Building Pathology and Rehabilitation

J. M. P. Q. Delgado *Editor*

Case Studies in Building Rehabilitation

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Building Pathology and Rehabilitation

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Preface

Building pathology is the scientific study of the nature of building failure and its causes, processes, development and consequences, to help create the right remedial and management resolutions. Rehabilitation is a strategic area that is concerned not only with the monumental heritage and historic buildings, but also with other buildings that have been in use for some time and need to be adapted to the demands of the present. The evolution of degradation can be interpreted as the continuous reduction in performance over time.

The main purpose of this book, *Case Studies in Building Rehabilitation*, is to provide a collection of recent research works, case studies and real-life experiences of building pathology, to contribute to the systematization and dissemination of knowledge related to building pathologies (structural and hygrothermal), durability and diagnostic techniques and, simultaneously, to show the most recent advances in this domain. It includes a set of new developments in the field of building pathology and rehabilitation, bridging the gap between current approaches to the surveying of buildings and the detailed study of defect diagnosis, prognosis and remediation. It features a number of case studies and a detailed set of references and further reading.

The book is divided into six chapters that intend to be a resume of the current state of knowledge for the benefit of professional colleagues, scientists, students, practitioners, lecturers and other interested parties to network. At the same time, these topics will be going to encounter a variety of scientific and engineering disciplines, such as civil, materials and mechanical engineering.

Porto, Portugal J. M. P. Q. Delgado

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Characterization of Ancient Mixed Masonry Structures of Brickwork Infilled by Cobblestone Wall

I. Lombillo, Y. Boffill, J. Pinilla, E. Moreno, and H. Blanco

Abstract A great part of the Architectural Heritage is constructed with masonry walls. Certain interventions in this Heritage make it necessary to characterize the mechanical properties of these load-bearing elements. This article has the aim of proposing and using several complementary methods applicable to the characterization of the materials forming historical masonry structures, applying them to mixed masonry made up of bricks, lime mortars and cobblestones. In this research, tests were carried out on a building constructed in two clearly differentiated periods, 15–18th century and 19–20th century. A sample-taking campaign was done on bricks, mortars and portions of masonry, for later physical-chemical-morphological-mechanical testing in laboratory, and an in situ experimental minimally-intrusive campaign using techniques such as flat-jack, sclerometer and penetration-meter on mortars. The mechanical results obtained enabled the evaluation of the validity of some experimental formulas for estimating the strength of masonries from the strength of their component materials (brick and mortar), when applying them to historical constructions. In the same way, the physical-chemical characterization tests carried out enabled the justification, economically and minimally intrusively, the differentiation of the materials employed in the two construction periods.

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Keywords Masonry structures · Architectural heritage · Laboratory experiments · In situ campaign

1 Introduction

Within the intervention process, previous knowledge is fundamental when choosing the most suitable techniques and materials applicable in preservation and damage prevention in Cultural Heritage (Binda et al. 1999, 2009). Therefore, the refurbishment process should be based in precise previous investigation (Binda et al. 2008).

The masonry structures are composed of petrous or ceramic pieces joined in most cases by a conglomerate. The mechanical strength of the masonry depends on several factors such as the strength of the pieces and of the conglomerate, the size of the pieces, the humidity content, the emplacement method, etc. (Martínez et al. 2001). Specific interventions on architectural heritage presuppose a modification of the forces on the load-bearing walls, so in many cases it is necessary to know their mechanical properties when establishing the most suitable intervention criterion. There are diverse ways of obtaining the mechanical properties and strength of masonry, from in situ N-MDT (Non-Minor Destructive Techniques) (Binda et al. 2000; Lombillo et al. 2013), experimental approximations based on breaking samples in the laboratory, or through the use of formulas. Thus, numerous attempts have been made to obtain empirical formulas that provide the masonry strength from the geometrical and mechanical characteristics of the components. Among the most notable are: Hendry and Malek (1986), the one proposed in Eurocode 6 (EN 1996-1-1:2005), BD 21/93 (1993) or ACI 530/99 (1999). There are also phenomenological formulas that have the advantage over the empirical ones of adapting to distinct typologies of masonries and materials, and not only the conditions under which the empirical formulas were obtained. Among these, Olher's formula (Hendry 1998) and the UCI one (1995) should be mentioned. The most rigorous way of obtaining the properties of the historical masonries is through the use of in situ diagnostic techniques, such as the techniques based on flat jacks, given that they enable the masonries to be tested under real conditions, avoiding the extraction of samples for later testing in the laboratory, a process that can significantly affect the results obtained. In fact, the existing formulas require the extraction of samples for testing the pieces and the mortar of the masonry.

In the case of ceramic bricks, their compressive strength depends on the density, which in turn depends on the raw material and the temperature of manufacture. Thus, the physical-chemical characterization of the materials is a tool that helps in the interpretation of the results obtained in the mechanical tests.

As for the mortars, their strength can be estimated indirectly through tests such as rebound index or penetration index. The compressive strength of mortar depends on multiple factors such as the density, the type of conglomerate, the water/conglomerate ratio and the conglomerate/aggregate ratio or the curing conditions.

