Chapter 2.4

MECHANICAL CHARACTERISTICS OF ROMAN "OPUS CAEMENTICIUM"

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Abstract: The masonry of many Roman buildings had a composite structure made of two external brick walls and a concrete nucleous; this inner nucleous was a concrete composed by a pozzolanic lime mortar containing large pieces of stones, marbles, tuff and bricks. The mechanical characteristics of the wall depended almost exclusively on the strength of the opus caementicium. As a consequence, it is essential to know the mechanical characteristics of the opus caementicium. An extended experimental project has been carried out in the University of Roma "La Sapienza" to define these characteristics and they are described in this paper.

Keywords: opus caementicium; roman concrete; mortar; pozzolana; lime; mechanical properties; stones; tuff.

1. THE ROMAN OPUS CAEMENTICIUM

It is a common belief that the extraordinary development of civil engineering and of the building industry in roman times was correlated to the quality of the building materials and to the attention reserved to their production and selection. The astonishing rapidity of the Romans in rising huge buildings such as the Maxentius Basilica (Basilica Nova) was possible thanks to the availability of great amounts of materials produced in industrial quantities (Giavarini, 2005). One of the most important and innovative techniques was based on the so called "opus caementicium", which in practice replaced the use of stones in the construction of bearing structures and, generally, of the whole building, including arches and vaults or domes.

The masonry of many roman buildings had a composite structure made of two external brick walls (opus latericium) and a concrete nucleous or core (Figure 1). The inner nucleous was a conglomerate composed by a pozzolanic

S.K. Kourkoulis (ed.), Fracture and Failure of Natural Building Stones, 107–120.

lime mortar containing large pieces of stones marbles, tuff and bricks. Sometimes the external walls were made of square pieces of tuff (opus reticulatum).

In fact, the term "caementum" was referred to the pieces of stones inserted into the mortar and tamped inside. Without the side bricks, the opus caementicium was used for the foundations, but it was normally included inside layers of bricks (opus latericium) or tuff (opus reticulatum). The bricks were triangular in shape disposed as indicated in Figure 1 (Samuelli, 2000, Giavarini, 2005).

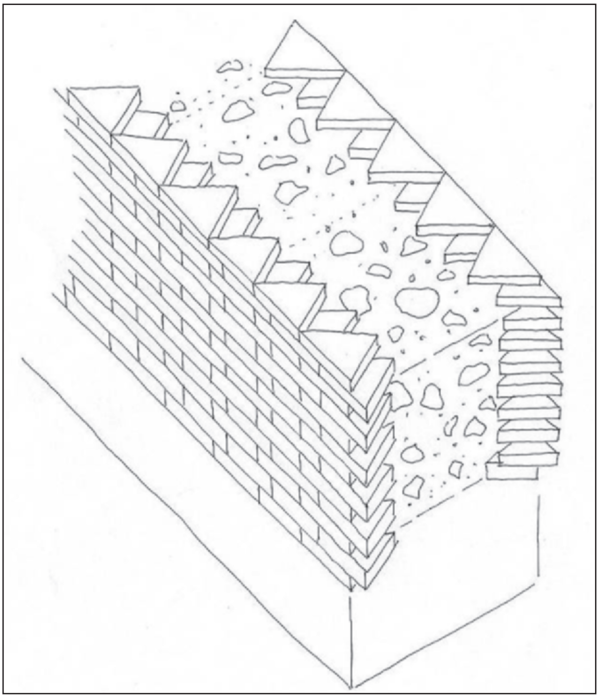

Figure 1. Opus caementicium contained within two facing walls of triangular bricks (opus latericium).

Considering the most common walls delimited by triangular bricks and obtained by diagonally cutting square bricks (typically 20 x 20 cm) the real bearing width of the masonry was only 7 cm, i.e. absolutely negligible when referred to walls with a thickness of some meters (e.g. 4-5 m for the Maxentium Basilica walls). Therefore, the mechanical characteristics of the wall depended almost exclusively on the resistance of the opus caementicium: in fact, 14 cm (7 + 7) out of 500 cm is only about 3%.

