Study of vernacular building materials used in cultural heritage as a guide for architectural restoration: Colegio Máximo de Cartuja. Granada-Spain (19th century)

Estudio de materiales de construcción vernáculos empleados en el patrimonio cultural: guía para la restauración arquitectónica del Colegio Máximo de Cartuja. Granada-España (siglo XIX)

Honorato Justicia Muñoz (*), Mª Paz Sáez-Pérez (**), Jorge Durán-Suárez (***) , Mª Ángeles Villegas Broncano (****)

ABSTRACT

Colegio Maximo de Cartuja in Granada (Spain) was built by the Jesuits in 19th century. Using an archaeometric study of the building materials: bricks, glazed tiles, stained glass windows and lime-gypsum mortars (mortar masonry and concrete masonry), the vernacular concept of this construction was established within the geological framework of the “Alhambra formation”, and raw materials and techniques first used by the Nasrids in the 13th century have been identified. The results of XRD, XRF and DTA analyzes indicate the use of local clays in the manufacture of bricks and tiles fired at temperatures of ≤750 ºC. The clays contained NaCl additives, which improved the ceramic sintering, and traditional Nasrid colours (Cu, Fe, Sn) were used in the glazes and stained glass windows. Local raw materials were also used for air binders. These results have been combined to create a good-practice guide for the sustainable restoration of cultural heritage buildings.

Keywords: Architectural heritage; Conservation; Archeometry study, Vernacular architecture.

RESUMEN

El Colegio Máximo de Cartuja en Granada fue construido por los jesuitas en el siglo XIX. El estudio arqueométrico de sus materiales: ladrillos, azulejos, vidrieras y morteros, define el concepto vernáculo de esta construcción, referenciada en el marco geológico de la “formación Alhambra”, junto a la identificación de materias primas y técnicas utilizadas por los nazaríes desde el siglo XIII. Los resultados de XRD, XRF y DTA confirman el uso de arcillas locales para fabricación de ladrillos y losetas que se hornearon a temperaturas de ≤750 ºC. Las arcillas debieron contener aditivos de NaCl que beneficiaron la sinterización cerámica, y se comprobó el uso de colores de tradición nazarí (Cu, Fe, Sn) en los esmaltes y vidrieras. Las materias primas locales también se usaron para producir aglomerantes aéreos. Estos resultados se han combinado para crear una guía de buenas prácticas para la restauración sostenible de los edificios del patrimonio cultural.

Palabras clave: Patrimonio cultural arquitectónico; Restauración; Arqueometría; Arquitectura vernácula.

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1. INTRODUCTION

The characterization of building materials has become an important aspect in restoration research, so much so that it forms a perfect symbiosis with the conservation of historical heritage in sites of universal value. Previous studies based on the characterization of materials using quantitative and qualitative techniques (1), (2), (3), (4), (5), (6), (7), (8), (9) confirm the validity of this approach. Also it is necessary highlighting the importance of the analyzes it was performed, which provide precise information about the properties and characteristics of the materials involved (4), (10), (11), (12). It is also important to find out more about the manufacturing process of these materials as this can affect their performance (13), (3) and can help researchers to reach conclusions regarding the possible causes of damage they have suffered (14), (15) guarantee the suitability of the restoration products and ensure that only those with similar or appropriate properties of the materials will be used in the restoration work required by most heritage buildings (16), (17), (18), (19), (20), (21), (22), (23), (24).

Colegio Máximo de Cartuja (Granada-Spain) is situated in the Cartuja campus of the University of Granada, a site that is well-known for a large number of interesting constructions from burial sites from the Neolithic period to the most modern building housing the Mind and Brain Research Centre. Remains from a Roman era pottery workshop have also been discovered (1st and 2nd centuries CE), along with Arabic water channels, necropilises from the Al-Andalus period (7th-9th centuries) and post-Renaissance religious buildings. The site also has an infinite range of examples of its long and interesting history over the centuries as a historic town outside the walls of Granada.

