Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Journal of Cultural Heritage 5 (2004) 137–148
Journal of Cultural Heritage
www.elsevier.com/locate/culher

Original article

The ornamental stones of *Caserta* province: the Campanian Ignimbrite in the medieval architecture of *Casertavecchia*

Domenico Calcaterra [a], Piergiulio Cappelletti [b], Alessio Langella [c,*], Abner Colella [b], Maurizio de Gennaro [b]

[a] *Dipartimento di Ingegneria Geotecnica, Università Federico II, Piazzale V. Tecchio 80, Naples, Italy*
[b] *Dipartimento di Scienze della Terra, Università Federico II, Via Mezzocannone, 8, Naples, Italy*
[c] *Dipartimento di Studi Geologici ed Ambientali, Università del Sannio, via Port'Arsa, 11, Benevento, Italy*

Received 11 December 2002; accepted 1 August 2003

Abstract

A detailed mineralogical and petro-physical characterization was carried out on Campanian Ignimbrite (CI) formation, a volcaniclastic rock widespread over the Campania region. This stone represented and still is an important building material since historical times. Given the huge extension of this formation (about 30 000 km^2) the attention was mainly focused on the historical exploitation areas that provided building materials for the medieval village of *Casertavecchia*. Building stones (different *facies* of CI) used *facciavista* in some relevant monuments of this village were also characterized to carry out a comparison with the in situ corresponding rock. At the same time a complete survey of all the lithotypes used for the façades of the village as well as their state of conservation and weathering phenomena was also performed. As expected, CI in its different *facies* resulted the most common building stone, also affected by severe weathering such as lacks, alveolization and biological patinae, decay forms likely related to the high textural heterogeneity of the rock. Mineralogical and petro-physical characterization allowed to distinguish, within the investigated outcrop area, three different *facies*: dark, light and earthy grey tuff (DGT, LGT and EGT, respectively). Differences in mineralogical data mainly consist in the presence of clay minerals in the EGT *facies* only. K-feldspar always occurs in very high amounts (80–90%). As far as geomechanical parameters are concerned, the most pronounced differences are recorded in water absorption capacity, ultrasonic velocities and UCS values. These tests evidenced a substantial homogeneity of DGT and LGT *facies* and an overall worse behavior of EGT. Tests performed on CI samples from both monuments and outcrops gave similar results. This evidence strengthened the former hypothesis of a location of CI historical quarrying sites close to *Casertavecchia*. The only exception is the tuff used for the *Mastio* of the castle, whose chemical features are definitely referable to a different volcaniclastic formation.

Keywords: Campanian Ignimbrite; Grey tuffs; Building stone; Mineralogical and petro-physical features; Weathering; *Caserta* province; Italy

1. Introduction

Italian territory is characterized by wide occurrences of volcanic tuffs that, due to their large availability, agreeable aesthetic aspect and good geomechanical properties represented, still and are excellent building stones mainly used for structural purposes. Many examples of their use are widespread over the areas where these volcaniclastic deposits crop out, such as south-western Tuscany, Latium and *Campania* regions and, to a lesser extent, *Basilicata*. In *Campania*, since Greek–Roman ages the most common building stones were the Neapolitan Yellow Tuff (NYT) and the Campanian Ignimbrite (CI). The occurrence over the whole regional territory makes the CI the most used building material; furthermore, its easy workability favored the use also as sculpture stone (e.g. *Matres Matutae*, VII–I century B.C.) [1]. In spite of a thorough knowledge from volcanological and petrographical standpoints, scarce attention was devoted to the study of the mineralogical and petro-physical features of this stone and the interpretation of its behavior when used as building or ornamental stone. This material, even though almost homogeneous in chemical and mineralogical terms, usually displays different lithological features within the different outcrops. This is the reason why the present research was limited to a sector of the *Caserta* province where the CI has been intensively used and where it is still possible to identify some ancient exploitation sites. The research also

* Corresponding author.
E-mail address: langella@unisannio.it (A. Langella).

doi:10.1016/j.culher.2003.08.003

aims at comparing the materials cropping out on the slopes of the *Caserta* mountains (Mount Virgo Complex) and those collected during the detailed survey of the medieval village of *Casertavecchia*, whose main building stones belong to the different *facies* of CI formation.

2. Materials

CI is the product of a fixural eruption that occurred in the eastern sector of the Phlegraean Fields, about 39 ka ago [2]; it is the most important volcaniclastic deposit of the *Campania* Region as it crops out over an area of about 30 000 km^2 [3–7]. Its most peculiar *facies* shows a chaotic texture (Campanian Grey Tuff *auct.*) and is constituted by a grey ashy groundmass (more than 50%), dark grey pumiceous scoriae and subordinate lava and crystal fragments (sanidine, plagioclase, green augite, biotite) [3].

Di Girolamo [3] distinguished four *facies* within the unit (Fig. 1a), from the top to the bottom defined as: *cinerazzo* (ashy layer)—tuff—pipernoid tuff—*piperno*, the main difference standing in an increasing welding degree that determines a progressive flattening by collapse of the pumiceous scoriae. In the lowest layers, where this transformation is more pronounced (*piperno* and subordinately pipernoid tuff) he recorded a re-crystallization of the glassy fraction with the formation of authigenic alkaline feldspar. Sometimes the CI also shows a typical yellow or reddish-yellow *facies* related to secondary mineralization processes, which led to the crystallization of chabazite and phillipsite [8,9].

Its widespread occurrence and ease of workability along with the good technical features made this volcaniclastite one of the most demanded building stone in the Campanian architecture [5,10,11]. Although its utilization has a prevailing local character, the main example of regional exportation is towards Naples, where the stone has been used to replace locally the more valuable *Piperno* for architectural elements and less exposed portions of the buildings [12,13].

The most developed exploitation areas were located in the *Caserta* area and in the *Sarnese-Nocerino* campagna even though several quarries were identified over the whole regional territory [14]. Since CI characterizes the most important periods of the architectural history of the *Caserta* province, the research was addressed to sectors of the territory where the urban settings evidenced a massive use of this stone. Two still evident quarries were located at *Pozzovetere*, two more at *Piedimonte di Casolla* and another one at *Puccianello* on the slopes of the carbonate hill where the medieval village of *Casertavecchia* had been built (Fig. 1b). Samples used for mineralogical and petro-physical characterization were collected from the well preserved site in *Piedimonte di Casolla*, where an 8 m high quarry front is exposed (Fig. 1b, inset). Beneath a thin alteration patina different *facies* are distinguishable on the basis of macroscopical features, (a) light grey tuff, hereafter LGT; (b) dark grey tuff (DGT); (c) earthy grey tuff (EGT).

Data on microcores previously collected [11] on the façades of *S. Michele Arcangelo* Cathedral (samples C1 ÷ C5) and of the *Mastio* of the castle (samples M1 ÷ M2) are also reported as comparison.

3. Methods

The research was developed in two distinct phases: the first one was aimed at surveying the lithotypes occurring on