This research aims to evaluate the validity of different techniques and methods generally applied in assessment of existing masonry buildings, applying them to the specific case of mixed masonry structures of brickwork infilled with lime mortar and cobblestones, a construction type which has been studied very little by the scientific community. Therefore, as a practical application, the characterization tests carried out on the load-bearing walls of a historical building, '*Los Aragoneses*' mill, are reported. Its current structure is the result of the union of two different volumes with diverse reforms, Fig. 1. The oldest dates from the middle of the 15th century, having being rebuilt some years later. The second part was attached to the first around 1780 with the aim of providing a new production module with a mill and a chapel. What is more, at the end of the 18th century the whole building was remodeled, with no information about whether remains of the original building were maintained. Finally, between the 19 and 20th century, a neo-mudejar-style back building was added, to house a steam engine press.

Independently of the construction era, the load-bearing walls of the building, both exterior and interior, are of mixed masonry structures of brickwork infilled with lime mortar and cobblestones, Fig. 2, with variable thicknesses between 35 and 80 cm, composed of:

- Masonry of brick and lime-based mortar: in vertical pilasters every 4–5 m and at the corners, in horizontal rows every 1–1.5 m, and in the edges of windows and doors. The bricks are solid of dimensions 28 × 14 × 3–5 cm, with bed joints of mortar ranging from 3–6 cm.

Fig. 1 General perspective of the emplacement of the 'Los Aragoneses' mill, Monachil (Spain)


Fig. 2 Mixed masonry of brickwork infilled with cobblestones and lime mortar

- Masonry of infilled cobblestones and lime-based mortar outlined by bricks.

A total of 4 manual trial pits were made to verify the conditions of the foundations of the load-bearing walls. Thus, what could be original foundations of the first construction are made of lime mortar and cobblestone masonry of depths ranging from 60–80 cm, while the more modern ones are made of brick masonry of depths greater than 90–120 cm.

In the physical-chemical-morphological characterization of materials, the following tests have been used: hydric to establish physical properties, X-Ray Diffraction (XRD) to find the crystalline structure, Polarized Optical Microscopy (POM) to obtain information about mineralogy, Scanning Electron Microscopy (SEM) for chemical and morphological characterization, and Thermal Gravimetric Analysis (TGA/DTA) to find out the proportion of each component. Moreover, several compressive strength tests were carried out on pieces, mortars, and portions of masonry in the laboratory and various in situ N-MDT tests were done (flat jack, sclerometry and mortar penetration tests) oriented to estimate the mechanical characterization of the masonry structure.

2 Materials and Methods

This section describes the tests used with the aim of obtaining useful information about the physical, chemical, morphological and mechanical characterization of the materials used in the existing masonries, and the methodologies used in situ for the mechanical characterization of the masonry walls.

The walls, pieces and mortars in the building have been denominated according to the date of construction figuring in the historical studies, thus, being either of the period 15–18th or 19–20th.

2.1 Characterization of Materials in the Laboratory

Twenty-three samples of materials were extracted manually (6 corresponded to complete brick samples, 12 samples of mortars, 3 of stone and 2 of brickwork) and 7 cylindrical samples of walls were obtained using a hollow-crown coupled to a perforator.

2.1.1 Physical-Chemical-Morphological Characterization of Materials

Hydric tests were carried out, with a hydrostatic balance, to calculate the apparent density, the coefficient of absorption and the accessible porosity. The real volume was also obtained using the Le Chatelier volumenometer, calculating the real density of the samples.

With the aim of finding the crystalline phases in the samples analyzed and, therefore, their chemical composition, X-Ray Diffraction (XRD) techniques were used (Lombillo et al. 2013; Middendorf et al. 2005; Isebaert et al. 2016; Arizzi et al. 2013; Van Hees et al. 2004; Nóbrega De Azeredo et al. 2015; Franzoni et al. 2017). For this purpose, a Bruker D8 Advance powder diffractometer was used fitted with a high-stability copper anode X-Ray supply, and a SOL-X detector of energy dispersion and large active area for X-Ray diffraction, enabling a shorter measurement time than other detectors combined with a low background level.

Using a Scanning Electron Microscope (SEM) (Lombillo et al. 2013; Middendorf et al. 2005; Arizzi et al. 2013; Van Hees et al. 2004; Nóbrega De Azeredo et al. 2015; Franzoni et al. 2017; López-Arce et al. 2016) a morphological examination of the topographical structure of the fracture planes of the samples was performed. Moreover, managing a range of augmentation scales, a view of both the whole element and of the details was obtained. In the same way, coupling a dispersive energy X-Ray spectrometer, the elemental analysis of the samples was made possible. The study was done with a Jeol JSM-820 microscope operating at 20 kV and equipped with Oxford EDX analysis. The samples were covered with Au (Emitech K550X metalizer) to ensure good conductivity of a beam of electrons. Complementarily, using a Polarized Optical Microscope (POM) (Middendorf et al. 2005; Arizzi et al. 2013; Van Hees et al. 2004), information was obtained about the mineralogy of the samples under study (petrographic analysis). Thus, to identify aggregates and binder through observation of thin laminas, a Kyowa, mod. BIO-POL, transmitted and polarized light petrographic microscope was used. The photographs were taken with a 5Mpixel Moticam, model 2300.

Finally, Thermal Gravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) (Middendorf et al. 2005; Nóbrega De Azeredo et al. 2015; Franzoni et al. 2017; Verstrynge et al. 2011) enabled the estimation of the proportion of each component, so the dosage of the mortars and presence of unfired clays could be estimated.

