# Some special geotechnical properties of pumice deposits

L. Esposito · F. M. Guadagno

**Abstract** This paper describes the characteristics of pumice soils from the area of Mount Vesuvius and discusses sinking, watering and other geotechnical tests on pumice from a number of sites. Attention is drawn to the presence of both inter- and intra-particle voids within this material and appropriate modifications to the standard solid-water-air phase diagram are suggested to take account of this. The importance of understanding the structure of the pumice and its response to rainfall/ground water conditions is discussed in relation to both landslips and stabilisation works.

**Resumé** Cet article décrit les caractéristiques des sols constitués de ponces dans la région du Vésuve et discute les différents essais concernant le comportement de ces sols vis-à-vis de l'eau dans un certain nombre de sites différents. L'attention est attirée sur la présence de vides inter aussi bien qu'intraparticulaires et les auteurs proposent des modifications du diagramme traditionnel des phases solide-eau-air pour tenir compte de ces phénomènes. L'importance d'une bonne compréhension de la structure de ces sols et de leur comportement vis-à-vis des circulations d'eau est illustrée a l'aide d'exemples de glissements et de travaux de confortement.

**Key words** Pumice · Vesuvius · Density · Porosity · Landslides · Stability

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## Introduction

A major component of pyroclastic material is the pumice clast, defined by Fisher and Schmincke (1984) as highly vesicular glass. The clasts are usually found over a large area in the vicinity of the volcanic vent, being deposited by flow and/or air fall.

Whitam and Sparks (1986) described the main physical properties and behaviour of this material in relation to both volcanology and volcanogenic sedimentation. The experiments they undertook to examine the interaction of pumice with water drew them to the "unexpected conclusion" that "nearly all the pores in the pumice are interconnected". This does not support the earlier work of Pellegrino (1967) for example, who showed the existence of unconnected voids in the pumice from the Phlegraean Fields, Naples (Fig. 1). As can be seen in the SEM photograph (Fig. 2) however, most voids are clearly interconnected, such that the deposits have both inter- and intra-particle voids. Following the work of Whitam and Sparks (1986), the writers have undertaken laboratory tests to characterise the pumice deposits and the clasts.

Extensive pumice deposits are found around the volcanic vents in the vicinity of Naples. As in other areas which have experienced explosive volcanic activity, they are associated with landsliding and instability, with the sub-surface (foundation) materials often exhibiting unusual behaviour. Guadagno (1991) described the debris slides, evolving into debris flows, in the relief surrounding the Campanian Plain (Fig. 3) where the activity of Somma-Vesuvius has resulted in a mantle of volcanic deposits covering the carbonate ridges. Shallow failures are usually related to short periods of very intense rainfall (Hutchinson 1988) but the landsliding phenomena of the Campanian mountain slopes ap-


**Fig. 1**
Voids within a pumice clast (after Pellegrino 1966). *1* Solid material; *2* external voids; *3* internal voids

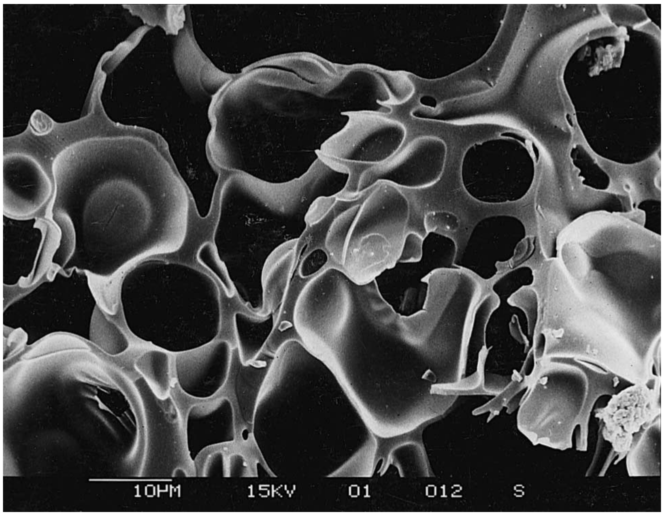



**Fig. 2**
SEM photograph showing the internal voids of a pumice clast

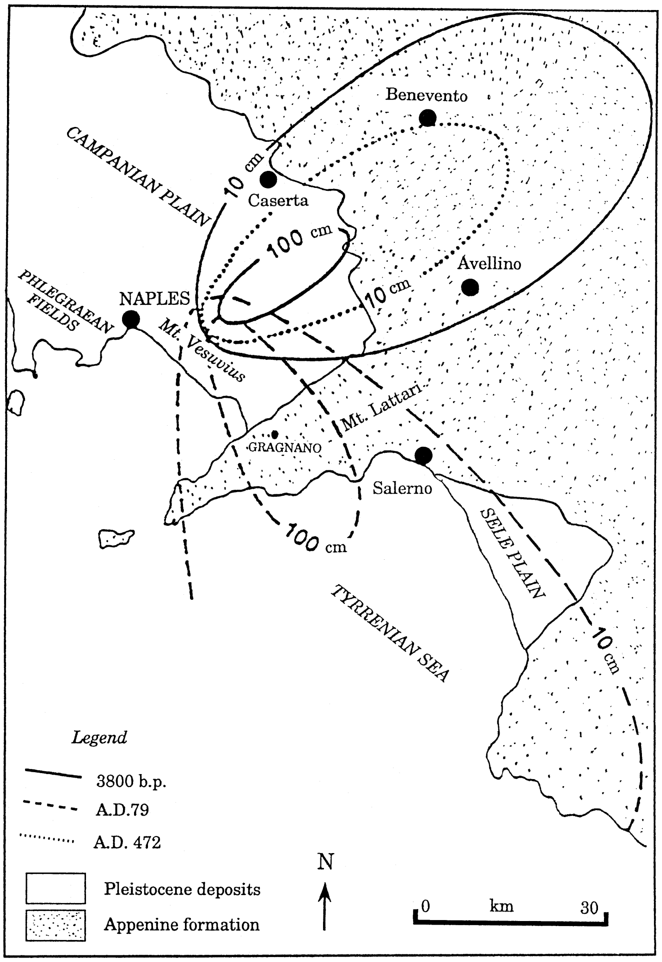



**Fig. 3**
Schematic geological map showing fall deposits of typical Plinian eruptions, Somma-Vesuvius

pears to be the consequence of precipitation over a long period (Guadagno 1991). Instability is also known to occur when engineering measures have been undertaken. For instance, if cement is injected to improve the mechanical behaviour of the soil when pumice clasts are dry or have a low moisture content, segregation phenomena hinder the penetration of the solid cement particles into the material itself and reduce the effectiveness of the engineering measures.
This paper presents the results of tests undertaken to determine the properties of the pumice and the behaviour of the related soils. It highlights the unique characteristics of these materials which contain both inter- and intra-particle voids and draws attention to the fragility of the particles themselves, which in the mass frequently have a density less than that of water.

