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Physico-chemical material characterization of historic unreinforced masonry buildings: The first step for a suitable intervention

I. Martínez [a,*], A. Castillo [a], E. Martínez [b], M. Castellote [a]

[a] IETcc, Spanish National Research Council (CSIC), C/Serrano Galvache, no 4, 28033 Madrid, Spain
[b] ETS Arquitectura (UPM), Campus Ciudad Universitaria Avenida Juan Herrera, no 4, 28040 Madrid, Spain

HIGHLIGHTS

- ▶ Use of IR thermography as a complementary NDT in structural assessment.
- ▶ Establish an evaluation procedure for historical structures.
- ▶ Mortar characterization: lime mortar, discarding the possibility of cement or gypsum as binder material.
- ▶ Mechanical resistance lower than expected.

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ABSTRACT

In this paper, a methodology to determine the physico-chemical characteristics of the original mortar used during the construction of the structure was applied as a first step prior to the intervention process. Due to the bad conservation state of the structure, an exhaustive damage analysis was applied to the structure using among others, infrared thermography. Mechanical characterization was also necessary to determine the structural stability of the element and the cohesion and resistance of the original materials. The mortar characterization was carried out using complementary analysis techniques and the conjunction of the results obtained allows the determination of binder type, possible mortar degradations and other characteristics, allowing the selection of the most suitable repair material for the intervention process. The results lead to conclude that we are talking about a lime mortar, discarding the possibility of cement or gypsum as binder material. Particularly, the binder has been characterized as sub-hydraulic or feebly lime, in the middle between pure and hydraulic lime, and it is possible to precise that it was developed using the so called hot lime technology.

1. Introduction

In this paper an intervention method has been applied to a particular structural element, the bell gable of the church of St. Mary Magdalene, in the Convent of Our Lady of Consolation in Alcala de Henares. This church was built around 1672. European architecture of the 17th century, referred to as Baroque, is characterized by magnificence, grandeur and richness in invention, design and, usually, in scale. Despite the damage caused during the Spanish Civil War, the convent has retained its Baroque character, although it has undergone several interventions since its construction, which makes it possible to find material heterogeneity in the structure.

It is a brick building construction with stone details in the gaps. The bell gable is a ceramic brick wall structure that protrudes vertically from the rest of the building. It consists of two bodies separated by a cornice. The lower body has two holes in the form of arch and the upper one has only one arch topped with a triangular frieze. The material is primarily brick masonry in different sizes and layouts. The cornices are made with molded brick. The mortar is of unknown composition and with heterogeneous aggregates.

In relation to the possible origin of the mortar, a first question is what type of binder was used in the existing mortar. Common binders and binder components are lime, hydraulic lime, cement, pozzolans and clay. Gypsum is common in plasters and decorations, but has also been used for external joints in specific locations.

From the ancient times to the early 19th century, in Europe, mortars were generally pure lime (also called non-hydraulic lime, or aerial lime, as they need air to carbonate and set), hydraulic lime (hardened under water) or pozzolanic. Pure lime is produced from

* Corresponding author. Tel.: +34 91 3020440; fax: +34 91 3020700.
E-mail addresses: isabelms@ietcc.csic.es (I. Martínez), acastillo@ietcc.csic.es (A. Castillo), enrimar@arquired.es (E. Martínez), martaca@ietcc.csic.es (M. Castellote).

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pure limestone while the hydraulic lime mortar is produced from a limestone containing small amount of clay and other siliceous minerals. Dolomitic (magnesium–calcium) lime mortars are common in some areas, and their properties are different form calcium lime mortars.

The problem is that present nomenclature for pure lime binders and hydraulic binders intended for use in masonry mortars and renders is tailored to the materials available on the market today. Following present standards, such as EN 459-1 [1] European Normative for building limes), a large proportion of historical mortars fall into the category of non-hydraulic mortars (pure lime binder, CL 90), although their functional properties often reflect a significant content of hydraulic components in the binder. For this reason, some authors [2] have included the category of sub-hydraulic binder in historical mortars. It would be misleading to regard these mortars as pure lime mortars, although they generally do not harden under water. The hardening of these mortars occurs largely through carbonation. This results in a mortar with higher final strength and generally lower porosity. So, this is an important group of mortars that requires special attention and to some extent provides an opportunity to use more durable mortars in applications that are exposed to severe climatic conditions.

