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A micro- and macro-scale investigation of the geotechnical properties of a pyroclastic flow deposit of the Colli Albani

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ABSTRACT: This paper presents the results of a recent investigation of the geotechnical properties of a pyroclastic flow deposit of the Colli Albani volcanic complex, locally known as *Pozzolanelle*. The investigation focused on the micro-structural features of the material, as observed in thin sections and SEM micrographs, on its physical and mechanical properties at the scale of the laboratory sample, and on its macro-structural features at the scale of the *in situ* deposit. The geotechnical properties of the material are related to its geological origin and to its formation mechanisms and environment, which give to the material its peculiar micro-structural features. In the paper, the results of triaxial compression tests on intact samples are presented and discussed. Finally, based on an original descriptive model for volcanic soils, recently proposed by the authors, the paper provides the compiled technical sheet for the classification of the deposit.

1 INTRODUCTION

This paper examines a pyroclastic flow deposit belonging to the IV cycle of the Tuscolano-Artemisia eruptive phase (De Rita et al., 1995; 2000) of the Colli Albani volcanic complex (Rome, Italy), locally known as *Pozzolanelle*. Similarly to other pyroclastic flow deposits of the same volcanic district, the material has not been extensively investigated in the laboratory, mostly because of the difficulty of intact sampling.

Only relatively recently, the strength of intact samples of *Pozzolanelle* was investigated by direct shear tests carried out in a range of vertical effective stress from 10 to 400 kPa, on both dry and fully saturated specimens (Cecconi et al., 2010). The shear strength of the dry material was found to be always larger than that of the saturated material. Also, at all levels of vertical effective stress, the dry material had a brittle and pronounced dilatant behaviour, while the saturated material showed a more ductile behaviour and a reduced tendency to dilate. Truly contractant behaviour was only observed at vertical effective stress larger than about 200 kPa.

This work presents further results of a recent investigation of the geotechnical properties of this deposit at different scales. Here the attention is focused on: *i*) the main micro-structural features of the material, as detected from the analysis of a relatively large number of thin sections, *ii*) the mechanical behaviour observed in triaxial tests carried out in a range of mean effective stress from 50 to 600 kPa, and *iii*) the structural features of the deposit *in situ*. With regard to this last point, the description of the deposit is carried out using the technical sheet proposed by the Authors in 2010 (Cecconi et al., 2010).

Figure 1 shows the typical succession of pyroclastic flow deposits of the Colli Albani volcanic complex as exposed on the sub-vertical cut in a quarry at Fioranello, South East of the city of Roma; the deposit of *Pozzolanelle* is the upper unit, delimited at the bottom by the dotted white line. According to Giordano et al. (2006), the *Pozzolanelle* are at the lower limit of the Tuscolano-Artemisio lithosome (De Rita et al. 1988). Diano (2005) defined four different *facies* of the eruption unit; the fourth unit, at the top of the Tuscolano-Artemisio lithosome, is mainly dark grey to dark red/brown, ashy, and reaches a maximum thickness of about 4 m. The composition is tephritic-phonolitic (Freda et al., 1997; Gaeta et al., 2006). At the macro-scale, *Pozzolanelle* is massive and chaotic; the deposit is un-cemented, although its lower portion can occasionally be lithified and show transitional features with the underlying unit of the *Tufo Lionato.*

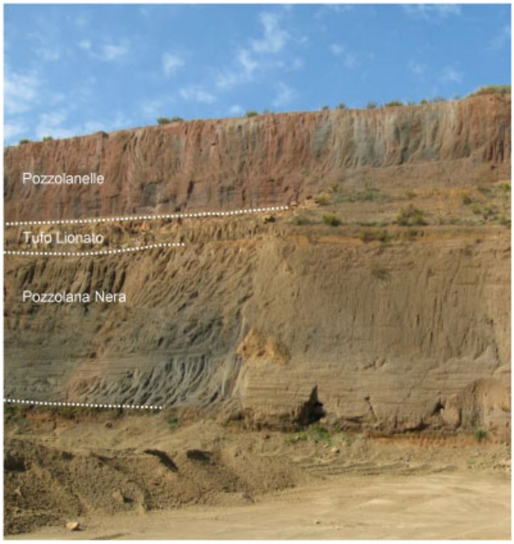


Figure 1. Sub-vertical cut in a quarry at Fioranello showing the sequence of pyroclastic flow deposits from the Colli Albani.

