constitutive materials produced a classification of five types of mortars and four groups of bricks. Therefore, there was not a direct relation between both types of materials in the samples sorting, which support the idea that masonry identification depends both on mortar (binder and aggregates) and brick characterization.

On the other hand, four masonry morphologies were identified in the building. Table 5 combines masonry morphology and constitutive materials and presents a new sorting which identifies six masonry typologies. When comparing material types found in the building to masonry morphology, it was observed that, once again, there is not a correspondence between morphology and constitutive materials. In some cases, there are stratigraphic units that can be differentiated by both morphology and materials characterization differences. However, there are also samples which were extracted from stratigraphic units with the same morphology but have different materials (samples D, H vs G or samples A, B vs C) and others with similar materials but different morphology (samples A, B vs D, H).

This apparent lack of consistency of the results indicates that both materials characterization and morphological analyses are necessary to fulfil the task of masonry identification, as far as they are not able to detect all the distinctive features separately.

Regarding the masonry typologies, those that were distinguished considering both morphology and constitutive materials can be considered undoubtedly different. However, those distinguished considering only one feature can be questioned, due to the low number of samples analysed. Although it is very likely that the masonry typologies defined considering only one dissimilarity really correspond to different construction periods, it is also possible that different materials and morphologies were used simultaneously in any particular historical period. To clarify this issue, the results must be double-checked to historical data.

5.2 Historical double check

Historical data can be used to support the differences found to establish the masonry sorting. The explanation must be based on double-check of the dissimilarities discovered by materials characterization and morphological analysis, considering the chronology of historical interventions done in the building. If there are documented works that justify the differences, then it can be considered that the sorting is scientifically supported. If not, the uncertainty remains and both hypotheses could be possible.

In the building studied, three cases of dissimilarities have been identified (Table 5). In two of them, the same morphology corresponds to two different types of materials: different bricks in one case and different mortar in the other, while the third case corresponds to typologies with the same type of materials but different morphology.

CASE 1: Same morphology and different materials. Samples D, H vs G.

The samples were extracted form stratigraphic units identified with morphology type I, although the materials characterization showed a very different composition of both bricks (B1 and B2) and mortars (M1 and M3). The difference can be supported considering the location of the samples (Fig. 2): samples D and H, which correspond to Brick masonry typology 1, can be found in ground and first floor of the four sides of the central patio. In all the cases, the stratigraphic units are associated to rammed-earth boxes, which was the original building technique used in the building (Table 1) [14]. On the other hand, Brick masonry Typology 3 was extracted from a large stratigraphic unit located in the south side of the patio (Fig. 2), where the clock tower was erected in the mid 17th century (Table 1). The construction of the tower involved several problems, included a fall down during the construction. This event can justify the use of high quality bricks, manufactured with higher firing temperature (Fig. 5), and a mortar with different composition (Table 4).

CASE 2: Same morphology and different materials. Samples A, B vs C.

Brick masonry typologies 2 and 4 share the same morphology, even though the types of mortars show dissimilarities. Both masonry typologies corresponded to stratigraphic units located in the three floors of the patio. However, masonry type 2 was located only in the north side of the patio, while the typology 4 was located in all of the walls. Typology 4 can be associated to the construction of the granite cloister in the 17th century because it led to the addition of a third floor to the patio (Table 1).

Masonry typology 2 corresponds to stratigraphic units associated to the window arches of the north side of the patio. Those arches match with the windows of the 16th century stone façade and are crossed by the floor slabs of the granite cloister, which also supports the hypothesis that they were constructed before the cloister. The location on the north side also strengthens the hypothesis.

CASE 3: Different morphology and similar materials. Samples D, H vs A, B.

In this case, the samples did not present dissimilarities concerning the constitutive materials, but the morphologies were different. The justification that they are masonry typologies that correspond to different chronological periods can be found on the location of the stratigraphic units. While the masonry typology 4 can be found in the second floor and can be associated to the construction of the 17th century cloister, the typology 1 was only found in the ground and the first floor, associated to the earth boxes. Consequently, typology 1 corresponds to the original building erected in the beginning of the 16th century. The lack of materials' differences can be related to the raw materials and manufacturing techniques available in the 16-17th centuries.

