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Comparison between experimental values and standards on natural stone masonry mechanical properties

D. García[1], J.T. San-José[1,2]*, L. Garmendia[1], P. Larrinaga[1]

[1]*TECNALIA, Ed 700, Parque Tecnológico de Bizkaia 48160 - Derio, Spain*
[2]*Engineering School of Bilbao – University of the Basque Country, Alameda Urquijo, s/n. 48013 – Bilbao, Spain*

ABSTRACT

The research presented in this paper investigates the mechanical properties under compressive loads of a natural stone masonry. Selected materials and arrangement are typical from the Romanesque period, the main architectural style in Europe from the 9th to the 13th centuries, found both in Heritage and conventional buildings. The characterisation of the basic materials and different stone masonry prisms is included. Sandstone and low strength lime-cement mortar were used for this experimental work because of their availability and similarity with the masonry found in many historic buildings from the North of Spain. The morphological characteristics of the original ancient walls were also taken into account, in order to manufacture prism specimens that were as representative as possible of the Spanish Romanesque typology (i.e. in terms of its geometry, composition of the internal core, relative size, etc.).

The experimental values were compared with the analytical ones provided by other author's equations, codes and main standards. The differences on the obtained results are analysed and the more suitable formulae are identified. The results permit a better understanding of these materials and a reliable source of data for the validation of the existing structures.

KEYWORDS: masonry, prisms, compression, test, stone, standards, codes, ashlar.

1. Introduction

Stone masonry was the most durable and dominant construction material until the 19th century. It is still present in most historic constructions and urban centres. It was generally constructed using different stones and low-strength lime mortars, arranged in irregular morphologies, and often composed of various leaves with little or no connection between them. Masonry structures are conceived of an association of resistant elements through which load transmission takes place by means of compression trajectories. As a result, it is a heterogeneous, discontinuous composite with good compressive strength, but weak tensile and shear strength. Hypotheses commonly applied to the analysis of current structures, such as homogeneity, isotropy and constant mechanical properties cannot, strictly speaking, be applied here.

In spite of being a very common structural element, calculation of the overall strength of masonry buildings is still a complicated task. It has been demonstrated that traditional methods, based on geometric relationships, are reliable and secure for non-seismic areas in most situations. However, large safety factors are included. Recent regulations about masonry calculation have been introduced but they are almost always related to regular masonry constructed brick or concrete blocks [1,2]. The equations derived from these codes are not directly applicable to natural stone masonry if not regular. Traditional masonry differs from current one as follows:

- Non periodic positioning and irregular shape of stone units.
- Units are much stronger than used lime mortar.
- Ductile lime mortar contributes to reduce the effects of stress concentrations.
- Very low tensile resistance.
- High ratio between the height of the units and the mortar bed joint thickness or dry joints (with no mortar).
- There are numerous combinations of parameters with regards to materials, the geometric form of the units used, the way in which these have been laid, etc. Each particular typology was a consequence of the geographic location, age of structure, and the purpose and economic power of its owners.

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* Corresponding author. Tel.: +34 94 607 33 00; fax: +34 94 607 33 49.
E-mail address: josetomas.sanjose@ehu.es (J.T. San-José).

For all these questions, the knowledge of the mechanical behaviour of stone masonry compressive elements is still limited, as well as the availability of standards and codes of practice for the proper design and control of appropriate interventions [3].

There are several ways in which the behaviour of stone masonry may be estimated. To date, non-destructive techniques (NDT) only allow approximated qualitative values to be established, such as the existence of discontinuities, humidity, and the hidden presence of voids or internal elements. Attempts to establish correlations between the values obtained and density or resistance are solely successful on small samples, and their extrapolation to the complete structure is not necessarily valid [4]. Destructive tests may be performed on large samples or cores cut from the original structure. Re-constituted masonry walls, representative masonry prisms, and/or scaled walls built in the laboratory have been used for the same purpose. Compressive strength experiments on masonry prisms are easily conducted [5]. Until a few years ago, importance was only attached to an evaluation of the ultimate load and, as a result, knowledge on global stress-strain and post-peak behaviour of stone masonry is still limited. Stacked bond prisms or wallets, such as the CEN test specimen [6], are frequently used to assess the uniaxial compressive strength of masonry [7].

