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ORIGINAL ARTICLE

Lava stones from Neapolitan volcanic districts in the architecture of Campania region, Italy

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Abstract Results of a research carried out on the lavas from Campi Flegrei and Somma-Vesuvius volcanic districts are reported here. The lavas have been widely employed, since Roman age, in several important monumental buildings of the Campania region, mainly in the town of Naples and in its province. They are classified as trachytes (Campi Flegrei products), tephri-phonolites and phono-tephrites (Somma-Vesuvius complex) from a petrographical point of view. Sampling was carried out from well-known exploitation districts. A substantial chemical difference between the products of the two sectors was confirmed, while petrophysical characterization evidenced similarity among the two different materials, although some differences were recorded even in samples coming from the same exploitation site.

Keywords Mineralogy · Stone decay

Introduction

Campania region, unlike many other Italian areas, has few rocks that, from a qualitative and quantitative point of view, are particularly suitable to be used as ornamental stones; notwithstanding this peculiarity, throughout all the different historical periods, a large number of lithotypes of local origin have been used in the architecture of this region, due to their good technical and aesthetical features which made these materials appropriate to be used as building stones. Most of them were used for architectural purposes close to the outcropping areas and only in few cases they were exported far from the exploitation areas or outside the regional or state boundaries.

The ornamental stones mostly used to these aims are mainly volcanic materials, above all those from the volcanic districts of the Somma-Vesuvius and Campi Flegrei, and the sedimentary rocks of the carbonatic ridges from the Campanian Apennine (Calcaterra et al. 2003).

As far as volcanic rocks are concerned, lavas, even though playing a marginal role if compared to other materials such as the Neapolitan Yellow Tuff, Campanian Ignimbrite and Piperno, represent a building materials and ornamental stones of a certain relevance in the architecture of the region and, more specifically, in that of Naples province.

The volcanic districts of Somma-Vesuvius and Campi Flegrei represent the main exploitation areas of lavas used in the historical architecture of the region, whereas a marginal role was played by materials linked to the activity of the Roccamonfina volcano (Penta 1935; Calcaterra et al. 2003). For these reasons, the study carried out during the present research was mainly focused on Vesuvian and Phlegraean lavas. It should be remarked that these rocks have been deeply investigated from a volcanological, petrographical or geochemical point of view whereas few data are so far available in terms of physical characterization and, in particular, on the behaviour of the stone once used as building material, its response to the decay agents or any

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other characterization aimed at providing the necessary information for a correct conservation of the architectural portion made of this stone.

Actually lava, as any other material, once used as building stone, undergoes a series of transformations depending both on the anthropic activity and the surrounding microenvironment. From this assumption, derives the need of a correct conservation and recovery of these materials in order to avoid the irretrievable loss of important cultural heritage.

Also, the above considerations led many researchers deeply concerned towards the conservation of the cultural heritage from all the points of view, to carefully characterize this material in terms of composition, genesis, response to the action of external agents and identification of the exploitation areas.

Therefore, the present research aims at acquiring all the basic knowledge necessary to draw possible restoration guidelines. The work is framed within a wider project undertaken since several years by the group of Applied Mineralogy operating at the Earth Science Department and Geotechnical Engineering Department of “Federico II” University of Naples and at the Geological and Environmental Study Department of Sannio University (Benevento). This research team carried out a systematic study on the stone materials used in the historical architecture of some towns of Southern Italy and, in particular, the ancient centre of Naples, Salerno, Benevento, Sassari, Casertavecchia, focusing the attention also on the weathering processes affecting these stones when used *facciavista* (Calcaterra et al. 1995, 2000a, b, 2004, 2005; de’ Gennaro et al. 1995; Carta et al. 2005; de’ Gennaro et al. 2003).

Lava stone in the Campania region architecture

Lava has been used as a building stone in the Campanian architecture in a very discontinuous way, mainly after the second half of the seventeenth century and particularly between the eighteenth and nineteenth century. Examples of uses of these rocks since Greek–Roman ages are nevertheless occurring, above all for paving roads. Among several examples, worth to be cited are the roads within the Cuma acropolis, those present in the archaeological area of the *Arco Felice* made of Phlegraean trachyte or even those within the old Pompei town made of Vesuvian lava. Even though the use of this stone all throughout the historical periods is definitely subordinate if compared to other more easily workable materials such as the Yellow tuffs of the Campanian Ignimbrite, uses of Vesuvian lava in Pompei to perform architectural details such as *opus reticolatum* (Odeon/Theatre) and columns, or of Phlegraean lava in Pozzuoli (piers of brick arches within the Flavio Amphitheatre) are not lacking (Cardone and Papa 1993). Roughly around the fourteenth century (1317) a large amount of Phlegraean trachyte was used to pave many roads of Naples town by arrangement of Roberto d’Angiò (Rodolico 1953).

Fig. 1 Main colonnade of the S. Francesco di Paola Church (Naples 1817)

The period between the end of thirteenth and fourteenth century signs an important step in the use of the Phlegraean lava in the Neapolitan architecture as testified by the S. Lorenzo Maggiore (1270–1275; basement and some columns), San Domenico Maggiore (1283–1324; piers of the arches), Santa Chiara (1310–1328; columns of the arcade), S. Maria Donnaregina (1307–1316; pillars of the choir), S. Giovanni a Carbonara (1343–1418; big triumph Arch) Churches. Some architectural elements of the Maschio Angioino Castle (1281–1284; base of the triumph arch and frames in the Barons’ Hall) were also made with lava from Campi Flegrei whose use continued also in the following centuries as confirmed by the sixteenth century building at Spirito Santo (1539) currently hosting the Banco di Napoli, and the central colonnade (Fig. 1) of the S. Francesco di Paola Church (1817) (Penta 1935; Cardone and Papa 1993).

From the end of the seventeenth century up to the end of the eighteenth century a decrease in the use of Phlegraean lava progressively replaced by the Piperno, displaying better technical features is recorded (Cardone and Papa 1993; Aveta 1987).

Vesuvian lava, also known as *Pietrarsa* (*burned stone*), only from the nineteenth century became a fundamental stone in the religious and civil architecture of the town of Naples. This aspect is related to the fact that, only after the 1631 AD Vesuvius eruption and the following ones, a certain amount of material qualitatively and quantitatively suitable for that purpose was available (Penta 1935; Rodolico 1953). The main use of lava stone was in slabs for basal coatings [basal facings, such as in S. Giorgio Maggiore Basilica, rebuilt in 1631 and restored in the second half of nineteenth century (Capuano Castle, twelfth century–1857); “Federico II” University (1908)], or to perform architectural elements such as portals, corner stones, frames, sills, brackets, stairs, etc. (Penta 1935; Fiengo and Guerriero 1999). The use of lava for internal coatings or decorative elements was testified by Vanvitelli’s work in the Caserta Royal Palace (1752) (Patturelli 1826). Worth to remark is also the combined use of Vesuvian lava (*Pietrarsa*) and Piperno in the Schilizzi Mausoleum (currently war memorial Votive Altar) at Posillipo (Penta 1935) and the huge use in the funeral architecture of the historical part of the Poggioreale Cemetery (Penta 1935).

Geological settings

Campi Flegrei

Campi Flegrei, along with Ischia and Procida islands, represents a complex volcanic system constituted by a east–west oriented net of small monogenic apparatus.

The volcanic activity, started about 50,000 y.b.p., is characterized by a high number of eruptions connected to several emission centres. Campi Flegrei current setting is the result of two collapse episodes (Orsi et al. 1996) following the emplacement of Campanian Ignimbrite (39,000 y.b.p.) (Fedele et al. 2008; De Vivo et al. 2001) and of Neapolitan Yellow Tuff (15,000 y.b.p., ^{40}Ar/^{39}Ar) (Deino et al. 2004; Insinga et al. 2004). After these collapse events the volcanic activity was confined within the collapsed area (Di Vito et al. 1999) with prevalent explosive character: only five effusive episodes are here recorded followed by the emplacement of lava domes.