5.3 Brick masonry integrated classification

The different brick masonry typologies were established considering the morphological sorting and the materials characterization. Preliminary studies defined six chronological construction periods (Table 1) and four masonry morphological types (Table 2), while materials characterization revealed five groups of mortars (Table 4) and three types of bricks (Fig. 5).

The integration of these results allowed sorting six brick masonry typologies, ordered according to the historical chronology of the building (Table 5). The sorting procedure considered the masonry morphologies identified by a stratigraphic survey (Table 2) combined with the materials characterization results. Samples with the same morphology and materials were grouped defining masonry typologies. To confirm the masonry sorting when only different morphology or constituent materials was found, a double-check procedure was performed based on historical data (Table 1). The historical analysis also allowed ordering the masonry types considering chronological issues. Table 5 shows both the masonry typologies identified and their chronology.

6. Conclusions

Historic complex buildings present difficulties to identify the brick masonry types used in the subsequent interventions along time. A combination of historical data, planimetric survey and materials characterization is necessary To analyze a historic building. This paper proposes an integrated methodology for the study of brick masonry historic buildings which involves four main steps: preliminary historical and morphological studies, materials sampling, materials characterization and integration of the results. Materials characterization, both brick and mortar components, produces a classification of constitutive materials which can be combined with masonry morphologies. The dissimilarities can be double-checked with historical data. Brick masonry typologies can be identified linking constructive stages, morphology and constitutive materials.

The integrated methodology was used for the study of the brick masonry units of the Saint Ildephonse's College of the University of Alcalá (Madrid, Spain), founded in 1495 and declared World Heritage Site by the UNESCO in 1998, to identify the building materials of the constructive units recently discovered. The preliminary results showed six historic periods and four masonry morphologies. The materials characterization of mortars and brick samples allowed the identification of five mortar types and four groups of bricks. The combination of morphology and constitutive materials produce six brick masonry typologies. The typologies differentiated only by considering different morphology or constitutive materials were contrasted with historical data. The double-check procedure allowed both to confirm that they were different masonry typologies and to establish a chronological sequence of the building construction.

Additionally, several specific conclusions concerning the characterization techniques were found:

- Materials characterization was not able to identify significant differences among some bricks and mortars of the 16-17th centuries. This can be explained considering the similar raw materials and manufacturing techniques used.
- The same applies when considering the brick masonry morphologies of this period, as far as the same brickwork and brick shape and size appears in different chronological stages.
- The combined analysis of morphology and materials samples characterization allowed to distinguish all the typologies existing in the building, although the historical double-check confirmed the sorting.

The integrated methodology applied to the present case has proved to be useful for the study of historic complex buildings.

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References

[1] RILEM Technical Committee. Rilem TC 203-RHM: Repair mortars for historic masonry. Testing of hardened mortars, a process of questioning and interpreting. Materials and Structures 2009;42:853-65.

[2] González-Longo C, Theodossopoulos D. Construction and materials in the stratification of S. Maria Nova (S. Francesca Romana) at the Roman Forum. Constr Build Mater 2013;41:926-41.

[3] Baronio G, Binda L, Tedeschi C, Tiraboschi C. Characterisation of the materials used in the construction of the Noto Cathedral. Constr Build Mater 2003;17:557-71.

[4] Binda L, Saisi A, Tiraboschi C. Investigation procedures for the diagnosis of historic masonries. Constr Build Mater 2000;14:199-233.

[5] Giovannini P, Parenti R, Camporeale S. Material structure and constructive history. J Cult Herit 2002;3:73-82.

[6] Castillo Oreja MA. Colegio Mayor de San Ildefonso de Alcalá de Henares: génesis y desarrollo de su construcción: siglos XV-XVIII. Madrid: Algar, 1980.