2.1.2 Mechanical Characterization

Mechanical compression tests were performed using a hydraulic press on a part of the samples extracted (7 bricks, 4 of mortar and 4 masonry testpieces). To this end, the samples were cut with a circular saw and capped with Betolevel 15 CT-C30-F6 self-leveling mortar whose compressive strength is over 30 MPa. The testing machine used for the tests on bricks and masonry testpieces was an Ibertest MIB-60 servo-hydraulic press in accordance with the norm UNE-EN 772–1 (2011). The breaking of mortars was done with two test presses, an Autotest 200–10 SW and another Wykeham Farrance, in accordance with the norm UNE EN 1015-11 (2007).

2.2 In Situ Experimental Campaign

2.2.1 Flat Jack Test

The flat jack technique was developed by the Italian researcher Paolo Rossi in the early 1980s (Rossi 1982), although it was not until 1985 that the first application in situ took place on the brick walls of the '*Palazzo della Ragione'* de Milan (Rossi 1985). Later, tests were performed on other construction types (Lombillo 2010) such as ashlars, irregular rubblestones and even rammed-earth (Lombillo et al. 2014), which contributed to the progressive calibration of this technique.

Following the criterion for characterizing the masonry walls of the constructions built in the 15–18th and 19–20th centuries, the tests were performed at the points shown in Fig. 3.

2.2.2 Sclerometer and Penetrometer Tests on Mortars

The use of a pendulum sclerometer provides a rapid qualitative indication of the quality of mortar through the correlation with the energy absorbed by the mortar during the impact (Tavares et al. 2008; Tavares and Veiga 2007). It is considered as a low-impact test for monitoring the quality of mortars through the evaluation of its surface hardness. The equipment utilized in this study was a SCHMIDT PM-type pendulum hammer.

Another test used for the in situ characterization of mortars was the penetrometer technique, for which a portable PNT-G penetrometer was utilized. The penetrometry of mortars used, based on the PNT-G method developed by Gucci and Barsotti (1995),

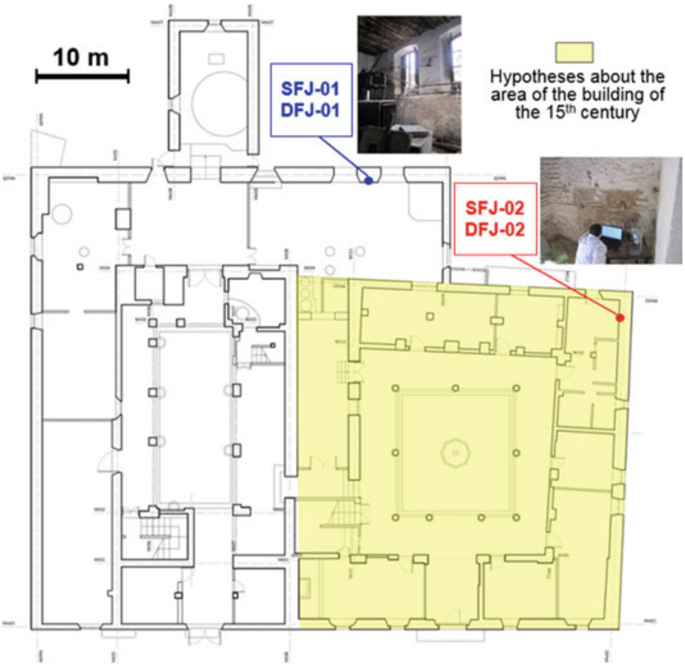

Fig. 3 Floorplan of emplacement of the flat jacks. SFJ-01 and DFJ-01 were performed in the semi-basement of SE wall of the 19–20th century building, while SFJ-02 and DFJ-02 were performed on the ground floor of the SW wall of the 15th century building, supposedly remodelled in the 18th century

Gucci and Sassu (2002), provides a rapid qualitative indication of the compressive strength of the material through the correlation with the energy necessary for performing a standardized perforation.

The procedures followed to carry out the previous tests are included in the RILEM MS-D.7 (1997) and RILEM MDT. D.1 (2004) recommendations respectively.

3 Results

Table 1 details the experimental campaign carried out. The stones analyzed correspond to the columns of the central patio and the ashlars of the main wall.

Table 1 Experimental campaign carried out

Material	XRD	SEM	POM	TGA/DTA	Mech. character		SCL	PEN
					Lab.	DFJ		
Brick	X	X	X	X	X			
Mortar	X	X	X	X	X		X	X
Stone	X	X	X					
Masonry structure					X	X		

XRD: X-Ray Diffraction; **SEM**: Scanning Electron Microscopy; **POM**: Polarized Optical Microscopy; **TGA/DTA**: Thermal Gravimetric Analysis and Differential Thermal Analysis; **DFJ**: Double Flat Jack; **SCL**: Sclerometry; **PEN**: Penetrometry

3.1 Results of the Characterization of Materials in the Laboratory

3.1.1 Physical-Chemical-Morphological Characterization of Materials

Table 2 shows the compounds identified in the XRD analysis. 15–18th century bricks and mortars, 19–20th century bricks and mortars, and stone were studied. In the case of the mortars, the fine and coarse fractions were analyzed.

