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AXIAL COMPRESSION TESTS ON RUBBLE STONE MASONRY REPRODUCING *OPUS INCERTUM* OF ANCIENT POMPEII

FRANCESCA AUTIERO[1*], GIUSEPPINA DE MARTINO[1], MARCO DI LUDOVICO[1], ANDREA PROTA[1]

[1]Department of Structures for Engineering and Architecture
University of Federico II
Edificio 6-7, Via Claudio 21, 80125 Naples, Italy
e-mail: francesca.autiero@unina.it

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Abstract. *In order to investigate the mechanical behaviour of the typical ancient rubble stone masonry type at the archaeological Pompeii site, an experimental program was carried out on masonry panels realized with the aim of reproducing the ancient technique opus incertum. Three panels (1.20m x 1.20m x 0.45m) were realized by using original rock units from ruins emerged in the excavation works at Regio V at the site and pozzolanic lime-based mortar realized according to the traditional technique. The first phase of the experimental program involved the accurate reproduction of Pompeii-like masonry panels and the execution of sonic pulse velocity tests to be compared with those carried out on original structures at the site. Thus, three in-situ diagonal compression tests were carried out to derive masonry shear strength and relevant correlation with sonic velocities. The last phase of the experimental program focuses on laboratory axial compression tests on five specimens extracted from the three panels analyzed in the first phase and is herein described in detail. The results of axial compression tests on two of such specimens in terms of axial compression strength and elastic modulus as well as the analysis of the crack pattern and failure mode is herein presented and discussed.*

1 INTRODUCTION

The achievement of a deep knowledge of the mechanical behaviour of ancient masonry structures is a critical issue for the preservation of the built heritage, especially in the archaeological field [1]. Indeed, the main mechanical properties of the single building materials and the masonry assemblages are required for the structural assessment of the masonry structures and for the definition of proper restoration interventions. However, the need to preserve the built heritage clearly set restrictions to the collection of standard specimens for the execution of laboratory tests on materials and assemblages and also set restrictions to the execution of destructive and minor-destructive *in situ* tests. Thus, the development of new methodologies and investigation protocols for the knowledge of the built heritage is required and should include: i) the contribution of different disciplines to achieve a comprehensive knowledge and to limit the number of tests needed; ii) the application of non-destructive methodologies, to ensure the preservation of the heritage [2,3].

In the archaeological Pompeii site, a specific database on the mechanical properties of the different building materials and masonry type is still lacking. Therefore, the present study is a part of a wide experimental programme aimed to the mechanical characterization of one of the most common masonry building technique at the archaeological Pompeii site: the rubble stone masonry, traditionally known as *opus incertum*. Since the investigation of the original masonry structures at the site is restricted to the execution of Non-Destructive Tests, NDTs, this part of the experimental programme involved the realization of masonry panels reproducing the ancient technique *opus incertum*, for the execution of Destructive Tests, DTs. The design of the panels (i.e. definition of the mortar; shape, size, nature and arrangement of the rock units; arrangment of the cross-section and wall thickness) was defined based on datailed geometric and material surveys of the original structures at the site. Original rock units from the ruins emerged in the excavation works in *Regio V* started in May 2018 and pozzolanic lime-based mortars compliant with the traditional typologies were selected to built the panels. Thus, a preliminary investigation of the mechanical properties of the single building materials was carried out including the execution of both NDTs and DTs [4,5]. Therefore, three panels (1.20m x 1.20m x 0.45m) were built and sonic pulse velocity tests were performed in order to provide a useful tool for a comparison with the same tests performed on original structures at the site. Thus, three in-situ diagonal compression tests were carried out to derive the masonry shear strength and relevant correlation with sonic velocities. The last phase of the experimental program focuses on laboratory axial compression tests on five specimens extracted from the three panels analyzed in the first phase.

In this paper, the results of the first phase of the experimental programme as well as the realization of the specimens are summarized, while the axial compression tests performed on two specimens are described in detail. The results in terms of axial compression strenght and elastic modulus as well as the analysis of the crack pattern and failure mode of such specimens is herein presented and discussed.

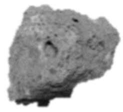
2 BUILDING MATERIALS

The definition of the building materials for the construction of the panels was based on a in-depth knowledge process on the typical rubble stone masonry type at the Pompeii site, i.e. the ancient *opus incertum*. Specifically, the definition of the shape, size, nature and arrangement of the rock units was based on datailed surveys of original structures, particulartly focusing in the area of the *Regio V* at the site, while the defintion of the mortar was mainly based on the the traditional composition and materials knowledge.