Lava flows emplaced to very limited volumes at Astroni (4,500 y.b.p.) (Di Vito et al. 1999; Orsi et al. 2004), at the bottom of mount Spina (4,100 y.b.p., ^{40}Ar/^{39}Ar and ^{14}C datings) (de Vita et al. 1999), at Mount of Cuma (before Campanian Ignimbrite eruption; no absolute dating available) (Rosi and Sbrana 1987; Pappalardo et al. 1999), at Punta Marmolite (before Campanian Ignimbrite eruption; no absolute dating available) (Rosi and Sbrana 1987; Pappalardo et al. 1999) and at Mount Olibano (4,000 y.b.p.) (Fig. 2).

Monte Olibano lava flow, definitely representing the most important deposit, was the object of a significant exploitation activity, even made easier by via the sea transportation facilities (Cardone and Papa 1993). Within this deposit, three different types of lava were identified by Sinno (1955): a basal one, apparently homogeneous, ash grey in colour, where feldspar phenocrysts are hardly distinguishable due to the colour of the matrix; a “powdery” intermediate one, with well visible feldspar phenocrysts; an upper one with feldspar phenocrysts well evident in a dark grey matrix.

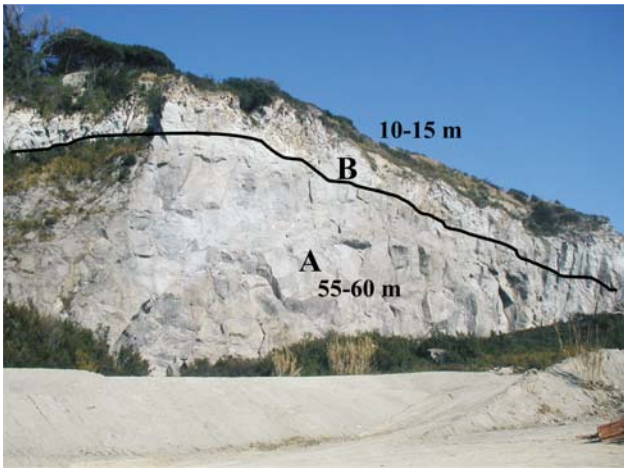


Fig. 2 Front wall of Cava Regia (Pozzuoli)

From a petrographic point of view, this rock is defined as a holocrystalline, porphyritic, alkali-trachyte (Rosi and Sbrana 1987), with alkaline feldspar, clinopyroxenes, biotite, olivine and opaque oxides as phenocrysts; apatite is the unique accessory phase (D’Antonio et al. 1999).

As far as petrophysical features are concerned, Maggiore (1936) distinguishes two different typologies of Phlegraean trachytes: a “compact” and a “porous” one. These two different types can even occur within the same flow unit, gradually passing from one variety to another from the bottom to the top of the formation.

The exploitation areas of the so-called Phlegraean trachyte were located in the aforementioned outcrops. The still well preserved old quarries are sited close to the west side of the Pozzuoli town: “Cava Regia”, “Cava Muso” and “Cava Morganti”.

Cava Regia is undoubtedly the most important both in terms of thickness and amount of exploited material. This is also the only accessible quarry, as the others are placed in a military area protecting the Aeronautic Academy.

The front wall of the Cava Regia quarry (Fig. 2) is about 70 m high and two different layers can be identified from the bottom to the top:

A. An ash grey compact “trachyte” with lighter areas. Thickness: 55–60 m.
B. A light grey less compact and powdery trachyte, deeply fumarolized. Thickness: 10–15 m.

Somma-Vesuvius

The activity of the Somma-Vesuvius volcanic complex started in submarine environment contemporarily to the first tectonic phases by interesting this area between the end of Pliocene and the beginning of Pleistocene age (Santacroce 1987; Brocchini et al. 2001; Bernasconi et al.

1981). Since that time the volcanic activity went on till today (the last eruption being in 1944) following a cyclic scheme. Each cycle starts with a very-powerful explosive "plinian" eruption, followed by a quiescence period of several hundreds of years. A semi-persistent activity continues with minor explosive episodes interspaced by effusive manifestations and by shorter stillness periods. Lava flows, most of them quite recent as referable to the 1631–1944 activity period (from the first to the seventeenth cycle of the Somma-Vesuvius recent activity—Arnò et al. 1987), are located just in the southern sector of the complex and depart from the highest slope of the volcano. In some instances, they reach the sea. Most of the exploitation areas are located in this sector of the Vesuvius.

From a minero-petrographical point of view, the scientific interest towards these materials has always been high as witnessed by the wide literature on the subject covering a span of time of about 3 centuries (Santacroce 1987 and therein references).

As far as petrophysical properties of this rock are concerned literature data available are few and often in evident disagreement.

Also, the historical data on the exploitation activity are scarce and incomplete. According to Fiengo (1983), in mid '800s about ten quarries were still active in an area located around Somma-Vesuviana, Terzigno, S. Giorgio a Cremano, Torre del Greco, Torre Annunziata, Granatello (Portici), and Resina (Ercolano). All these exploitation sites provided a very-tough material, particularly suitable for flag-stone roads. Fiengo again (1983), starting from data in Maggiore (1936), reports that one century later, few decades before their definitive falling off, the exploitation sites became 74, in most of which lavas emplaced after the 1631 eruption were quarried.

Only the paper by Penta and Del Vecchio (1936) reports a complete list of the main quarries, (both active and abandoned) occurring on the Vesuvian territory. Most of them, however, were likely placed on old quarry fronts.

Among all those reported, only a few can be still recognized and just a couple are active, at the sampling time, as a consequence of the intense urbanization of the area (Fig. 3).

The exploitation activity was mainly concentrated in three sectors characterized by important lava outcrops. In the eastern sector, in Terzigno and Boscoreale territory, three sites were identified: the Vitiello quarry, likely representing the old De Medici quarry as reported by Penta and Del Vecchio (1936), which gave the so-called "Mauro lavas" from the flow activity of 1754. The other two sites of this sector, the D'Oriano and Ranieri quarries, are placed on the same lava flows (6th cycle of the Vesuvius recent activity—Arnò et al. 1987).

The most important exploitation site of the whole Vesuvian district is located in the southern sector of the volcanic apparatus, within the urban limits of Torre del Greco; known as "Villa Inglese" quarry, this site was active up to the first half of '70s. Two superimposed lava flows separated by a paleo-soil have been deeply exploited:

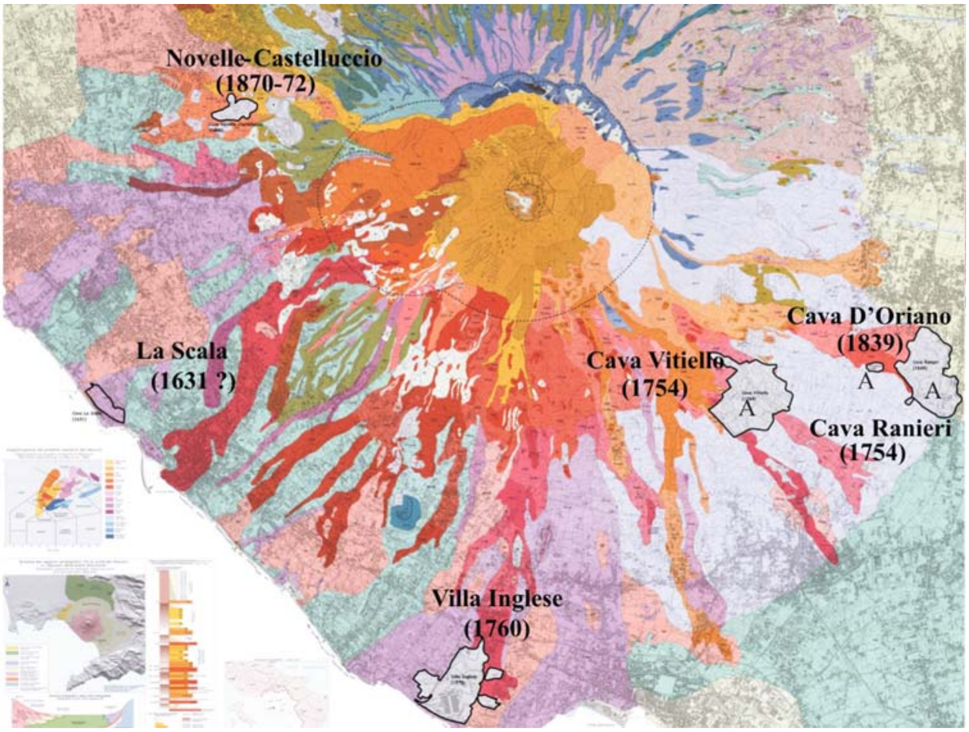


Fig. 3 Location of the Vesuvius lava exploitation sites; in brackets the activity age (Vesuvius Geological Map 1:15,000: Santacroce et al. 2003). *A* active quarry (in 2002)