As a consequence, for the evaluation of the structural behaviour of a roman building, it is essential to know the mechanical characteristics of the opus caementicium. Published works on this subject are relatively scarce: some data are reported by Rondelet (1831); more information has been published by Lamprecht (1968) who gives, however, values which are not in agreement with Rondelet and with the present work; this is due to the fact that the samples were taken from waterproofing materials made with special care and with carefully selected small aggregates ("cocciopesto"). Some structural considerations are also due to DeLaine (1985).

Generally, the building materials used in ancient times are considered "rigid systems", compared to elastic materials such as steel and concrete, widely used in modern buildings. This is not completely true; in fact, materials such as the Roman opus caementicium show a "strange" elastic behaviour in a relatively large range of stresses in spite of the fact that it is more subjected to static deformation than modern materials.

An experimental research on the mechanical characteristics of "opus caementicium" can add useful information for the evaluation of the safety margins of the still standing roman monuments and, moreover, it can contribute to the understanding of the design criteria of the ancient architects.

2. THE EXPERIMENTAL WORK

An extended experimental work was carried out by CISteC with the help of the Materials & Structures Laboratory of the University of Roma "La Sapienza". Portions of masonry as well as the constituent materials (bricks, mortar, opus caementicium, different types of stones) were tested in the laboratory, both using original ancient samples (when available) and new samples prepared in the lab following the ancient recipes and procedures.

The resistance to axial stresses, mainly compression, was considered most important. The elastic modulus (ratio between stresses and corresponding strains) and the Poisson's coefficient (ratio between axial and transverse deformations) were determined from the linear elastic portion of the deformation curves. During the testing it was important to evaluate how the deformations evolved after the peak stress. Important physical properties included were the density, the porosity, and the ductility. A number of non-elastic deformations were also important, as well as the dimensional changes due to temperature and to the absorption of humidity.

2.1 Bricks

The components of the opus caementicium first studied were bricks. Bricks were used both as "side walls" of the opus caementicium and inside it as fragments (recycled from other uses).

For the tests, prismatic samples were used. Their base had dimensions 15x15 mm while their height was 30 mm. The square base was perpendicular to the applied load; the samples were suitable for compression, direct traction and elastic modulus tests. Four strain gauges were applied to the rectangular faces during the compression tests, while the traction tests were carried out by applying two metal plates each connected to a steel wire, in order to ensure a good aligning of the load. A number of tests carried out on modern bricks of similar strength allowed the definition of a "shape coefficient" necessary to correlate samples with different dimensions. A "rigid" test equipment was used with controlled deformation, suitable for tests beyond the peak stress.

Ductility was considered to be the ratio between the peak axial deformation (during the compression test) and the deformation after the sample collapsed and reduced its resistance down to 50% of the original one: $\sigma=\varepsilon_{50\%}/\varepsilon_{ult}$. The results of the tests carried out on about 30 samples taken from different roman bricks (II-IV century a. D.) are shown in Table 1 and Figures 2 and 3. The stress - strain curves are characteristic of a fragile material. Considering the different origin of the bricks and, therefore, the different production materials and procedures, the results are not homogeneous. For the compressive resistance the values vary from about 10 to almost 40 N/mm^2.

A study was also carried out on 30 bricks (hand-made in the laboratory) to evaluate the influence of the specimen shape on the compression strength. The shape factor of the first series of specimens (15x15x30 mm) was 1.00; the shape factor of the second series (cubic specimens, 30x30x30 mm) was 1.14; finally, the third series (125x125x30 mm) had a shape factor of 1.26.

2.2 Stones

A number of pieces (average dimensions 5-25 cm) of bricks and of various stones were inserted in the opus caementicium mortar: mostly tuff, but also marble, travertine, basalt, etc. Tuff square pieces were sometimes used as external components ("walls") of the opus caementicium, as well as the characteristic tuff truncated pyramids of “opus reticulatum”. Therefore, it was important to evaluate their contribution to the total strength of the opus. Tuff stones were particularly important in the vaults and as roofing concrete components due to their lower density.