2.1 Original rock units

Three different rock types were defined to be used for the construction of the masonry panels: travertine, lava and foam lava (i.e. "*calcare del Sarno*", "*lava*" and "*cruma*"). Over the course of the archaeological excavation work started in May 2018 at the *Regio V*, it was possible to collect original units of such rock types from the newly-emerged ruins [5]. A brief description of such rock types is summarized in Table 1.

Table 1: Brief description of the rock types defined for the construction of the masonry panels

Travertine	**Lava**	**Foam lava**
		
Carbonate rock, whitish coloured, cavernous fabric	Effusive rock, dark grey coloured, scoriaceous, glass-rich	Tephrite subtype, dark red to grey coloured, air bubble fabric

Ten units (i.e. three travertine units, five lava units and two foam lava units) were used for a preliminary experimental programme that included both NDTs and DTs for the machanical characterization of these materials. As NDTs, the experimental programme involved the execution of Schmidt hammer rebound tests, SHR, and ultrasonic pulse velocity tests, UPV: the first allowed obtaining the rebound number, H_r, that was related to the surface hardness of the material; the second allowed obtaining the compression wave velocity, V, that gived information on the homogeneity of the specimen and and can be used for the estimation of physical and mechanical properties of the material [6–10]. In detail, the units were tested by SHR and UPV first, then UPV and uniaxial compression tests were performed on thirty-two cubic specimens 70mm x 70mm x 70mm obtained from the units according to [11] for the definition of the uniaxial compressive strenght and correlation with NDTs results. Table 2 reports a synthesis of the main results of the tests performed on the rock specimens [4]. In detail it reports for each investigated rock type: the number of units involved, n_{units}; the average value of rebound number obtained on the units, H_r; the number of cubic specimens tested for each rock type, n_{cubes}; the average bulk density of the cubic specimens, ρ; the average compression wave velocity evaluated along the same direction of the compression load, V; the average compressive strenght, σ.

Table 2: Main results of tests performed on the rock specimens

Rock type	$\mathbf{n_{units}}$	$\mathbf{H_r}$ **[-]**	$\mathbf{n_{cubes}}$	**ρ [kg/m³]**	**V [m/s]**	**σ [MPa]**
Travertine	3	17	11	1382 (CoV = 14%)	2315 (CoV=19%)	5.88 (CoV = 75%)
Lava	5	29	8	2300 (CoV = 4%)	1987 (CoV=26%)	38.43 (CoV = 40%)
Foam lava	2	15	13	904 (CoV = 10%)	1532 (CoV=13%)	3.90 (CoV = 35%)

The main outcomes showed a significant difference among the investigated rock types. Moreover a notable variability of the outcomes resulted for each rock type, especially as regards the compressive strenght. This is probably due to the natural heterogeneity of the investigated materials and the mechanical and physical decay of the collected units. As concerns the correlation between NDTs and DTs results, the uniaxial compressive strenght was correlated with: i) the rebound number, H_r, and ii) the parameter V·ρ, where V is the ultrasonic pulse velocity evaluated along the direction of the compression load and ρ is the bulk density of the specimen evaluated before the execution of the DTs [4]. In the first case a linear function was defined, while in the second case a quadratic function was defined. Both correlation showed a good matching between analytical formulation and experimental results (R^2 = 0.75 and R^2 = 0.80 respectively), as reported in Table 3.

Table 3: Empirical correlation between NDTs and DTs

Parameters	Empirical correlation	Coefficient of determination
σ, H_r	$\sigma = 1.9454\ H_r - 25.254$	$R^2 = 0.80$
σ, V, ρ	$\sigma = 3^{12}\ (V\rho)^2$ - 1E-05 $V\rho + 13.507$	$R^2 = 0.75$

2.1 Pozzolanic lime-based mortar

A mortar consisting of putty lime as a binder and pozzolana as a aggregate with a ratio 1:3 by volume was defined for the construction of the panels. The constituent materials were defined to be very similar to the ones traditionally used in the ancient techniques [12,13]. In particular, the pozzolana used came from the area of the Phlegrean Fields in Campania, Italy, as the volcanic ash that the ancient builders in Roman time used and called *pulvis puteolanus.* For the mechanical characterization of such mortar six prismatic specimens 40mm x 40mm x 160mm were realized for the execution of flexural and compression tests according to [14]. In order to evaluate the strenght evolution, a set of three specimens was tested at one month and another set of three specimens was tested at two months from casting [4]. The main average otucomes obtained on each set of specimens are summarized in Table 4. In detail Table 4 reports: the age at which the tests were performed; the number of prismatic specimens, n_{prisms}; the average bulk density evaluated on the prismatic specimens, ρ; the average flexural strength evaluated on the prismatic specimens, f; the number of cubic specimens, n_{cubes}; the average compressive strength evaluated on the cubic specimens, σ. The results showed an increase of +21% of the compressive strength moving from one month to two months of curing time.