The University of Granada now plans to put all this on display via the restoration and enhancement of these different constructions, which will carry out as a cultural route (25) (see Figure 1A), that includes other buildings of enormous heritage value, such as the Monastery of Cartuja (Cent. 16), the Cathedral (Cent. 16) and the Royal Hospital (Cent. 17). The building studied in this paper, Colegio Máximo de Cartuja (see Figure 1B), which currently belongs to the University of Granada, is situated near the Carthusian Monastery (Monasterio de La Cartuja) which gives the area its name. Colegio Máximo was the first construction built by the Jesuits in this area at the end of the 19th century (1891-1894), on a site that had been highly praised by Muslim chroniclers and poets (26). It was later followed by other buildings, such as the Astronomical, Geophysical and Meteorological Observatory (1901-1902) (27). The building was designed by the architect Francisco Rabanal, who had close links with the Jesuits. It followed various architectural tendencies in vogue in Spain at the time, becoming a clear exponent of the Neo-Mudejar style (28). The use of this neo-Arabic style was vogue in Spain at the time, becoming a clear exponent of the Neo-Mudejar style (28).

2. DESCRIPTION OF THE BUILDING

The building stands alone and has a rectangular floor plan which is organized around four courtyards, two large ones in the front parallel to the main axis of the building and situated around the neo-Arabic chapel, and two other narrower courtyards towards the rear (Figure 1B). The building has three floors. The west, north and south façades (principal and lateral) follow the same lines in terms of composition and use of materials, while the east façade (rear), above all due to the slope of the terrain, is different from the rest of the building in that the ground floor is obscured from view and only the two upper floors are visible. The building occupies an area of 1.2 ha and each façade is over 100 m long. The main façade is flanked by towers situated at either end and there are two more towers framing the main entrance (32).

The façades are composed of large “boxes” of masonry, supported by lines of bricks, corner supports and plain, undecorated brick friezes. In certain areas (main entrance and win-
dows) the bricks are painted dark red (Figure 1C). The whole building is surrounded by brick skirting (although the section on the rear façade is different from the rest), which varies in height between 1.0 and 1.5 metres above the ground. The bricks have similar compositional characteristics and come in two sizes. The bricks used on the main façade measure 6.0 x 11.5 x 23.0 cm, while those used on the sides measure 5.0 x 13.5 x 27.0 cm. Some of them bear the stamp of the factory (see Figure 1f) with the inscription “ROOF TILES AND BRICKS - ALL KINDS OF FLOORS TILES IN JUN”; Jun is a village near Granada in which there are large clay deposits and a long tradition in handcrafted pottery.

Together with the façades of Colegio Máximo, in this study it will also be investigated the chapel, which has various constructed areas. Of particular interest is the ropework ceiling simulating polychrome wood, and the three walls decorated with polychrome plasterwork and striking Nasrid-style epigraphic inscriptions. The walls are crowned by the windows in horseshoe arch shape and trimmed beneath with tiles with geometric and ropework decoration. The tiles are glazed with the typical palette of colours used in Nasrid Islamic architecture, which is based on white colour for solid background made of tin and lead oxides and green, blue and earth colours for geometric decoration made from copper, cobalt and iron oxides, respectively. The windows are made up of 3mm-thick pieces of stained glass which are joined together using soldered strips of lead (Figure 1E). Other interesting features include the glazed tiles on the outside of the building decorated with geometric motifs, and the stamp or hallmark of the brickmaker, which appears on a lot of the bricks used in this building (Figures 1D).

From a geological point of view, Colegio Máximo de Cartuja is based on white colour for solid background made of tin and lead oxides and green, blue and earth colours for geometric decoration made from copper, cobalt and iron oxides, respectively. The windows are made up of 3mm-thick pieces of stained glass which are joined together using soldered strips of lead (Figure 1E). Other interesting features include the glazed tiles on the outside of the building decorated with geometric motifs, and the stamp or hallmark of the brickmaker, which appears on a lot of the bricks used in this building (Figures 1D).

3. MATERIALS AND METHODS

3.1. Materials

The samples analyzed are representative of the wide range of building materials (bricks and mortars from the façade, tiles and stained glass windows) used in different parts of the building. A total of 21 samples were characterized, as can be seen in Table 1. The samples were classified into five groups corresponding to the different types of materials studied (masonry concrete, masonry mortar, brick, wall tile and stained glass). The location and the construction feature from which each sample was extracted are also indicated. In all cases, the most important materials extracted (masonry concrete, masonry mortar, brick, wall tile and stained-glass) were found, on a visual inspection, to be in a good condition, and to have a suitable size and weight for transportation and storage (specific plastic bags).