In a stacked-bond prism loaded in uniaxial compression, the mortar tends to expand laterally more than the stone, due to their respective elastic properties. The continuity between stones and mortar, assured by cohesion and friction, leads to the lateral confinement of the mortar. As a result, shear stresses develop at the mortar-stone interface, producing a tri-axial compressive stress state in the mortar and bilateral tension coupled with uniaxial compression in the stone. Failure generally occurs due to the development of cracks in the stones, parallel to the loading direction [8]. Both strength and cracking behaviour are influenced by the boundary conditions. Usually, both top and bottom units remain undamaged when standard steel plates are used as an interposition material, due to the confinement effect. On the other hand, the end units crack when polytetrafluoroethylene (Teflon®) is used.

This work sets out to extend the experimental data on the mechanics of stone masonry and the validation of available codes for design and assessment of these structures under compression loads.

2. Experimental investigations

Two kinds of stone and a lime-cement mortar were selected as representative materials of the present stone masonry. Those materials were tested separately and combined together with different arrangements. The combinations are based on the existing masonries. Basically, dry joint ashlar, mortar joint ashlar, rubble masonry and inner filling mortar were reproduced in a set of masonry prisms. The goal was to obtain masonry assemblies from available materials similar to the ancient ones found in heritage buildings [9].

2.1. Material components

2.1.1 Stone

The stone used in this research is a sandstone named “Aguilar sandstone” from the province of Palencia, North-central Spain. Two varieties of this stone were used:

- Sandstone1. A regular sandstone was used for the ashlar units. It was quarried at “Quintanilla de las Torres” (Spain). It is a uniform, fine-grain, yellowishgrey sandstone rock with light rose-coloured tones that is somewhat weak to the touch. It is made up of 85% quartz grains and also contains phillosilicates (clays and muscovite) and a few iron oxides. This stone is currently used for substitutions in real heritage buildings. The prismatic ashlar units for the prisms were prepared with a cutting machine equipped with a Ø600mm diamond disc.
- Sandstone2. A darker rock, extracted from “Cordovilla de Aguilar” (Spain), was used for the rubble masonry. It is a dendrite rock with a predominantly reddish colour that is found in natural layers. The stone was manually broken up for obtaining irregular units for the prisms.

Figure 1

The specimens to be tested under uniaxial compression were prepared in accordance with UNE EN 1926:2007. Cores with diameters of 50 mm and heights of between 115 mm and 150 mm were extracted from the selected stones. The compression tests were performed on a servo-controlled universal testing machine with fixed-end platens. This equipment has a load cell connected to the vertical actuator with a maximum capacity of 200 kN, particularly appropriate for concrete specimens. A cardboard sheet was placed between the machine platens and the specimen, in order to avoid stress concentrations.

The stone exhibits a behaviour that is typical of ceramic materials: low tensile strength and high compressive strength. It is not strictly correct to refer to an “elastic modulus”, nevertheless it may be estimated by considering the first section of the tension–deformation line as straight. In this research, a deformability modulus was estimated by considering the deformation-stress ratio from 0 to 40% of the maximum strain, in accordance with internal lab procedures.

Similar cores were also used to perform Brazilian (indirect tensile) tests, in line with UNE 22950-2: 1990, on the same testing machine. Density was calculated on the basis of UNE EN 1936: 1999. The samples showed considerable disparity due to the stone nature. Even so, the values were taken into account for estimating the compressive strength of the later masonry prisms. With regard to the above tests, between 6 and 9 cores of each stone were used. Average values for the results are presented in the following table. The variation coefficients are given between brackets (%).