Table 4: Main average results of tests performed on the mortar specimens

Age	n_{prisms}	ρ [kg/m^3]	f [MPa]	n_{cubes}	σ [MPa]
1 month	3	1181 (CoV = 3%)	0.77 (CoV = 6%)	6	2.39 (CoV = 3%)
2 month	3	1105 (CoV = 2%)	0.55 (CoV = 9%)	6	2.87 (CoV = 5%)

3 RUBBLE STONE MASONRY SPECIMENS

Three panels 1.20m x 1.20m x 0.45m were specifically designed based on in-depth survey of the original structures at the site (Figure 1 (a)). Specifically, a newly-emerged *opus incertum* masonry structure as part as the archaeological excavation at *Regio V* was selected, analysed and used as a reference for the realization of the new panels. The panels were realized with original units and putty-lime-and-pozzolana-based mortar, as described above. The wall thickness was defined to be 0.45m based on a survey of similar ancient structures at the same area at the site. The cross-section was defined to be double-leaves without connecting elements. The leaves were realized with travertine, lava and foam lava ancient units with irregular size and shape plus some fragments of other nature as in the real masonries. The units were embedded in the putty-lime-and-pozzolana-based mortar, without any vertical or horizontal alignment. The internal part of the masonry was filled with the same mortar and rock fragments or smaller units.

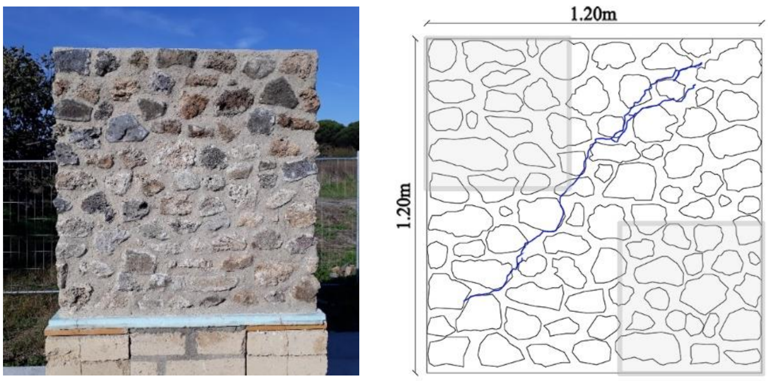
A campaign of sonic tests was performed on the panels as a preliminary phase to the execution of DTs at different ages in order to: i) evaluate the evolution of the curing of the panels; ii) compare the results with the ones of the DTs to be performed; iii) provide useful data to set up comparison with similar old structures at the site. Indeed, sonic pulse velocity tests is one of the most common NDT used for the assessment of old masonry structures and some experimentation at the Pompeii site are already present in literature [15,16].

Afterwards, the first phase of the experimental programme of DTs involved the execution of three in-situ diagonal compression to derive the masonry shear strength and relevant correlation with sonic velocities. Diagonal compression tests were performed according to [17], with a specific set-up designed for the execution of outdoor tests. The main results of the diagonal compression tests and sonic pulse velocity tests are summarized in Table 5 in terms of: average sonic pulse velocity detected before the execution of the diagonal compression tests, V; average shear strenght evaluated according to [17], τ_{max}; average shear strain corresponding to the maximum shear stress, γ_{max}; average shear modulus, G. Note that the shear modulus G was evaluated only for two specimens due to inaccurate local recordings detected on one panel.

Table 5: Main experimental outcomes of the diagonal compression tests

V [m/s]	**τ_{max} [MPa]**	**$\gamma_{\tau max}$ [-]**	**G [MPa]**
2767 (CoV = 11%)	0.23 (CoV = 16%)	0.16% (CoV = 3%)	520.83

Finally, after the diagonal compression tests five masonry specimens were extracted from the undamaged portion of the panels to perfom laboratory axial compression tests (Figure 1 (b)). In the following the first axial compression tests performed on two of such masonry specimens are described in detail and their results in terms of axial compression strenght and elastic modulus as well as the analysis of the crack pattern and failure mode are presented and discussed.