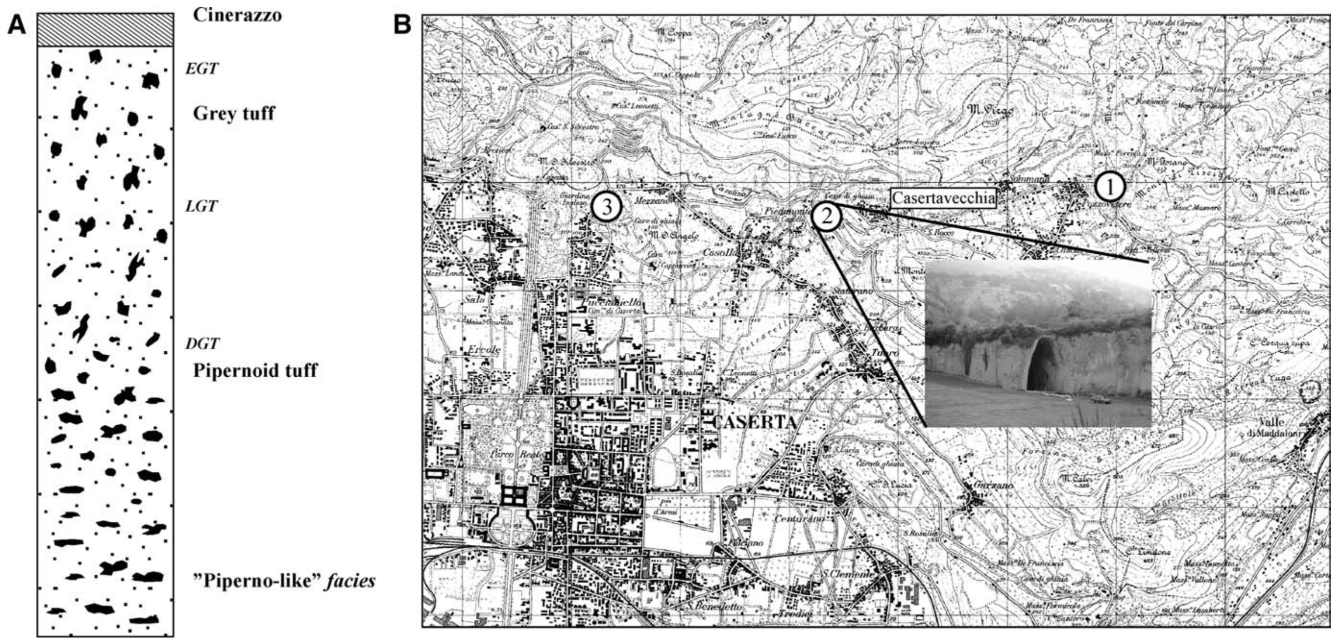

Fig. 1. (a) Stratigraphic reconstruction of the CI grey *facies* in the *Casertavecchia* area. Modified after [3]. EGT, earthy grey *facies*; LGT, light grey *facies*; DGT, dark grey *facies*. Thickness not in scale. (b) Location of ancient quarry sites of CI on the carbonate slope of Mount Virgo. (1) *Pozzovetere* quarry; (2) *Piedimonte di Casolla* quarry; (3) *Puccianello* quarry.

the building façades of *Casertavecchia*, as well as their state of conservation and weathering phenomena. The survey was carried out on the perimetral façades of each building following the methodology described in detail by de' Gennaro et al. [15].

Afterwards, the minero-petrographic and geomechanical study of the materials sampled in the ancient exploitation areas and from the main monuments of *Casertavecchia* was carried out.

The following laboratory tests were performed: X-ray diffraction; mineralogical quantitative analyses using the "Reference Intensity Ratio" [16]; thermal analyses (carried out at the CISAG, Centro Interdipartimentale di Servizio per Analisi Geomineralogiche, Federico II University of Naples); microscope and SEM observations; chemical analyses by ICP (carried out at the ACME Analytical Laboratories Ltd., Vancouver, Canada) and by XRF (at the CISAG).

Specific gravity and open porosity were determined by means of a He-pycnometer (Micromeritics MultiVolume Pycnometer 1305); bulk density was measured on some microcores by means of a Ruska He-porosimeter and a Chandler Engineering Co. Hg-pycnometer. Water absorption tests by total immersion and by capillarity; ultrasonic velocity on saturated and dry samples; uniaxial compressive tests (UCS); wet–dry and salt crystallization tests.

The testing procedures were already described in [17] and [18] and references therein.

4. Results

4.1. Building materials and related weathering state at Casertavecchia

The results of the surveys of building materials and their state of conservation are reported in the computerized cartography (CENTRANTICO GIS) consultable on www.Centrantico.DST.unina.it. The methodology used for the graphical representation is described in [15].

Five categories of building stones were identified: grey tuffs (CI) and reddish-yellow tuffs (CI), due to their importance, represent two specific categories, whereas the remaining ones group different building stones according to their origin (magmatic, metamorphic and sedimentary). Artificial materials are represented by two more categories: bricks and plaster.

It is evident an almost regular distribution of the grey *facies* of the CI on the whole area. In the mid-eastern side of the village, limestones seem to prevail in the walls or those architectural parts with a particular structural function (e.g. the bell tower, basement of the *Mastio*, buttresses of the castle, breast walls, etc.). Also, limestone is represented in architectural elements such as columns, portals and steps as well as in fencing walls in the western area.

Table 1 shows the percentages of the different surveyed materials. The following considerations can be drawn:

1. The most used natural material for walls and façades is the CI in its Grey *facies* (44%) and, contrary to what has been found for another ancient historical center (*Naples* [15]), its percentage exceeds that of plaster. As far as natural stones used *facciavista* are considered (Fig. 2a), CI represents about the 78% of the exposed surfaces and the most diffused stone of the village both in outstanding monuments (e.g. the *S. Michele Arcangelo* Cathedral with the enclosed bell tower and the castle) and ordinary buildings or fencing walls.
2. Limestones, mainly used for fencing walls, are the second most diffused building stone. However, it is not unusual to find this stone in some relevant architectural elements such as the basement of the *Mastio*, the columns and the basement of the bell tower and some portals of the Cathedral.
3. Among the "minor" materials, marbles are the most used for some architectural elements such as brackets, portals, frames and columns. White marbles are the most diffused even though some uses of Cipoline or *Bardiglio* varieties are recorded (*Piazza Duomo, via S. Michele Arcangelo*).
4. The reddish-yellow tuff was mainly used for the *Mastio* of the castle.
5. Lavas and granites were just found in some steps and columns at *Piazza del Duomo*. Other architectural elements are also made of lavas.
6. Sandstones, mainly represented by pebbles, constitute the main façade of a building in *via della Contessa Iolanda*.
7. Some brackets and other architectural elements such as the mullioned window of the same building in *via della Contessa Iolanda* are made of bricks.

As far as weathering grades are considered diffuse alterative phenomena are evident both on *facciavista* materials and on those covered by plaster. No relationship was noted between the intensity of the alteration process and the exposure of the buildings.

The analysis of weathering data points out the bad state of conservation of most building stones. In fact, about 74% of the surface is affected by severe weathering phenomena (Fig. 2b). The grey tuffs are the worst preserved natural stone with about 93% of their surface characterized by high or moderate weathering (Fig. 2c). The unique exception is the

Table 1
Percentage of exposed surface for each material

Material	Exposed surface (%)
Grey tuffs (CI)	44.1
Plaster	43.0
Limestones	10.9
Marbles	1.0
Lavas	<1
Granites	<1
Sandstones	<1
Bricks	<1
Reddish-yellow tuffs (CI)	<1