[7] Escandell Bonet B. El Antiguo teatro escolástico del patio de Santo Tomás en la universidad cisneriana. Alcalá de Henares: Sociedad de Condueños, 1991.

[8] González Ramos R. La chimenea francesa de la sala rectoral del Colegio Mayor de San Ildefonso. Anales Complutenses 2002;14:111-22.

[9] González Navarro R. Fundación del Colegio Mayor de San Ildefonso y Universidad de Alcalá de Henares. Aulas y saberes 2003;1:479-96.

[10] Pérez López Á. Colegio Mayor de San Ildefonso Fábrica de la fachada (1537-1553). Alcalá de Henares: Universidad, Ayuntamiento, Brocar, 1998.

[11] González Ramos R. José de Sopeña: El Patio Mayor de Escuelas del Colegio Mayor de San Ildefonso. Anuar Dep Hist Teor Arte 2000;12:61-73.

[12] Barluenga G, Ramón-Laca L, Undurraga R, Estirado F. Estudio de los paramentos del Patio de Santo Tomás del Colegio Mayor de San Ildefonso. In: López AM, Collado F, Medina V, Espejo T, García A, editors. Proceedings of 18th International Congress on Heritage Conservation, Granada: University of Granada; 2011, p. 155-158.

[13] Barluenga G, Undurraga R, Ramón-Laca L, Estirado F. Methodology for the study of the walls of the Patio de Santo Tomás, University of Alcalá. In: Lazzari M, Rochette S, editors. Proceedings of International Congress on Science and Technology for the Conservation of Cultural Heritage, Santiago de Compostela: University of Santiago de Compostela; 2012, p. 1-4.

[14] Barluenga G, Undurraga R, Ramón-Laca L, Estirado F. An integrated methodology to identify the original materials and constructive techniques of complex historic buildings. J Cult Herit.

[15] Barluenga G, Undurraga R, Estirado F, Conde JF, Agua F, Villegas MÁ et al. Bricks and mortars from the Patio de Santo Tomás, Alcalá University (Madrid, Spain): a combined study of fabric characterization and building morphology. In: Lazzari M, Rochette S, editors. Proceedings of International Congress on Science and

Technology for the Conservation of Cultural Heritage, Santiago de Compostela: University of Santiago de Compostela; 2012, p. 1-4.

[16] Middendorf B, Hughes JJ, Callebaut K, Baronio G, Papayianni I. Investigative methods for the characterisation of historic mortars- Part 1: Mineralogical characterisation. Materials and Structures 2005;38:761-9.

[17] Martínez I, Castillo A, Martínez E, Castellote M. Physico-chemical material characterization of historic unreinforced masonry buildings: The first step for a suitable intervention. Constr Build Mater 2013;40:352-60.

[18] Gleize PJP, Motta EV, Silva DA, Roman HR. Characterization of historical mortars from Santa Catarina (Brazil). Cement and Concrete Composites 2009;31:342-6.

[19] Böke H, Akkurt S, İpekoğlu B, Uğurlu E. Characteristics of brick used as aggregate in historic brick-lime mortars and plasters. Cem Concr Res 2006;36:1115-22.

[20] Çavdar A, Yetgin Ş. Investigation of mechanical and mineralogical properties of mortars subjected to sulfate. Constr Build Mater 2010;24:2231-42.

[21] Rice PM. Pottery Analysis: A Sourcebook. Chicago: University Press, 1987.

[22] García-Heras M, Ruiz Conde A, Avilés Escaño MA, Sánchez Soto PJ, Ruiz Guzmán R, Reyes Trujeque J. Estudio arqueométrico de figurillas cerámicas mayas de Calakmul: (Campeche, México). Boletín de la Sociedad Española de Cerámica y Vidrio 2006;45:245-54.