Table 1. Characteristics of roman bricks (29 specimens)

		Average	Standard dev.	Variation coeff.
Compression strength, f_c	N/mm^2	17.02	5.90	0.35
Tensile strength, f_t	N/mm^2	3.33	1.25	0.30
Young’s modulus	N/mm^2	13400	4748	0.35
Ductility ratio	-	2.26	0.35	0.16
Apparent volumic mass	kN/mm^3	24.00	1.02	0.04
Dry volumic mass	kN/mm^3	16.03	0.91	0.06
Real volumic mass	kN/mm^3	27.70	0.46	0.02
Porosity	%	13.9	4.37	0.31

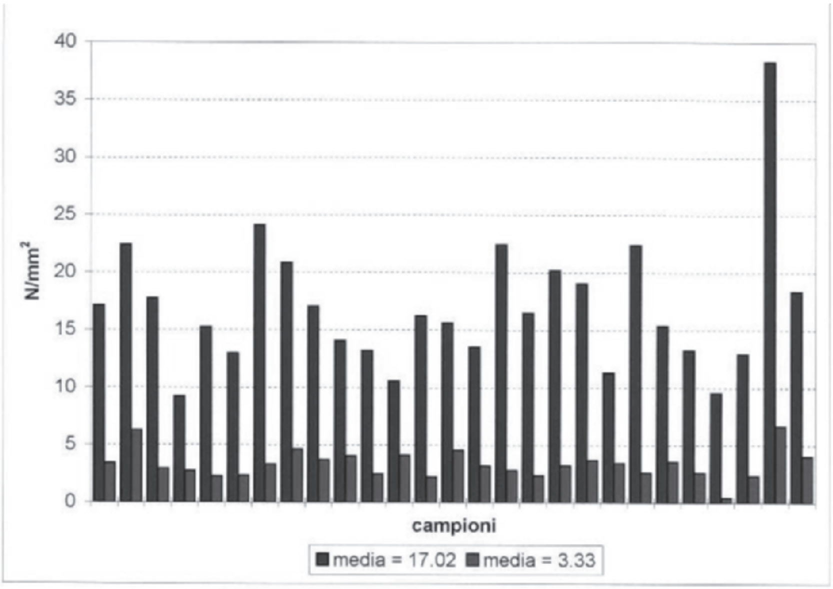

Figure 2. Histogram of the compression (long bars) and the traction (short bars) test on brick specimens.

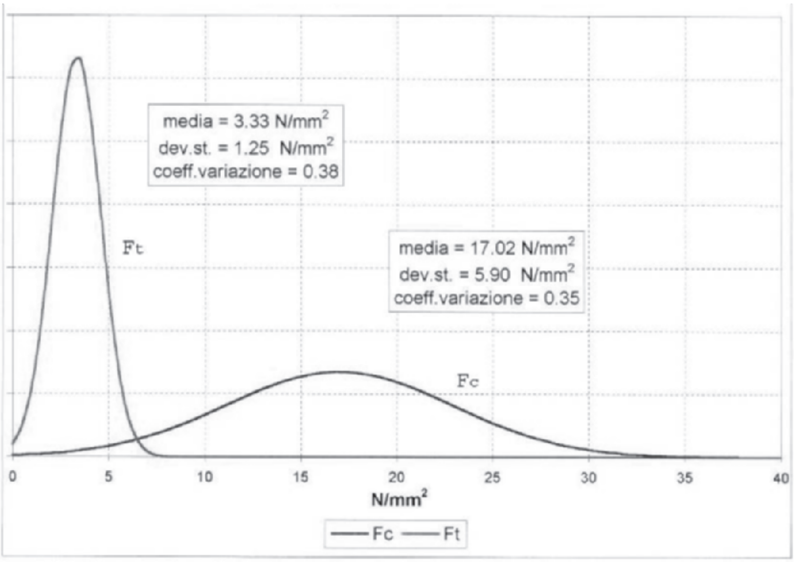

Figure 3. Gauss distribution of the compression (Fc) and traction (Ft) test on bricks.