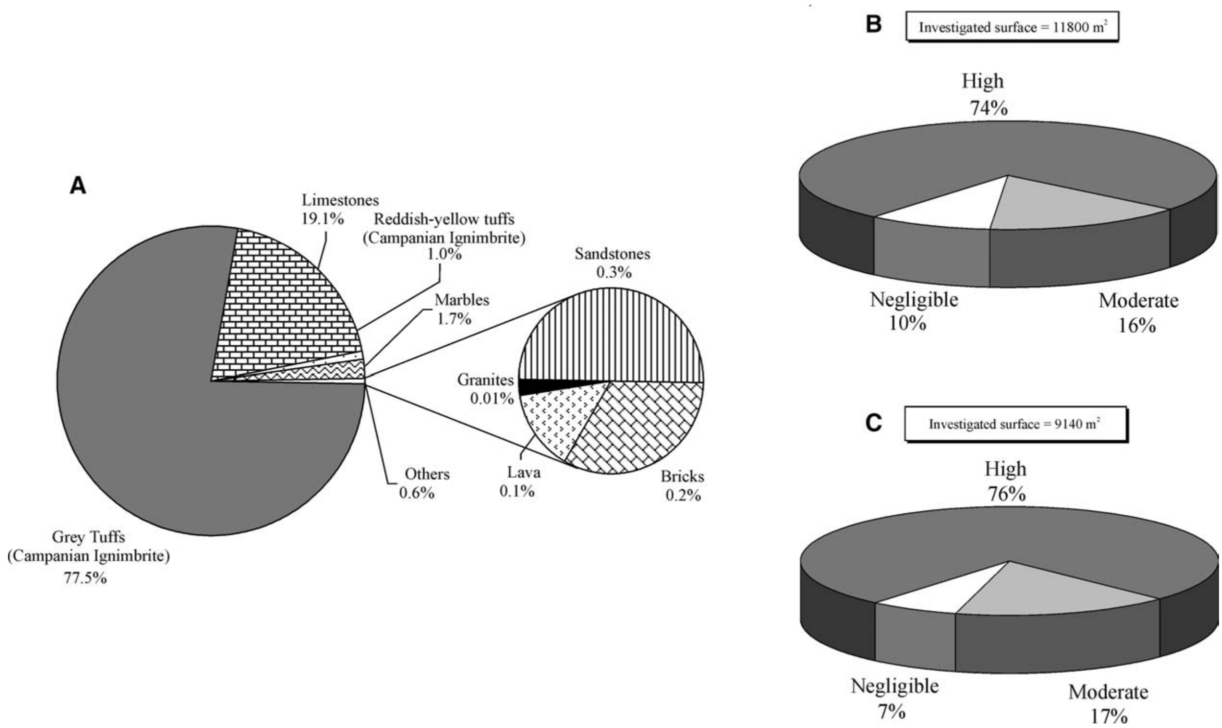

Fig. 2. (a) Pie-chart showing distribution of building stones of *Casertavecchia*. (b) Weathering grades of investigated building stones. (c) Weathering grades of CI grey tuffs.

main façade of the Cathedral that shows a good state of conservation due to a recent restoration.

The most widespread decay forms are: lacks, alveolization and biological patina.

As far as grey tuffs are considered, lacks and alveolization (Fig. 3a) are linked to the high textural heterogeneity, which favors a differential decay. Patina mainly affects limestones (Fig. 3b), often associated to vegetation. Exfoliation, that sometimes leads to the detachment of thin layers, is characteristic of the reddish-yellow tuff of the *Mastio* of the castle.

Chromatic alteration affects the Cipoline marble of the *Vescovado* portal. Finally, a diffuse occurrence of biological forms (Fig. 3c) is found on all the north-facing tuff surfaces (Fig. 3d) or on those affected by high humidity (Fig. 3e).

Architectural elements are generally better preserved than façades. The weathering typologies, whenever occurring, are those aforementioned, along with evidences of jointings.

The intense and diffuse weathering of the buildings of the village requires urgent restoration and conservation works. As far as the most relevant monumental buildings are considered it should be remarked that the local administration (*Soprintendenza ai Beni Architettonici di Caserta*) is carrying out, or has already performed, some restorations that interested the main façade of the Cathedral and the remnants of the Castle. In the latter case a total integration of large portions of the masonry with new material was required. In situ observation of these new dimension stones evidenced the presence in the tuff of several fluoriferous geodes, quite common in the CI [19] (Fig. 3f).

The reddish-yellow tuff of the *Mastio* tower has been probably used for a recent restoration and is currently affected by widespread moss and lichens in the north-facing parts (Fig. 3d) and by wide exfoliation likely due to the modern technique used for the production of dimension stones.

4.2. Minero-petrographical characterization of the grey tuff of Casertavecchia

A minero-petrographical characterization was carried out on samples from the outcrop of *Piedimonte di Casolla* and, whenever possible due to the limited available amount, on samples collected from the main monuments of *Casertavecchia* in a previous research [11]. As far as quarry materials are concerned, it should be remarked that LGT shows features very similar to those described for the "grey tuff" by Di Girolamo [3]; on the contrary, DGT is representative of the uppermost portion of the pipernoid tuff *facies*, characterized by weakly flattened and non-oriented black scoriae set in an ashy matrix from light to dark grey in color. Generally, the LGT and the DGT are more coherent and consequently, more easily workable. The EGT occurs in the uppermost portion of the outcrop and its macroscopical features likely witness a transitional *facies* between the grey tuff and *cinerazzo* (Fig. 1a).

On polarizing microscope observations the three *facies* can be distinguished for their different degree of alteration of the matrix that, in the EGT, is partly transformed in clay minerals and reddish in color for a diffuse presence of Fe-

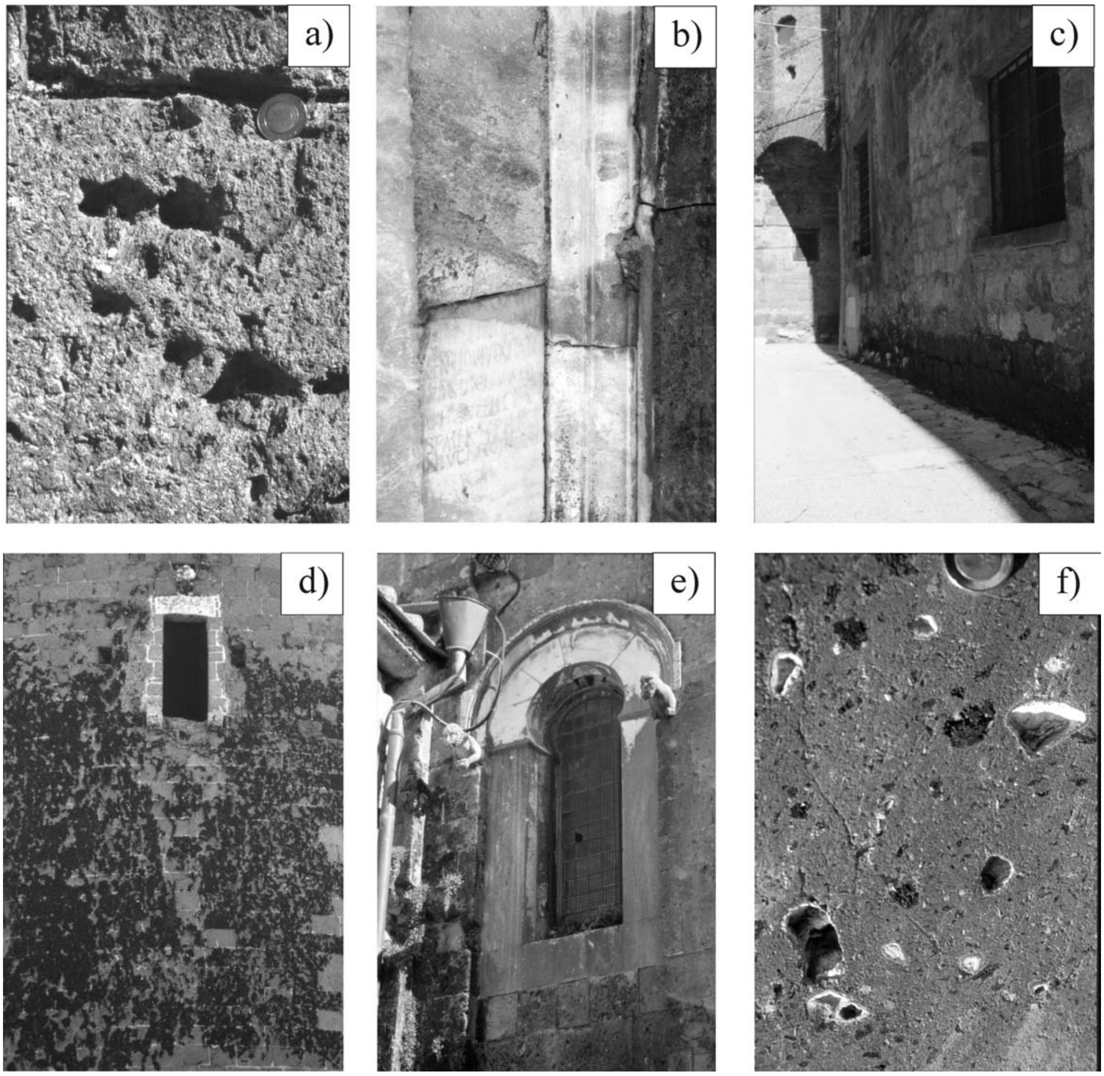

Fig. 3. Main features of the most representative investigated building stones along with some weathering typologies. (a) Alveolization on DGT; (b) patinae and cracks on limestones; (c) biological forms by raising damp on grey tuff; (d) biological forms on north-oriented tuff surface of the *Mastio*; (e) vegetation on high humidity portion of a building; (f) dimension stone (grey tuff) with fluoriferous geodes.

hydrated oxides. Sanidine phenocrystals and subordinate pyroxenes and amphiboles occur in the three *facies*. The groundmass of the matrix is weakly birefrangent.