## Testing

The experiments were undertaken on five pumice samples collected from fall deposits from the 79 AD Mount Vesuvius eruption (Fig. 3). Due to the prevailing wind at the time of the eruption, the fall deposits mantled the Mount Lattari ridge (Sheridan et al. 1981). The samples were taken from pits excavated at the top of Mount Pendolo, near the town of Gragnano, in the area where the deposits are more than 2 m thick. The "white pumice" layer samples have a phonolitic composition although some lithic elements are also present (Sigurdsson et al. 1985; Lirer et al. 1993). For comparison, pumice materials were also collected from air fall deposits in other volcanic areas typical of southern Italy (including the Eolian Islands) and from the flow deposits of the Phlegraean Fields. Some relevant data reported by Whitam and Sparks (1986) are also considered.
Index and physical-volumetric properties were determined following the ASTM procedures. Specific gravity (Gs), dry unit weight ($\gamma_p$), porosity (n) and void index (e) were calculated for particles in each grain size fraction. In addition, as the pumiceous soils may also include some lithic material, a dry volume weight for the pumiceous particles only has also been determined ($\gamma_{psp}$). Where the volume of the larger particles was determined by immersion in mercury, the volume of the smaller particles was obtained by the pyknometer technique using saturated particles. Parameters were then derived from the mean values.
Pore size distribution was determined using the mercury intrusion porosimeter. This assumes that no wetting fluid, such as mercury, can penetrate into a porous medium if pressure is applied. The apparatus used was the Carlo Erba Porosimeter 2000, which can reach a maximum test pressure of 2000 MPa. As the pressure is increased, smaller pores can be penetrated. However, the influence of the shape of the pores and the size of the pore throats is important, as is the frictional resistance to flow through the passageways (Whitam and Sparks 1986). As a consequence, porosity measurements obtained by the mercury intrusion method under-estimate the proportion of voids in the pu-

mice. In order to obtain more accurate information on such constricted pores, the two-intrusion methodology proposed by Pellerin (1979) was followed in these experiments.

Scanning electron microscopy was also undertaken using the Cambridge stereoscan. The images were used to obtain measurements of specific surfaces by fractal mathematics (Mandelbrot 1982; Falconer 1990). Fractal geometry has been used in recent years to determine the specific surface of clayey soils (Serrà 1989) and to model the fabric of cohesive soils (Moore and Krepfl 1991).

The structure of the pumice clast was treated as an irregular or fractal set. The analysis was carried out by fractal image projection which allows a three-dimensional structure to be obtained by projection onto a plane along an arbitrary direction (Falconer 1990). The box dimension of the projected shadow was determined following Serrà (1989) with a mathematical interpretation of the images. If $F$ is an at least partially filled bounded subset and $N_\sigma(F)$ is the smallest number of sides whose diameter is $\sigma$, the box dimension of $F$ is defined by the following equation:

$$\dim_B F = \frac{\lim}{\sigma \to 0} \; \frac{\log N_\sigma(F)}{-\log \sigma}$$

where $N_\sigma$ can be considered, for example, the smallest number of closed balls (bubbles in the case of the pumice) with a radius or cube side of $\sigma$ which cover $F$ (Falconer 1990). The use of box dimensions implies that the initial set can be covered by the smallest number of cubes with a side $\sigma$. The initial set is then included in another set, as shown in Fig. 4.

Sinking tests were carried out to investigate the behaviour of the pumice when it came into contact with water. The procedures proposed by Whitam and Sparks (1986) were followed hence the variation in water content and the percentage of sunken pumice were determined as a function of time. Sinking tests also allowed the porosity of the clasts

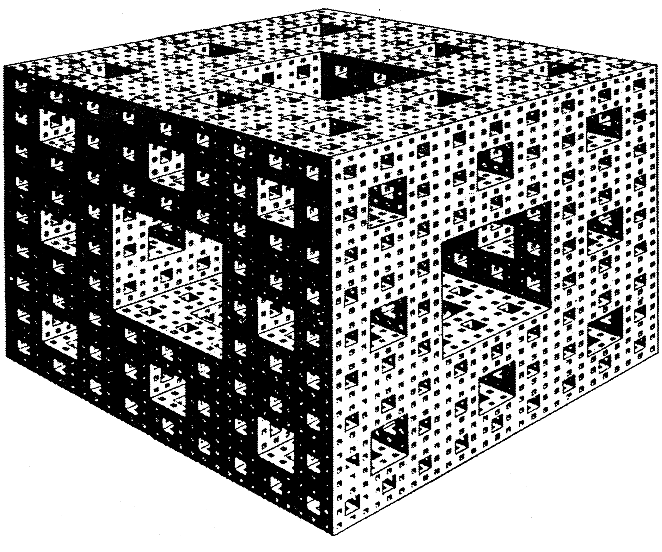


**Fig. 4**
The Menger sponge

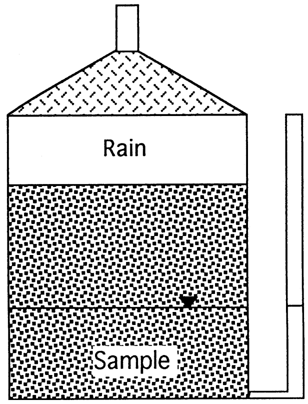



**Fig. 5**
Apparatus used in the watering tests

to be established by measuring the volume of water absorbed at the end of the tests when the weight remained constant.