Because of the microstructure of cementitious materials is so heterogeneous, Polarized Optical Microscopy (POM) was firstly used to quantitative image analysis about volume fractions of phases of epoxy-impregnated and polished samples. After that, in particular areas, Scanning Electron Microscopy analyses (SEM) were carried out. As an example of obtained results of the petrographic thin section study (POM), Fig. 4 shows the analysis by parallel nicols, NP $\times$ 40, of 15–18th century mortar, and Fig. 5 shows the analysis by crossed nicols, XP $\times$ 40, of 19–20th century mortar.

Table 3 shows the results of the Scanning Electron Microscopy analyses carried out.

From the POM and SEM analyses, it can be seen that the mortars of the 15–18th century period are basically composed of calcium-dolomite aggregate and smaller quantities of additions of siliceous aggregate (quartz and feldspar). The mortars of the 19–20th century period are composed of crushed calcium aggregate, and a smaller proportion of silica, especially in one of the samples analyzed. In this sample, clays of varied mineralogy were also found (based on an XRD analysis using oriented aggregates Mica/Paragonite: 60%, Smectite: 28% and Chlorite: 12%). Moreover, the SEM images showed that in none of the mortars was SCH gel present (calcium silicate hydrates). No crystals of $Ca(OH)_2$ was observed either, which indicates that all the lime had been carbonated.

The Thermal Gravimetric Analysis (TGA/DTA) were used to find out the dosages of the mortars. Up to 420 °C, losses due to absorbed water and crystallization of salts were found. Results above 700 °C showed the decomposition of magnesium carbonate of the dolomite, and at 800 °C the decomposition of the calcite.

Table 2 Compounds identified using XRD (%)

Compounds identified		Brick		Mortar				Stone
		15–18th	19–20th	15–18th		19–20th		
				Coarse fraction	Fine fraction	Coarse fraction	Fine fraction	
Dolomite	$CaMg(CO_3)_2$	–	–	77.13	83.64	81.18 85.35 77.82	62.49 27.08 30.43	–
Plagioclase	(Na0.84Ca0.16)Al1.16Si2.84O8	–	–	6.93	3.00	1.77 1.13 0.50	3.07 1.33 1.81	–
Quartz	SiO2	98.48	85.24	74.15	72.96	39.93 17.54 10.20	71.14 30.03 63.29	11.68
Calcite	CaCO3	33.85	7.01	56.67	82.00	15.86 24.33 7.69	81.49 81.56 46.61	84.07
Phyllosilicates	$(K0.82Na0.18)(Fe0.03Al1.97)(AlSi_3)O10(OH)_2$	11.62	4.14	5.36	3.50	0.75 1.32 0.31	3.85 1.55 1.82	–
Galenite	$Ca_2Al_2SiO_7$	9.12	11.72	–	–	–	–	–
Wollastonite	$CaSiO_3$	2.56	19.01	–	–	–	–	–
Diopside	$Ca(Mg,Al)(Si,Al)_2O_6$	8.21	16.90	–	–	–	–	–
Hematite	Fe_2O_3	3.34	8.09	–	–	–	–	–

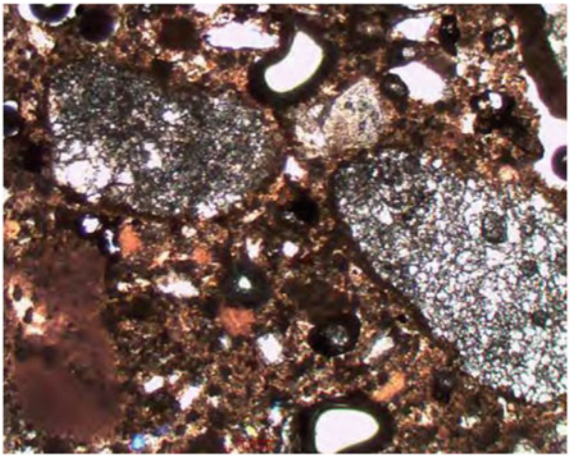

Fig. 4 Analysis by parallel nicols, NP × 40, of 15–18th century mortar

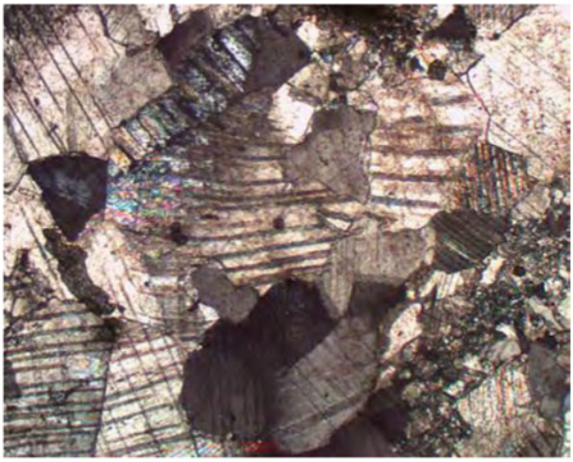

Fig. 5 Analysis by crossed nicols, XP × 40, of 19–20th century mortar

Table 3 Analysis of SEM results (%Components)

Material	Sample	CO_2	MgO	SiO_2	CaO	Al_2O_3	K_2O	FeO	Aggregate
15–18th century mortars	01	23.19	22.34	7.13	47.34	–	–	–	Calcium
19–20th century mortars	01	–	7.04	17.93	67.25	7.77	–	–	Calcium
	02	27.01	4.97	2.99	65.03	–	–	–	Calcium
	03	16.43	2.07	4.44	77.06	–	–	–	Siliceous
15–18th century brick	01	15.13	1.41	39.54	11.6	20.19	6.96	5.17	–
Stone	P				100				–