the upper horizon was attributed by Penta and Del Vecchio (1936) to the 1760 AD eruption, whereas the lower one, to a presumed effusive event linked to the 1631 AD eruption by Penta and Del Vecchio (1936); Penta (1937); Vittozzi and Gasparini (1964); Rapolla and Vittozzi (1968) and by others to older activities (Arnò et al. 1987; Principe et al. 1987). In the same town of Torre del Greco, NW to Villa Inglese quarry, another important site named “La Scala” set out on a lava flow that, according to Penta and Del Vecchio (1936), belongs to the presumed effusive event of 1631 AD.

In the north-western sector of Vesuvius area (Ercolano and Somma-Vesuviana) four inactive quarries are present. They can be considered as historical sites quarrying two superimposed lava flows both referable to the 6th cycle of Vesuvius activity (Arnò et al. 1987). Among these sites, only the so-called “Novelle-Castelluccio” quarry (Penta 1935) still shows a well evident front wall.

Materials and methods

The mineralogical and petro-physical characterization of Phlegraean and Vesuvian lavas was carried out on a significant number of samples collected in the main outcrops of the two volcanic districts.

Mineralogical and chemical characterization

All traces of weathering were removed from the laboratory samples and, according to each testing methodology; various sets of samples were then obtained. For chemical and mineralogical analyses, samples were obtained after grinding and quartering rock fragments of about 5 kg mass.

Mineralogical characterization was carried out both by optical microscope observations (Leitz Laborlux Pol 40) and by X-ray powder diffraction analysis (XRPD—Philips PW1730/3710) using a CuKα radiation, incident- and diffracted-beam Soller slits, curved graphite crystal monochromator, 2θ range from 3° to 100°, step size 0.02° 2θ and 10 s counting time per step. Quantitative mineralogical analyses were also performed by XRPD using an internal standard, α-Al_2O_3 (1 μm, Buehler Micropolish) added to each sample in amount of 20wt%. Powder data set were analysed both by RIR (Chipera and Bish 1995) and Rietveld methods (Bish and Post 1993), the latter using GSAS package (Larson and von Dreele 2000).

Spectrochemical analyses were carried out at the “Centro di Servizi Interdipartimentale per le Analisi Geomineralogiche” (CISAG, Napoli).

Major and trace elements were analysed with a Philips PW1400 X-ray fluorescence spectrometer, following the methods described by Melluso et al. (2005). Precision is generally within ±1% for SiO_2, TiO_2, Al_2O_3, Fe_2O_3t, CaO, K_2O, and MnO; ±4% for MgO, Na_2O and P_2O_5.

Apparent density

Bulk unit weight, expressed as kg/m^3 and function of the bulk density of constituents and of unaccessible porosity, was measured with a He-pycnometer (Micromeritics Multivolume Pycnometer 1305) on cylindrical specimens (2.5 cm diameter; height $\leq$3 cm) and a ±0.1 to 0.2% accuracy. The measured apparent and real volumes allowed the open porosity to be calculated.

Capillarity absorption

The amount of water absorbed as a function of time was measured according to the Italian-suggested standard reported in Raccomandazione NorMaL (1985). Specimens used for this test had a cylindrical shape and a surface (s)/apparent volume (v) ratio of $1\ cm^{-1} \leq s(cm^2)/v(cm^3) \leq 2\ cm^{-1}$.

Water absorption by total immersion

This test enables to determine the amount of water absorbed by a natural stone sample after immersion at atmosphere pressure. Cubic specimens (7.1 cm) have been used and the tests were carried out following the suggestions Raccomandazione NorMaL (1981).

Hg intrusion

Mercury intrusion test allows measuring the volume and dimension of macro and mesopores in solid porous materials. This technique is based on the mercury property to act as a non-wetting liquid towards a large variety of solids, including stone materials.

The instrument used for this test was a Pascal 140 porosimeter, for sample preparation and macropores determination, and a Pascal 440 porosimeter for macro and mesopores determination.

Uniaxial compressive strength

Uniaxial compressive strength (UCS) tests were carried out with a Controls C5600 testing device allowing a maximum axial load of 3,000 kN. The axial load was increased continuously at a constant rate of 1.0 ± 0.5 MPa/s. Tests were carried out following the procedure suggested by Norma Italiana UNI (2000) on cubic shaped specimens (7.1 cm).

Secant modulus of elasticity (Young's modulus)

The Young's modulus and stress-strain curve was determined by means of uniaxial compressive tests on cubic shaped specimens (7.1 cm) and following the procedures suggested by Norma Italiana UNI (1992). Two strain gauges were applied on each specimen to continuously record the strains as a function of the applied increasing pressure. The test was carried out with the same device used for the determination of the UCS at a constant load rate of 0.5 MPa/s; load and strain were continuously recorded by an automatic data logger.

Field survey of weathering forms

A field survey on the buildings of the Ancient Centre of Naples with lava used "facciavista" was carried out to get an exhaustive picture concerning the behaviour of these materials towards the weathering agents. This part of the research was developed using a published cartography of Naples and taking into account data concerning a previous survey (de' Gennaro et al. 2000). Field survey and weathering forms were mapped following the method described in Giamello et al. (1992) and modified by de' Gennaro et al. (2000). On some samples showing the most representative decay forms optical microscope observations were also carried out.

Results

Tables 1 and 2 summarize the main minero-petrographical features of Campi Flegrei and Vesuvius lavas, respectively.

All the samples from Campi Flegrei show a porphyritic texture on microscope observation with a trachytic groundmass. Main phenocrysts are elongated alkaline feldspars (sanidine) (Fig. 4) and clinopyroxene, subordinately. Microphenocrysts are mostly magnetite and strongly zoned Na-plagioclase; rarer olivine, apatite and biotite also occur. Groundmass is mainly constituted by feldspar, diopsidic pyroxene, brown biotite, magnetite and very-rare plagioclase.

XRD quantitative analyses gave the following results in order of abundance: sanidine (>80%), Na-plagioclase (6.9–4.5%), diopside (5.7–5.4%), and biotite, magnetite and horneblende in very low amount (<1%).

Samples evidence a good chemical homogeneity and can be classified as trachytes (Fig. 5). Major oxides and trace elements variations are quite limited.

All the samples from Somma-Vesuvius district (Table 2) have a porphyritic texture; clinopyroxene represents the only phenocryst, sometimes along with leucite. Microphenocrysts are leucite, clinopyroxene and biotite.

The results of the optical microscopy were also confirmed by the XRD analyses. In order of abundance, the following minerals were identified: clinopyroxene (42.0–26.6%), Na-plagioclase (33.9–25.1%), leucite (22.6–17.3%), sodalite (4.3–3.4%), sanidine (5.5–3.7%,), biotite (3.3–1.9%), horneblende (2.6–0.2%) and magnetite (0.8–0.1%).

From a chemical point of view (Fig. 5) all the samples show a quite sensible variation, also within the same flow unit, either in terms of major or trace elements, scattering within the fields of phonotephrites and tephriphonolites.