Watering tests were undertaken to verify the diffusion of the water in a soil mass when water percolated from the surface. The specimens were reconstituted to in situ density in a glass cylinder equipped with a standpipe piezometer. Rainfall of varying intensity was simulated and when the water rose to the top of the 170-mm-high specimens (Fig. 5) the piezometric levels were measured.

## Results

### Mass-Volume

Figure 6 shows the two extremes of the grain size distributions obtained on the five 79 AD pumice samples. As would be anticipated for material collected within a small area, all the results were very similar and can be classified as sand/gravel with a Cu (coefficient of uniformity) of between 68 and 92 and a $D_{10}$ (effective size) between 0.6 and 0.11. The histogram in Fig. 7 illustrates the unimodal dis-

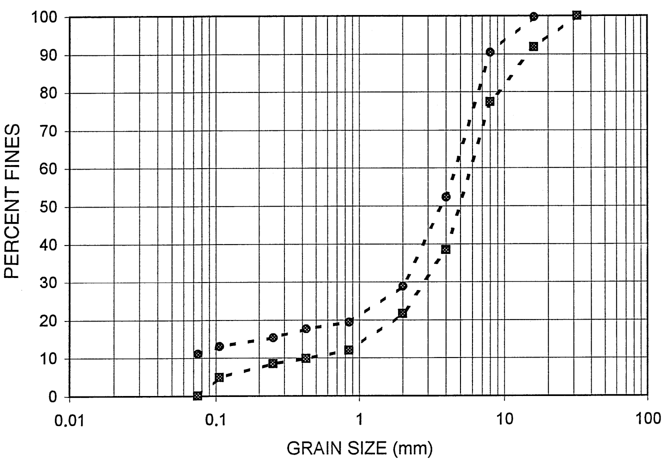



**Fig. 6**
Grain size distribution curves for the sampled deposits

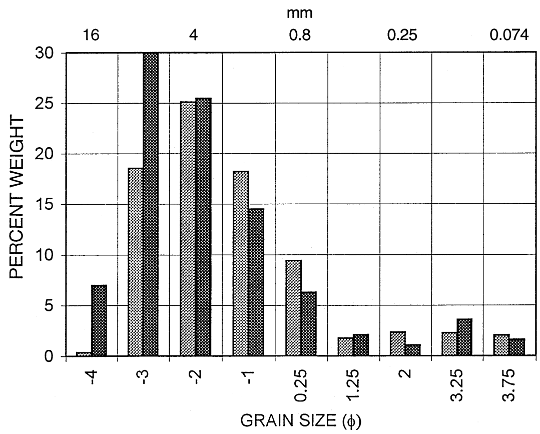



**Fig. 7**
Isograms of the grain size distributions for the sampled deposits

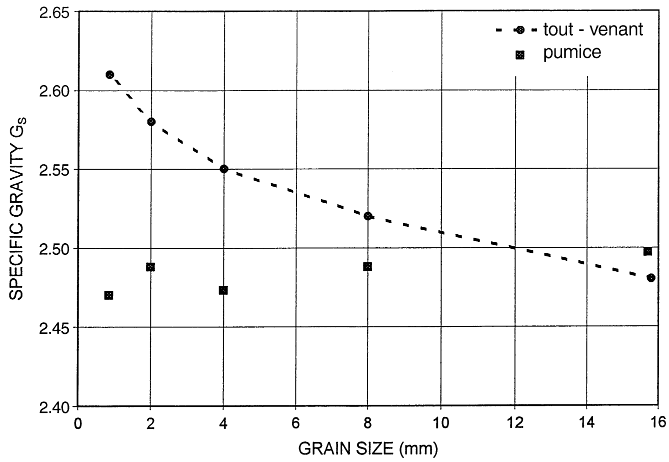



**Fig. 8**
Specific gravities of the sampled pumice deposit

tribution of the samples which can be seen to be typical of air fall deposits (Fisher and Schmincke 1984).

Table 1 summarises the results of some geotechnical measurements. A minimum of 20 elements were analysed for each individual grain size fraction identified in the five pumice samples and the mean values obtained. For the specific gravity (Gs) and dry unit weight ($\gamma_p$) of the particles, the standard deviation was always less than 0.0054 and 0.58 respectively.

Figure 8 shows the variation in specific gravity for the tout-venant and pumice clasts with different grain sizes. The range in values from 2.47 to 2.62 has been attributed to the increased presence of lithic material in the smaller grain size fraction. This is supported by the value obtained for the 16 mm fraction, i.e. a sample wholly composed of pumice clasts, which is close to that determined for the isolated pumice clasts. The specific gravity of the 16-mm-size clast is 2.48. Pellegrino (1967) determined a similar value for the solid substance forming the pumiceous elements of the Phlegraean Fields, but it is somewhat higher than the value of 2.3 reported by Whitam and Sparks (1986).

The dry unit weights ($\gamma_p$) of the tout-venant and pumice clasts are plotted against granulometric fraction in Fig. 9. An inverse relationship can be seen with the ($\gamma_p$) values of both the tout-venant materials and the isolated pumice

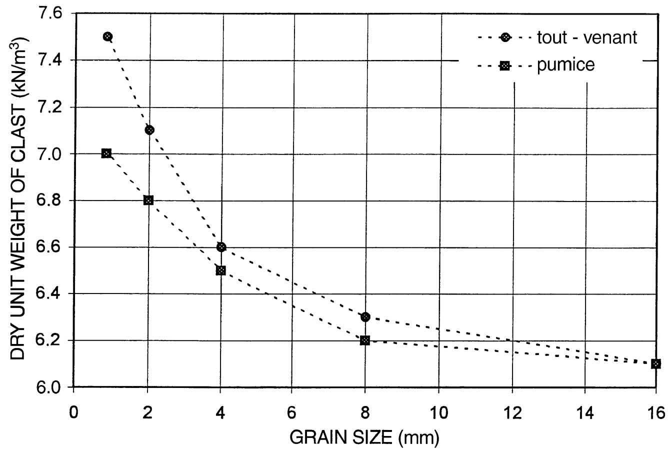



**Fig. 9**
Unit dry weights of particles of the sampled pumice deposits

material decreasing with increased grain size. The derived values of the void ratios (e) and porosities (n) of the clasts are high, generally in the range of 2.3–3.1 and 69–71% respectively. Porosimetric measurements were undertaken on clasts with grain size fractions of 4 and 8 mm. The results gave values of between 42 and 49%.