Table 1

2.1.2 Mortar

The characterisation of an ancient mortar, used hundreds of years ago in a masonry construction, is a very complicated task. In many cases, the possibility of extracting reliable samples is very expensive and sufficient material to constitute an experimental series is not always available.

A single point load test (PLT) can be used to obtain approximate values. It is a rock mechanics testing procedure used for the calculation of a rock strength index. This index can be correlated with the uniaxial compression strength, taking account of the overall geometry of the sample (UNE 22.950 - Part 5, 1996). Despite being a standard test for stone, it has been used for mortars in this research. Previous studies developed in Tecnalia on mortars used in Romanesque buildings in the province of Palencia show very low strengths, of between 0.2 and 0.5 MPa. It is also of great interest to evaluate the deformability or the elastic modulus of the masonry, although precise results are also difficult to obtain for the same reasons. The heterogeneity of the constituents adds further difficulties. In some cases, small pieces of wood, and carbon and lumps of lime were found inside the specimens. X-ray diffraction test indicates the presence of lime ($CaCO_3$), however the best way to identify the original materials is through the study of specialised historical references.

Preliminary research involved the extraction of mortar samples from a number of Romanesque buildings. These mortars were in the bed and head joints of the inner leaf of load-bearing stone masonry walls and in other masonry elements (vaults and domes). High levels of degradation were observable in many of the samples. In some cases, the mortar crumbled to the touch and could be reduced to a handful of sand. The size of the samples restricted the compression tests to the PLT.

A dosage of 0.5-1.5-19 (lime – white cement – sand) was considered similar to the original ancient mortars. Cylindrical (∅100x200mm) and prismatic (40x40x160mm) specimens were cast from different mixes during the construction of the prisms. These specimens were stored at a controlled humidity and temperature (20ºC and RH 60%) over the first 28 days. They were then stored inside, in a draft-free area. The hardened mortar was characterised by means of compression and flexural (UNE EN 1015-11: 2000) tests at different ages. Compressive strength evolution is presented in Fig.2.

Figure 2

2.1.3 Masonry prisms

A total of 16 stone masonry prisms and 4 mortar prisms were constructed and tested under compression load. The specimen sizes were defined base on the CEN recommendation [6] and bearing in mind the restrictions of the testing equipment, as well as the manufacturing restrictions relating to the stone dimensions. Prismatic specimens of 40mm in height, 50mm in length and 30mm in width were prepared.

Figure 3

The prisms were manufactured according to the most common compositions found on a Romanesque wall. The stone bedding orientation was taken into account during the preparation of the prisms, as normally done during substitution of stone units in the rehabilitation works. In this way, 5 series were prepared:

- dry joint ashlar masonry,
- negligible strength mortar joint ashlar,
- low strength mortar joint ashlar,
- rubble masonry and
- inner filling made of mortar and small stone pieces.

They were all built over steel plates to facilitate transport and to assure a flat surface on the universal-testing machine. Special care was taken to ensure parallel ends during the construction of the prism specimens and furthermore, some specimen tops were suitably covered with a thin layer of mortar to obtain a smooth surface.

Figure 4

In the case of the ashlar masonry prisms, the bed mortar joints were about 15mm. The stone/mortar ratio in the rubble masonry prisms was roughly 3/1. The prisms that were constructed to represent the inner core were composed of low-strength mortar, small stone pieces and a significant percentage of voids (≈5%). Masonry prisms were stored at lab conditions (20ºC - RH 50%) for several weeks before testing to avoid the effect of different relative humidity. All prisms were tested at 120 days. Tests were load-controlled at 100N/s. Loading misalignment was avoided by the hinge of the upper platen of the testing machine. Specimens were preloaded until a 5% of their ultimate load in order to eliminate the effects of the settlement and deformation of the capping system.

Load history and crack pattern development were recorded. In this experimental activity, the available time for using the compression machine was too brief and the media to fix the LDVT to the sides of the prisms were not available, so the displacements were measured by means of four digital LVDTs located at the prism corners. In this way, the deformability modulus was estimated by considering the displacement between platens. The obtained stress-strain ratios do not exactly coincide with the real Elastic Modulus of the masonry (1.1-1.2 times higher, based on the authors' experience).