Table 1. List of samples studied in this paper, highlighting location and kind of material

<table>
<thead>
<tr>
<th>Material</th>
<th>North façade</th>
<th>South façade</th>
<th>East façade</th>
<th>West façade</th>
<th>Chapel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>FNB1</td>
<td>FSB3</td>
<td>FEB5</td>
<td>FWB7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FNB2</td>
<td>FSB4</td>
<td>FEB6</td>
<td>FWB8</td>
<td></td>
</tr>
<tr>
<td>Glazed tile</td>
<td></td>
<td></td>
<td>FWT1</td>
<td>CHT3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>FWT2</td>
<td>CHT4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CHT5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stained glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CHSG1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CHSG2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CHSG3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mortar Masonry</td>
<td>FNMM1</td>
<td></td>
<td>FWMM2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete masonry</td>
<td>FNCM1</td>
<td></td>
<td>FWCM2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2. Methods

Chemical analysis

The samples were analyzed using a PANalytical Zetium X-ray fluorescence spectrometer (XRF) with a ceramic x-ray tube, a 4 kW rhodium anode x-ray generator and a non-coupled gonimeter of 0°/2° (Granada University Scientific Instruments Centre). The XRF samples were ground mechanically in an agate mortar and then sieved to a grain-size fraction of <0.354 mm (mesh size 45).

X-ray diffraction

The X-ray diffraction samples were analyzed with an MPD Pananalytical X'Pert diffractometer, using Cu Kα radiation (1.54056 Å), under working conditions of 45 kV and 40 mA. The diffractograms were recorded between 2θ = 5-600 from a powder sample ground in an agate mortar to a grain size of < 30 µm. The composition was determined with the Xpowder software (34), which takes into account multiple iterations of models of the mixture, so as to guarantee greater precision with the real diffractogram. The samples for the XRD analysis were separated and sieved in a fraction of <1 mm (mesh size 18).

Differential thermal analysis

The mineralogical characterization tests and the tests on the texture and the microstructure of the samples were performed with a polarized optical microscope (Olympus BX-60) and a Zeiss DMS 950 scanning electron microscope (SEM) coupled with Microanalysis Link QX 2000. Apparatus conditions include maximum magnification of 300,000x, acceleration voltage of 1–30 kV, a tungsten filament electron source and SE detector, together with EDX microanalysis Röntec, series M, Edwin, Si (Li), from the University of Granada Scientific Instruments Centre. The samples for SEM observation were prepared for morphological and analytical study by adhering them to the base with colloidal silver and covering them with nano-carbon particles.

Optical and SEM-EDX microscopy

The samples for colorimetric assessment were measured in the visible range using a Konica Minolta CM-2500c spectrophotometer or a non-coupled goniometer of θ/2 (Granada University Scientific Instruments Centre). The XRF samples were measured while combining the X-ray tube, a 4 KW rhodium anode x-ray generator and a quartz anode x-ray generator with specific mortars). 400 samples were measured on site (20 for each group). The diffuse spectral reflectance curves for the different materials studied were measured in the visible range using a Konica Minolta CM-2500c spectrophotometer, with a wavelength of 360 nm to 740 nm, a 2° and 10° observer, CIE 1931/2, CIE 1964/10 (36), (37) and a D65 illuminant.

4. RESULTS AND DISCUSSION

XRD

The XRD results of brick fragments (FEB5 and FWB7) from two different façades of the building (east and west) can be seen in Figure 2. The significant presence of calcite without thermal alteration suggests that brick samples FEB5 and FWB7 were fired at temperatures < 750 °C as the studies show (38), (39) (40). The presence of dolomite may be due to the raw materials used in the manufacture of the bricks, the vast majority of which come from the Paleosols (Pleistocene) geological formation based on red clays, gravels and sands, composed of calcareous, ferruginous and dolomitic clays, together with illite minerals and lime, and dolomitic grogs (33). The presence of feldspars and muscovites was found in the geological formation and the quarries from which the raw materials used in pottery and brickmaking were extracted. In addition, the presence of analcime in the diffractogram could be due to the clay raw materials of geographical context that could contain sodium, or due to the alteration by soluble salts coming from subsoil, deposited in the bricks once laid in the building (41), (42). Another interpretation of the provenance of analcime in these bricks may be due to the addition of sodium chloride in raw bodies by brickmakers, which, as has been proved, improves its plasticity and workability, as well as reduces the sintering temperature and provides greater compaction and mechanical strength of the ceramic materials obtained (39), (43). All of this verify that the clay raw materials used are of low temperature, a fact which coincides with the geological chart of the area that indicates the presence of sediments and red clays, which chemical composition does not allow high temperature firing (33), (44).