The stones considered in our experimental work were different types of tuff and travertine. The elastic modulus and the results of the compression tests performed on parallelepiped samples are shown in Table 2.

Table 2. Compression strength and elastic modulus on tuffs and travertine samples

Sample	Volume mass kN/m^3	Compressive strength, f_c N/mm^2	Elastic modulus E N/m^2
Soft tuff	11.63 12.78	1.96 3.66	-- --
Medium tuff	14.21	9.88	--
Peperino tuff	18.15 18.85	36.03 50.16	-- 16950
Travertine	24.88 24.65	44.37 38.95	-- 64540

2.3 Mortars

Ancient mortars cannot be tested because of the practical difficulty to have suitable test samples. Therefore, the samples (40x40x160 mm) were prepared in the laboratory by using industrial lime ("calce fiore") and pozzolanic material from Pomezia ($\phi \leq 2$ mm). The recipe, taken from Vitruvius (1997), used one part by volume of lime, three parts of pozzolana and ~ 0.7 parts of water (1.39 liters per kg of lime); the weights of lime and pozzolana were about the same. The exact amount of total water was determined by the slump test, using a small scale (1/3) Abram's cone. It was found that a 5 mm slump, referred to the original height of 100 mm, could provide both sufficient workability and good consistency.

The term "harena" used by Vitruvius was supposedly referred to the coarse pozzolana from the quarries near Rome, while the term "pulvis puteolana" indicated the finer material from Pozzuoli. The samples were subjected to the traction test following the Italian standards. The flexural strength was deduced from a three point bending test; the two fragments obtained were then inserted in the compression equipment. For each curing period (7, 28, 90, 180, 360 days) 15 samples were prepared in order to have 15 values of the traction resistance and 30 values for the compression strength. The average values of the compression, traction and elastic modulus at various curing periods are given in Table 3.

Table 3. Mechanical characteristics of the mortars

Curing time [days]	f_c, compression strength [N/mm^2]			f_t, traction strength [N/mm^2]			Elastic modulus [N/mm^2]		
	Ave.	St. dev.	St.var. %	Ave.	St. dev.	St.var. %	Ave.	St. dev.	St.var. %
7	5.92	0.15	2.6	0.85	0.09	10.5	969	40	4.3
28	9.68	0.67	6.9	1.31	0.12	9.1	3429	127	9.1
90	13.32	1.24	10.1	1.35	0.14	10.1	2960	131	4.4
180	13.04	0.77	6.0	1.09	0.06	5.0	3244	103	3.0
360	12.07	1.02	8.5	0.95	0.10	10.2	3077	110	2.9

The compression strengths were high, especially when related to the Italian standards for the lime/pozzolana mortars (2.5 N/mm^2 at 28 days curing); values in this range are usually characteristic of cement - sand mortars. The unusual decrease of the strengths after 180 days has not been explained.

An important conclusion can, also, be drawn by considering the stress-strain curves (not reported here): the large deformations recorded after the peak stress (in the seven days tests) indicated that the mortar can tolerate quite large settings even when significant hardening is reached.

2.4 Ancient roman concrete

2.4.1 Mechanical tests

The availability of original samples is very restricted for obvious reasons (the responsibles do not like any destruction of the ancient monuments!); moreover, the ancient samples are usually far from perfection, due to the presence of various defects (cracking, missing parts, etc.).

Thanks to the interest of the Soprintendenze responsible for the Italian monuments, a number of samples were taken from:

- Warehouses of Nerva in the ancient harbour of Emperor Claudius in Ostia.
- Villa Adriana in Tivoli (three exedras hall).
- Maxentius' Basilica in Rome.