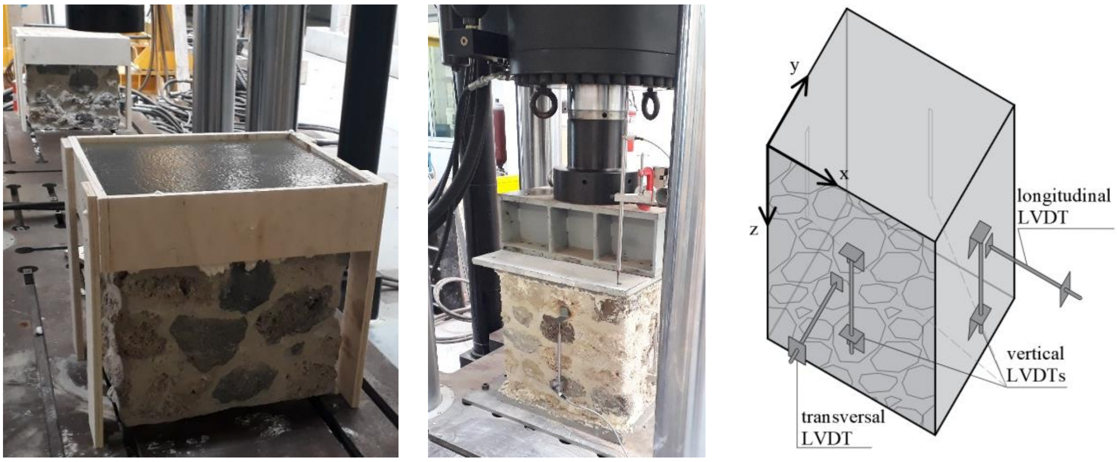
(a) (b)

Figure 1: Masonry panel 1.20m x 1.20m x 0.45m (a); scheme indicating the portion of one of the panels extracted for the execution of the axial compression tests

4 COMPRESSION TESTS

The axial compression test allows obtaining important information on the mechanical properties of masonry specimens in the vertical direction: the ultimate compressive strength; the deformation capacity; the elasticity properties (i. e. modulus of elasticity and Poisson's coefficient). The tests consist in applying monotonically or cyclically an uniform compression load to the masonry specimen. To obtain the compressive strength of the masonry and investigate the deformation capacity in compression, the load must be applied to the specimen up to the failure and the maximum load achieved and the vertical displacement must be recorded. If the modulus of elasticity, E, is to be determined, specific measuring devices must be applied to the specimen for measuring the vertical shortening. Moreover, for the definition of the modulus of elasticity the compressive load should be applied by several loading cycles until a load stage estimated to be in the elastic range with respect to the maximum load expected [18].

In the present study, the axial compression tests performed on two masonry specimens C1 and C2 are presented. In order to ensure that the load distribution faces of the specimens were flat, parallel between them and perpendicular to the direction of application of the load and als in order to prevent local brittle damages, a layer of about 30 mm-thick shrinkage-free and quick-setting mortar was applied at the top and bottom surfaces of each specimen. Between the specimens and the hydraulic cylinder of the testing apparatus, a steel beam and a steel platen were placed on the top surface of the specimens in order to ensure a uniform loading. The test on C1 was performed under displacement control with a rate of 0.02 mm/s in order to define the maximum force attained. Conversely, a cyclic testing protocol including three loading ramps until one third of the maximum expected force with the same rate was used in case of C2 specimen in order to investigate the elastic behaviour of the specimen. At the achievement of each relative maximum load, a constant ramp of 120s was defined, in order to stabilize the state of stress in the specimen. Several measuring devices, i.e. linear variable displacement transducers, LVDTs, were applied to the specimens. Given a reference system with the axes x parallel to the leaves of the masonry specimen, the axes y parallel to the cross section and the axes z in the vertical direction, the measuring devices were positioned for each specimen as follows: i) one longitudinal LVDT (i.e. positioned along the direction x and fixed to an external support; ii) one transversal LVDT (i.e. positioned along the direction y and fixed to an external support); iii) four vertical LVDTs (i.e. positioned along the direction z and directly fixed to the specimen). Figure 2 shows the preparation of the specimens, the test set up and the location of the measuring devices.