Colorimetry

All the samples were subjected to a colorimetric assessment so as to establish colour patterns for the main building materials used in Colegio Máximo de Cartuja (masonry concrete, masonry mortar, bricks, wall tiles and stained glass), in order to facilitate standard restoration tasks (cleaning, consolidation, replacement or filling in cracks and holes with specific mortars). 400 samples were measured on site (20 for each group). The diffuse spectral reflectance curves for the different materials studied were measured in the visible range using a Konica Minolta CM-2500c spectrophotometer, with a wavelength of 360 nm to 740 nm, a 2° and 10° observer, CIE 1931/2, CIE 1964/10 (36), (37) and a D65 illuminant.
Figure 2 shows also the diffractograms for the ceramic body or biscuit of the wall tiles (FWT1 and FWT2). These materials have different characteristics from those of the bricks because they must have been fired at higher temperatures of around 1000°C, in particular in the second firing in which the thick glazes coating the tiles are melted. The XRD peaks for calcite are less frequent, suggesting greater presence of calcium oxide, which is obtained at temperatures of over 900°C. The analcime (FWT2) may result from the decomposition of the vitreous phase of the tiles (as noted in samples from archaeological sites in Switzerland (42), (46), (47), (48), or preferably of the use of NaCl as an additive to make the body more fluid. The remaining components observed in the analysis, such as anhydrite, are typically found in local clayey soils and/or in efflorescence.

**Table 2.** Chemical composition by XRF analysis (wt %) of bricks (FEB5, FWB7), glazed tiles (FWT1, FWT2), concrete masonry (FNCM1), mortar masonry (FWMM3) and stained glass (CHSG1).

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>CaO</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>Fe₂O₃</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>CaO₃</th>
<th>PbO</th>
<th>SO₃</th>
<th>CoO</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEB5</td>
<td>72.99</td>
<td>0.98</td>
<td>68.92</td>
<td>1.35</td>
<td>5.77</td>
<td>0.59</td>
<td>2.90</td>
<td>0.93</td>
<td>62.70</td>
<td>3.01</td>
<td>0.67</td>
<td>0.71</td>
</tr>
<tr>
<td>FWB7</td>
<td>72.35</td>
<td>1.11</td>
<td>44.44</td>
<td>1.59</td>
<td>3.85</td>
<td>1.45</td>
<td>3.76</td>
<td>1.11</td>
<td>68.92</td>
<td>3.01</td>
<td>0.94</td>
<td>0.89</td>
</tr>
<tr>
<td>FWT1</td>
<td>74.22</td>
<td>0.95</td>
<td>14.14</td>
<td>1.59</td>
<td>3.85</td>
<td>1.45</td>
<td>3.76</td>
<td>1.14</td>
<td>69.92</td>
<td>3.01</td>
<td>0.94</td>
<td>0.89</td>
</tr>
<tr>
<td>FWT2</td>
<td>74.22</td>
<td>0.95</td>
<td>13.92</td>
<td>1.35</td>
<td>2.32</td>
<td>1.92</td>
<td>3.94</td>
<td>1.14</td>
<td>69.92</td>
<td>3.01</td>
<td>0.94</td>
<td>0.89</td>
</tr>
<tr>
<td>FNCM1</td>
<td>72.99</td>
<td>0.55</td>
<td>14.44</td>
<td>1.33</td>
<td>5.57</td>
<td>0.50</td>
<td>2.90</td>
<td>0.93</td>
<td>63.70</td>
<td>3.01</td>
<td>0.67</td>
<td>0.71</td>
</tr>
<tr>
<td>FWMM3</td>
<td>74.22</td>
<td>0.95</td>
<td>14.44</td>
<td>1.59</td>
<td>3.85</td>
<td>1.45</td>
<td>3.76</td>
<td>1.14</td>
<td>69.92</td>
<td>3.01</td>
<td>0.94</td>
<td>0.89</td>
</tr>
<tr>
<td>CHSG1</td>
<td>70.10</td>
<td>0.63</td>
<td>0.25</td>
<td>0.28</td>
<td>5.80</td>
<td>0.66</td>
<td>15.50</td>
<td>0.03</td>
<td>0.70</td>
<td>0.59</td>
<td>24.50</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**OPTICAL MICROSCOPY**