The composition of roman opus caementicium has been already described, however in the actual study the following were observed:

- the mortar content in the opus caementicium varied between about 40% and 60%.
- the quality of the pozzolana was better in the more stressed structures.
- the aggregate (bricks and stones, mostly tuff) were roughly placed in horizontal layers.
- in the barrel vaults the content of light materials as aggregates was significantly higher; as an example, the vaults of the Basilica of Maxentius showed higher pumice contents.

The results of the tests, as well as the size and form of the samples, are shown in the Table 4. The data of the table and additional experimental results suggest that the compressive strengths of a "good" opus caementicium can be estimated to be averagely 5-6 N/mm^2.

2.4.2 Wetting-drying cycles

The purpose of this part of the experimental work was the evaluation of the effect of wetting and drying cycles on a number of ancient cores taken from ancient roman monument.

Table 4. Mechanical tests on ancient opus caementicium samples

	Origin	Shape	Vol. mass kN/m^3	f $_c$ N/mm^2	f $_t$ N/mm^2	Elast. mod. N/mm^2	Poisson's ratio
1	Nerva's warehouses	Cylinder	15.9	4.29	-	2550	-
2	"	"	15.3	2.22	-	2500	-
3	"	"	14.6	0.98	-	800	-
4	Villa Adriana	Prism	17.7	5.87	0.88	9170	-
5	"	"	17.4	6.7	-	3000	0.18-0.19
6	"	"	17.7	4.5	0.77	5740	-
7	Slope fill. Terrace	Cylinder	13.5	2.35	-	-	-
8	"	"	13.5	2.43	-	-	-
9	Caem.. Second vault	"	13.5	6.07	-	-	-
10	"	"	15.0	4.97	-	-	-
11	"	"	14.8	5.82	-	-	-
12	"	"	-	4.84	-	-	-
13	First wall	Prism	-	6.0	-	2800	-
14	Filling N-E side	"	-	4.2	-	1750	-
16	S-W foundation	"	-	5.3	-	3500	-
17	"Ladrone" arch	"	16.5	6.16	-	-	-

Small dimensional variations, when referred to huge walls, could give interesting results and, possibly, explain a number of phenomena (cracks, failures, variations of wall heights) previously attributed exclusively to ground movements.

The consolidation project of Domus Tiberiana included the application of a number of tie bars and the drilling of the walls to allow the bars to be put in place. The most suitable cores obtained from the drilling process were used for the present study; their characteristics and the coarse aggregates (>10mm) are listed in Table 5. Observed by stereoscopic microscope, the thin sections of all mortars showed the presence of a fine red pozzolana and tuff (aggregate <4mm). In sample 2 the tuff was a typical roman yellow tuff, while in the other samples the tuff was a red tuff (*lionato* tuff). An aggregate with dimension >4mm, made of a grey and a grey/red pozzolana, was present in the mortars of the samples 1 and 4, respectively.

Table 5. Main characteristics of the core samples

Sample	Diameter (cm)	Length (cm)	Pozzolana type	Coarse aggregates
1	10	40	Red	Red tuff (~ 33%)
2	9	37	Red	Yellow tuff (~14%) Brick (~18%)
3	9	52	Red	Red tuff (~33%)
4	9	43	Red	Red tuff (~29%) Marble (~2%)
5	8	33	Dark red	Brick (~30%) Yellow tuff (~12%)

Three couples of metallic datum-points were applied on all cores in various points in order to obtain three different measures in each sample (Figure 4). Each sample was longitudinally immersed in tap water covering only half of its diameter to damp gradually the total core by capillary rise and to allow the entrapped air to escape. A series of measurements were taken at regular periods for a month or more. Afterwards, the wet samples were left in open air in the laboratory for a month or more until they were dry. Six complete wetting-drying cycles were carried out on each sample.

The results of the wetting - drying cycles are given in Figure 5. The data show that, on average, the concrete's behaviour is similar for all cycles, i.e. the length variation (ΔL/L) of samples of roman concrete subjected to a number of wetting/drying cycles is quite repeatable. For the purposes of this research it was assumed that, on average, the length variation of the samples is about 3-4‰, or 3-4 mm for each meter. Such a variation is quite important for a material normally considered dimensionally stable.