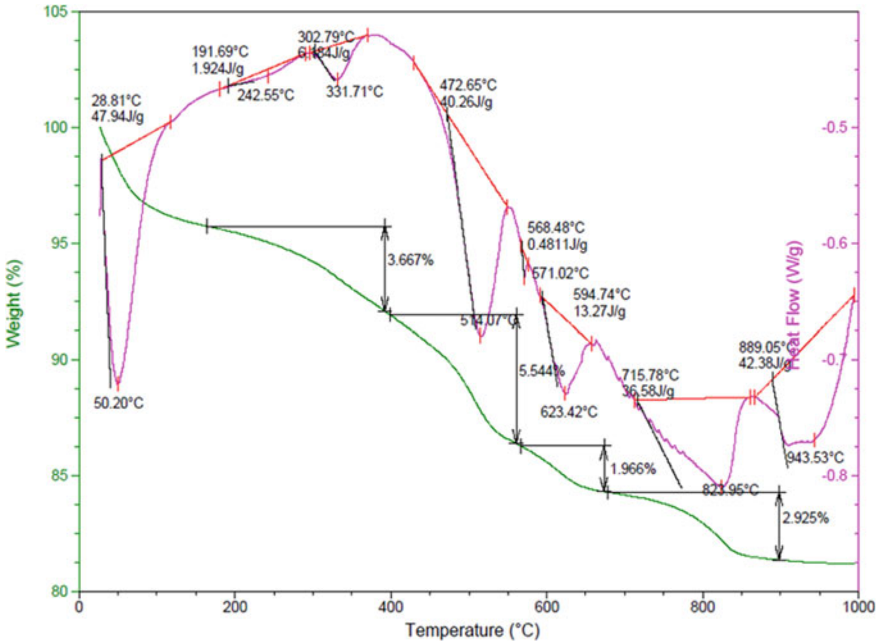

Fig. 6 TGA/DTA analysis of the 15–18th century brick

This (TGA/DTA) technique was similarly used on samples extracted from the pieces of brick. Figures 6 and 7 show a loss of weight due to evaporation of water up to 100 °C, indicating greater humidity and thus porosity in the sample from the first period, 15–18th century, with respect to the second period, 19–20th century. The loss of weight at 800 °C indicates the presence of calcium carbonate caliches, the samples from the first period showing greater presence of caliches than in those of the second period. In the first period brick, a greater number of endothermic peaks was observed, which indicates the presence of a greater quantity of clays that have not been fired, given that in their manufacture they underwent lower temperatures.

3.1.2 Mechanical Characterization

Table 4 details the compressive strengths obtained in the laboratory.

The mortars of the 15–18th century provide an average compressive strength of 0.96 MPa and the 19–20th century ones of 3.16 MPa. The great variability shown by the 15–18th century mortars are related partly to the effect on the material of the extraction from the masonry and, partly to the conditioning and preparation of the samples before the test. In the case of the 15–18th century half-bricks tested, the value was 15.94 MPa with a notable variability of 21.25%, which was reasonable given its manufacture period. As for the 19–20th century bricks, the average compressive

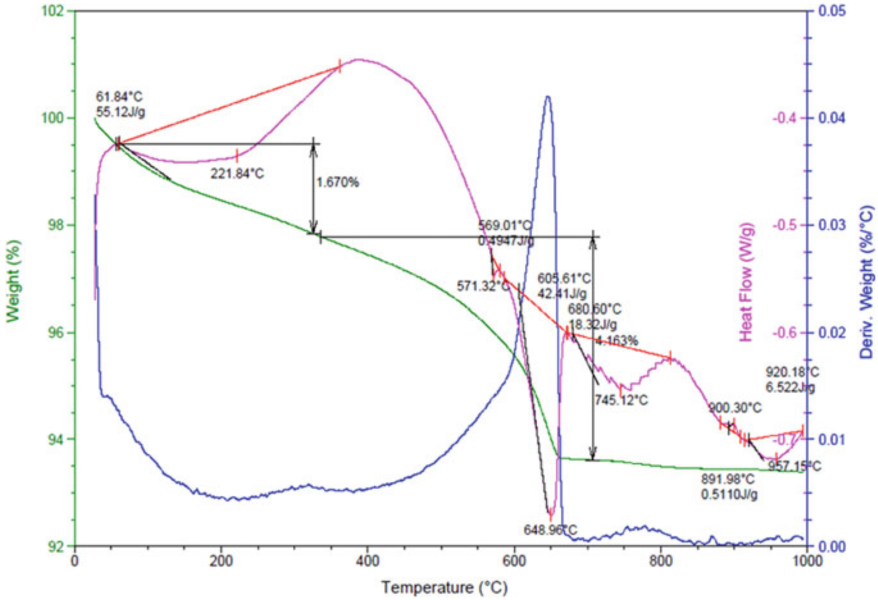

Fig. 7 TGA/DTA analysis of the 19–20th century brick

Table 4 Compressive strengths of the samples of materials and masonry structures under study