On SEM observations the glassy fraction preserves its original structure in EGT (Fig. 4a) whereas it is almost totally devitrified with the formation of feldspar microcrystals in both LGT and DGT (Fig. 4b, c). Furthermore, the EGT is characterized by amorphous threadlike masses (Fig. 4d).

XRD patterns of DGT and LGT showed the presence of sanidine, albite, pyroxene, hematite and calcite. Feldspar turned to be the most abundant phase (Table 2) with values ranging between about 91% in the bulk samples and 95% in the matrix. Calcite was recorded only in the bulk sample of the LGT (3%), whereas traces of biotite were found in the matrix; mizzonite was only found in very low amount (<1%) in the DGT. The EGT is characterized by a higher content of amorphous fraction and corresponding lower feldspar content. A small amount of illite is also present.

In the most external portions of the microcores sampled from cathedral, gypsum and calcite are constantly present even though never exceeding 2–3% in weight.

The façades interested by intense raising damp are affected by diffuse efflorescences (thenardite, mirabilite, glauberite).

Gypsum was also found on the surfaces of the reddish-yellow tuff of the *Mastio*. This natural building material is completely different from tuffs previously described for the presence of high content of authigenic zeolites (chabazite 41%, phillipsite 10%, analcime 3%), traces of halloysite along with pyrogenic phases such as feldspar (19%) and biotite (1%).

DTA curves display a weak endothermic effect at 100 and 120 °C in LGT and DGT, respectively, whereas two minima at low temperature (100 and 140 °C) and two others at 480 and 780 °C, likely due to small amounts of illite (Fig. 5) characterize EGT.

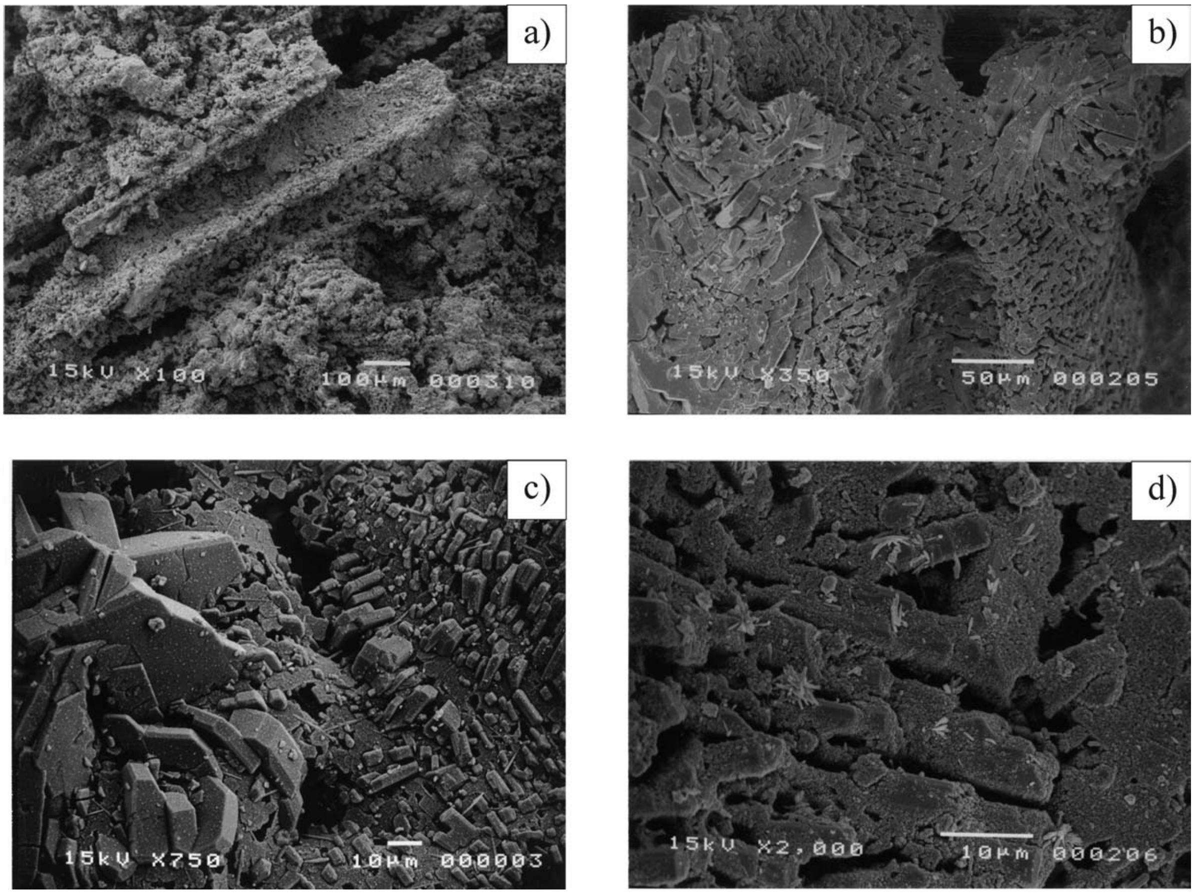

Fig. 4. SEM micrographs from different *facies* of the CI. (a) EGT, original structure of the glassy fraction; (b) LGT and (c) DGT, evidence of deep feldspathization; (d) EGT, amorphous threadlike masses.

DTA curves very similar to those of LGT and DGT were recorded for the sample C1 (0–5 cm) from the Cathedral that also evidences an endothermic effect at about 850 °C, typical of $CaCO_3$. DTA curve of sample M1 (1–3 cm) from the *Mastio* shows a typical shape of chabazite-rich rocks characterized by a wide endothermic effect at low temperatures (120–220 °C) followed by another one at about 320 °C.

The chemical analyses evidence a good compositional homogeneity between the bulk rock, the matrix and the black scoriae (Table 3) and enable to classify all the investigated samples as trachytes.

The different alteration degree of the rock determined a different loss on ignition between the three *facies* and in particular, between the scoriae and the matrix of the EGT.

Table 4 reports the chemical analyses of tuff samples collected from microcores of the façades of the *Casertavecchia* Cathedral. The analogy with the chemical analyses of Table 3, both for major and minor elements, leads to hypothesize that the materials used for the façade of the *S. Michele Arcangelo* Cathedral was likely extracted from the quarries of *Piedimonte di Casolla*.

Table 2
Mineralogical composition (% wt.) of investigated grey *facies* of CI

Facies	Fraction	Illite	Feldspar	Biotite	Calcite	Mizzonite	Others *
DGT	Bulk	–	90	–	–	<1	9
	Matrix	–	94	<1	–	tr.	6
	Pumice	–	93	–	–	–	7
LGT	Bulk	–	91	–	3	–	6
	Matrix	–	96	<1	–	–	4
	Pumice	–	95	–	–	–	5
EGT	Bulk	2	82	<1	–	–	16
	Matrix	–	85	<1	–	–	15
	Pumice	–	91	<1	–	–	8
Cathedral	Bulk	–	95	<1	2	–	2

* Include glass.

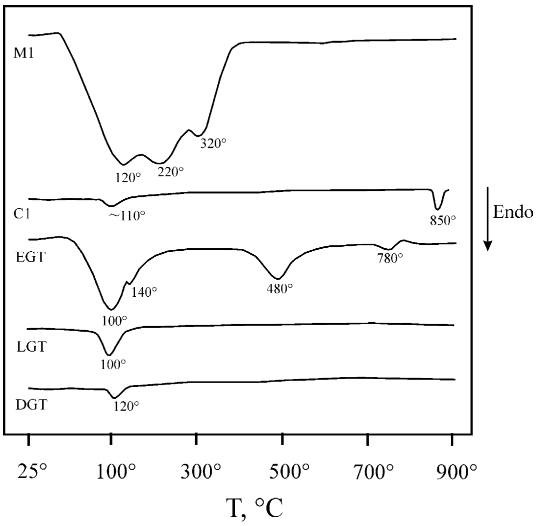

Fig. 5. DTA curves of DGT, LGT, EGT samples and of two microcores (C1, LGT from the Cathedral; M1, reddish-yellow tuff from the *Mastio*).