**Table 1**
Mean values of the mass-volume properties of the analysed samples

| Diam (mm) | $G_s$ | $\gamma_p$ (kN/m³) | $\gamma_{psp}$ (kN/m³) | n (weight-volume relationship) (%) | e | n (porosimetry) (%) | n (absorbed water) (%) |
|---|---|---|---|---|---|---|---|
| 16 | 2.48 | 6.1 | 6.1 | 75 | 2.98 | | 67 |
| 8 | 2.52 | 6.3 | 6.2 | 74 | 2.94 | 42 | 68 |
| 4 | 2.55 | 6.6 | 6.5 | 73 | 2.81 | 49 | 70 |
| 2 | 2.58 | 7.1 | 6.8 | 71 | 2.58 | | 70 |
| 0.85 | 2.62 | 7.5 | 7.0 | 70 | 2.45 | | 69 |

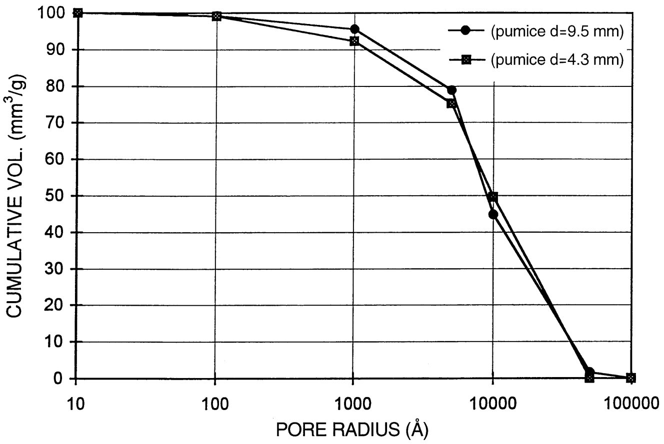



**Fig. 10**
Pore distribution as determined by porosimetric measurements

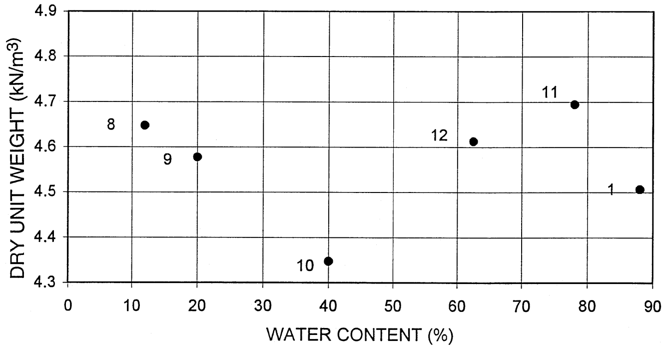



**Fig. 11**
Variation in unit dry weight and water content of the pumiceous deposits during the annual meteorological cycle. *Numbers* correspond to months of the year

Comparison between the porosity values obtained by the weight/volume method and those obtained by porosimetric tests (Table 1) indicates the intrusion of mercury under-estimates the presence of voids in the pumiceous clasts. This may be due to the difficulty of mercury entering into pores with smaller diameters. It is of note that the test results reported in Fig. 10 indicate 90% of the pores have a radius >2000 Å while the average radius values are circa 11 000 Å. However, the qualitative analyses carried out on the SEM images (Fig. 2) show a larger percentage of smaller pores.
It is also interesting to note that the porosity values determined at the end of the sinking tests – and therefore through the volume of absorbed water at constant weight – are lower than those calculated by means of the weight-volume relationship. The effect appeared to be more pronounced in the larger pumices, suggesting it could be associated with the air entrapped in the higher number of internal voids.
Table 2 compares the specific surface estimated from porosimetric measurements with that obtained from fractal analysis on 4 mm and 8 mm diameter grain sizes. In each case, the fractal analysis results are some 30–40% higher. Ignoring possible genetic causes, in particular the nucleation theory of bubbles (Sparks 1978), the specific surface of the pumice will depend on clast diameter; the voids being smaller in the smaller particles (Cas and Wright 1987). Bearing in mind the porosimetric measurements under-estimated the presence of voids of small dimensions, the testing suggests fractal mathematics would give a more realistic approximation of the exposed surface.
Although the measured values are similar to those characteristically obtained for clay minerals such as kaolinite (Mitchell 1976), it must be remembered that, unlike the clayey materials which are superficially active, volcanic glass is completely inert. For this reason the phenomenon of cation exchange is not relevant in the study of these pumices.
Figure 11 shows the dry unit weight plotted against water contents measured at various periods during the year. Although the dry unit weights of the soil mass ($\gamma_d$) are relatively consistent (4.34–4.7 kN/m$^3$) the water contents vary noticeably during the annual cycle as the superficial deposits dry during hot periods.

**Table 2**
Specific surface from fractal and porosimetric analyses

| Diameter (mm) | Specific surface from fractal analysis (m$^2$/g) | Specific surface from porosimetry (m$^2$/g) |
|---|---|---|
| 8 | 10.8 | 7.43 |
| 4 | 11.5 | 8.71 |

### Behaviour in contact with water

Due to their low density, pumices may float when deposited on water. The sinking of the pumice clasts is due to the intrusion of water into the pores. Figure 12 shows the progressive variation in the unit weight of clasts (g) of different diameters when they are placed in water during the