(a) (b) (c)

Figure 2: Compensating layer on the up and bottom surfaces of the specimens (a); test set up (b); location of the measuring devices for each panel (c)

4.1 Experimental outcomes

The specimens showed similar maximum compressive load, thus similar compressive strenght (i.e. F_{max}=369.12 kN and F_{max}=368.12 kN, σ_{max}=1.52 MPa and σ_{max}=1.49 MPa, for C1 and C2 respectively). For the evaluation of the vertical strain, the average measurements recorded by the four vertical LVDTs fixed on the specimens were used. Similar results were obtained in terms of vertical strain corresponding to the achievement of the maximum compressive stress also (i.e. $\varepsilon_{\sigma max}$=0.0050 mm/mm and $\varepsilon_{\sigma max}$=0.0052 mm/mm, for C1 and C2 respectively). For C2 the modulus of elasticity, E, was evaluated as the average of the slopes of the loading ramps in the stress-vertical strain curves.

The main experimental outcomes obtained for C1 and C2 are summarized in Figure 3, Figure 4 and Table 6. In detail, Figure 4 reports the compression stress-vertical strain curves for C1 and C2 and Figure 4 reports the compression load-displacement curves in the direction x, y and z for C1 and C2.

The recordings were stopped on the post-peak phase in correspondence of the attainement of the 85% of the maximum stress, except where the measurements were stopped before due to the low quality of the acquisition or the detachment of the measuring devices. From the curves it is possible to observe that the specimens showed very similar behaviour in terms of compression stress-vertical strain relationship despite the different loading protocols applied. A more relevant difference between the two specimens can be detected for the displacement in the horizontal plane. However, both specimens showed a more significant expansion in the direction x than in the direction y.

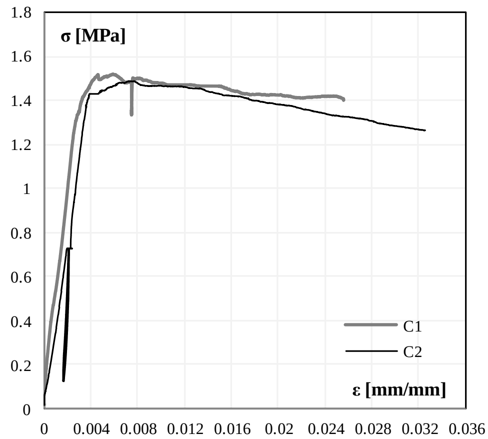


Figure 3: Compression stress-vertical strain curves for C1 and C2

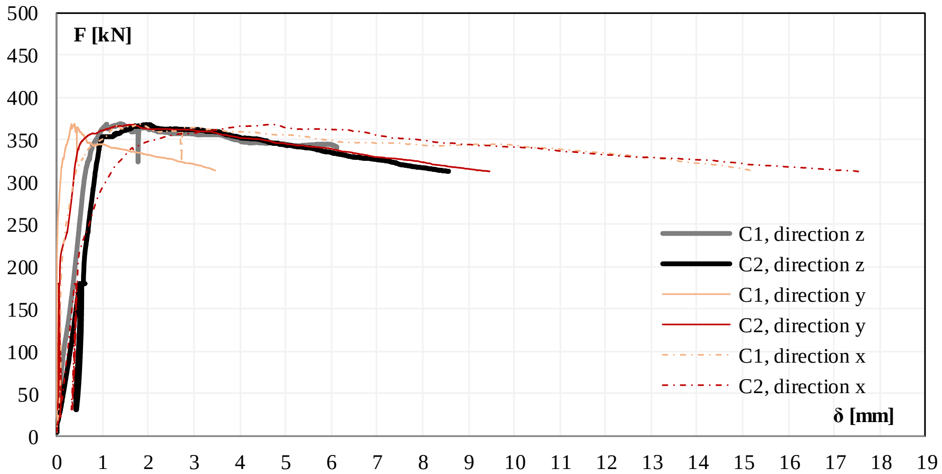


Figure 4: Compression load-displacement curves in the direction x, y and z for C1 and C2

Table 6 summarizes the main experimental outcomes in terms of: maximum compressive load attained, F_{max}; area of the cross section, A; compressive strenght, σ_{max}; vertical strain corrsponding to the achievement of the compressive strenght, $\varepsilon_{\sigma max}$; modulus of elasticity, E.