Material	P_{max} (kN)	Area (cm^2)	f_c (MPa)	Average (MPa)	Std. deviation (MPa)	Var. Coef. (%)
15–18th century mortar	1.93	15.95	1.21	0.96	0.30	31.12%
	1.66	16.00	1.04			
	1.01	16.00	0.63			
19–20th century mortar	5.57	17.63	3.16	3.16	–	–
15–18th century brick	280.6	197.74	14.19	15.94	3.39	21.25%
	286.32	207.78	13.78			
	578.89	291.78	19.84			
19–20th century brick	607.56	290.14	20.94	18.67	2.12	11.36%
	581.58	300.09	19.38			
	491.38	309.43	15.88			
	351.61	190.37	18.47			
19–20th century brick masonry	40.49	99.98	4.05	4.50	0.47	10.37%
	50.41	100.02	5.04			
	47.34	99.87	4.74			
	41.73	99.83	4.18			

strength was 18.67 MPa with an optimum variability coefficient of 11.36%. Finally, the 19–20th century masonry workpieces provided an average compressive strength of 4.50 MPa with a variability coefficient of 10.37%, which was quite low for the type of construction analyzed. It should be noted that 15–18th century masonry samples could not be extracted for later testing in the laboratory due to the low quality of the mortars.

3.2 Results of the in Situ Experimental Campaign

3.2.1 Estimation of Stress Levels

Figure 3 shows the emplacement of the flat jacks. In the case of emplacement 01, the portion of the masonry wall under study corresponds to the inside of the external brick wall, which is a semi-basement, belonging to the part attached in the 19–20th century (over ground level, the wall is a mixed masonry of brick of 28 × 14 × 5cm with lime-based mortar in bed joints of 3 cm and cobblestones also with lime-based mortar). As for emplacement 02, the tests were carried out on the ground floor, on part of the inside of an external mixed masonry brick wall, of 28 × 14 × 3 cm with lime-based mortar in bed joints of 4 cm, and cobblestones also with lime-based mortar, belonging to the original part (15th century) supposedly remodeled in the 18th century.

The stress levels measured were 0.56 MPa in test SFJ-01, and 0.26 MPa in test SFJ-02.

3.2.2 In Situ Mechanical Characterization of the Masonry Structures

Test DFJ-01 had the aim of determining the modulus of deformation and Poisson's ratio of the inner leaf of the brick masonry forming one of the load-bearing walls of the extension built in the 19–20th century. While test DFJ-02 allowed to determine the equivalent parameters in the inner leaf of the 15th century load-bearing wall, supposedly remodeled in the 18th century, built of a mixed masonry of brickwork infilled with cobblestone and lime mortar. A comparison of the average σ-ε laws obtained in the tests is shown in Fig. 8.

From the curves shown in Fig. 8, it can be seen that in the case of DFJ-01 there is linear behavior until around 1.20 MPa, so that magnitude is related to the elastic limit of the masonry. From the study of the envelope curve of the non-linear behavior zone (Lombillo et al. 2013, 2014), a compressive strength of 3.88 MPa can be estimated associated to a deformation of 3‰ (Tassios 1988), a congruent value bearing in mind that the first fissure affecting one of the pieces forming the wall developed at a working pressure of the pump of 4 MPa. The secant modulus of elasticity determined was 3674 MPa and its Poisson's ratio was 0.06. In the case of DFJ-02, the elastic limit was of 0.40 MPa and, carrying out an analogous study to the previous one, the

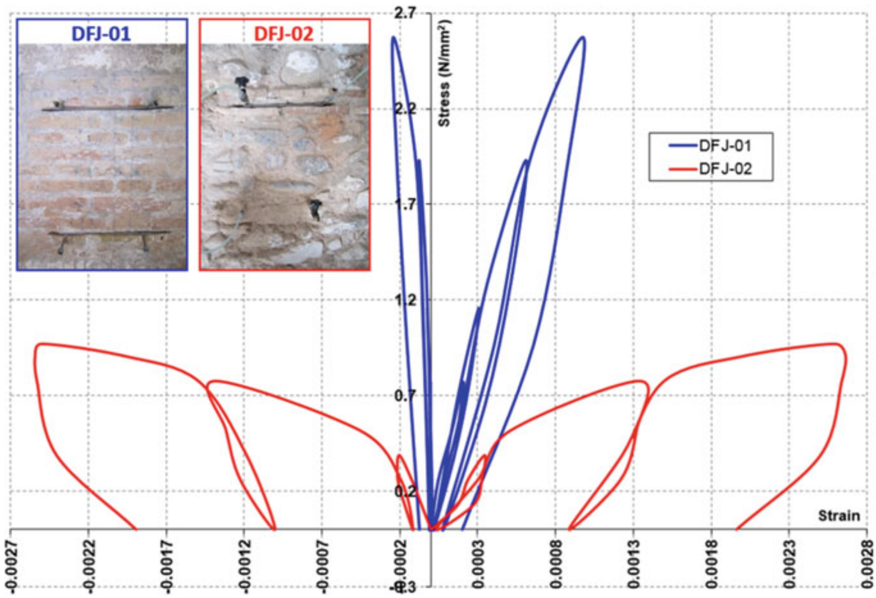

Fig. 8 Comparison of the average σ-ε laws obtained in test DFJ-01 (19–20th century wall) and in DFJ-02 (15th century wall supposedly remodelled in the 18th)

compressive strength was estimated to be 1.02 MPa, the secant modulus of elasticity was of 1513 MPa and Poisson's ratio 0.47.

3.2.3 Penetrometric and Sclerometric Tests on Mortars

The tests were carried out in areas near the flat jack test zones. In each test multiple repetitions were performed to, as far as possible, reduce the uncertainty of the average value obtained.