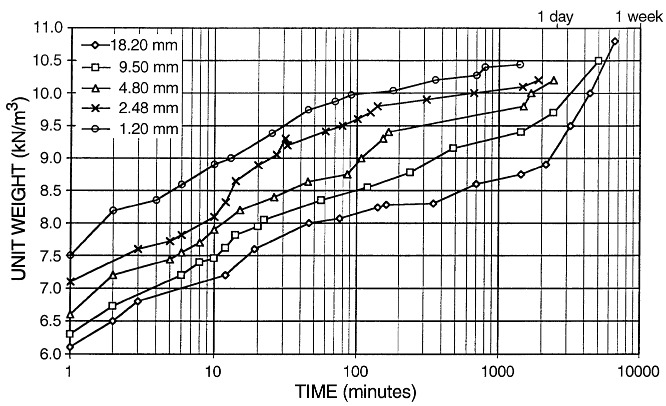



**Fig. 12**
Variation in unit weight of clasts during the sinking tests

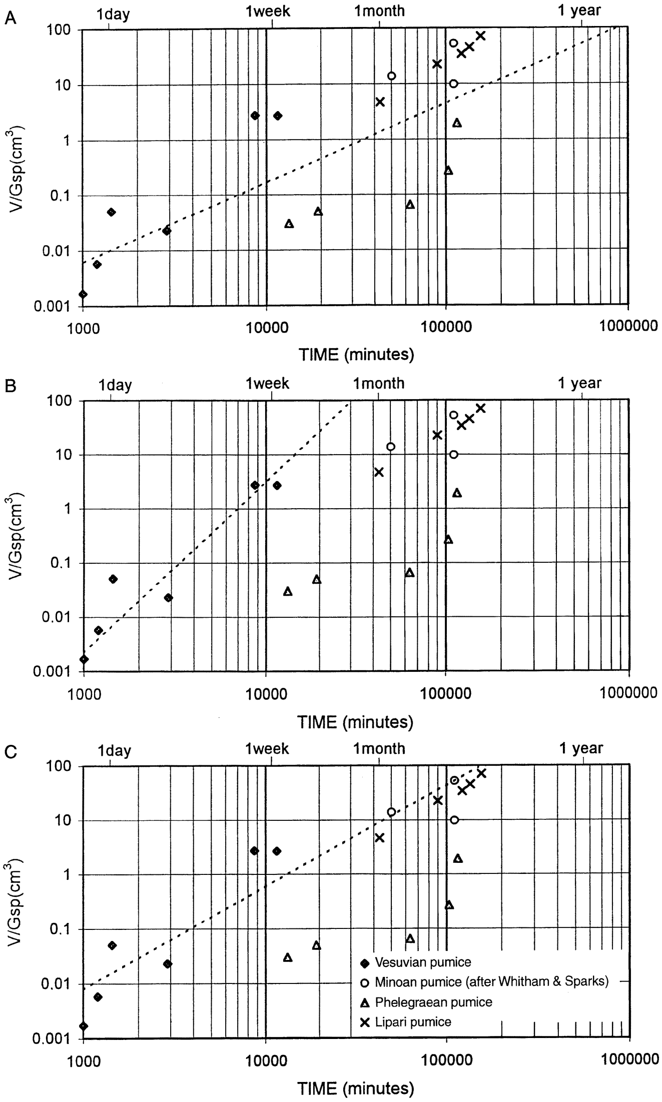



**Fig. 13**
Influence of volume and specific gravity of the clasts on sinking time showing interpolated lines: **A** for all data; **B** Vesuvian pumice only, **C** for all data except the Phegraean pumices

sinking test. This is a time-dependent process governed by the logarithmic law

$\gamma = a \ln t + b$

although as observed by Whitam and Sparks (1986) the initial phases are accompanied by bubbling.

The similarity of the angular coefficient values (0.39–0.44) suggests that the variation in unit weight of the clasts – and therefore the sinking time – is mainly related to the volume and specific gravity of the particles ($G_{sp} = \gamma_p/\gamma_w$). This is generally supported by the relationship between the ratios of volume to specific gravity of the particles ($V/G_{sp}$) and the sinking time (Fig. 13); the exception being the Phlegraean pumices.

Figure 14 shows the percentage of sunken pumice for each grain size fraction as a function of time. It can be seen that

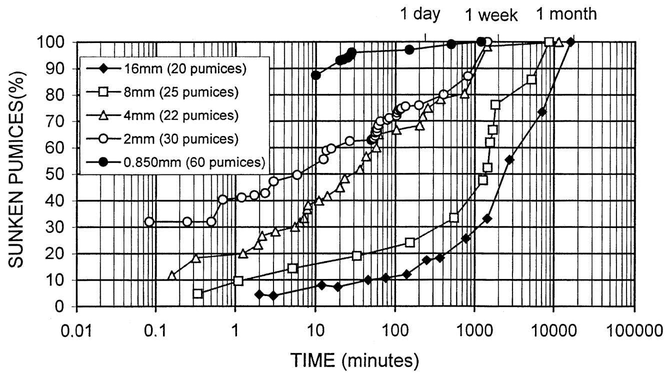



**Fig. 14**
Sinking of pumice versus time for different grain size fractions

all the samples had sunk within a period of approximately eleven days (ca. 16000 min). However, as sinking takes place when the density of the particles exceeds that of water, it takes longer to achieve apparent saturation (constant weight) of the particles. The 16-mm-grain-size samples sank in 4200 min (some 3 days), for example, but the apparent saturation was not reached for some 7000 min (approximately 5 days).

Bearing in mind the pore dimensions, it is clear that the water penetration process is regulated by capillary forces. As the voids within the pumice have a mean diameter of 1 μ, the corresponding capillary depressions are in the range of 300–400 kPa (Klausner 1991).