The complete load-displacement diagram that characterises the behaviour of all tests is the result of average displacement measured by four displacement transducers. The normal stress is calculated as the ratio between the applied vertical load and the initial cross section. All the diagrams exhibited the common initial adjustment between the specimen and the machine platens (usually termed as "bedding down"), which is initially reflected on the stress-strain graph as a curve followed by a linear portion.

Some of the cracks in the stone units appeared suddenly and, in some specimens, were accompanied by a clear cracking sound. The stress corresponding to the first crack in the stone units, or in the mortar face in the case of inner mortar specimens (PM), is noted as $f_{M'}$ in Table 2. The ratio between this value and the ultimate load could be an attempt to estimate the remaining resistance in a masonry element, despite the appearance of cracks due to compression. For example, the ultimate load was more than 5.5, 3.0 and 4.9 times the load at the first crack for the dry ashlar, mortar joint ashlar and rubble masonry respectively.

Table 2

It is difficult to define a single value of Young's modulus from the compressive test results. Table 3 summarise the elastic properties, calculated for different stress levels using the linear least-square regression for the 30%-60% stress interval and the tangent approach for modulus at 25%, 50% and 75% of the maximum stress. It should be noted that, even if stones from the same delivery were used, different Young's modulus from the prism specimens were observed. Since tests were conducted under load velocity control conditions, post-peak behaviour has not been obtained.

Figure 5

The disparity in the test results of the ashlar masonry specimens is a consequence of the variations in the preparation of the specimens and the execution of the tests. The first group of ashlar specimens was made with the same mortar as that used in the construction of the rubble ordinary masonry and inner-core prisms. A mortar with a higher binder content was used in the three remaining specimens, similar to the one used for rendering in current interventions in heritage buildings. Due to a problem that occurred during testing, specimen PA2 was subjected to two load cycles of approximately 40% and 30% of the test failure load that was considered valid.

A clear softened S shape was observed in the curves obtained from the test. The values of the final load and the modulus of elasticity for ashlar masonry are higher than those of the rough masonry prisms. The curves of the rough masonry prisms show less disperse results, as the four specimens were constructed and tested in the same way, and their behaviour is more linear from start to failure. In contrast, the specimen representing the inner filling of the wall presented two very different sections during testing: a first pseudo-linear portion, and a second portion that showed deformation under maintained load with rapid extension of cracking.

No direct comparison may be made between the resistance values and the elastic modulus obtained from these tests and the previous ones of the individual materials. In the first place, small pieces of stone and air pockets are present in the prismatic specimen, despite being the same mortar. The so-called "specimen effect" should also be considered, as they are specimens of a different geometry and size. Nevertheless, the proximity of both results in the case of the mortar core confirms the characterisation of this material. The following conclusions may be drawn:

- Dry-ashlar masonry has the highest deformability modulus and a greater load capacity than the other combinations under compression load.
- The quality of the mortar and workmanship affects the masonry strength. The values fail to comply with current standards, as an extremely poor mortar was used to simulate ancient degraded mortar.
- Both ashlar (with bed-mortar joints) and rubble masonry exhibit uniform behaviour, with a strain-stress slope that is practically constant.
- The deformability modulus is greatly influenced by the previous load history.
- The results for the ashlar masonry prisms show greater variation than the others. Further tests are needed for them to be developed in the future; nevertheless, the tendencies are sufficiently well defined to be able to compare the load bearing capacities of three leaf walls (ashlar blocks / inner core / rubble masonry).

3. Analytical results

Compressive strength values from previous test are compared with the calculated ones provided by the equations and tables from bibliography. For ease of interpretation, the average test results and the closest theoretical values taken from the equations and standards all appear in bold in Table 3.