Petrophysical characterization

Table 3 reports the main physico-mechanical parameters of the investigated samples. The whole set of petrophysical tests was carried out only on samples TZ, Erc and VI of Vesuvian lavas as only these materials were collected in a sufficient amount to provide an adequate number of specimens.

As expected, due to the low values of open porosity, these materials show a reduced difference between bulk and apparent density, with consequent low values of total water absorption (Fig. 6) and capillarity absorption coefficients (Fig. 7). A substantial homogeneity was recorded for the water absorption curves after total immersion in samples from different outcrops (Fig. 6).

Table 1 Lavas from Campi Flegrei

	Quarry	Age[a]	Classification	Petrographical description
Ol1	Regia inferiore	4,000	Trachyte	Porphyritic structure and groundmass with fluidal texture. Sanidine, clinopyroxene and plagioclase phenocrysts. Na-plagioclase, olivine, biotite, magnetite and apatite microphenocrysts. Pyroxene, biotite, magnetite and plagioclase as groundmass
Ol2	Regia	4,000	Trachyte	
Ol3	Regia	4,000	Trachyte	
Ol4	Regia inferiore	4,000	Trachyte	
Ol5	Regia inferiore	4,000	Trachyte	
Ol6	Regia	4,000	Trachyte	
Ol7	Regia	4,000	Trachyte	

[a] Di Vito et al. (1999)

Table 2 Lavas from Somma-Vesuvius volcanic complex

	Quarry	Penta	Age[a]	Cycle[b]	Classification	Petrographical description
Tz1B	Vitiello	1764	1754	VI	Phono-tephrite	Porphyritic structure with abundant clinopyroxene, plagioclase, opacized biotite and magnetite phenocrysts. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, biotite and apatite crystals
Tz3A	Ranieri	1834	1754	VI	Phono-tephrite	Porphyritic structure with abundant clinopyroxene, plagioclase, opacized biotite and magnetite phenocrysts. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, biotite and apatite crystals
Tz3B	Ranieri	1834	1754	VI	Phono-tephrite	Porphyritic structure with clinopyroxene, plagioclase, opacized biotite and magnetite phenocrysts. Clinopyroxenes glomerules. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, biotite and apatite crystals
Tz2A	D'Oriano	1834	1839	XII	Phono-tephrite	Porphyritic structure with clinopyroxene, plagioclase, opacized biotite and magnetite phenocrysts. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, biotite and apatite crystals
Tz2C	D'Oriano	1834	1839	XII	Phono-tephrite	Porphyritic structure with abundant clinopyroxene, rare olivine, plagioclase, opacized biotite and magnetite phenocrysts. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, biotite and apatite crystals
VI1	Villa Inglese Sup	1760	1760	VI	Phono-tephrite	Porphyritic structure with clinopyroxene, plagioclase and leucite crystals. Clinopyroxenes glomerules. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, biotite and apatite crystals
VI3	Villa Inglese Sup	1760	1760	VI	Phono-tephrite	Porphyritic structure with clinopyroxene, plagioclase, biotite and magnetite phenocrysts. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, biotite and apatite crystals
VI5	Villa Inglese Sup	1760	1760	VI	Phono-tephrite	Porphyritic structure with clinopyroxene and large leucite crystals. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, biotite and apatite crystals
VI6	Villa Inglese Sup	1760	1760	VI	Phono-tephrite	Porphyritic structure with clinopyroxene and leucite crystals. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, biotite and apatite crystals
SC	La Scala	1631 ?	?	?	Tephri-phonolite	Porphyritic structure with abundant leucite, clinopyroxene and rare olivine. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, olivine, biotite and apatite crystals
Erc1	Novelle-Castelluccio	1868	1870–72	XVI	Phono-tephrite	Porphyritic structure with clinopyroxene and leucite crystals. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, biotite and apatite crystals
Erc2	Novelle-Castelluccio	1868	1870–72	XVI	Phono-tephrite	Porphyritic structure with clinopyroxene, leucite and rare olivine. A microcrystalline groundmass is constituted by abundant leucite, plagioclase, opaque oxides, clinopyroxene, olivine, biotite and apatite crystals

[a] Santacroce et al. (2003), [b] Arnò et al. (1987)

The same remarks can be done for capillarity water absorption curves also showing an overall homogeneity with the only exception of samples VI characterized by a higher value, along with the highest total apparent porosity value. A unimodal mesocurtic pore size distribution was also evidenced with highest concentration of pores in the 0.3–1.2 μm size range (Fig. 8).

As far as Phlegraean lavas are concerned, petrophysical tests were carried out on samples collected from the two layers of the investigated outcrop at Mount Olibano (Table 3).

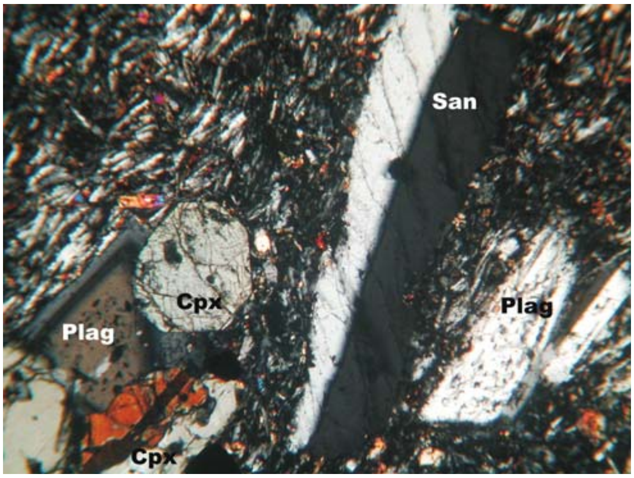


Fig. 4 Sample OL1—sanidine, plagioclase and clinopyroxene crystals

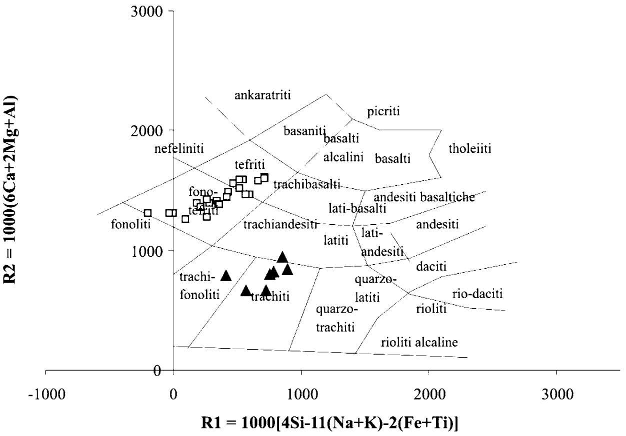


Fig. 5 R1–R2 diagram (De La Roche et al. 1980) for the analysed samples (*triangles* Campi Flegrei, *squares* Somma-Vesuvius)

Lava samples collected from the lower layer of Mount Olibano outcrop (OL1, OL4 and OL5) show a negligible difference between bulk and apparent density (Table 3) and much wider from those belonging to the upper one (OL2 and OL3). This difference is confirmed by the values of total open porosity, close to 10% for the former set of samples and close to 20% for the latter.

Pore size distribution also allows distinguishing of two different typologies of material: the first one, typical of lava samples OL1, OL4 and OL5 shows low values of open porosity and a unimodal platicurtic pore size distribution; the second one, typical of all the other lava samples, a bimodal distribution (Fig. 9).

Such variability also occurs in terms of water absorption by total immersion (Fig. 6) and by capillarity (Fig. 7) with the highest values perfectly corresponding to those of porosity (Table 3).

Table 4 reports the main mechanical properties of Vesuvian and Phlegraean lavas. As far as uniaxial compressive strength values are concerned, a substantial homogeneity of mean values was recorded for vesuvian samples ranging between 165 MPa (sample VI) and 181 MPa (TZ2). These data are well fitting with those, as well homogeneous, of total open porosity, always lower than 10%.