Figure 4. The core samples used for wetting-drying cycles, showing large pieces of aggregates, typical of the roman opus caementicium.

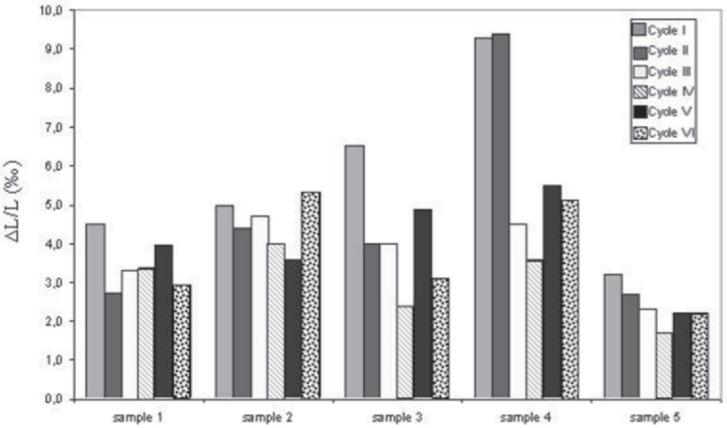

Figure 5. Visualization of the dimensional variations during wetting/drying cycles on five samples of opus caementicium.

2.5 Opus caementicium prepared in the laboratory

Prismatic elements of opus caementicium (300x300x600 mm) were prepared in the laboratory. Several samples were then taken from the prismatic elements by means of a core-drilling procedure. The samples were tested by the equipment shown in Figure 6. The sample rests on two semi-circular steel cradles, lined by a layer of teflon. A central steel cradle with similar teflon strips applies the shearing load. The gap between the loading and the supporting devices must be accurately defined, because it must allow a "guillotine" behaviour, without introducing any disturbing effect. The two supports rest on rollers, in order to avoid interference with the applied axial load. The test is performed by applying a given value of compressive stress σ, which is kept constant by means of an automatic device, and then increasing the shearing action until collapse is reached. The results are shown in Figure 7.

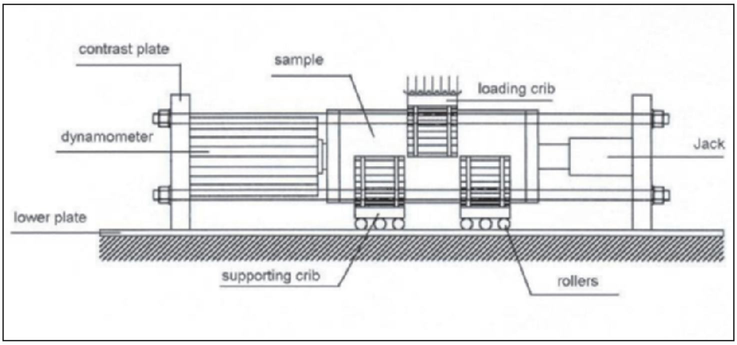

Figure 6. Compression-shear equipment for testing the laboratory cylindrical specimens.