As far as the reddish-yellow tuff surveyed at the *Mastio* of the castle is considered, no outcrop has been identified in the neighbors of the village. The mineralogical composition of this tuff suggests this *facies* as belonging to the yellow variety of the CI. Notwithstanding this similar mineralogical association, chemical analyses of this tuff do not support this hypothesis. In fact, chemical analyses of Table 5 show marked differences among all the samples of the *Mastio* and those representative of some outcrops of the CI (yellow *facies*). It is hypothesized a different provenance for the *Mastio* tuff, likely referable to other zeolitized tuffs from *Campania* region.

4.3. *Physico-mechanical characterization of the grey tuff of* Casertavecchia

The physico-mechanical characterization of the three *facies* gave the results summarized in Table 6.

4.3.1. *Density and specific gravity*

Values of dry and bulk density and specific gravity for LGT and DGT are generally slightly higher than those of EGT. Mean values of open porosity are not substantially different, even though a wider range was recorded for the EGT (50.4–58.6%) if compared to LGT and DGT ones (52.1–58.6% and 52.1–56.8%, respectively).

de' Gennaro et al. [11] evaluated the porosity variability on microcores samples for the façades of the Cathedral (LGT, sample CV3) and of the *Mastio* (Reddish-yellow tuff, sample MCV2). Sample CV3 showed porosity increasing from the inner to the outer portions. Similar results have been obtained from other microcores available from that sampling but tested for the present research (microcores CV1 and CV2, Table 6). It should be remarked that porosity values of the inner portion of the microcores are similar, even slightly lower than those of the quarry samples (49% vs. 55%), whereas porosity of the outermost portions is significantly higher (65% vs. 55%).

4.3.2. *Imbibition capacity*

EGT, even showing a slight lower mean porosity value if compared to the other two *facies*, displays an imbibition coefficient and water absorption markedly higher. In general, it should be remarked that the saturation degree never exceeds 80%.

4.3.3. *Capillarity absorption*

The results of these tests also confirm a substantial homogeneity for all the three *facies*, being their mean values ranging between 2.5 and 4 × 10^{-2} g cm^{-2} $s^{1/2}$. The water absorption is almost completed within the first 20 $s^{1/2}$ but with a very slow increase up to 800 $s^{1/2}$ for all the investigated samples (Fig. 6). Slight differences between specimens of the same *facies* should be related to the heterogeneity of the materials.

Table 3
Chemical analyses (major elements: % wt.; traces: ppm) of the three considered *facies* (CI)

	DGT			LGT			EGT		
	Bulk	Matrix	Scoriae	Bulk	Matrix	Scoriae	Bulk	Matrix	Scoriae
SiO_2	62.09	61.58	60.98	60.65	61.50	61.41	59.97	58.65	61.46
TiO_2	0.48	0.41	0.44	0.44	0.43	0.43	0.41	0.44	0.40
Al_2O_3	17.99	18.20	18.24	18.17	18.24	18.03	17.60	18.28	18.06
Fe_2O_3	3.77	3.55	3.44	3.55	3.41	3.59	3.39	3.60	3.18
MnO	0.14	0.18	0.16	0.20	0.18	0.20	0.20	0.19	0.17
MgO	0.50	0.52	0.57	0.54	0.47	0.59	0.55	0.55	0.49
CaO	2.08	2.11	2.24	2.43	2.19	2.23	2.15	2.34	2.05
Na_2O	4.85	5.02	5.32	4.60	5.12	5.16	5.15	4.43	5.36
K_2O	6.90	6.68	7.15	7.07	6.71	7.30	7.15	6.54	6.80
P_2O_5	0.03	0.01	0.02	0.09	0.04	0.05	0.06	0.08	0.11
LOI	1.57	1.68	1.65	1.20	1.60	1.00	4.00	4.80	2.60
Total	100.40	99.94	100.21	98.95	99.90	100.00	100.64	99.91	100.68
Sr	145	98	125	133	89	137	148	125	147
Y	41	45	47	46	48	46	44	40	44
Zr	515	498	522	495	564	524	507	461	510
Nb	159	169	157	163	188	174	158	156	168

Table 4
Chemical analyses (major elements: % wt.; traces: ppm) of microcore samples (CI) from *Casertavecchia* Cathedral

	C1 0–5	C1 10–12	C2 0–3	C2 8–12	C3 0–3	C3 7–11	C4 0–3	C4 10–14	C5 0–3	C5 10–14
SiO_2	61.12	61.66	60.89	61.50	61.32	61.03	61.03	61.82	60.41	61.46
TiO_2	0.42	0.44	0.44	0.46	0.44	0.45	0.45	0.44	0.43	0.44
Al_2O_3	16.97	18.76	18.12	18.32	18.39	18.15	18.15	18.56	17.72	18.21
Fe_2O_3	3.76	3.94	3.93	3.88	3.96	3.90	3.90	3.94	3.70	3.78
MnO	0.24	0.24	0.24	0.24	0.24	0.23	0.23	0.24	0.22	0.24
MgO	0.71	0.43	0.46	0.38	0.50	0.60	0.60	0.49	0.56	0.43
CaO	4.48	2.11	2.35	2.14	2.32	2.11	2.11	2.13	2.58	2.09
Na_2O	4.36	3.91	5.01	4.57	4.29	5.06	5.06	3.94	5.20	5.47
K_2O	6.64	7.24	7.20	7.27	7.29	7.19	7.19	7.25	7.10	7.07
P_2O_5	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03
LOI	1.18	1.20	1.28	1.18	1.18	1.22	1.22	1.13	2.00	0.75
Total	99.95	99.96	99.96	99.96	99.96	99.96	99.96	99.96	99.96	99.96
Sr	213	155	141	139	155	154	173	141	128	122
Y	52	58	55	58	58	54	52	56	55	58
Zr	500	565	553	575	552	567	549	561	557	556
Nb	72	84	87	86	87	86	82	87	84	87

Table 5
Chemical analyses (major elements: % wt.; traces: ppm) of investigated reddish-yellow *facies* samples (CI) from the *Mastio* of the Castle and literature data

	M1 1–3	M1 7–10	M1 14–16	M2 1–4	M2 10–13	M2 18–23	*Dugenta**	*La Schiava**	*Balzarama**
SiO_2	47.15	47.69	48.29	47.27	47.59	46.92	54.80	54.86	55.62
TiO_2	0.82	0.87	0.90	0.86	0.87	0.85	0.46	0.43	0.48
Al_2O_3	13.98	14.37	14.61	14.33	14.22	14.41	15.99	15.88	16.32
Fe_2O_3	6.99	7.29	7.67	7.32	7.47	7.33	4.39	3.83	4.47
MnO	0.15	0.16	0.17	0.19	0.18	0.17	0.16	0.17	0.16
MgO	2.77	2.50	2.50	2.51	2.84	2.81	0.81	0.87	0.36
CaO	4.82	3.93	3.99	4.75	4.66	4.78	4.06	4.24	3.77
Na_2O	3.04	2.90	2.46	2.05	2.01	2.27	0.58	0.95	0.96
K_2O	4.98	5.43	5.47	5.03	5.35	5.59	6.11	6.74	6.82
P_2O_5	0.23	0.23	0.22	0.25	0.29	0.22	0.10	0.11	0.07
LOI	14.90	14.45	13.56	15.26	14.32	14.50	12.54	11.93	11.28
Total	99.84	99.82	99.83	99.82	99.79	99.84	100.00	100.00	100.30
Sr	1230	1302	1405	1328	1333	1456	565	392	490
Y	38	47	51	43	43	47	37	40	38
Zr	284	301	298	292	278	293	316	382	323
Nb	38	40	39	41	37	39	46	58	48

* Unpublished data.