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Table 1. Historic phases of the Saint Ildephonse's College [13,14]

Historic phases	Dates	Works	Author
Phase 1	1501-1508	Original two-story building	Master architect Pedro Gumiel
Phase 2	1537-1553	Three-story stone façade	Architect Rodrigo Gil de Hontañón
Phase 3	1599-1615	Clock tower	Juan Ballesteros - Juan García Atienza
Phase 4	1656-1670	Three-story granite cloister	José de Sopeña
Phase 5	19^{th} century	Reconditioning	Army-Priarist Phathers
Phase 6	20^{th} century	Restoration -refurbishment	Ánibal Álvarez (1914-27) S. Climent & E. Martín-Sonseca (1959-60)

Table 2. Brick masonry morphologies identified by brick and mortar joint dimensions.

Morphology	High (cm)	Length (cm)	Width (cm)	Mortar joint (cm)	Samples
i	4	16-18	8-10	2	D, G, H
ii	4	24-26	12-14	4	A, B, C
iii	5	24	12	1.5	E, F
iv	9	24	11.5	1.5	I, J, K

Table 3. Qualitative EDS analyses of mortars' binder samples.

Samples	Binder	CaO	SiO_2	Al_2O_3	Fe_2O_2	MgO	SO_3	K_2O
A, B, D, G, H	Group 1	>95%	<4%					
C	Group 2	40-60%	<50%	>5%	<4%	<4%		
E, F	Group 3	30-50%	30-50%	>10%	>5%	<4%	<4%	<4%
I, J, K	Group 4	30-40%	30-40%	>5%	>5%	<4%	>5%	<4%

Table 4. Mortars classification according to binder and aggregate.

Mortars	Samples	Binder	Aggregate
M1	A, B, D, H	Group 1	Na-K feldspar sand with traces of illite
M2	C	Group 2	Na-K feldspar sand with traces of illite
M3	G	Group 1	K feldspar sand with traces of illite
M4	E, F	Group 3	Na-K feldspar sand without traces of illite
M5	I, J, K	Group 4	-

Table 5. Brick masonry typologies identified by the combination of chronology, morphology, constitutive materials and samples studied.

Brick masonry	Historic phase	Morphology	Brick	Mortar	Samples
1	Phase 1	i	B1	M1	D, H
2	Phase 2	ii	B1	M2	C
3	Phase 3	i	B2	M3	G
4	Phase 4	ii	B1	M1	A, B
5	Phase 5	iii	B3	M4	E, F
6	Phase 6	iv	B4	M5	I, J, K