2 MICRO-STRUCTURE

2.1 *Thin sections*

To characterise the microstructure of the material and relate it to the observed mechanical behaviour, some thin sections were taken from different areas of the samples that had undergone triaxial compression (see following section) both near the shear surface and in the relatively un-deformed rigid blocks into which the sample separated at the end of the test. The following refers to thin sections retrieved in relatively undisturbed material.

Figure 2 shows a typical thin section using parallel nicols of undisturbed *Pozzolanelle*, at two values of the magnification factor. In thin section, the material consists of a compact matrix containing darker clasts, scoria with various degrees of vesiculation and frequent crystals, recognizable from their straight edges. The main minerals are leucite, biotite and clinopyroxene. Cross- and star-wise microlites of leucite are visible in Figure 2(a) and Figure (2b) at higher magnification factor. Pores appear as white areas with no defined edges. Inter-granular pore features, such as size, shape, and orientation are very variable. Inter-granular pores appear to be partially filled by altered material and secondary minerals.

The closed porosity, within the clasts, is very small, as confirmed by measurements of the apparent unit weight of the soil particles carried out using a helium picnometer on increasingly finer, powdered material. This is almost constant with grain size with a value $\gamma_s = 27.29\,\text{kN/m}^3$ and a scatter $<2\%$; the calculated vesiculation index is nil.

Figures 3(a) and (b) show other two example of clast configuration. Sub-angular clasts, of variable size, are randomly oriented; only occasional contact points between clasts can be identified.

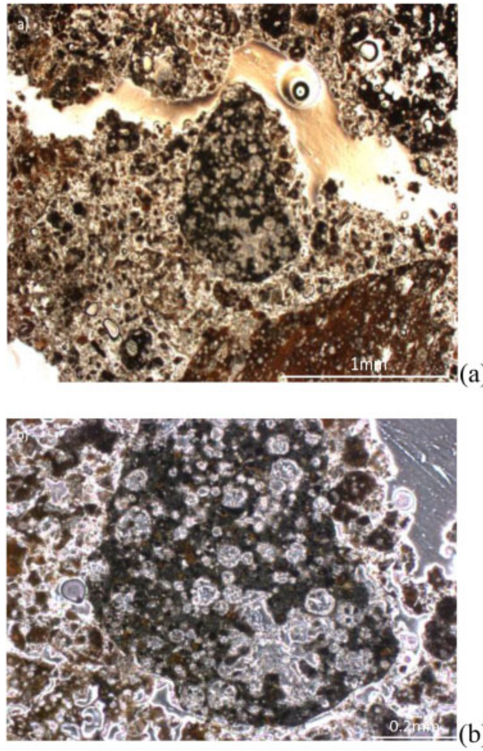


Figure 2. Thin section of *Pozzolanelle* at MF of: a) 2×; b) 10×.

Finally, in Figure 4, at large magnification (10×), some pyroxene crystals (coloured in green) about 0.2 mm in size are detected, dispersed in the matrix.

2.2 *SEM analyses*

SEM analyses were performed on dried samples of *Pozzolanelle*, without sputter coating, as the observation times where brief enough to ensure no electron charging of the sample under high vacuum and high voltage.

Figures 5(a) and (b) show two SEM micro-graphs at different magnification factors. Again, the size of recognisable clasts is very variable, varying from a few millimetres to some centimetres. At larger magnifications, it is possible to recognise secondary minerals growing in the pores. This may indicate that the bonding is partly diagenetic, *i.e.*, due to lithification by formation of hydrated aluminosilicates (zeolites).

3 MECHANICAL BEHAVIOUR AT THE SCALE OF THE LABORATORY SAMPLE

3.1 *Physical properties*

At the scale of the laboratory sample, the material is quite heterogeneous. Table 1 reports the average values of its physical properties.