Phlegraean lavas, on the contrary, show quite variable mean values of UCS. Two different classes are therefore distinguished: a first one with values ranging between 138 MPa (OL4 and OL5) and 208 MPa (OL1), and a second one with definitely lower values (38 and 63 MPa, OL3 and OL2 samples, respectively). It should be remarked that lava samples characterized by porosity values close to or lower than 10% belong to the first class whereas those with higher porosity values (up to 20%) to the second one.

Young's modulus values confirm the previous considerations even though a higher variability was recorded for Vesuvian lavas (26.92–49.98 GPa). The already reported two class division for Phlegraean lava is also verified. In this case, a marked homogeneity of the values is noted

Table 3 Main physical properties of Vesuvian and Phlegraean lavas

	Vesuvian lavas				Phlegraean lavas (lower level)				Phlegraean lavas (upper level)			
	Mean	Min	Max	Dev.st.pop. (*n* samples)	Mean	Min	Max	Dev.st.pop. (*n* samples)	Mean	Min	Max	Dev.st.pop. (*n* samples)
Apparent density (kg/m^3)	2,630	2,570	2,710	0.05 (43)	2,430	2,350	2,500	0.06 (11)	2,190	2,130	2,240	0.02 (7)
Bulk density (kg/m^3)	2,860	2,830	2,900	0.02 (43)	2,690	2,660	2,710	0.02 (11)	2,700	2,680	2,720	0.01 (7)
Open porosity (%)	8.03	6.46	9.25	1.14 (43)	9.82	7.67	11.39	1.57 (11)	18.85	17.14	21.11	0.01 (7)
Porosity (%) (macro + meso)	7.11	6.34	8.12	0.66 (12)	7.49	5.77	9.65	1.61 (9)	15.71	14.79	16.40	0.01 (6)
Pore mean radius (μm)	0.53	0.31	0.62	0.12 (12)	0.25	0.005	0.69	0.31 (9)	1.12	0.79	1.20	0.10 (6)
Imbibition capacity (%)	1.54	1.41	1.63	0.09 (45)	1.84	1.43	2.51	0.83 (9)	6.51	5.46	7.31	0.27 (6)
Capillarity coefficient (g/cm^2 × s$^{0.5}$)	6.7E-04	5.8E-04	8.2E-04	0.86 (45)	1.6E-04	1.1E-04	2.3E-04	0.5 (9)	3.8E-04	3.4E-04	4.3E-04	(2)

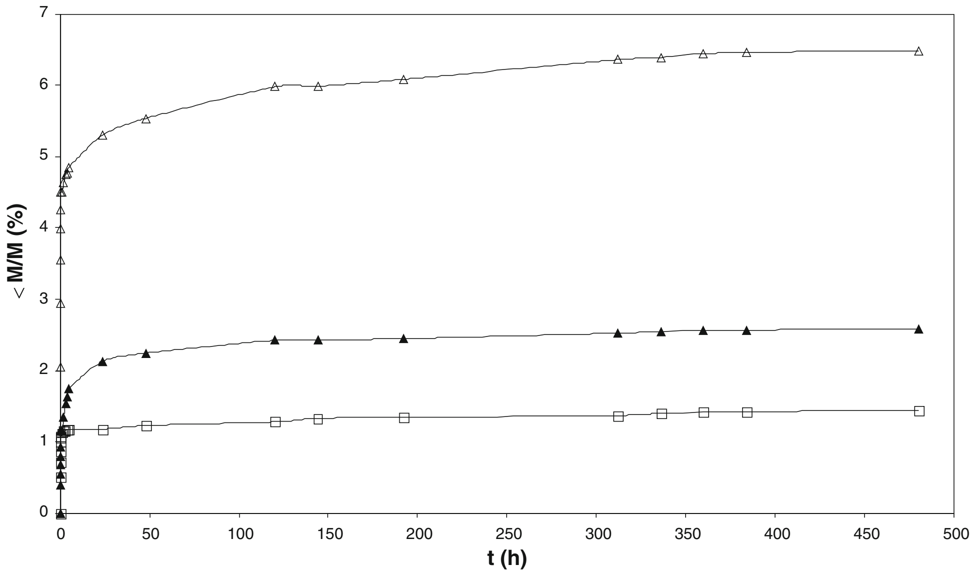


Fig. 6 Water absorption curves by total immersion as a function of time [*solid triangles* Phlegraean lavas (lower level), *empty triangles* Phlegraean lavas (upper level), *empty squares* Somma-Vesuvius]

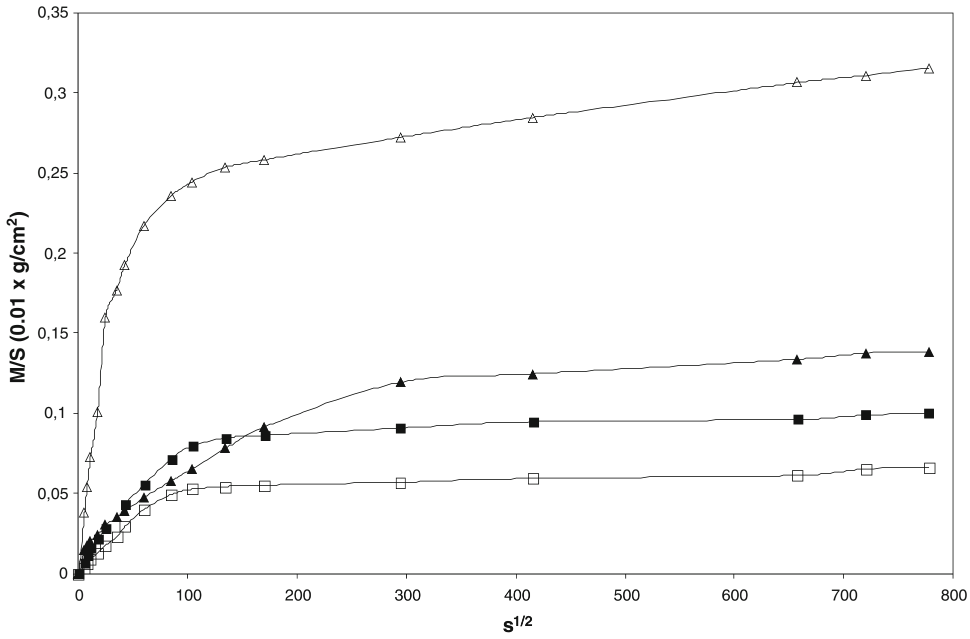


Fig. 7 Capillarity water absorption curves as a function of time [*solid triangles* Phlegraean lavas (lower level), *empty triangles* Phlegraean lavas (upper level), *empty squares* Somma-Vesuvius, *solid squares* VI samples]

within each class. Following the Deere and Miller classification (1966) Vesuvian lavas are defined as strong to very strong and on an average stiff to stiff materials; Phlegraean ones are considered as strong to very strong and stiff (Fig. 10).

Weathering phenomena affecting lavas

Previous literature data (Calcaterra et al. 2000a, b) evidenced the limited use of the Campanian lavas as ornamental stone. An ideal example is provided by the Ancient Centre of Naples, where this stone mainly of Vesuvian origin, represents about 14% of total dimension stones surveyed (~120,000 m^2 of face brick stone). Its main use is recorded in the peripheral areas of the Ancient Centre of Naples and, generally, in the reclaimed lands of the town immediately after the epidemic cholera (1884) within the so-called *Risanamento* zone.