4.3.4. Ultrasonic velocity

This is the only physical parameter that shows a pronounced difference between the three *facies*, in terms of both dry and saturated velocities; in particular, as far as dry velocities are concerned, LGT evidences the highest values followed by DGT (–8%) and by EGT (–23%). Analogous results were recorded for saturated specimens with a decrease of the velocity of about 6% between LGT and DGT and about 31% between LGT and EGT. For all these varieties, however, a constant decrease in velocities up to about 19% was measured between dry and saturated samples. Fig. 7 reports the percent variation of the velocity in saturated and dry specimens as a function of the porosity. As a matter of fact, negative variations are recorded for all those materials showing a porosity higher than 48%.

The different behavior of the three *facies* and, within the same *facies*, between dry and saturated samples could be due to the high heterogeneity of these materials, likely derived by a different aggregation or by welding degree of their constituents.

4.3.5. Uniaxial compressive strength (UCS)

Uniaxial compressive tests (Fig. 8) on LGT and DGT gave strength values between 3.4 and 5.1 and 3.6 and 5.8 MPa, respectively. Due to the weakness of the EGT, it was not possible to shape cubic samples; the unique test carried out on this material gave a value of about 1 MPa.

Data are typical of weak rocks and confirm the poor mechanical features of CI. Curves of Fig. 8 evidence the peculiar trend of non-elastic high porosity materials, characterized by a first portion with a very low angular coefficient and a second one with a higher slope angle. In other words, samples underwent early pronounced deformations, probably due to the compaction of the solid framework, leading to

Table 6
Main petro-physical values of the analyzed rocks

	Dry density (kN m^{-3})	Bulk density (kN m^{-3})	Specific gravity (kN m^{-3})	Open porosity (%)	Imbibition capacity (%)	Capillarity absorption (g cm^{-2} s$^{1/2}$)	Dry ultrasonic velocity (m s^{-1})	Saturated ultrasonic velocity (m s^{-1})	UCS (MPa)	Elastic tangent (50%) modulus (MPa)	Elastic average modulus (MPa)	Elastic secant modulus (MPa)
LGT												
Number samples	24	5	24	24	6	6	16	16	5	5	5	6
Mean	11.29	11.81	25.39	55.5	42.2	0.034	1774	1612	4.2	821	796	415
Min	10.53	10.40	25.12	52.1	40.5	–	1634	1462	3.4	493	483	205
Max	12.14	13.44	25.90	58.6	44.3	–	1950	1878	5.1	1241	1229	697
S.D.	0.45	1.10	0.16	1.8	1.4	–	86	106	0.6	242	245	163
EGT												
Number samples	6	1	6	6	2	2	4	4	1	1	1	1
Mean	11.05	10.99	24.45	54.7	52.3	0.040	1358	1112	1.1	121	111	148
Min	10.42	–	22.26	50.4	50.3	–	1254	1038	–	–	–	–
Max	11.63	–	25.20	58.6	54.3	–	1504	1225	–	–	–	–
S.D.	0.44	–	1.01	2.8	–	–	96	76	–	–	–	–
DGT												
Number samples	8	4	8	8	4	4	4	4	3	3	3	3
Mean	11.56	11.31	25.76	55.1	42.2	0.025	1626	1521	4.7	468	464	260
Min	11.13	11.09	25.55	52.1	40.4	–	1571	1478	3.6	384	335	210
Max	12.42	11.48	25.95	56.8	42.9	–	1692	1586	5.8	546	529	339
S.D.	0.43	0.17	0.12	1.7	1.05	–	51	40	0.9	66	91	57

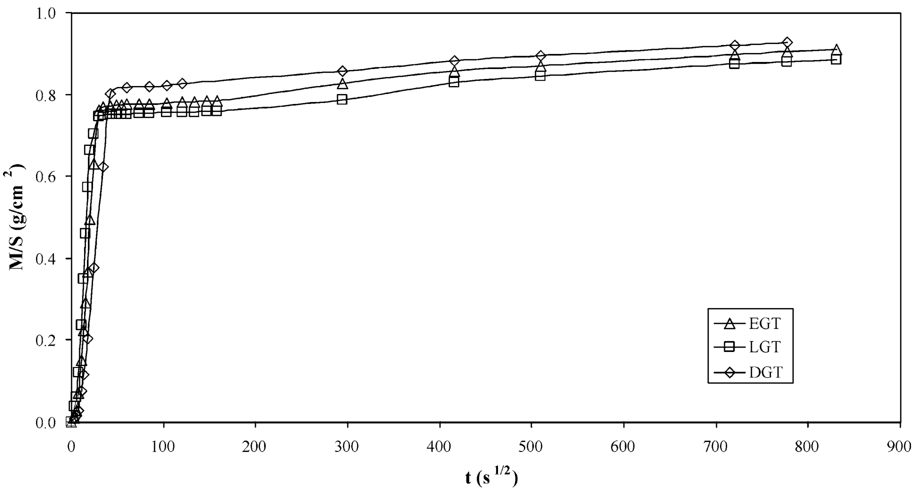

Fig. 6. Water absorption curves by capillarity for DGT, LGT and EGT *facies*.

a porosity decrease. As the load increases the samples display a better elastic behavior.

4.3.6. Aging tests

Aging tests were carried out only on LGT samples as this *facies* turned to be the most used in the *Casertavecchia* village. This investigation was aimed at verifying the weathering phenomena affecting the stone after dry and wet cycles and crystallization of soluble salts. The results of these aging tests evidence quite limited differences of the measured parameters between the untreated and the weathered samples, with the only exception of the weight loss after the salt crystallization (–11%) and of UCS values after both wet–dry (–17%) and salt crystallization cycles (–30%).

5. Discussion and conclusions

CI in its different varieties has been widely used as building stones in the historical and modern architecture of many towns of *Campania* region [12,15]. Among them, *Casertavecchia* certainly represents an important case history, as this stone was used in both monumental and ordinary buildings; in many cases, the most used *facies* is a “grey tuff” [3]. The only documented exception is the *Mastio* of the Castle, where a reddish-yellow variety has been employed.

Such a massive use of the “grey tuff” is related to the presence of important deposits of this material distributed on the slopes of the carbonate hill on which the medieval village rests. This tuff was preferred to the locally more available

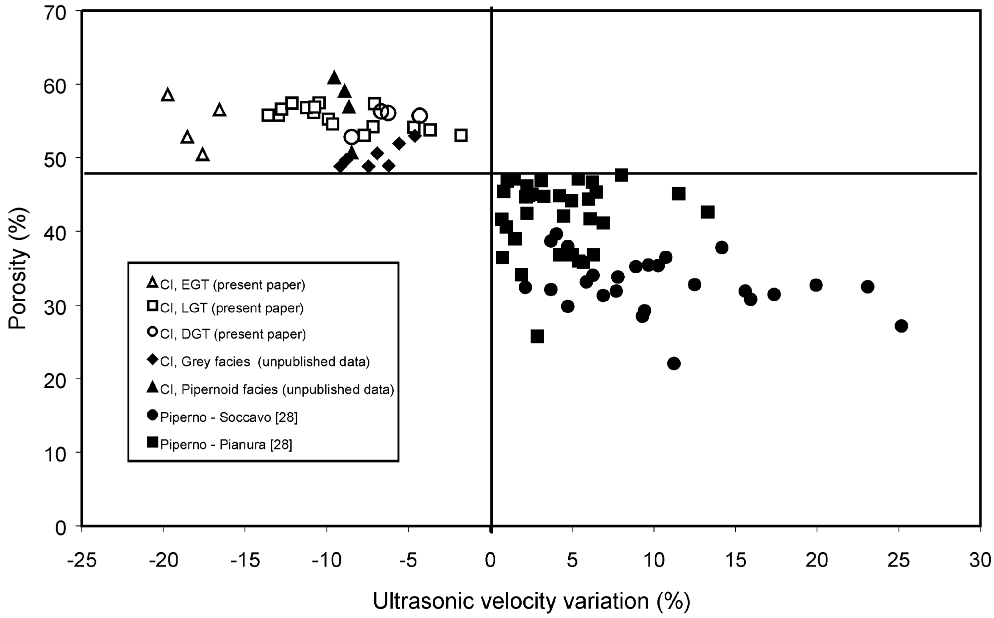

Fig. 7. Variation of ultrasonic velocities from dry to saturated samples as a function of porosity.