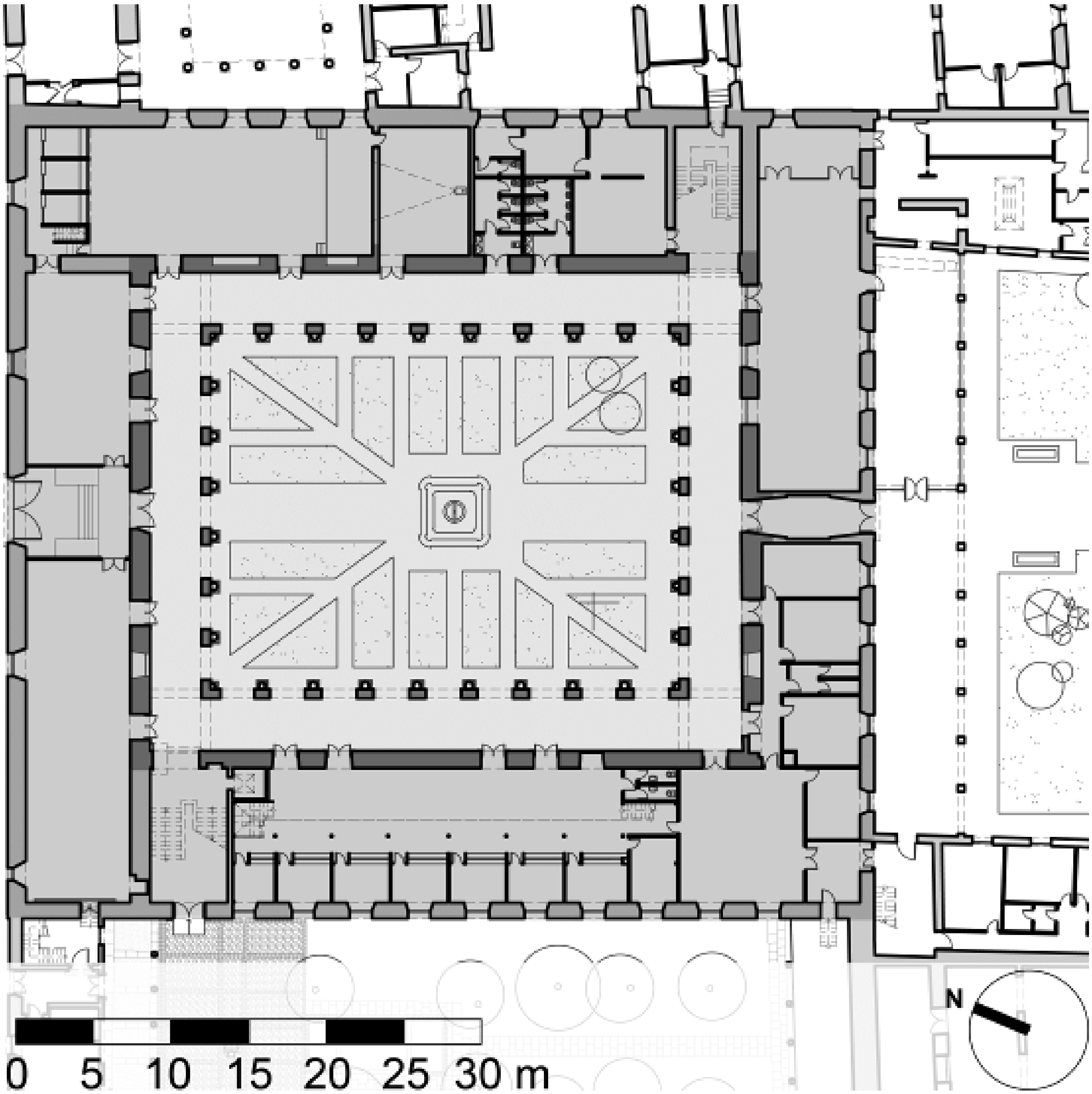

Fig. 1. Ground floor plan of the Patio of the Saint Ildephonse's College, University of Alcalá (Madrid, Spain).

Fig. 2. Patio of the Saint Ildephonse's College (University of Alcalá) and location of samples. a) North wall. b) East wall. c) South wall. d) West wall.

Fig. 3. Different brick morphology identified in the building: a) type i. b) type ii. c) type iii. d) type iv.

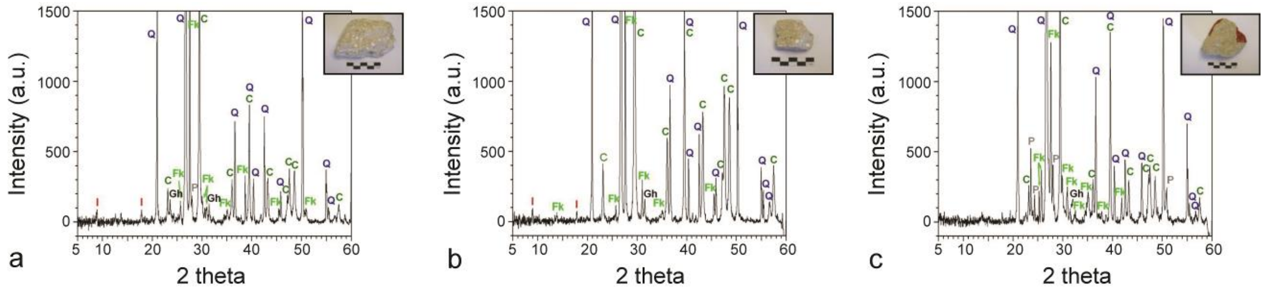

Fig. 4. Diffractograms from representative mortar samples. a) Sample A. b) Sample G. c) Sample E. Phases: C calcite, Fk K-feldspar, G gehlenite, I illite, P Na-feldspar, Q quartz.