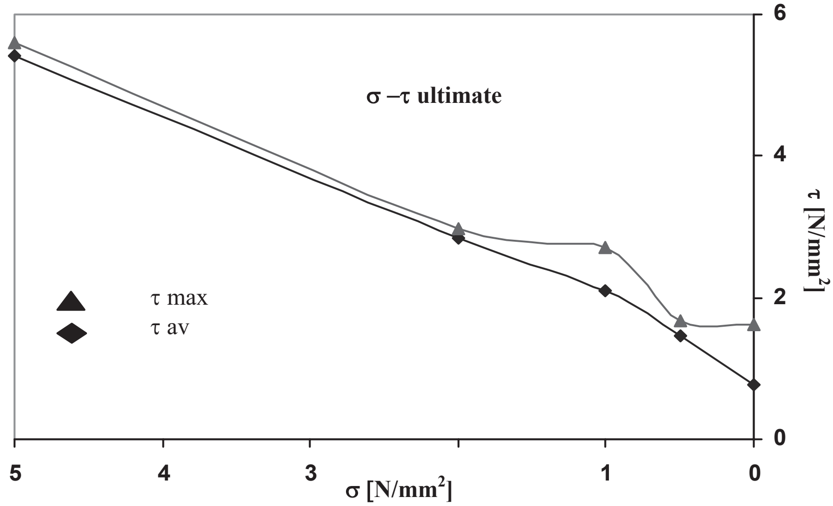

Figure 7. Results of the shear-compression ultimate tests on opus caementicium samples.

2.6 Roman-type wall made in laboratory

The purpose of the last phase of the work was to test panels representing portions of the whole Roman wall, composed of two external layers of bricks containing the core of opus caementicium (Figure 8). The triangular bricks were handmade, in order to obtain a strength (average 19.3 N/mm^2) similar to that of the original bricks. The filling of the core followed the procedure suggested by a number of authors (Adam 1984, Giuliani 1990). The wall samples were built on steel plates in order to move them from the building site to the testing machines. Two of the samples were subjected to axial compression. The most significant results are the following:

- the ultimate average strength is 6.3 N/mm^2.
- the wall samples follow good linear behaviour up to around 5 N/mm^2.
- the collapse is preceded (at around 4.5 N/mm^2) by vertical (columnar) cracking. The Poisson's ratio in the elastic region increases from its initial value of 0.18 to more than 1 near collapse.

Figure 8. An example of roman – type wall during the preparation in the laboratory (Engineering Faculty, University of Rome "La Sapienza").

The remaining eight wall samples were subjected to combined shear compression, by using two different pieces of equipment, especially made for the test. The first one (Figure 9), which was employed in case the ratio τ/σ was larger than one, was composed of two diagonal steel bands contrasting an actuator (jack and dynamometer); in this way equal components of compression and shear were imposed: $\sigma=\tau$. The second equipment was of the guillotine type as it is shown in Figure 10. The results are shown in Figure 11. In the low compression region the structure behaves as a cohesive material, while for higher values of σ a friction mechanism prevails. The friction coefficient, in this case, is considerably lower (0.2 instead of 0.8). This is presumably due to the sliding of the lateral brick layers.

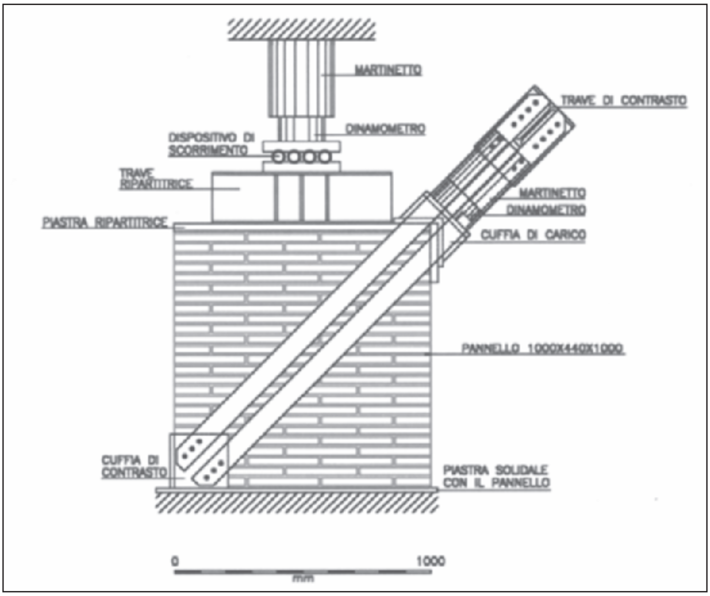

Figure 9 . Diagonal-type equipment for testing the roman wall.