As can be seen from Fig. 13, the data on the sinking process for the Vesuvian pumices are generally consistent with those reported by Whitam and Sparks (1986) who analysed cut (cubic) samples from pumice fall deposits compared to the intact clasts used in the testing reported here. Other fall pumices from different volcanic areas have shown similar behaviour to the 79 AD Vesuvius pumice clasts but longer sinking times were recorded for pumices taken from pyroclastic flow deposits of the Phelgraean Fields. Figure 15 shows the results of sinking tests on pumices from Astroni, a vent in the Phlegraean Fields active some 11000 years B.P. It can be seen that the majority of the clasts between 4

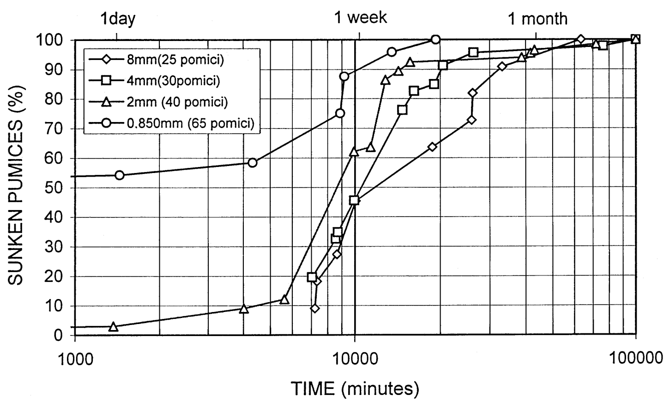



**Fig. 15**
Sinking tests on pumice from the Astroni flow deposits

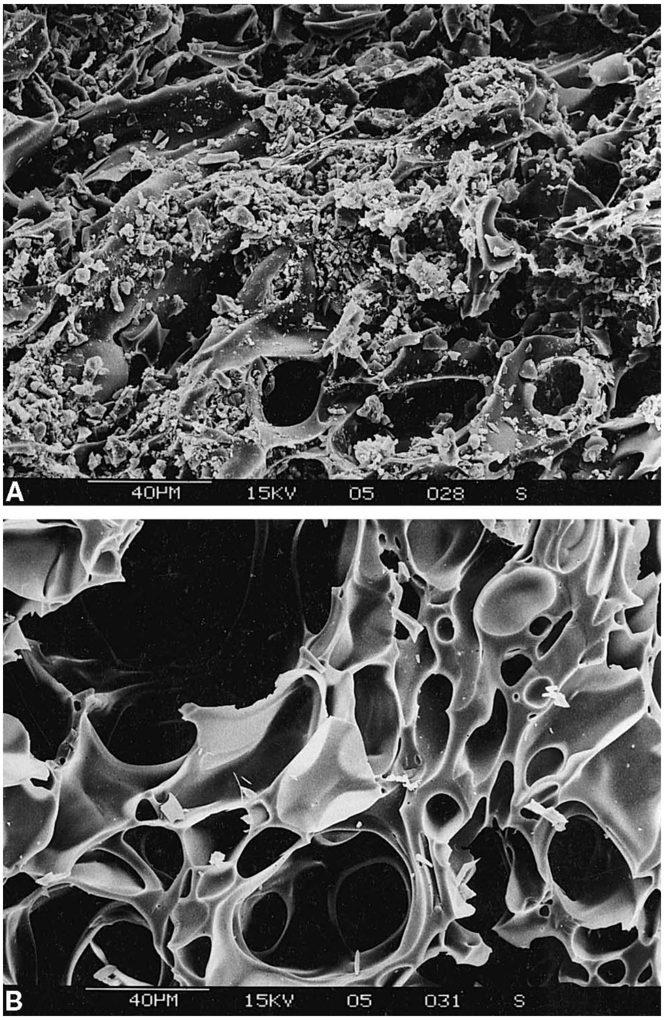



**Fig. 16**
SEM photograph showing (**A**) surface of a flow pumice and (**B**) its internal voids

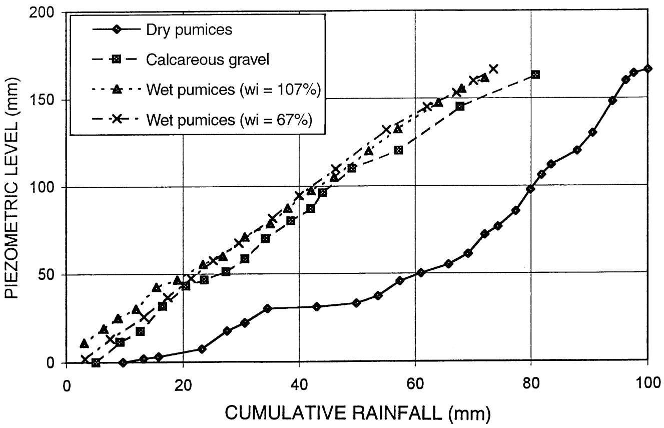



**Fig. 17**
Watering tests on pumiceous and calcareous samples

and 8 mm in size required about 10 000 min (1 week) to sink, while the apparent saturation of the clasts with larger grain size fractions took more than 2 months.
As these clasts have similar physical-volumetric properties to those from the 79 AD Vesuvius eruption, they were also analysed by SEM. Figure 16a shows the surface of an 8-mm clast. The presence of chips and fragments of a vitreous nature can be discerned, welded to irregularities in the surface created as a result of the autometamorphic processes. As can be seen, they partially occlude the apertures of the pores. In contrast, Fig. 16b shows an internal structure very similar to that of the Vesuvius pumices and those reported by Sparks (1978). This would suggest that the type of depositional mechanism can influence the behaviour of the pumice clasts.
The sinking tests carried out on pumices taken from the tuffaceous rocks in the Phlegraean Fields were of particular interest. These pumices have undergone significant alteration during hardening processes. The contact with water frequently caused implosion of the structure, which did not resist the negative pressure induced by the capillary forces developed during the intrusion of the water.
Whilst the sinking tests can assist an understanding of the processes of intrusion of water into the pumice, watering tests are required in order to obtain an appreciation of the behaviour of the pumice deposits when subjected to rain fall. Figure 17 shows the piezometric levels related to simulated rainfall. The average intensity was 10 mm/h and the piezometric measurements were taken 24 h after the watering. It can be seen that for dry specimens, the accumulation of water at the base of the cylinder (Fig. 5) began when rainfall exceeded 10 mm/h. In the initial phase of the test, the water spread and penetrated the pores of the pumices, sucked in through capillary action such that it never reached the bottom of the cylinder. The correlation between rainfall and piezometric level indicated that the accumulation of the water followed two different phases, characterised by the gradient of the increase in water level. During the first phase of the process (rainfall $<65$ mm) suction phenomena appeared to be predominant; in the second phase (rainfall $>65$ mm) the process of water accumulation became the more significant as the effects of capillary action decreased.
Figure 17 also shows the results obtained on a sample of calcareous gravel, reconstituted with a void index similar to that of the pumice ($e=0.51$). It can be seen that following the initial phase of water retention, there is a linear relationship between rainfall and water level. Similar behaviour was observed when pumice material was reconstituted to its initial water content of 66% (retention water content of the pumice pores). In this case also there was a linear correlation between rainfall and piezometric level, although the results indicate the influence of the initial water content.
From the sinking tests, water accumulation in the pumiceous layers has been shown to be a time-dependent process. Figure 18 shows the typical decrease in piezometric level with increase in time, from a level of 27 mm immediately after watering of a dry specimen and therefore in a phase in which suction processes are dominant.