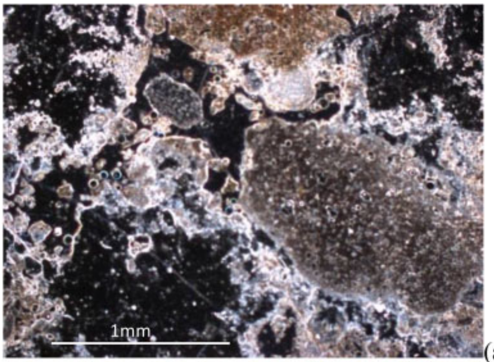


Figure 3. Thin section of Pozzolanelle at MF of: a) 2×; b) 10×.

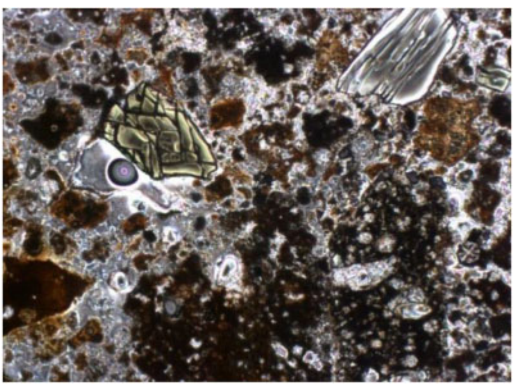


Figure 4. Thin section of Pozzolanelle at MF of 10×.

The grain size distribution depends strongly on the techniques adopted to separate, before sieving, clasts forming larger aggregates and on the methods and time employed for sieving (see O'Rourke and Crespo 1988; Lee 1991).

In this case, two different techniques were adopted: breaking the material by hand while immersed in water with a detergent additive to favour separation of small aggregates, or breaking the material through cycles of freezing and thawing and then by hand. In both cases, the material was then oven-dried at 105°C before the grain size distribution was determined by dry sieve analysis. While the grain size distribution of other pyroclastic flow materials of the same volcanic district, such as *e.g.*, *Pozzolana Nera* and *Conglomerato Giallo* is not affected by the sieving time or number of sieving cycles (Cecconi et al., 2010), in this case the grain size distribution seems to depend on the number of sieving cycles, with a tendency for the fine fraction to increase with increasing number of cycles, indicating imperfect separation of small aggregates (see Figure 6).

The grain size distribution obtained with the first procedure stabilizes after about 5 sieving cycles; a more pronounced shift of the grain size distribution is observed for cycles of freezing and thawing, showing how the second procedure is much more effective in breaking the original structure of the material. Again,

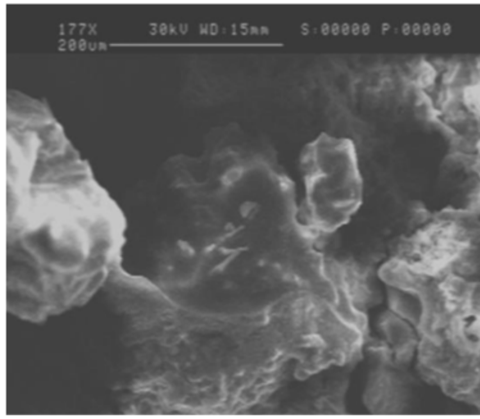


Figure 5. SEM micrographs of *Pozzolanelle* at MF of: (a) 177× and (b) 456× (adapted from Cecconi et al., 2010).

Table 1. Main physical properties of *Pozzolanelle*.

w/c (%)	G_s (–)	γ (kN/m^3)	γ_d (kN/m^3)	n (–)	S_r (%)
16.3 ± 1.9	2.74	11.92 ± 0.06	9.93 ± 0.03	0.64 ± 0.01	25 ± 5.2

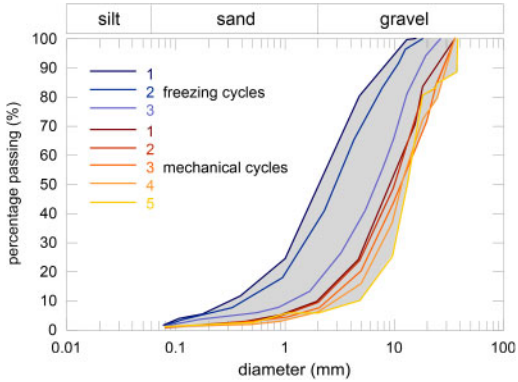


Figure 6. Effects of experimental procedures on grain size distribution (adapted from Cecconi et al., 2010).

after 3 cycles of freezing and thawing the grain size distribution of *Pozzolanelle* tends to stabilize.