The ceramic materials studied have matrixes composed of clays and tempers made of crushed rock (mixed into the base pastes) and other ceramic residues (groses). The relative compactness of these ceramics suggests low sintering and low firing temperature. Pores of 10-20 µm can be observed. The brick fragment from the east façade (FEB5) can be seen in Figure 3 (image A). It has large pores throughout the matrix, which is based on phyllosilicates and large amounts of quartz groses of varying size ranging from very small (250 µm) to the largest measuring around 3 mm. The laminar illite-type grogs are highlighted in red, together with the carbonate grains. The temper was hardly altered by heating, as can be seen in the quartz with well-defined, clear-cut edges. Mineralizations can be detected which coincide visually with analcime (highlighted in red). Image B of sample FWB7 from the west façade shows a ceramic material with high porosity and low compactness, with a hardly sintered clay matrix, dominated by illite grogs and schist fragments from the geological area, which range in size from 70 µm to 2 mm. A large number of unaltered quartz groses can also be observed, marked in red in the image. Feldspar is also present as part of the clayey material from the quarry.

The mortar sample (FNCM1) from the north façade, seen in Figure 3 image C, is a very porous mortar-concrete material, with a pore size ranging from >250 µm down to micropores of ~20 µm. The matrix is calcareous with well-carbonated lumps and fragments of aggregate of muscovite and quartz (marked in red) of between 40-50 µm in size. Image D shows sample FWMM3 from the west façade. This is an air lime mortar with a very porous matrix in which retraction fissures and isolated carbonate lumps can be observed. Acicular lumps of gypsum can also be seen, marked in red in the Figure 3 (image D).
La glasa de la imagen muestra que la glasa es aproximadamente de 0.20-0.25 mm de espesor con algunas fisuras y microbultos bien adheridos al ladrillo. Para las baldas y vidrios de ventana vidriada, los resultados muestran que se usa policlorito.

**SEM-EDX**

La Figura 4A (muestras FNB1) muestra que el material cerámico no ha sinterizado (una matriz de arcilla poco compactada) y contiene cantidades de poros. No hay signos de fusión de partículas. Pueden verse bordes definidos sin signos visuales de sinterización. La EDX confirma que los ladrillos son ricos en ilita debido a la presencia de magnesio, potasio y hierro. Se puede inferir que la presencia de sodio es debido a analcima. La Figura 4B muestra un material cerámico sin sinterización, sugiriendo el uso de un aglutinante de baja temperatura. La EDX se observa coherente con calcita. Los detalles de imágenes F, mortero de cal (FWMM3), 40X, cruzados nicols, la presencia de cuarzo y muscovita agregados es marcada en rojo. Imágenes E, mortero de concreto (FNCM1), 40X, cruzados nicols, con detalle del cemento y la matriz de las partículas. Las partículas de ilita sin suavización térmica se pueden observar debido a la baja temperatura de sinterización. La EDX analiza el coherente con la composición calcárea y ilítica (Fe-K), frita a altas temperaturas y con trazas de magnesio y sodio, el uso probablemente debido a la adición de plásticos o agentes de fusión. En ambos casos, los resultados obtenidos son coherentes con los materiales locales de arcilla en los diferentes estratos geológicos.

La Figura 4C muestra un mortero de concreto (FNCM1), de alta porosidad, con agregados de cal y latita. La Figura 4D muestra un mortero de concreto (FNCM1), de alta porosidad, con agregados de cal y latita. La Figura 5A muestra un ladrillo de grande espesor (CHT4), un mortero de concreto. El SEM muestra que la glasa es de aproximadamente 0.20-0.25 mm de espesor con algunos fisuras y microbultos adheridos al cerámica. Un número importante de poros pueden ser observados en el mortero. Se observan bordes definidos con poros visibles. Los análisis SEM confirman la composición de una temperatura de fusión férrica-calcarea con potasio. La análise de la glasa muestra que es una capa glasa que se aceleró a una temperatura aproximada entre 900-1000ºC. Los elementos de coloración en el cobre y el hierro de la glasa también se encuentran juntos con una opacidad de zinc. La Figura 5B muestra un ladrillo de color blanco con un espesor aproximado de 0.2 mm y pequeñas burbujas de aire. Aunque el mortero de glasa es poroso, tiene un nivel aceptable de compactación debido a la adición de un segundo fuego para fundir el mortero. La EDX analiza el coherente con la mezcla de cálculos y agregados de cerámica. En ambos casos, los resultados obtenidos son coherentes con los materiales de cerámica locales en los diferentes estratos geológicos.