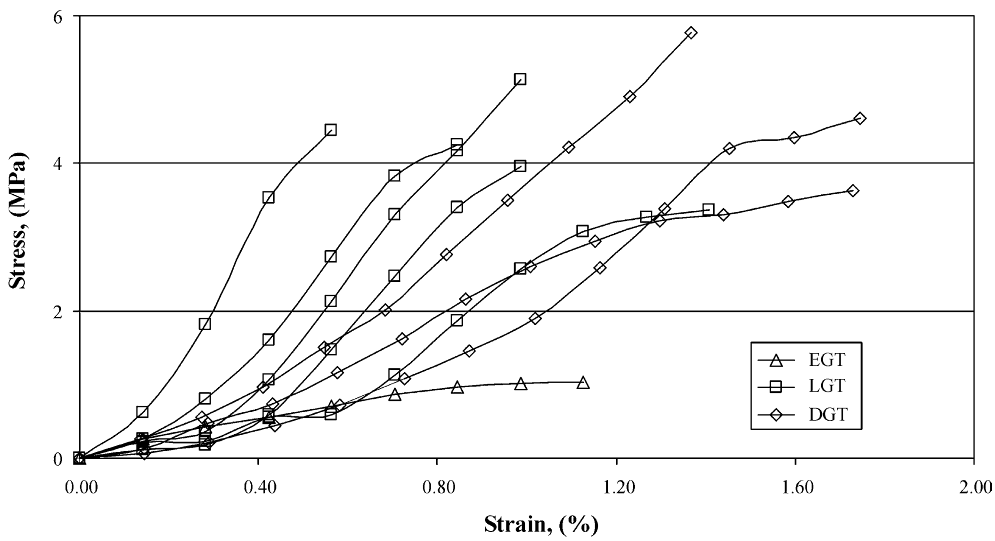

Fig. 8. UCS tests for the three investigated varieties of CI.

limestone, probably for its ease of workability as well as its good physico-mechanical features. Whenever materials with better mechanical properties were required, local limestones, the second most represented lithotype of the village were used; the only exception is the basement of the bell tower built with dimension stones from pre-existing Roman buildings [20].

More questionable is the provenance of the reddish-yellow tuff used for the *Mastio*. A previous paper [11] ascribed this stone to the yellow *facies* of the CI on the basis of macroscopical features and mineralogical composition, characterized by chabazite as prevailing phase. Nevertheless, the chemical analyses carried out for the present research on microcore samples previously collected [11], evidenced a composition quite different from the most common yellow *facies* of CI as testified by lower SiO_2 and Al_2O_3 and higher MgO values. Slight differences were also noted in minor elements. These data certainly exclude this material as belonging to the CI.

The different grey *facies* (LGT, DGT and EGT) from *Piedimonte di Casolla* quarry show a high feldspar content (~90%): only a small part of it is pyrogenic, the rest being the result of syn- or post-depositional authigenic processes. A limited amount of glass in the EGT was altered to illite-like clay minerals and amorphous components. The likeliness of mineralogical and chemical composition between the samples from the Cathedral and those from the *Piedimonte di Casolla* quarry leads to hypothesize this outcrop as a possible exploitation area of the stone used for this monument and, presumably, for the whole medieval village.

On the basis of the geomechanical characterization and by the comparison with the features of other Italian volcaniclas-

Table 7
Comparis on of the main physico-mechanical parameters for some macroporous volcaniclastic rocks from Italy

Rock type	Bulk density ($kN\ m^{-3}$)	Specific gravity ($kN\ m^{-3}$)	Porosity (%)	H_2O absorption (%)	UCS (MPa)	Source
Ignimbrite of Bomarzo	21.08	25.98	18.7 ± 1.9	13.7 ± 1.8		[23]
Peperino from Marino	19.66–20.84	25.20–27.65	25.32	13–18	26.7–28.1	[24]
Via Tiberina Tuff	11.57–13.43	23.82–24.80	44.43–52.07		1.6–12.7	[25]
Ignimbrite of Orvieto	10.78–13.14	23.92–24.12	45–55	22–34	2.9–6.9	[26]
NYT	10.3–14.1*	22.06–22.65	39.5–63.2	32.51–38.37	0.7–11.9	[27]
Piperno	12.95–22.57*	24.97–26.26	12.03–49.9	11.6–27.8	4.7–67.5	[27,28]
CI	10.4–13.4*	22.26–25.90	50.4–58.6	42.23–52.28	1.1–5.2	Present paper

* Dry density.

tic rocks (Table 7) CI from *Casertavecchia* can be defined as a weak, macroporous rock, characterized by low values of dry density, porosity always higher than 50%, UCS comprised between 1 and 5.5 MPa, ultrasonic dry velocities lower than 2000 m s^{-1}. However, it is remarkable that worse mechanical features characterize the EGT *facies*. A possible explanation of this worse behavior of the EGT samples could be the occurrence of this *facies* in those parts of the formation, close to the incoherent uppermost portion of the deposit, locally known as *cinerazzo*. On the contrary, LGT and DGT *facies* show a better behavior as they belong to the grey tuff *facies* s.s., close to the boundary with the underlying pipernoid tuff (Fig. 1a).

Notwithstanding the above considerations, all the three varieties are characterized by a decrease in velocities, from dry to "saturated" values. According to Gregory [21] this behavior, typical of macroporous materials, depends on a partial and unreached saturation of the sample. In samples with a porosity higher than 25%, a saturation degree lower than 80% would provoke a consistent velocity decrease.

The aging tests evidenced a worsening of some physical parameters after wet–dry and salt crystallization tests. The arising of pore pressures as a consequence of salt crystallization is the most common agent of the decay of these materials. It is generally considered that salt crystallization occurs first in the large pores and only moves into small pores once the larger ones are filled [22]. This process seems to have occurred in the investigated monuments as testified by the presence of $CaCO_3$ and $CaSO_4{\cdot}2H_2O$ in the outer portion of the dimension stones of the *S. Michele Arcangelo* Cathedral. However, calcite and gypsum content is always quite low (2–3%) if compared to the total porosity of this rock, thus they do not appear to be sufficient to fill the macropores and to determine a crystallization pressure on their walls.

Furthermore, as far as the grey *facies* is considered, it resulted that porosity increases from the inner to the outer portion of the façade (Table 8). This is in obvious contrast with a crystallization process that would be mostly pronounced close to the surface where evaporation is the highest. In fact, the water content measured immediately after the sampling of microcores [11] turned to be close to 0% in the outermost portion (up to 15 cm) and ranging between 10% and 15% in the deepest parts (from 15 to 20 cm). The increase in porosity could be interpreted as due to the leaching of the glass portion of the rock or, in minor amount of the crystalline fraction, by raising water. However, the leaching is not followed by any precipitation of amorphous or crystalline phases. This porosity increase, even determining a slight decay of the stone, does not cause a real weathering which is actually confined within the most superficial (few millimeters) portions of the dimension stone, affected by $CaCO_3$ patinae and sodium sulfate efflorescence. On the contrary, the different behavior of the reddish-yellow tuff of the *Mastio*, namely the decrease of porosity from the inner to the outer portion of the manufact, could be due to the persistence of soluble salts also favored by exchange processes of zeolites occurring in this rock. The crystallization pressures determined by these salts would cause the evident decay phenomena affecting this rock such as spalling, exfoliation and disaggregation already evidenced for other similar rocks [15].

Table 8
Porosity values as a function of sampling depth from different microcores from *Casertavecchia*

Depth (cm)	CV1	CV2	CV3*	MCV1	MCV2*
0.5–3	66.0	65.2	65.7	46.0	45.4
10–13	64.2	63.1	63.8	48.6	47.8
18–20	49.1	50.2	48.6	55.0	53.3

CV, Cathedral (LGT); MCV, *Mastio* (reddish-yellow tuff).
* de'Gennaro et al. [11].