3.2 *Triaxial tests results*

The experimental work on *Pozzolanelle* consisted of one-dimensional compression tests and direct shear tests on reconstituted and intact samples, and triaxial compression tests on intact samples. These were carried out recently and are discussed in this section.

Triaxial tests were performed in conventional triaxial cells; axial and volume strains were measured using external displacement transducers and a volume gauge. Intact samples of *Pozzolanelle* for triaxial testing were obtained by hand carving small blocks of material of about $100\,\text{mm}^3$. The samples were immersed into de-aired distilled water for a few days, after which the samples were weighed and the procedure repeated twice. The samples were then located in a baker under vacuum and weighed again. They were modelled with gypsum to avoid irregularities on the external surfaces, which may have caused membrane penetration and piercing, and on the two ends to minimise bedding and sitting errors. Finally, the samples were saturated on the base pedestal of the triaxial cell under a back pressure of 350 kPa.

The samples were sheared to failure under drained conditions at constant effective radial stress ($50 < p'_0 < 600\,\text{kPa}$) and at a displacement rate of about 0.15 mm/h. Figures 7(a) and (b) show the stress-strain curves in terms of deviator stress, q, versus axial strain, ε_{ax} and the corresponding curves of volume strain ε_{vol} versus axial strain, respectively. As typical for geotechnical materials, the mechanical behaviour of intact *Pozzolanelle* gradually changes from brittle and dilatant to ductile and contractant with increasing confining pressure. At low confining pressures ($50 < p'_0 < 300\,\text{kPa}$) the observed stress strain behaviour was rather brittle with the deviator stress increasing roughly linearly up to a well-defined peak, attained at shear strains in the range of 1.5–2%. After a small initial volume reduction, the behaviour was dilatant throughout the test. Peaks were followed by a gentle decrease of the deviator stress towards an ultimate state where the rate of dilation was almost zero. At the end of the test, well defined shear surfaces separating the sample in two or more nearly rigid bodies were observed.

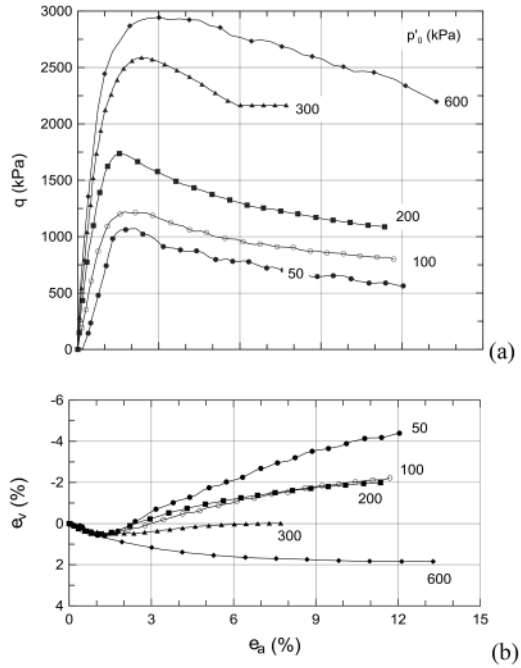


Figure 7. Drained triaxial compression tests on intact samples.

At larger confining pressures ($p'_0 = 600\,\text{kPa}$), the stress-strain curve was more ductile. However, although the behaviour was contractant throughout the test, the stress strain curve still showed a peak, at shear strains of the order of 3 to 4%.

The sample sheared at 200 kPa showed an intermediate behaviour, with a very small contraction at the beginning of the test, followed by dilation and a very small final value of the volume strain.