La Figura 5C muestra un vidrio con un espesor aproximado de 3 mm. En la superficie se ha acumulado polvo. La EDX analiza la composición característica de este tipo de vidrio (una caliza con un aglutinante de fundición).

**DTA**

Los resultados promedio de las medidas en línea con los resultados de la difracción de rayos X. Las temperaturas fueron calculadas por medio de un programa con el que se procesaron los resultados. En estos análisis se observaron picos endotérmicos que pueden ser observados en el 80-140ºC, probablemente debido a un gasto de agua que se disuelve. Estos picos se acompañan de un gasto de peso. Los picos endotérmicos posteriores a 728ºC (muestras FWB5) y 773ºC (muestras FWB7) se deben a la reacción del calcita (CaCO₃), que es muy abundante en ambas muestras. Este resultado también se traduce en una caída en el peso después de que se estabilizan. La respuesta del calcita se registró en los análisis de las muestras cerámicas que indica que el calcita estaba intacto en ambos; en otras palabras: no se había fundido en tiempo de fundición o de calentamiento a la temperatura de descomposición del calcita. La gráfica de la figura 6 indica que la temperatura de fundición podría haber sido ≈790ºC (FWB5) y 770ºC (FWB7), respectivamente. Esto confirma que los resultados se dedujeron de los rayos X. Es importante destacar la heterogeneidad de las muestras cerámicas y que todos los seres humanos han contribuido al fenómeno de fundición.
was artisanal, rather than industrial, and the manufacturers had limited technical resources at their disposal.

**ULTRASOUNDS**

Table 3 sets out the average values for the bricks and mortars measured at different locations with average velocity and standard deviation data. The ceramic materials show similar values to other ceramics fired at low temperatures of ≤750ºC. Some authors report similar values for common pottery type ceramics fired at low firing temperatures at which the clay bodies do not reach sintering (38). In addition, the mortars, concretes and renders made with air lime show expected values for this kind of material (51) both in air lime mortars and in those containing gypsum additives.

**Table 3.** Average/standard deviation values of ultrasound transmission speed of masonry bricks, masonry concrete and masonry mortar

<table>
<thead>
<tr>
<th>Site</th>
<th>Masonry brick</th>
<th>Masonry concrete</th>
<th>Masonry mortar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m/s</td>
<td>Vp1 Vp2 Vp3</td>
<td>Vp1 Vp2 Vp3</td>
</tr>
<tr>
<td></td>
<td>σ 82     84 79</td>
<td>8092 79</td>
<td>7178 100</td>
</tr>
<tr>
<td>S FACAD</td>
<td>1075</td>
<td>1302 1188</td>
<td>1217 1198 1113</td>
</tr>
<tr>
<td></td>
<td>σ 89     91 95</td>
<td>77 93 89</td>
<td>79 72 85</td>
</tr>
<tr>
<td>E FACAD</td>
<td>1985</td>
<td>1340 1292</td>
<td>2127 1238 1208</td>
</tr>
<tr>
<td></td>
<td>σ 85     72 87</td>
<td>79 76 81</td>
<td>89 84 82</td>
</tr>
<tr>
<td>W FACAD</td>
<td>2438</td>
<td>1792 1545</td>
<td>2095 1943 1985</td>
</tr>
<tr>
<td></td>
<td>σ 92     91 82</td>
<td>76 69 73</td>
<td>84 93 76</td>
</tr>
</tbody>
</table>