The values registered are shown in Table 5. In the penetrometric test, the table includes the compressive strength value of the mortar, R_c, determined from Gucci's relationship, $R_c = (PI + 22)/134$ (Gucci and Barsotti 1995), which proposes a relationship between the values of the penetrometric index (PI) and the compressive strength of the mortar, in the case of mortars with a compressive strength less than 4 MPa.

4 Discussion of Results

In summary, Table 6 provides details about the most representative properties of the different materials studied in the laboratory.

Table 5 Penetrometric index (PI) and surface hardness values obtained in the area of the flat jack tests

Position	DFJ-01 (19–20th century)				DFJ-02 (15–18th century)			
Penetrometric index (PI)	267	1115	1441	1399	96	124	68	105
	814	1139	2383	2093	60	54	20	12
	887	2040	680	1069	193	61	39	291
	763	2297	582	890	183	60	86	106
	1038	1441	1226	1636	31	26	149	37
Average (PI)	1260.00				90.05			
R_c (MPa)	9.57[a]				0.83			
Rebound index (RI)	26	17	20	15	14	18	12	14
	25	12	15	42	16	24	14	18
	25	35	25	40	18	20	22	17
	25	35	23	22	17	15	16	19
Average (RI)	25.13				17.13			
Class	B–Moderate (25–35)				A–Weak (15–25)			

[a]In this respect, it should be commented that the value of R_c in the area of DFJ-01 must be considered questionable given that it is above 4 MPa, the maximum value established by Gucci for the use of his correlation equation

The tests carried out confirmed that all the mortars analyzed were of limes with dolomite and/or silicate aggregates (quartzes and feldspars). Moreover, coincidentally with the periods of construction of the building (Torices et al. 2015), 2 types of mortars were found, clearly differentiated, some poorer, with lime:aggregate (l:a) ratios between 1:2 and 1:2.5 and densities around 1.23 g/cm^3, corresponding to the 15–18th century walls, and other richer ones, with a l:a ratio of 1:1.3 and an apparent density more than 1.78 g/cm^3, in the 19–20th century walls. The presence of calcium silicate hydrates (CSH gel) or calcium aluminate hydrates (CAH compounds) was not detected, so the presence of Portland cement or natural cements was totally discarded, which dates these masonries in the 19th century or the beginning of the 20th century, given that the first Portland cement masonry was used in the Spanish region of Andalucía by the '*Sociedad Financiera y Minera de La Caleta*' in Malaga in 1921, and in Granada by 'Inocencio Romero de la Cruz', in Atarfe, also in 1921 (Puche and Mazadiego 2000). The samples of 15–18th century mortar provided an average compressive strength of 0.96 MPa and the 19–20th century ones of 3.16 MPa. This considerable difference in values can be explained by the physical-chemical characterization, given that the mortars of the 15–18th century have a low density due to the sandiness of the mortar, which was induced by the low content of conglomerate (low l:a ratio).

Table 6 Most representative properties of the materials studied in the laboratory

Material	Description		D (g/cm^3)	l:a	A (%)	P (%)	Compressive strength (MPa)			SCL (class)
							Lab	PEN	DFJ	
15–18th century mortar	Dolomite[a] lime mortar, with 44% dolomite	Very sandy mortar	1.23	1:2.5	30.88	37.96	–	–	–	–
		Well-preserved mortar	–	1:2	–	–	0.96	0.83		A–Weak (15-25)
19–20th century mortar	Dolomite[a]lime mortar, with 20% dolomite	Well-preserved mortar	1.78–1.97	1:1.3	11.13–15.87	21.89–28.48	3.16	9.57		B–Moderate (25-35)
15–18th century brick	Made with clay with high content of siliceous sand and high presence of caliches		1.59	–	18.89	29.98	15.94	–	–	–
19–20th century brick	Made with clay with high content of siliceous sand and low presence of caliches		1.80	–	10.23	18.32	18.67	–	–	–
15–18th century brick wall infilled with lime mortar and cobblestone			–	–	–	–	–	–	1.02	–
19–20th century brick wall			–	–	–	–	4.5[b]	–	3.88	–

D: Apparent density; **l:a**: lime:aggregate ratio; **A**: Absorption coefficient; **P**: Accessible Porosity; **PEN**: Penetrometry; **DFJ**: Double Flat Jack; **SCL**: Sclerometry
[a]Dolomite: calcium carbonate with magnesium common in many limes
[b]Average compressive strength obtained from 4 experimental tests in the laboratory (Table 4)

As for the bricks, all of them have been made with the same type of clay and siliceous sand. However, different firing temperatures have been observed corresponding to the 2 periods of construction identified. The bricks from the zones built in the 15–18th century were fired at low temperature, with a less purified raw material, and greater content of caliches, a high content of unfired clay (XRD detected greater presence of phyllosilicates, as well as quartz, calcite and clays) and high porosity. In contrast, the bricks used in the 19–20th century show lower content in caliches, a lower unfired clay content and a lower porosity, indicating a higher firing temperature. Their mineralogical composition shows greater presence of silicates and little calcite. The average compressive strength found for the 15–18th century bricks tested was 15.94 MPa with a variability coefficient of 21.25%. As for the 19–20th century bricks, it was 18.67 MPa with an optimum variability coefficient of 11.36%.