The shear strength of *Pozzolanelle* was examined in terms of stress invariants q, p'. Figure 8 shows the stress states at peak deviator stress from triaxial tests, compared to the peak stress envelope previously obtained from direct shear tests (Cecconi et al., 2010). The peak invariants from triaxial tests are slightly above the strength envelope from direct shear tests, probably due to the different modes of failure, but this is still being examined in more detail.

Figure 9 shows the stress–dilatancy relationships observed during triaxial compression in terms of dilatancy, $d = \delta\varepsilon^p_v/\delta\varepsilon^p_a$ versus stress ratio $\eta = q/p'$. At high confining stress, a peak of η occurs in a contractant regime ($\delta d > 0$), while at low confining stress, in a dilatant regime ($\delta d < 0$) the peak of η always precedes the point in the test where the dilatancy is minimum. The most striking feature of the experimental curves

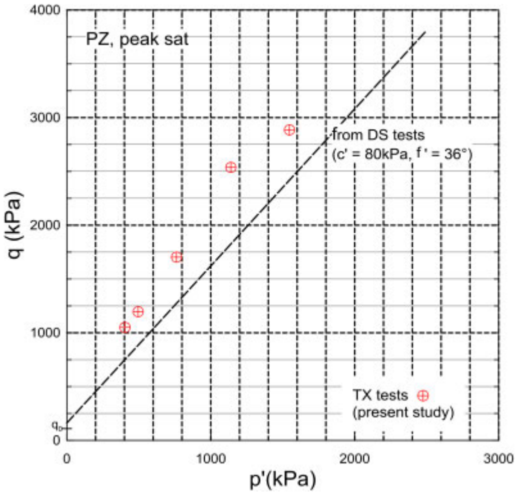


Figure 8. Peak deviator stress from triaxial tests and peak failure envelope from direct shear tests on saturated *Pozzolanelle*.

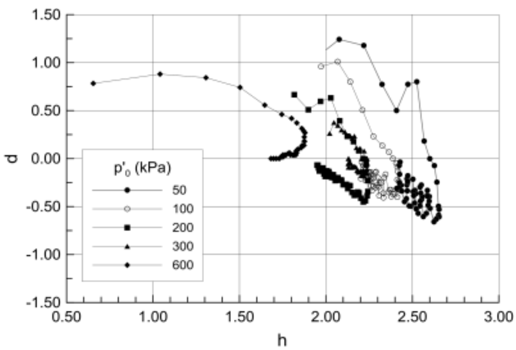


Figure 9. Stress-dilatancy relationship for intact *Pozzolanelle*.

is that they are inconsistent with a one-to-one relationship between dilatancy and stress ratio. In particular, the condition $d = 0$, which in classical critical state models defines the friction of the material, is attained under different values of stress ratio. This behaviour is very similar to that observed for the parent deposit of *Pozzolana Nera* (Cecconi & Viggiani, 2001) and was explained by Cecconi et al. (2002) as due to a progressive reduction of the friction angle of the material connected to progressive grain crushing. The analyses of thin sections of the material in the proximity of the shear surfaces should provide evidence of grain crushing, if any.