Despite the fair homogeneity shown by *Casertavecchia* CI to many of the tests performed, the overall behavior of the formation, as concerns its lithified terms, should be evaluated only after a wider sampling program, involving all the main quarrying districts spread over the Campanian territory. To this respect, some preliminary data are already available, which refer to the ongoing research on the materials coming from *Sorrento* Peninsula and *Nocerino-Sarnese* campagna. In both settings tuff *facies* showing highly different properties have been so far tested, generally varying in a range wider than that typical of *Casertavecchia* CI.

Acknowledgements

The research was carried out with the financial support of Italian National Council of Research (C.N.R.) Progetto Finalizzato "Beni Culturali", contr. n. 97.00630.PF36 granted to MdG.

References

[1] C. Colella, M. de'Gennaro, R. Aiello, Use of zeolitic tuff in the building industry, in: D.L. Bish, D.W. Ming (Eds.), Natural Zeolites: Occurrence, Properties, Application, 45, Mineralogical Society of America, Washington, DC, 2001, pp. 551–588 Reviews in Mineralogy and Geochemistry.

[2] B. De Vivo, G. Rolandi, P.B. Gans, A. Calvert, W.A. Bohrson, F.J. Spera, H.E. Belkin, New constraints on the pyroclastic eruptive history of the Campanian volcanic Plain (Italy), Mineral. Petrol. 73 (2001) 47–65.

[3] P. Di Girolamo, Petrografia dei tufi campani: il processo di pipernizzazione (tufo > tufo pipernoide > piperno), XXXV, Rendiconti Accademia di Scienze Fisiche e Matematiche, s. IV, Giannini, Naples, 1968, pp. 5–70.

[4] P. Di Girolamo, J. Keller, Zur Stellung des Grauen Campanischen Tuffs innerhalb des quartaren Vulkanismus Campaniens (Sud-Italien), Ber. Naturf. Ges. Freiburg i. Br. 61/62 (1972) 85–92.

[5] P. Di Girolamo, V. Morra, The Campanian Ignimbrite. Petrographical, petrochemical and volcanological characters, Rendiconti Accademia di Scienze Fisiche e Matematiche, Special Issue, Liguori, Naples, 1987, pp. 177–199.

[6] L. Civetta, G. Orsi, L. Pappalardo, R.V. Fisher, G.H. Heiken, M. Ort, Geochemical zoning, mixing, eruptive dynamics and depositional processes of the Campanian Ignimbrite, Campi Flegrei, Italy, J. Volcanol. Geotherm. Res. 75 (3–4) (1997) 183–220.

[7] A. Perrotta, C. Scarpati, Plinian versus co-ignimbrite volume in large explosive eruptions: the example of the Campanian Ignimbrite eruption, Mineral. Petrol. 79 (2003) 67–78.

[8] M. de'Gennaro, E. Franco, M. Rossi, A. Langella, A. Ronca, Epigenetic minerals in the volcaniclastic deposits from central-southern Italy: a contribution to zeolite genesis, Rendiconti Accademia di Scienze Fisiche e Matematiche, Special Issue, Liguori, Naples, 1987, pp. 107–131.

[9] M. de'Gennaro, A. Langella, Italian zeolitized rocks of technological interest, Mineral. Deposita 31 (1986) 452–472.

[10] V. Cardone, Il tufo nudo nell'architettura napoletana, Cuen, Naples, 1990.

[11] M. de'Gennaro, C. Colella, A. Langella, P. Cappelletti, Decay of Campanian ignimbrite stoneworks in some monuments of the Caserta area, Sci. Technol. Cultural Heritage 4 (2) (1995) 75–86.

[12] G. Fiengo, L. Guerriero, Murature tradizionali napoletane, Cronologia dei paramenti tra il XVI ed il XIX secolo, Arte Tipografica, Naples, 1999.

[13] D. Calcaterra, P. Cappelletti, M. de'Gennaro, A. Langella, V. Morra, Edifici rinascimentali a Napoli: primi dati sui materiali, in: U. Zezza (Ed.), Proceedings of "Quarry—Laboratory—Monument" International Congress, Pavia, 26/30 Settembre 2000, pp. 195–202.

[14] F. Penta, I materiali da costruzione dell'Italia meridionale, 2, Fondazione politecnica del Mezzogiorno d'Italia, Fondazione Politecnica del Mezzogiorno d'Italia, Naples, 1935.

[15] M. de'Gennaro, D. Calcaterra, P. Cappelletti, A. Langella, V. Morra, Building stones and related weathering in the architecture of the ancient city centre of Naples, J. Cultural Heritage 1 (2000) 399–414.

[16] S.J. Chipera, D.L. Bish, Multireflection RIR and intensity normalizations for quantitative analyses: applications to feldspar and zeolites, Powder Diffraction 10 (1) (1995) 47–55.

[17] A. Langella, D. Calcaterra, P. Cappelletti, A. Colella, M. de'Gennaro, R. de Gennaro, Preliminary contribution on durability of some macroporous monumental stones used in historical towns of Campania region, Southern Italy, Proceedings of the Ninth International Congress on Deterioration and Conservation of Stone Venice, Elsevier, Amsterdam, 2000, pp. 59–67.

[18] R. de Gennaro, D. Calcaterra, P. Di Girolamo, A. Langella, M. de'Gennaro, Discovering the stone heritage of southern Italy: technical properties of the Mondragone marble from Campania region, Environ. Geol. 44 (2003) 266–276.

[19] D. Stanzione, Il tufo campano dell'Agro, Falerno Mondragone (Caserta) XXXIII, Rendiconti Accademia di Scienze Fisiche e Matematiche, s. IV, Giannini, Naples, 1966, pp. 3–30.

[20] N. Gnarra, Il Duomo ed il Borgo Antico di Casertavecchia, Ist. Poligrafico dello Stato, Istituto Poligrafico dello Stato, Rome, 1998.

[21] A.R. Gregory, Fluid saturation effects on dynamic elastic properties of sedimentary rocks, Geophysics 41 (5) (1976) 895–921.

[22] B. Fitzner, R. Snethlage, Über Zusammenhänge zwischen Salzkristallisationsdruck und Porenradienverteilung, GP News Lett. 3 (1982) 13–24.

[23] C. Fratini, C. Manganelli del Fa', E. Pecchioni, A. Scala, The sculptures in Bomarzo Park, Viterbo, Italy, in: A.E. Charola, R.J. Koestler, G. Lombardi (Eds.), Proceedings of the International Meeting on Lavas and Volcanic Tuffs, Easter Island, 1990, pp. 129–141 25–31 October, ICCROM, Rome.

[24] P.L. Bianchetti, G. Lombardi, S. Marini, C. Meucci, The volcanic rocks of the monuments of the Forum and Palatine (Rome): characterization, alterations, and results of chemical treatments, in: A.E. Charola, R.J. Koestler, G. Lombardi (Eds.), Proceedings of the International Meeting on Lavas and Volcanic Tuffs, Easter Island, 1990, pp. 83–105 25–31 October, ICCROM, Rome.

[25] G. Nappi, G. De Casa, E. Volponi, Geologia e caratteristiche tecniche del "Tufo Giallo della Via Tiberina", Boll. Soc. Geol. Ital. 98 (1979) 431–445.

[26] G. Nappi, M. Chiodi, S. Rossi, E. Volponi, L'ignimbrite di Orvieto nel quadro dell'evoluzione vulcano-tettonica dei Vulsini Orientali: Caratteristiche geologiche e tecniche, Boll. Soc. Geol. Ital. 101 (1982) 327–342.

[27] D. Calcaterra, P. Cappelletti, A. Colella, M.P. d'Albora, M. de' Gennaro, R. de Gennaro, A. Langella, V. Morra, Mineralogical and technological characterization of "Piperno", a widely used building stone of Napoli (Italy), in: D. Rammlmair, J. Mederer, Th. Oberthür, R.B. Heimann, H. Pentinghaus (Eds.), Applied Mineralogy in Research, Economy, Technology, Ecology and Culture, 2, Balkema, Rotterdam, 2000, pp. 963–966.

[28] D. Calcaterra, P. Cappelletti, A. Langella, V. Morra, R. de Gennaro, A. Colella, The building stones of the ancient centre of Naples (Italy): the Piperno from Phlegrean Fields. Contributions to the knowledge of features of a long-time used stone, J. Cultural Heritage 1 (4) (2000) 415–428.