Table 3

On the basis of these values, the following observations may be made:

- Estimates of masonry resistance vary greatly according to the method used. It should be remembered that the various formulae were developed in a specific manner for particular materials and geometric forms, which is why any attempt to use them as values for masonry with such a weak mortar will lead to erroneous results. For instance, it was found that the Khoo and Hendry equation [10], with resistance in compression ratios of over 10 for masonry units and mortar, failed to provide an acceptable estimate.
- Within the range of responses, it was found that the equations in standards and specifications that refer to ashlar units all provide similar results.
- In any case, after having used a mortar which is present in very many real cases, but which has such a low-resistance, the difficulty of predicting a value for maximum resistance is evident.
- If, in the method for estimating the resistance of the masonry, the strength value of the stone material is used, without taking account of the bond, then the resistance values obtained for the rough masonry units are, in general, higher than those obtained for the ashlar units, given that the compressive strength of the former is greater than the latter.
- Taking into account the type of masonry (ashlar units or rough masonry), the strength values of the ashlar units are greater than those of the rough masonry.
- In the case of the ashlar units, it was found that the results given by the EuroCode equation EC-6 adapted to the Spanish Technical Building Code [11] were the closest to those of the test results. This code specifies the conditions to be considered (slenderness, eccentricity) when using the aforementioned values to test walls and other structural elements.
- In the case of rough masonry, none of the equations came close to the values obtained in the laboratory tests. The general value recommended by Segurado in 1908 [12] is the closest and could serve as a starting point when testing ordinary masonry structures that have very degraded mortars. Nevertheless, due to the extreme complexity presented by these constructions, laboratory testing is recommended in order to obtain more detailed results.

4. Conclusions

Stone masonry is a high complex material. From the constituent components to the geometric arrangements in real structures, there is a huge number of parameters involved in its behaviour. Two kinds of sandstone were used during the presented experimental tests. In spite of the same origin of the stone specimens, petrographical differences were found among. It results in high variation coefficients for their mechanical properties.

Mortars found in many historic constructions present very low resistance values, even below 0.5 MPa. In some cases, the mortar crumbled to the touch and could be reduced to a handful of sand. The low strength of the joint mortar is in line with the hypothesis of zero tensile strength when undertaking simplified design calculations.

The enormous difference between the strength of stone as opposed to mortar means that the majority of the existing equations, which are used to estimate resistance on the basis of the masonry components and their properties, do not square with reality. In any case, it has been shown how current standards do not set out calculations for the design or verification of structural elements made with irregular masonry blocks. It is recommended that in these cases, and on the basis of the observed results, laboratory testing should be performed with masonry prisms made of similar materials and configuration.

In the case of rough masonry, none of the consulted equations came close to the values obtained in the laboratory tests. Only values from traditional tables [12, 13] are close to the obtained results and could serve as a starting point when testing ordinary masonry structures that have very degraded mortars. Nevertheless, due to the extreme complexity presented by these constructions, laboratory testing is again recommended in order to obtain more detailed results.

Dry joint masonry prisms show a slightly lower compressive strength than those built with mortar joints. This can be explained by the lack of interlayer material, which promoted stress concentrations in a few discrete contact points, leading to the formation of vertical cracks in the stones. However, since ashlar units were prepared with common dimensions, when the contact is through a smooth surface, the ultimate compressive load could be higher than the same with mortar, as obtained in one of the dry joint prisms.

The influence of the mortar strength on the modulus of elasticity of prisms is very small. The masonry prisms had virtually the same initial tangent modulus of elasticity for both medium and low strength mortars or dry joint. Nevertheless, the ratio mortar / stone volume has an important role in the deformability of the structure, as observed in the average values.

The modulus of elasticity is influenced by the load history. After a few cycles, the deformability decreases. Future results about long term loading and cyclic loading will help to improve the knowledge about this matter.