The classification used by Boynton [3] based on the cementation index, CI, developed Eckel [4], it is very useful to estimate the mortar hydraulicity. To obtain the CI, it is essential to analyze calcium and silica dissolved in acid solution. For a more accurate calculation, expression (1) must be applied. The CI is defined as

$$CI = \frac{2.8 \times SiO_2 + 1.1Al_2O_3 + 0.7Fe_2O_3}{CaO + 1.4 \times MgO} \quad (1)$$

Even though this calculation does not provide direct information about the binder composition, it is very useful to know the hydraulicity properties of the mortar. The CI lower limit for the least hydraulic binders, classified by Boynton as feebly hydraulic, is 0.30. Under this limit, all mortars are supposed to be considered as pure lime. So, this index do not distinguish between different types of historical mortars and provide an insufficient basis for the choice of restoration mortars. For this reason, the Rilem [2] include the sub-hydraulic category in the following classification:

Pure (aerial) lime: $CI < 0.15$.
Subhydraulic lime: $0.15 < CI < 0.30$.
Feebly hydraulic lime: $0.3 < CI < 0.5$.
Moderately hydraulic lime: $0.5 < CI < 7$.
Eminently hydraulic lime: $0.7 < CI < 1.1$.

A binder with CI near 1 is comparable with a Portland cement.

In general, if the mortar is from around 1850 or later, it may contain a hydraulic lime as binder. It was the precursor of Portland cement. From the end of the 19th century, Portland cement and its derivatives became the major binding material in construction.

Cases of damage are known to have been caused by the use of cement in the conservation of historic buildings because cement is too hard, rigid and impermeable. Cement also contains more soluble salts, which can be harmful to historic buildings. These salts not only produce unaesthetic layers on the building, but can also develop large crystallization pressures thus damaging the historic building; so, in order to undertake a repair, it is crucial to date the original materials as well as determine the exact type of compatible mortars.

The structure mentioned in this paper and shown in Fig. 1 was assessed and analyzed using an intervention method [5] to determine the degree of deterioration and its physico-chemical characteristics. .Therefore, the main objective is to determine the type of binder and other original mortar characteristics, such as hydraulicity or carbonation degree. It enables the proper selection of the retrofitting material. Even though it is not probable to find cement as binder in the original mortar composition, it could be present in some restored areas due to different intervention processes carried out in the structure during the XX century. So, it will be helpful to localize these areas and determine possible damages due to the wrong use of cement mortar in previous restorations.

Fig. 1. Bell gable of the church of the Convent of Our Lady of Consolation in Alcala de Henares.

The mortar characterization was carried out using complementary analysis techniques as are analysis techniques, such as chemical analysis, mercury intrusion porosimetry (MIP), X-ray diffraction (XRD), Scanning electron microscopy (SEM) coupled with Energy dispersive X-ray microanalysis (EDX) and thermal analysis. The combined results obtained from the different techniques enabled the determination of the specific type and properties of the binder used.

2. Experimental program

2.1. Non destructive evaluation by infrared thermography

Infrared thermography was used as a complementary tool for the on site structural inspection, showing defects and damages to the structure not detected by visual inspection [6–9].

The infrared study was carried out with a camera with an image quality of 320×240 pixels and thermal sensitivity lower than 50 mK. The temperature range was from -20 up to +120 °C. The infrared radiation detector used was a microbolometer without refrigeration which works within wave length interval from 8 to 13 μm.

2.2. Material characterization

Four samples were extracted from different affected parts of the bell gable to make a complete study of the mortar composition and properties. Its adhesion to the brick and strength characteristics were also examinated. The mortar characterization was made following the recommendations given by Rilem in [2] and [10] as well as other indicators given by different authors [11–18].

Chemical analysis, mercury intrusion porosimetry (MIP), X-ray diffraction (RDX), Scanning electron microscopy (SEM) coupled with Energy dispersive X-ray microanalysis (EDX), thermal analysis and mechanical tests were performed on the samples. This enabled an in depth examination of the binder and aggregate composition, as well as the different phases presented, possible mortar degradations and other binder characteristics, e.g. hydraulicity. In this way, the selection of the treatment to apply to the structure as well as the material choice for the intervention process were made easier.

The elemental chemical analysis was made on two representative samples of the mortar, one from the external part, in contact with the environment, and the other from an internal part. After grinding the samples, oxides Al_2O_3, CaO, Fe_2O_3, MgO, P_2O_5, SiO_2, K_2O, Na_2O and TiO_2 were quantified using an Optical Emission Spectrometer. ICP. For the SO_3 quantification, standard UNE 196-2 [19] was followed.

The SEM images were taken with a field emission scanning electron microscope (cold cathode), coupled to a Energy dispersive X-ray microanalysis (EDX). The general analytical conditions were: acceleration voltage, V_{ac} = 20 KV and excitation cur-