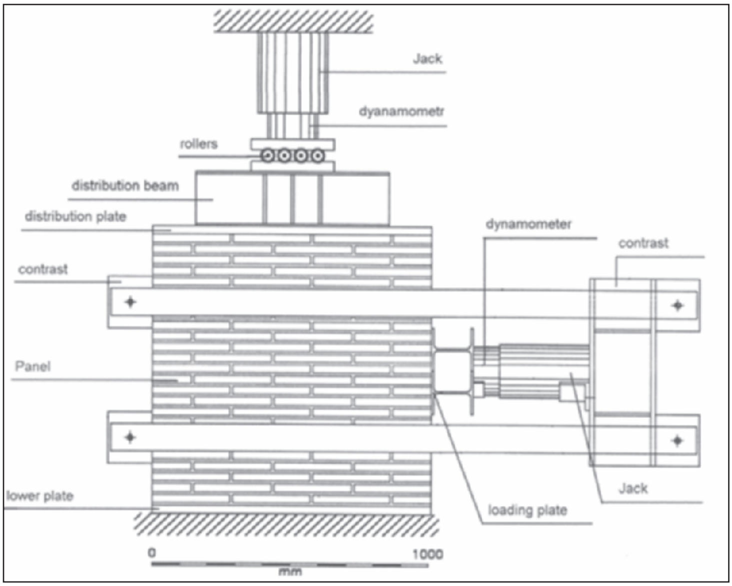

Figure 10. Guillotine-type equipment for testing the roman wall.

3. CONCLUSIONS

Some important mechanical characteristics of the construction materials used by ancient Romans have been measured both on authentic archaeological

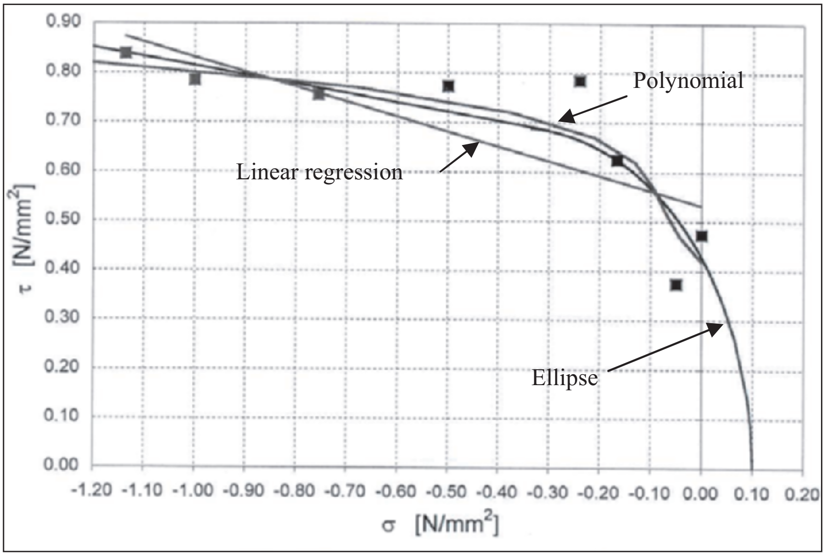

Figure 11. Shear-compression tests on roman walls. Experimental results and interpolations.

samples as well as on new samples prepared following the roman receipts. Mortars, concrete (opus caementicium) and pieces of masonry have been tested. The mechanical characteristics of roman walls depend almost exclusively on the resistance of the opus caementicium. For compositions in the range of the samples used in this work, it can be safely assumed that the compression strength is equal to 5 N/mm^2. The shear stresses that can be foreseen are usually "safe" with respect to the corresponding strength.

One of the more significant results of this study is that a linear-elastic modelling of masonry buildings is possible. As a matter of fact the linearity of the opus caementicium extends for more than two thirds of the total range, up to collapse. The dimensions of the stones composing the opus caementicium seem sufficiently small to admit the use of Finite Elements analysis.

The results provide useful information for solving problems of structural analysis related to roman monuments. The behaviour of roman masonry is influenced by the humidity contained in the opus caementicium. In fact, dimensional variation of 3-4‰ was measured during wetting - drying cycles: referred to huge walls, these changes could be responsible of cracks and failures.

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