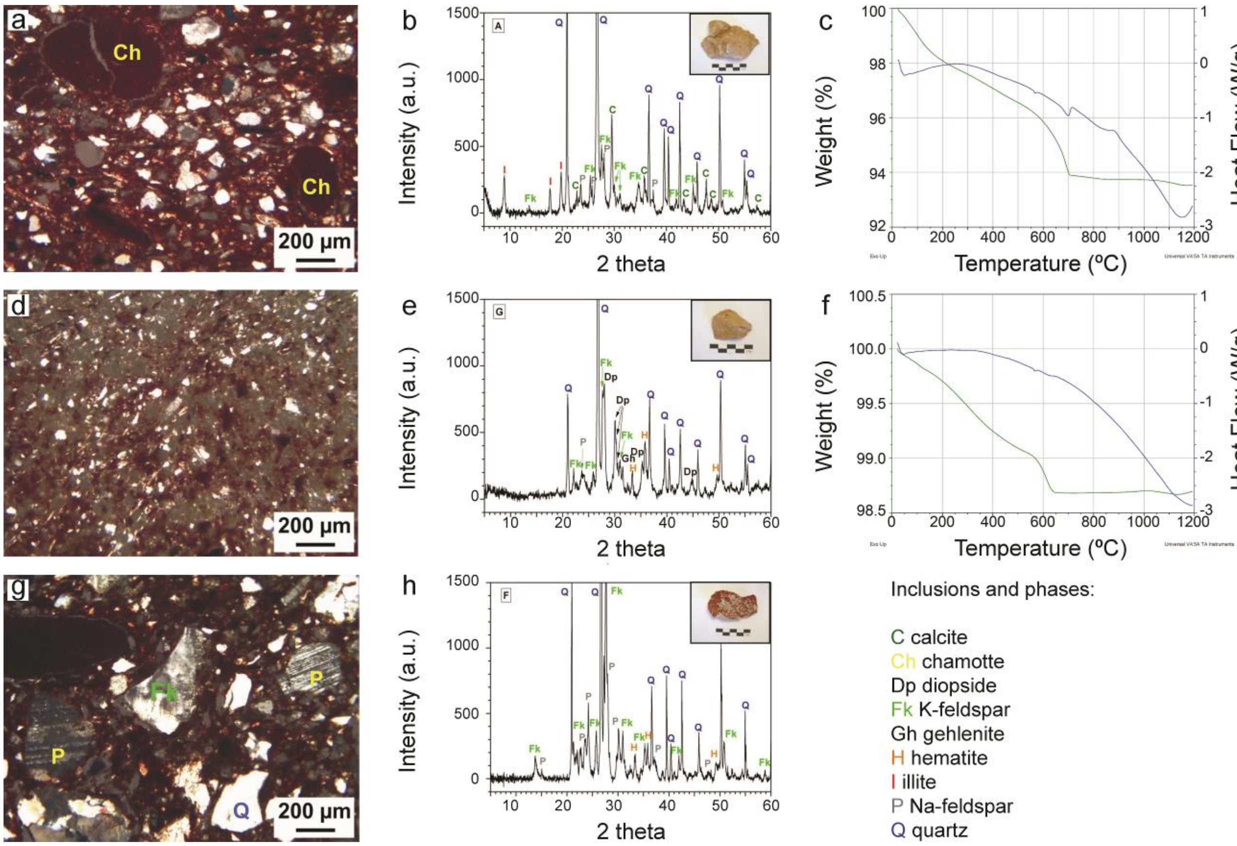

Fig. 5. Thin section micrographs, XR diffractograms and TG-DTA records from representative brick samples. Type B1: a) Sample B; b) and c) Sample A; Type B2: d), e) and f) Sample G; Type B3: g) and h) Sample F.