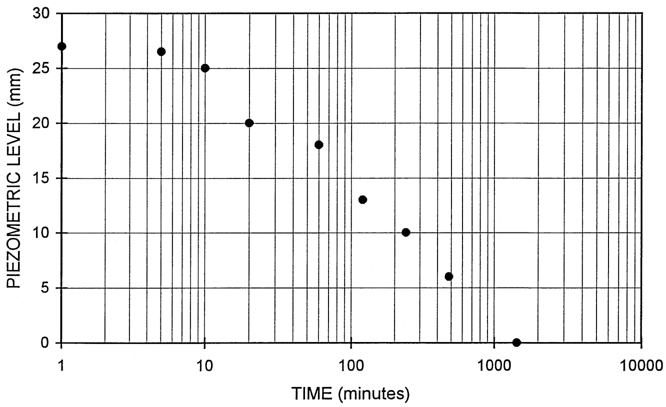



**Fig. 18**
Typical variation in piezometric level as a function of time for a dry pumiceous specimen

## Discussion

The laboratory tests confirmed pumice deposits to be a unique geotechnical material, due to the presence of both inter- and intra-particle voids. For this reason, the usual in situ material phases must be modified to introduce the intra-particle voids (Fig. 19).

As a consequence of these characteristics, there is a distinction between the specific gravity of the solid substance and that of the particles and it is possible to calculate both a total porosity and an interparticle porosity. The research has indicated the variation can be significant and should be taken into account when considering geotechnical data. As can be seen from Table 3, which summarises the mass-volume properties of the Vesuvius pumice deposits, there are notable differences between the porosity of the mass and the inter-particle porosity.

It has been shown that the unit weights of the particles ($\gamma_p$) reflect the water content. The intrusion of water into the particles may modify the unit weight by up to 7 kN/m$^3$, depending on the degree of saturation, without affecting the volume of the particles. However, the waters within the pores of the pumice clasts are an integral part of them,

**Table 3**
Typical values of the mass-volume properties of an AD 79 pumice layer

| $G_s$ | $\gamma_p$ (kN/m$^3$) | $\gamma_d$ (kN/m$^3$) | $e_t$ | $e_i$ | $n_t$ | $n_i$ | $W_{sat}$ (%) |
|---|---|---|---|---|---|---|---|
| 2.51 | 6.3 | 4.4 | 4.7 | 0.43 | 82 | 30 | 187 |

being in a capillary state. A variation in the physical-volumetric state of the mass will therefore affect its behaviour.

Figure 20 shows the results of resunant column tests carried out on samples of reconstituted pumice (Guadagno, Nunziata and Rapolla 1992). It can be seen that the wet specimens had higher shear moduli than the dry material, probably due to the different physical characteristics of the pumices and hence their vibrational motion and shear wave moduli (Richart, Hall and Woods 1970).

These significant differences in the behaviour of the pumice deposits according to the saturation condition of the particles are also seen when methods of ground treatment are undertaken. There is a considerable variation in the effect of the injection of water, Portland cement and bentonite depending on the initial water content of the material. Dry pumices and samples with a water content of 80% were subjected to a cementation process, at the end which the compression tests indicated $\sigma_c = 25$ kPa for the initially dry material and $\sigma_c = 600$ kPa for the partially saturated pumice. These findings were supported by SEM (Fig. 21) which highlighted the metamorphosis of volcanic glass in the zeolite minerals of the partially saturated pumice; undoubtedly caused by the heat generated during the hardening process. As a consequence, it is likely that attempts to stabilise dry materials may have little effect as the water content of the cementitious grout injected is likely to be sucked into the pores by capillary action, such that the segregated solid particles do not offer any additional stabilisation/strengthening of the pumice.

The sinking and watering tests also showed that the initial moisture content of the material affected the behaviour of