With respect to the mechanical characterization tests in the laboratory and the flat jack tests carried out, the different mechanical behavior of the 15–18th century and 19–20th century walls was evident. Table 7 details the mechanical parameters obtained in the masonry structures.

Table 7 Mechanical parameters obtained for the load-bearing walls of masonry

Mechanical parameter			15–18th century	19–20th century	
Type of masonry			Brickwork infilled with lime mortar and cobblestones	Brickwork (lime mortar)	
Elastic limit (MPa)			0.40	1.20	
Compressive strength (MPa)	(a) Double flat jack ($\sigma_{failure}$)		1.02	3.88	1.00*
	(b) Tests of masonry workpieces	Average value	–	4.50	–
		f_k		3.74	0.96*
	(c) Piet70 Estimation, f_k (p.i.e.t. 1971)		–	4.25	1.10*
	(d) Eurocode 6 estimation, f_k (EN 1996-1-1:2005)		–	6.03	1.55*
Elastic modulus through DFJ (MPa)			1513	3674	
Poisson's ratio through DFJ			0.47	0.06	

*Relation with respect to the value estimated in the double flat jack test, as it is considered the closest to the real behavior of the masonry

(a) The compressive strength provided by the flat jack ($\sigma_{failure}$) are not characteristic values (f_k) as they are from only one test

(b) In the case of laboratory tests on masonry testpieces, the characteristic compressive strength, f_k, was obtained from the tests listed in Table 4, in which an average strength of 4.50 MPa and variability coefficient of 10.37% were obtained

(c) As for the piet70 (1971), the value indicated corresponds to the characteristic strength, f_k

(d) Finally, with respect to Eurocode 6, EC6 (EN 1996-1-1:2005), the value indicted corresponds to the characteristic strength, f_k, obtained considering pieces of fired clay (group 1) and ordinary mortar

In this case, it can be seen that the compressive strength of the masonry samples tested in the laboratory provided similar results to the in situ double flat jack test. However, the estimations of strength included in the piet70 and EC6, envisaged for new construction, give rise to higher values than those obtained in the tests, which casts doubt on the validity of estimating values of strength of historical masonries.

The referred Fig. 8 allows to visualize this differential behavior of the two masonries under study directly, where the greater rigidity (2.4 times) of the 19–20th century masonry can be seen compared to the 15–18th century one as too its better mechanical performance (with a compressive strength 3.8 times greater).

With respect to the stress levels obtained through SFJ, above all in the case of SFJ-01, it can be stated that they were greater than those estimated theoretically. However, it is notable that, in cases such as this, when a high service stress is not foreseen (due to the low weight of the existing walls themselves), the results of the simple flat jack tests should be treated cautiously.

As for the mechanical characterization NDTs on the mortar of the masonries under study (penetrometric and sclerometric), the dispersion of the results in the two test zones should be highlighted. Generally, it was found that the mortar in the zone of test DFJ-01 (19–20th century) was of better quality than that in the zone of test DFJ-02 (15–18th century). In this respect, the correspondence with the results for the samples of mortar tested in the laboratory to compression and with those found for the masonries studied through S/D-FJ tests should be noted, where clearly different behavior was found in the two masonries.

The compressive strength of the mortars (R_c) obtained in the penetrometric test using Gucci's equation, Table 5, was 0.83 MPa for the 15–18th century mortars (a value close to the one obtained in the laboratory, 0.96 MPa) and 9.57 MPa for the 19–20th century mortars. In this latter case, given the estimated strength through the above-mentioned equation is greater than 4 MPa, the maximum value established by Gucci for its use, this value should be treated cautiously.

With respect to the results obtained with the sclerometric tests, they behave in a similar way to those obtained in the penetrometric test. Better classification of the mortars is obtained in the zone of the test DFJ-01 (19–20th century) with Class B–Moderate, compared to the zone of DFJ-02 (15–18th century) with Class A–Weak.

5 Conclusions

From the tests performed on the masonries existing in the '*Los Aragoneses*' mill in Monachil, Southern Spain, it can be concluded that there are 2 types of masonries, corresponding to a construction in two phases: 18th century (and before) and 19th and beginning of the 20th century, with materials of better performance.

Through XRD, it was possible to find the crystalline phases existing in the samples analyzed and their chemical composition. Through SEM, a morphological examination of the topographical structure of the fracture planes of the testpieces and elemental analysis of the distinct materials making up the walls were carried out.

Through POM, complementary information was found about the mineralogy of the samples. Finally, the TGA-DTA tests enabled the characterization of the properties of the materials that directly influenced the mechanical properties of the materials making up the historical masonries in question. In this way, the lime:aggregate ratio of the mortars and the firing temperature of the ceramic bricks was found.

The compressive strengths obtained when breaking masonry testpieces, in this specific case, were lower than those obtained in flat jack tests. This difference can be explained both by the weakening of the masonry piece caused by extraction from the wall and the lack of lateral confinement of the test pieces during the tests in the laboratory. The estimations of strength obtained from experimental formulas considering the mechanical strength of the pieces of brick and the mortars, piet70 and EC6, give rise to disparate values.

With respect to the NDTs applied to the characterization of the mortars, the dispersion of the results should be highlighted. However, both with the sclerometric tests, and with the penetrometric ones, it was demonstrated that the mortars of the 19–20th century were of higher quality than those of the 15–18th century, which is in line with the clearly different behavior of the two masonries.

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