A detailed analysis of the conservation state of this stone material evidenced that more than 50% of the exposed surfaces are affected by a high grade decay process, about 20% by a medium grade and about 23% by a negligible grade (Calcaterra et al. 2000a, b). Previous data have been supplemented with a more complete weathering evaluation, taking particular care to the decay forms and their

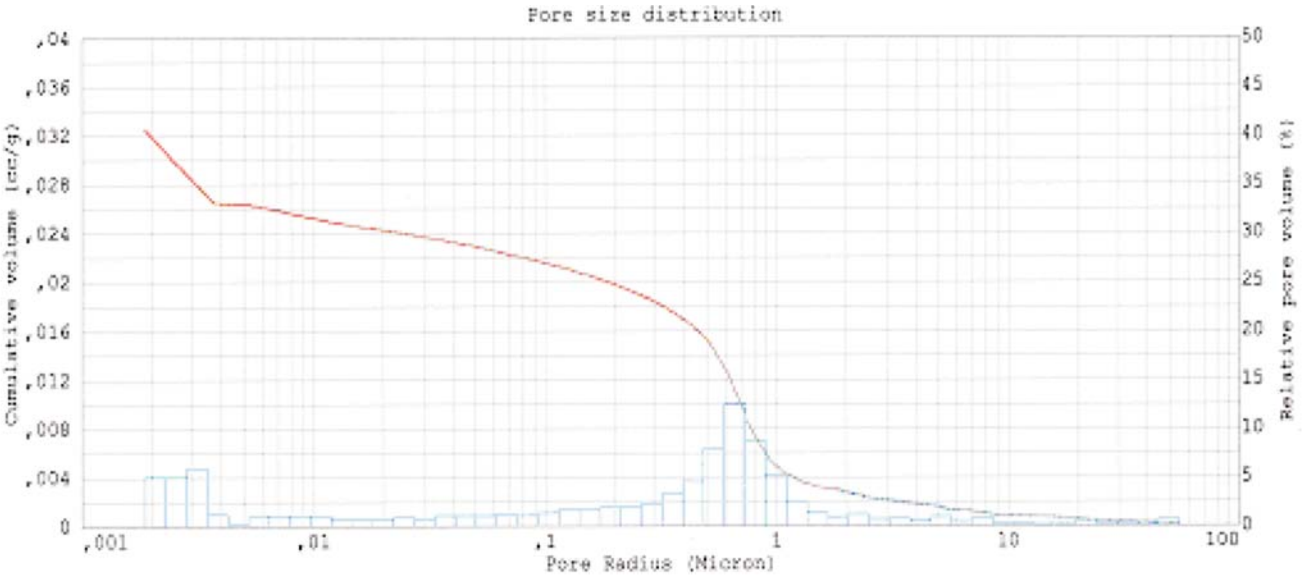


Fig. 8 Pore size distribution in sample Tz-1

percentage frequency. Figure 11 reports the weathering forms and the relative per cent frequency for the Vesuvian lavas in the Ancient Centre of Naples.

The most diffused weathering forms are patina and artificial patina. The latter, in particular, is mostly represented by writings and graffiti. More than 20% of the surfaces are affected by exfoliation processes which are manifested by a detachment, often followed by the fall, of one or more sub-parallel surface layers (Fig. 12a). Incrustations, scaling (Fig. 12b), lacks, alveolization and erosion are widespread almost everywhere but with a frequency always lower that 10%. All the remaining weathering forms never exceed 3%.

Optical microscope observation on microsamples collected on some buildings (*Policlinico* building on via del Sole) allowed to detect the constant occurrence of ≤0.2 mm thick black crusts, unresolvable, however, with this technique. XRPD investigation identified gypsum as the main mineralogical constituent of these crusts.

As far as Phlegraean lavas are considered, they are definitely subordinate (about 2% of the total), and are mainly concentrated (about 70%, 275 m^2) in the colonnade of the Clarisse Cloister (Santa Chiara Basilica). A comparison with the Vesuvian lithotype accounts for a slightly worse state of conservation of Phlegraean lava. In fact, disregarding the stone used in the colonnade of the Clarisse Cloister which is well preserved due to several restorations, 99% of the remaining surfaces are affected by a high grade of weathering processes.

The most diffused weathering typology is undoubtedly the exfoliation, followed by scaling and alveolization (Fig. 12c); these lavas are characterized by a more evident occurrence of efflorescences (Fig. 12d). The other typologies do not affect more than 10% of the exposed surface (Fig. 13).

Again, optical microscope observations on some microsamples (S. Maria La Nova Church) evidenced dark patinae about 0.1 mm thick, likely gypsum, and frequent fissures normal to the surface.

In order to avoid the occurrence of these weathering phenomena, both kinds of lavas could be treated with protective agents. According to Stück et al. (2008) the use of silicic acid ester, elastic silicic acid or acrylate resin on volcanic tuffs determined a porosity decrease within 20–30%. Such a decrease could not compromise the overall features of the lavas investigated in the present research whose pore size distributions mainly affect macro and mesopores. This hypothesis, however, requires a more-detailed experimental study.

Discussion

Conservation of the architectural heritage requires a deep knowledge of the building materials either to verify their compatibility with products used as consolidating and protective agents or to identify, whenever necessary, the provenance areas in order to have available materials for replacing operations. Within this frame, the present research aimed at thoroughly investigating the lava stones mostly used in the historical architecture of Campania region.

The evident compositional difference existing between the Phlegraean and Vesuvian lavas allows to clearly identify the provenance district of these materials once present in architectural manufacture as building or ornamental

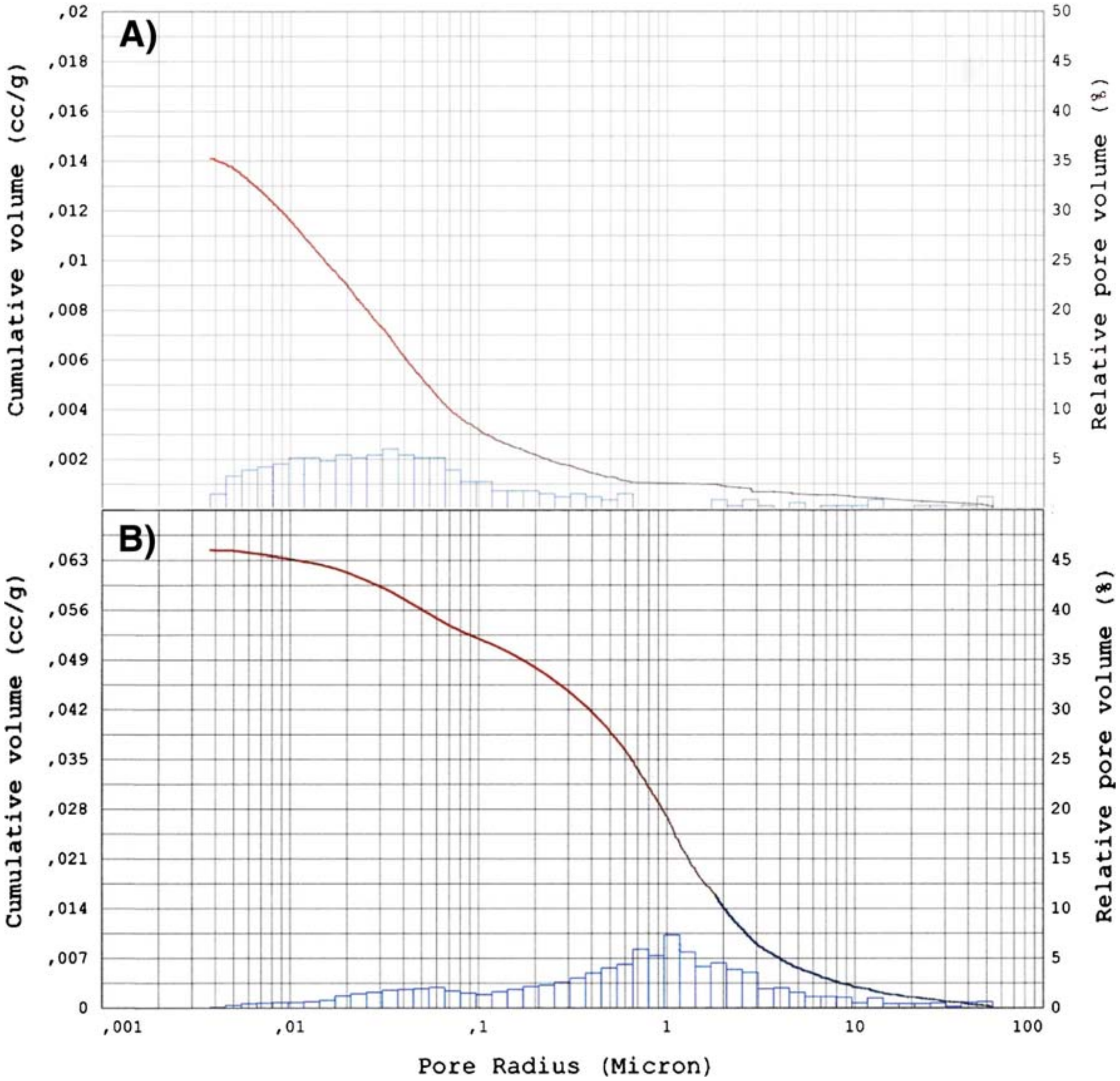


Fig. 9 Pore size distribution in samples Ol 1 (**a**) and Ol 2 (**b**)