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Table 1 - Mechanical properties of sandstones

	ρ (kg/m^3)	f_c (N/mm^2)		E (N/mm^2)		$f_{t'}$ (N/mm^2)	
Sandstone1	2.090	40.00	(34.02)	10.468	(12.58)	6.28	(39.20)
Sandstone2	2.066	64.60	(24.33)	10.620	(24.72)	5.14	(12.62)

Table 2 – Experimental results obtained from stone masonry prisms.

Material / specimen	f_M’	f_M	ε_{max}	$E_{[30\%-60\%]}$	$E_{[25\%]}$	$E_{[50\%]}$	$E_{[75\%]}$
	(MPa)	(MPa)	(mm/m)	(MPa)			
Dry joint ashlar masonry							
PdA1	3.20	13.13	25.9	1055	621	1166	829
PdA2 [1]	1.20	4.71	20.7	246	203	267	202
PdA3 [1]	0.31	3.52	25.3	412	168	456	316
PdA4 [1]	0.35	7.47	28.8	515	335	739	465
Average values	*1.27*	*7.21*	*25.2*	*557*	*332*	*657*	*453*
Ashlar masonry [2]							
PA1	2.09	4.54	32.8	151	136	158	153
PA5	2.29	8.18	19.6	461	344	498	701
PA6	2.62	7.85	20.8	504	406	514	652
PA7	3.92	9.81	25.1	628	487	707	513
PA8	1.96	9.99	26.8	486	396	514	614
Average values	*2.58*	*8.07*	*25.0*	*446*	*354*	*478*	*527*
Ashlar masonry [3]							
PA2 [4]	*	8.16	12.4	1220	1303	1035	529
PA3	*	11.25	27.4	458	337	451	518
PA4	*	10.39	34.6	323	270	369	410
Average values	*	*9.93*	*24.8*	*667*	*637*	*618*	*486*
Rough masonry							
PR1	*	2.83	43.5	79	59	75	95
PR2	0.39	1.66	42.4	52	52	52	41
PR3	0.36	1.10	27.7	49	49	49	18
PR4	0.36	1.76	37.4	69	68	78	62
Average values	*0.37*	*1.84*	*37.8*	*62*	*57*	*63.5*	*54*
Inner core / filling mortar							
PM1	*	0.16	26.5	15	14	15	3
PM2	0.12	0.20	23.4	16	11	12	6
PM3	0.13	0.18	13.4	13	17	12	6
PM4	0.12	0.22	21.4	18	26	17	7
Average values	*0.12*	*0.19*	*21.2*	*15.5*	*17*	*14*	*5.5*

* Not registered result

[1] Specimens built by non-expert masons

[2] Specimens with negligible strength mortar (white cement - lime - sand: 1.5 – 0.5 – 19)

[3] Specimens with low strength mortar (white cement - lime - sand: 2 – 0.5 – 10)

[4] Specimen preloaded 3 times before the final up-to-failure test

Table 3 – Compressive strength of masonry prisms: theoretical and experimental results

	PdA	PA	PA'	PR
	(MPa)			
Yvon Villarceau (sXIX)	4.00	4.00	4.00	6.46
Engesser (1907)	13.33	13.53	15.33	21.73
Segurado (1908)	-	1.50	0.80	**0.90**
PIET (1970)	2.00	0.8	1.00	0.5
Francis et al. (1971)	40.00	35.30	35.45	46.35
Khoo and Hendry (1973)	-	-	-	-
Ohler (1986)	32.44	32.46	32.66	52.42
Rozza (1995)	3.20	2.91	2.94	4.50
Eurocode 6 (2003)	-	**5.53**	**11.03**	7.73
ACI (2004)	**10.76**	**10.76**	**10.76**	15.68
BS 5628-1 (2005)	14.00	14.00	14.00	11.31
Spanish CTE (2008)	-	**4.88**	**8.69**	6.67
Test results	**7.21**	**8.07**	**9.93**	**1.84**

PdA: Dry-joint ashlar masonry
PA: Ashlar masonry with low strength mortar
PA’: Ashlar masonry with medium quality mortar.
PR: Rubble masonry.