**COLOUR**

The colour of the samples was also studied showing a wide palette of different tones. Figure 7 shows the chromatic coordinates L*, a* and b*, according to the CIELab1976 system (Hoffmann, 2010). The colours of the mortars, concretes and bricks from the building can be seen in image 7A. All the materials studied have a tonal position in the yellow and red quadrant except for group 2CM, which has yellow and green hints. Colorimetric heterogeneity over unpainted bricks is due to craft firing and can undergo selective oxidation reductions in kiln. The mortars and concretes have very low saturation and high levels of lightness, which results in the colour being perceived as off-white. The bricks in general are more saturated in yellow and red tones and also have high levels of lightness.
The colours of the glazed area of the tiles (Figure 7B) have very heterogeneous positions in all the chromatic quadrants together with a range of lightness values, so recovering in detail the palette of colours characteristic of Granada ceramics of Nasrid tradition (52). Figure 7C displays the range of colours in the glass from the stained glass window from the Chapel of Colegio Máximo de Cartuja. In general, these are simple colours (blue, green and ochres), which are technically easy to produce.

5. CONCLUSIONS

1. The archaeometric study of the construction materials used in Colegio Máximo de Cartuja highlights the use of locally sourced materials, as confirmed by references from geological area.

2. The techniques used to produce these materials were semi-artisanal, which means that they are not totally uniform. There are variations for example in the colour of the bricks as a result of both the heterogeneous nature of the raw materials and also of the firing processes (unintentional changes in the oxidizing and/or reducing conditions inside the kiln).

3. The unusual presence of analcime in this kind of ceramic materials fired at low temperatures suggests that common salt (NaCl) could be used as an additive in the unfired ceramic bodies used to make the bricks. In the right proportions, this additive can improve the workability and plasticity of clay-based ceramic bodies and reduces the thermal maturity temperature and the sintering temperature of the ceramics. This is a very important factor in the semi-artisanal production of ceramic materials when it comes to reducing costs.

4. The choice of local raw materials was another important aspect in the construction of this building. The proximity and ready availability of raw materials makes a possible restoration work easier, as does the long tradition of manufacturing building materials on the site itself, in the Albaicín neighbourhood and in villages nearby, as well as possible reuse of quarries for clays and grogs, quarries for the production of binders (air lime or hydraulic) or for the extraction of aggregates. All of this would enable the use of suitable conservation materials and techniques, thus reducing the impact of previous restoration works on heritage buildings of singular value.

5. The results of the colorimetric study were used to create a colour chart for the main building materials used in the construction of Colegio Máximo, thus facilitating future restoration work on heritage buildings of this kind.

6. All the materials used in the construction of this building are an integral part of the overall concept of the Jesuit architect, who sought to recover much of the Arabic legacy still present on the hill of La Cartuja. The result was a Neo-Mudejar design for the main parts of Colegio Máximo (Theology Faculty) together with a selection of colours that had a long, extended tradition in the Arab world (54), (55). In this sense the use of colours based on earths, iron, copper or cobalt was a clear tribute to the culture of Al-Andalus, ever present in the city of the Alhambra.

7. The recovery and enhancement of the architectural cultural heritage in different types of buildings and structures in different places poses a real challenge for those researching in the field of materials science and for those working in conservation. The composition of these materials, the way they are used in the building and their state of damage and deterioration are key aspects in the necessary analysis required prior to any restoration work. Furthermore, from the point of view of the restoration of historical buildings, the main focus of this research, when these buildings are part of the architectural and cultural heritage of a particular geographical area, they have their own unique features at a strictly conceptual, formal or compositional level and from the materials point of view, when it comes to construction, conservation, restoration, recovery and enhancement.

8. This research has shown that when building Colegio Máximo de Cartuja (C. 19), the Jesuits acted in much the same way as the Carthusians had when they built the nearby Monastery of Cartuja (C. 16), and the Iberian and Roman settlers had done in the construction of their pottery workshops (C. 1 and 2 C. E), using techniques involving “water and clay” from the hill itself and from the River Beiro that flowed alongside.

9. Analytical results of construction materials reveal the historical tradition of “water and clay” in Albaicín quarter, Cartuja Hill and Beiro River, from Roman times to the present, as well as the use of sodium chloride in ceramics for better vitrification at lower temperatures. Recovering of vernacular materials and techniques in the area can generate a culture of sustainable restoration that will result in an economic dynamization of this area for tourism sector. In addition, related to conservation works the mandatory restoring proposals would be surface cleaning, joining and replacement of detached parts, consolidation of materials and final protection.

6. ACKNOWLEDGEMENTS

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