Table 6: Main experimental outcomes

F_{max} [kN]	A [mm^2]	σ_{max} [MPa]	$\varepsilon_{\sigma max}$ [mm/mm]	E [MPa]
369.12	243000	1.52	0.0050	-
368.12	247500	1.49	0.0052	1252.7

A preliminary comparison is reported with reference to the elastic modulus computed through the sonic pulse velocity test and the elastic modulus experimentally obtained. Indeed, according to [19], it is possible to evaluate the dynamic modulus of elasticity, E_d, for a concrete specimen from the pulse velocity, V, of the longitudinal stress waves according to the following equation:

$$V = \sqrt{\frac{E_d(1-\upsilon)}{\rho(1-2\upsilon)(1+\upsilon)}}$$

Where

- V is the sonic pulse velocity of the specimen;
- E_d is the dynamic modulus of elasticity;
- υ is the dynamic Poisson ratio;
- ρ is the density.

Such equation was defined on the assumption of solid, elastic, isotropic and homogeneous material. Despite masonry is not an homogeneous material, the use of such equation has been considered in some studies for a primary estimation of the mechanical properties of a masonry specimen from the results of a sonic pulse velocity test [20,21]. Thus, in order to assess a comparison between compression tests and sonic pulse velocity tests results, the dynamic modulus of elasticity E_d was calculated, by assuming:

- V equal to 2767 m/s (i.e. average sonic pulse velocity of the specimen);
- υ equal to 0.25;
- ρ equal to 1406 kg/m^3.

The density was evaluated according to a simplified homogenization procedure based on the bulk density of the single components reported in Table 2 and Table 4. According to such procedure the the dynamic modulus of elasticity E_d resulted to be 8971.3 MPa.

In the present evaluation, the calculated value of E_d was significantly higher than the one evaluated through the compression test. This confirmed the need to establish specific experimental relationship for the estimation of mechanical parameters from the sonic test results, based on the specific masonry typology.

As concerns the crack pattern, almost vertical thin cracks developed in the mortar matrix at first, then the crushing of certain units and the expulsion of material outward also occurred. In particular, the units with a lower strenght, i.e. travertine, foam lava and clay fragments were mainly invlolved in the crack pattern. The view at failure of the two specimens is showed in Figure 5.

(a) (b)

Figure 5: Collapse of the specimens: C1 (a) and C2 (b)

4 CONCLUSIONS

Three rubble stone masonry panels 1.20m x 1.20m x 0.45m were realized reproducing the ancient technique *opus incertum* at the archaeological Pompeii site. The panels were realized with original rock units collected at the site and mortar made with putty lime and pozzolana. The experimental program on the panels involved a preliminary phase for the characterization of the building materials, including the execution of both NDTs and DTs on the rock units. Therefore, sonic pulse velocity tests were performed and then three in-situ diagonal compression tests were performed on the panels. Finally, five masonry specimens were extracted from the three panels and the first laboratory axial compression tests were performed on two specimens. The first outcomes showed:

- The axial compression strength were almost the same for C1 and C2 (i.e. σ_{max}=1.52 MPa and σ_{max}=1.49 MPa respectively) despite the variability of size, shape, nature and arrangement of the units within the two specimens;
- The modulus of elasticity of the specimen C2 resulted 1252.7 MPa;
- Despite the different loading protocols applied, the specimens showed very similar behaviour in terms of compression stress-vertical strain relationship with almost the same vertical strain corresponding to the achievement of the maximum compressive stress (i.e. $\varepsilon_{\sigma max}$=0.0050 mm/mm and $\varepsilon_{\sigma max}$=0.0052 mm/mm, for C1 and C2 respectively);
- Both specimens showed higher lateral expansion in the direction perpendicular to the cross section compared to the direction perpendicular to the main surfaces;
- The crack pattern mainly developed in the mortar matrix (σ_{max}=2.87 MPa at two months of age) and the expulsion of material outward occurred;
- The units with lower compressive strenght (i.e. travertine and foam lava with σ_{max}=5.88 MPa and σ_{max}=3.90 MPa respectively) were damaged while the units with higher compressive strenght were not involved in the crack pattern (i.e. lava with σ_{max}=38.43 MPa)

Based on the design process and the building materials adopted for the realization of the masonry specimens, the experimental results showed above could be a unique and useful tool for a preliminary examination of the mechanical behaviour of one of the most common masonry building technique at the archaeological Pompeii site.

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