stone. More complex or sometimes impossible was the discrimination of materials coming from the same volcanic district. This is not a relevant problem for the Phlegraean lavas as most of these materials occurring in the architecture of the region comes from the quarries located at Mount Olibano. On the other side, Vesuvian lavas are derived from several exploitation areas which have been active during a long period of time.

A minero-petrographic study of post 1631 AD activity Vesuvian lavas was aimed at confirming the already abundant literature data reporting an overall compositional homogeneity, regardless the age of the flow. Currently, it seems quite difficult to individuate mineralogical or geochemical markers which could enable to distinguish the different lava flows and, thus, to evaluate their provenance when the material used in the building is going to be studied.

This homogeneity of chemical, mineralogical and petrographical data was also found in terms of geomechanical features of this stone, which could lead to use, for possible replacement operations, materials coming from any of the sites analysed during this research. In fact, the above reported considerations are confirmed by data of Tables 3 and 4 which compare the main properties of Vesuvian and Phlegraean lavas.

The comparison evidences higher values of bulk and apparent density of Vesuvian lavas and a lower porosity and imbibition capacity. On the other hand, the higher capillarity coefficient should be likely due to a different pore size distribution mainly concentrated towards the macropores region.

As far as uniaxial compressive strength is considered, Vesuvian lavas show a higher mean value even though the absolute highest value was recorded for the Phlegraean

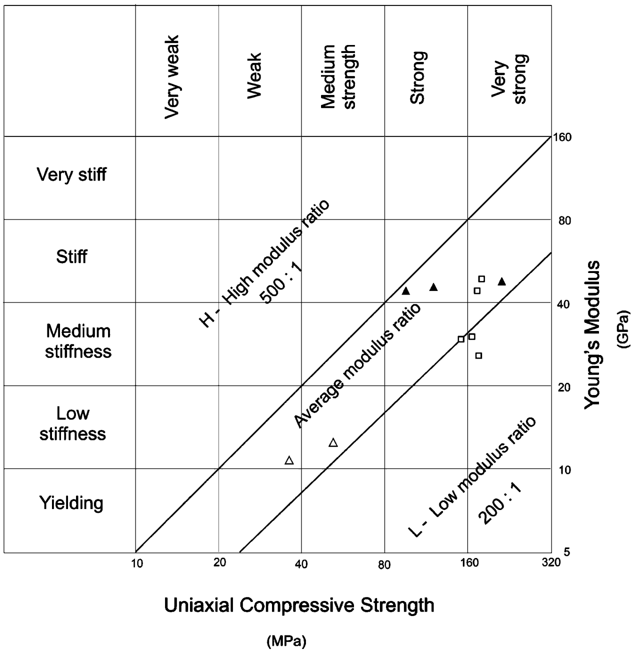


Fig. 10 Engineering classification of the investigated lavas according to Deere and Miller (1966) [*solid triangles* Phlegraean lavas (lower level), *empty triangles* Phlegraean lavas (upper level), *empty squares* Somma-Vesuvius]

lavas. Furthermore, higher Young's modulus account for a higher stiffness of Phlegraean lavas.

Considering only the lower layer of the M. Olibano outcrop, both the lithotypes are quite homogeneous, even though it should be reminded that Vesuvian lavas come from several exploitation sites and from flow units ascribed to different activities of the volcano.

Table 5 compares the mean values of some petrophysical data for Vesuvius and Campi Flegrei lavas with the available literature data referred to lavas of different volcanic districts (Strati 2003). Certain homogeneity of data is still evident even though the Campanian lavas can be distinguished for higher values of compressive strength and Young's modulus. The good technical features of these materials account for their past use in architecture and for the realization of engineering manufacts such as road pavings or many harbours of the coastal towns of Naples province.

Conclusions

The Vesuvian lavas and subordinately the Phlegraean ones, represent important building stones for the historical architecture of the town of Naples and its province. This is the main reason for promoting this research which aims at providing a complete picture of the mineralogical and petrophysical features as well as the weathering processes affecting this stone. This basic knowledge should be regarded as an essential tool for whoever is involved in the restoration of this kind of materials.

A fundamental need appears to be an adequate conservation of the historical quarrying sites of these rocks, not for further intense exploitation activity but just to have available amounts of material necessary for possible restorations requiring the replacement of the original rock.

Petrographical and chemical information which allow to distinguish univocally Phlegraean lavas from Vesuvian ones do not enable to attribute with the same accuracy to a specific effusive event of any lava stone of the Somma-Vesuvius complex. Such difficulties should be related to limited, but however evident, compositional variations often occurring within the same outcrop and to the lack of defined markers that univocally allow the identification. Nevertheless, it was possible to redefine the attribution to precise effusive events of the studied lavas, thus modifying the dating reported in the technical literature. This is particularly referred to the lava flows exploited in a large span of time and attributed to the 1631 AD eruptive event. Even though far from the aims of the present research, it is possible to establish that the materials formerly assigned to the 1631 AD lavas have to be referred to another effusive event which characterize the recent activity of the Vesuvius. So, the lack of historical data makes very hard to trace back and recognize the site or the lava flow from which the material occurring in a definite monument derives. This evidence even representing a distinct drawback, lead to be considered as useful for the above reported purposes, materials from any lava front as they will have substantially similar technical and aesthetic features. However, as testified by the lava stones from D'Oriano and Novelle

Table 4 Main mechanical properties of Vesuvian and Phlegraean lavas

	Vesuvian lavas				Phlegraean lavas (lower level)				Phlegraean lavas (upper level)			
	Mean	Min	Max	Dev. st. pop. (*n* samples)	Mean	Min	Max	Dev. st. pop. (*n* samples)	Mean	Min	Max	Dev. st. pop. (*n* samples)
Compressive strength (MPa)	171	165	181	5.35 (15)	161	138	208	33 (5)	50	38	70	8 (4)
Young's elastic modulus (GPa)	37.86	26.92	49.98	9.62 (5)	53.85	51.54	56.8	2.20 (3)	14.10	12.58	15.61	(2)