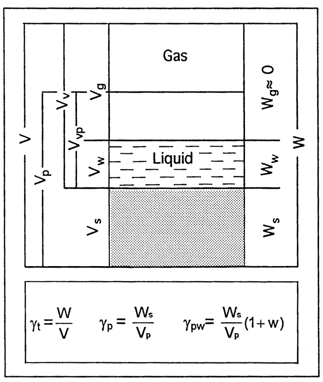



**Fig. 19**
Phase relationships for a pumice deposit

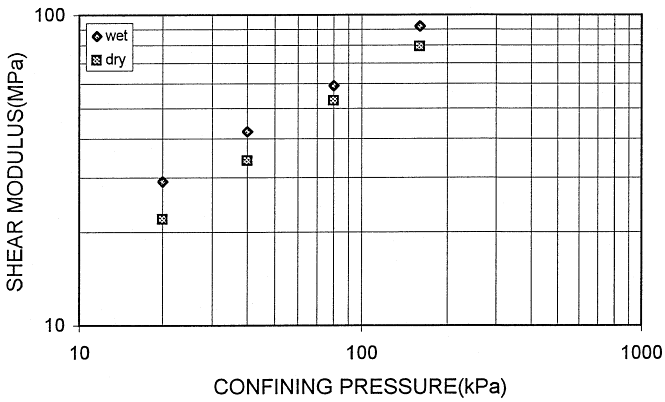



**Fig. 20**
Variation in shear modulus for wet and dry pumice samples

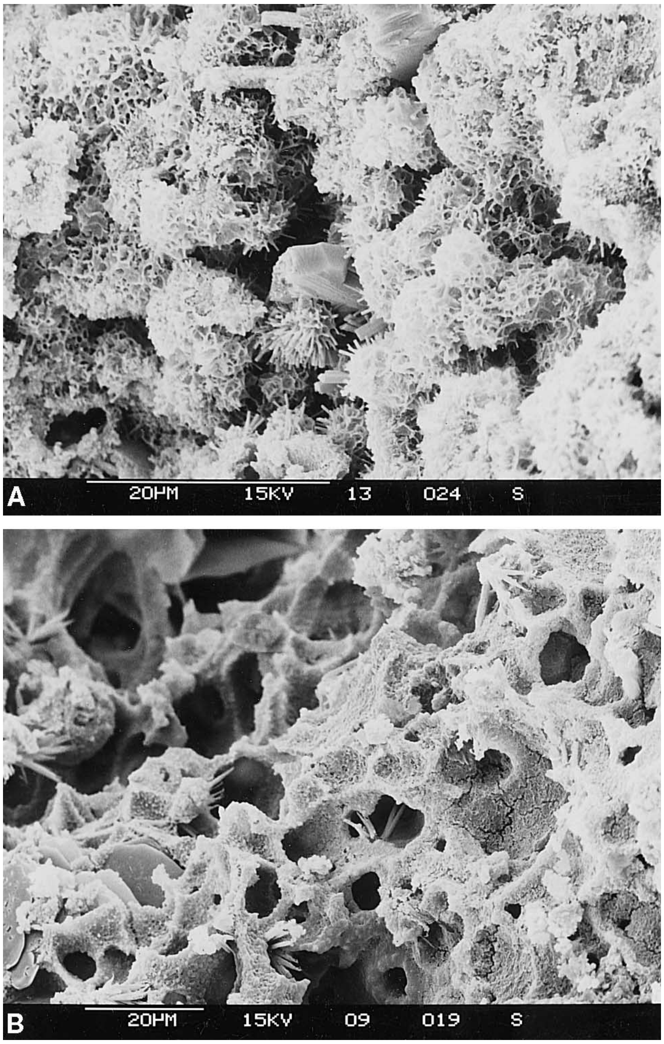


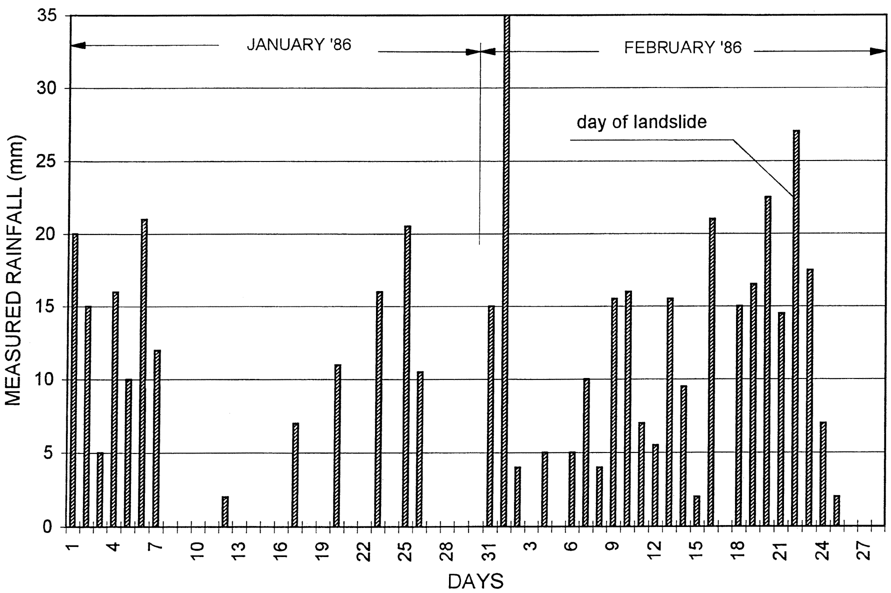

**Fig. 21**
SEM photograph showing (**A**) cemented wet and (**B**) dry pumiceous materials

pumiceous layers when they came into contact with water. The tests reported simulate two typical scenarios which occur in areas where the subsoil is pumiceous. In the area of Naples, for example, settlement may result in a sudden breakage of water pipes. The erosion and liquefaction which occurs as a consequence of the resultant high pressure water flows are exacerbated by the floating effects of the pumiceous particles.
Water tests were also undertaken to simulate the conditions which may occur along slopes mantled by pumiceous layers, such as were deposited by the Vesuvius eruption. Here the instability may be considered as a secondary and delayed effect of the volcanic eruption and is generally connected to a long period of wet weather. Figure 22 shows the daily rainfall data of a typical debris slide/flow in Palma Campania (Guadagno 1991). It is considered that the trigger mechanism for these shallow instabilities is also related to the degree of saturation of the material. While suction phenomena are predominant, water does not accumulate at the bottom of the layers. In a slope, saturation or partial saturation of the pumice particles will only be reached after a more prolonged period of rainfall than is required to destabilise soil consisting of solid clasts. This is particularly important in the typical Mediterranean climate with dry and rainy seasons which encourage the desiccation of the pumiceous soils. In the Campanian area, however, the pumice layers mantle fault slopes with angles similar to the friction angle of the material. As a consequence the pumiceous layers are near to limit equilibrium. However, it is only when specific metereological conditions pertain that sufficient pore pressures can build up in these materials to result in failure.

## Conclusions

Pumice soils can be considered unique in the panorama of geotechnical materials. Their behaviour is influenced by

**Fig. 22**
Rainfall in the period preceding the Palma Campania debris flow, 22 February 1986



the presence of both particle pores and interstices between clasts. It has been shown that this can cause differences in the physical and volumetrical parameters as well as in the behaviour of the soils. The penetration of water into the particle pores significantly modifies the weight-volume relationship and results in an increase in the weight of the particles. In addition to the influence on the dynamic behaviour of the material, this will have an important effect on the development of pore pressures and in the effectiveness of treatments to improve the mechanical characteristics of the soil mass.

It is considered that the presence of inter- and intra-particles voids within the pumice is the main cause of the unusual and apparently anomalous behaviour of these distinctive geotechnical materials.

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