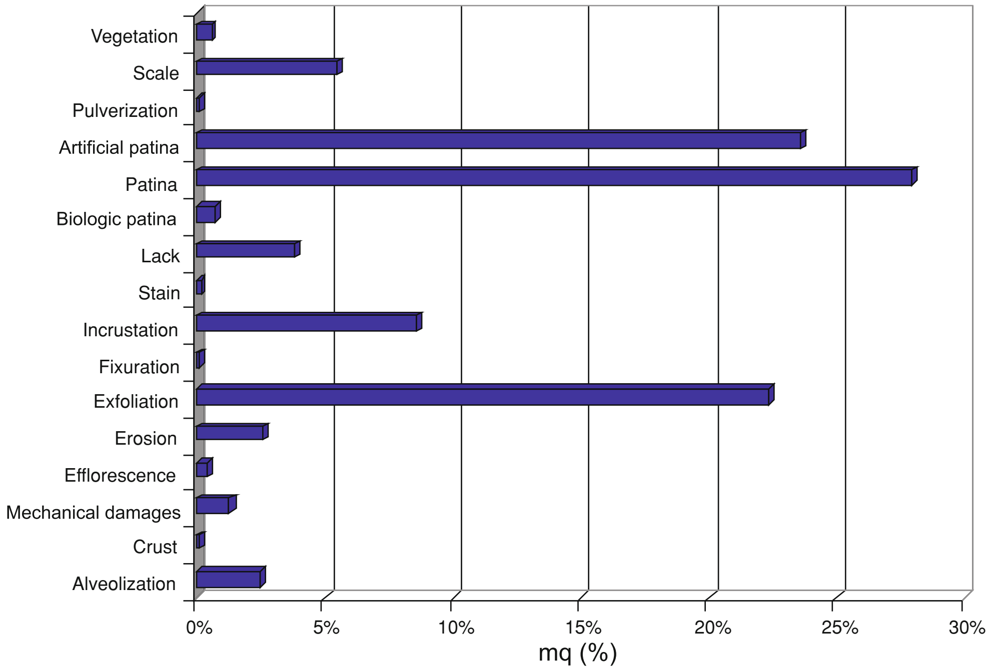
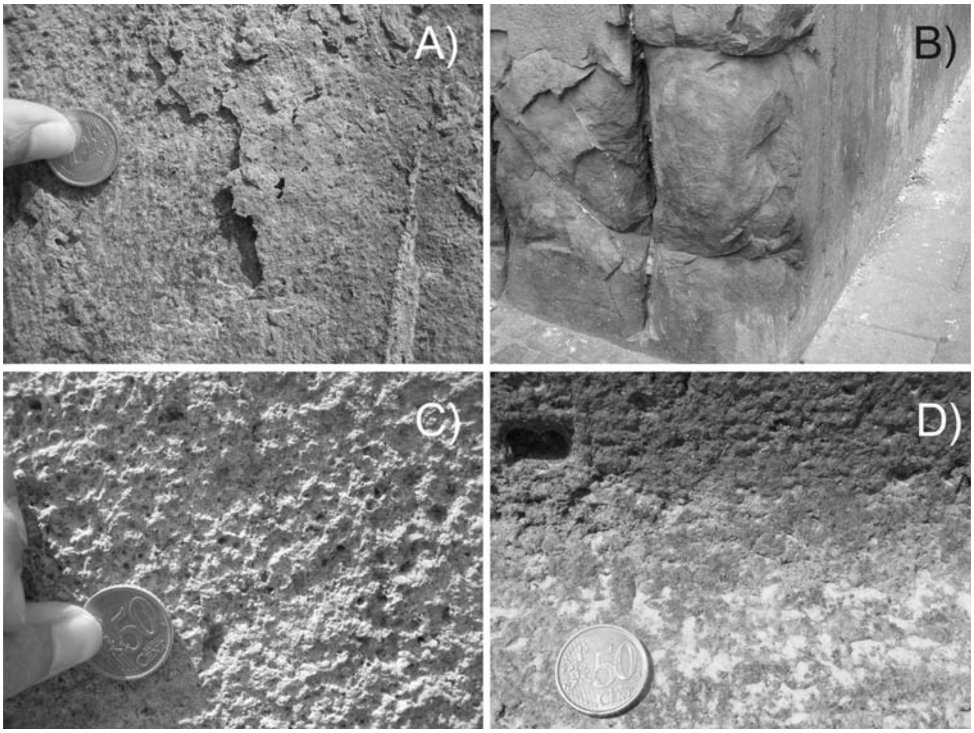


Fig. 11 Weathering typologies affecting Somma-Vesuvius lava stone of the Ancient Centre of Naples

Fig. 12 Some examples of weathering forms: **a** exfoliation,Via del Sole,Vesuvian lava; **b** scaling, on basal facing of the *Accademia di Belle Arti* Vesuvian lava; **c** alveolization, Clarisse cloister, S. Chiara Basilica, Phlegraean lava; **d** efflorescence, S. Chiara Basilica, Phlegraean lava



Castelluccio quarries characterized by abundant leucite phenocrysts, some exceptions occur. This aspect could determine either aesthetic problems (occurrence of whithish "eyes" which define a different pattern to the stone) or problems concerning some technical performances of the stone, linked to an easier weathering of the mineral which could determine possible alveolization phenomena. The research in progress aims at verifying whether leucite phenocrysts bearing lavas have ever been used in Naples and which is their state of conservation.

It can be foreseen that the present paper, which provides a significant contribution to the knowledge of Vesuvian

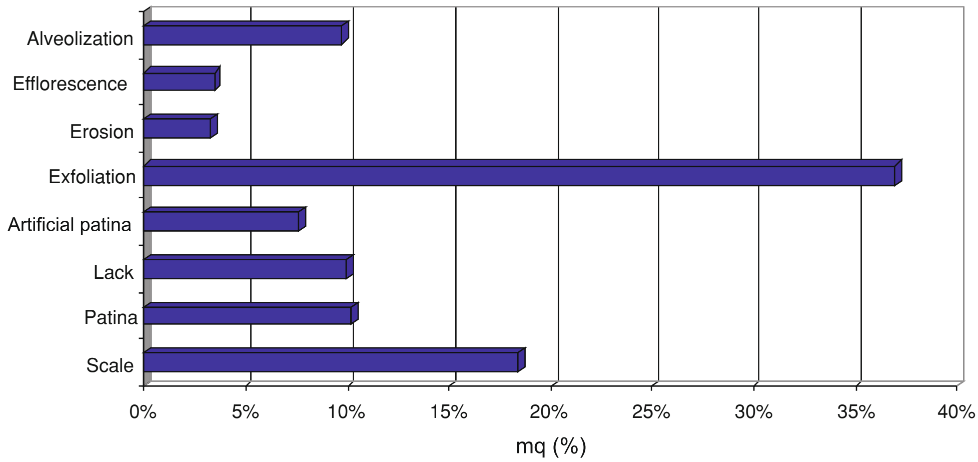


Fig. 13 Weathering typologies affecting Phlegraean trachyte of the Ancient Centre of Naples

Table 5 Comparison of some physico-mechanical features of Vesuvian and Phlegraean lavas with those of some similar ornamental stones (Strati 2003)

	Apparent density (kg/m^3)	Imbibition capacity (%)	Compressive strength (MPa)	Young's modulus (GPa)
Vesuvius lava	2,630	1.54	171	38
Phlegraean lava (compact)	2,430	1.84	161	54
Phlegraean lava (porous)	2,190	6.51	50	14
Basalt from Mount Etna (Sicily, Italy)	2,850	0.80	140	23
Basalt from Mount Iblei (Sicily, Italy)		1.62	109	
Trachyte from Colli Euganei (Veneto, Italy)	2,400	1.52	18	

and Phlegraean lavas, could be useful to all those operators involved in the restoration and conservation of architectural heritage. As far as the evaluation of the available stone resources is concerned, it was not possible to carry out analyses or field surveys as the exploitation activity is currently abandoned since all the described areas fall within the protected area of the Vesuvius National Park.

Aware of the fact that the protection of the landscape and the nature of the sites is the main need, it should not be disregarded the hypothesis of preserving the local tradition of working this stone which was and still is so important in the history and the culture of Naples and, more generally, of the Campania region, by authorizing quarrying with modern and less invasive techniques, exclusively for restorations or high architectural interest realizations. To this respect, the Regional Plan of the Quarrying Activities (Regione Campania 2006) allows the quarrying of ornamental stone historical sites also in protected areas, previously permitted by the competent authorities, on condition that the total area object of authorization does not exceed 1.00 Ha and 1,000 m^3 of annual production. This would allow to have an amount of material sufficient for any possible restorations and for relevant urban architectural fittings such as restyling of roads and squares of the town currently carried out with lava stone of Etna production (Mount Etna, Catania, Italy). It should be remarked, however that, displaying good technical properties, this stone does not respect the multi-millenary Neapolitan tradition.

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