4 TECHNICAL CLASSIFICATION OF THE DEPOSIT OF POZZOLANELLE AT THE MACRO-SCALE

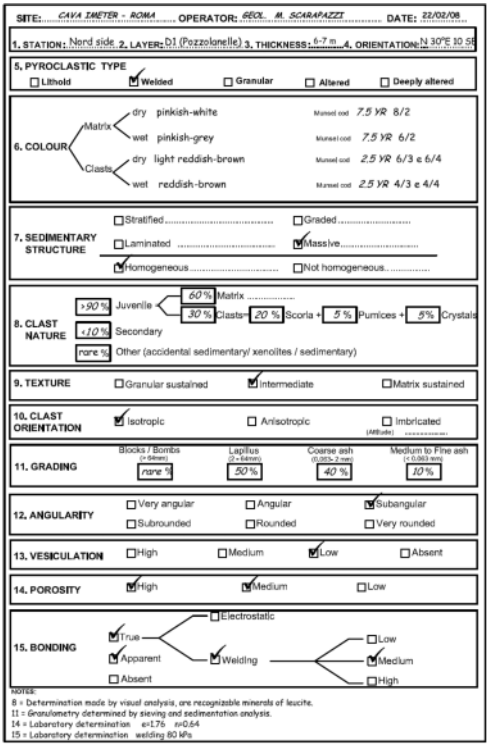
The geological complexity of pyroclastic rocks and soils makes it difficult to classify these deposits using conventional systems. The heterogeneity of the soil mass depends on several factors, such as viscosity, temperature, chemical interaction, eruption energy, distance from the magma chamber, *etc*. These factors may differ within the same depositional flow and they generally vary due to the interaction between the pyroclastic flow, the pre-existent morphology and the ground water. Further complexities may be induced by post-depositional processes such as welding, cementation, fissuring and chemical weathering. Therefore, for these materials, the geological and geotechnical classification systems commonly used for the majority of natural soils – probably less problematic than volcanic soils – may be inadequate or just incomplete. This is the reason which had motivated the Authors to develop an original descriptive model for volcanic soils (Cecconi et al., 2010). The technical classification is based on an operationally tested data sheet, shown in Figure 10, which can be compiled *in situ* for each eruptive unit observed on outcropping formations, or exposed in artificial cuts, or on cores obtained by sampling as well as on retrieved samples in the laboratory. The data sheet serves the double purpose of providing an index to follow for the standard description of pyroclastic soils and a working tool to define qualitatively and semi-quantitatively some physical and possibly mechanical properties of the material, taking into account also the results of in situ or laboratory tests, if any. In this case, the information on physical properties obtained from the laboratory complemented those obtained by visual inspection *in situ*.

The classification indicates that *Pozzolanelle* is a welded pyroclastic rock with light reddish brown clasts in a pinkish white matrix when dry and reddish brown clasts in a pinkish grey matrix when wet. Its structure is massive and quite homogeneous at the scale of the deposit, presenting limited local variations in grading. The pyroclasts are more than 90% juvenile, with 60% matrix and 30% clasts (20% scoria, 5% pumices and 5% crystals). The texture, describing the relation between the clasts and the fine matrix, is intermediate with few contacts between randomly oriented clasts.

The material falls in the lapilli-tuff field of Fischer's chart, consisting of lapilli (50%) coarse ashes (40%) and medium to fine ashes (10%), while blocks and bombs are totally absent. Clast shape is sub angular; vesiculation is low to absent. Porosity is medium to high (see Table 1). True bonding is medium and may be related to the formation of secondary minerals.

5 CONCLUDING REMARKS

This paper presented the results of a recent investigation of the geotechnical properties of a pyroclastic flow deposit of the Colli Albani volcanic complex, locally known as *Pozzolanelle*. The investigation focused on the micro-scale, *i.e*., the micro-structural features of the material, as observed in thin sections and SEM micrographs, on the meso-scale, *i.e*., the physical and



SITE: CAVA IMETER - ROMA OPERATOR: GEOL. M. SCARAPAZZI DATE: 22/02/08

1. STATION: Nord side 2. LAYER: D1 (Pozzolanelle) 3. THICKNESS: 6-7 m 4. ORIENTATION: N 30°E 10 SE

5. PYROCLASTIC TYPE
☐ Lithoid ☑ Welded ☐ Granular ☐ Altered ☐ Deeply altered

6. COLOUR
Matrix – dry pinkish-white Munsel cod 7.5 YR 8/2
Matrix – wet pinkish-grey Munsel cod 7.5 YR 6/2
Clasts – dry light reddish-brown Munsel cod 2.5 YR 6/3 e 6/4
Clasts – wet reddish-brown Munsel cod 2.5 YR 4/3 e 4/4

7. SEDIMENTARY STRUCTURE
☐ Stratified ☐ Graded
☐ Laminated ☑ Massive
☑ Homogeneous ☐ Not homogeneous

8. CLAST NATURE
>90 % Juvenile – 60 % Matrix; 30 % Clasts = 20 % Scoria + 5 % Pumices + 5% Crystals
<10 % Secondary
rare % Other (accidental sedimentary/ xenolites / sedimentary)

9. TEXTURE
☐ Granular sustained ☑ Intermediate ☐ Matrix sustained

10. CLAST ORIENTATION
☑ Isotropic ☐ Anisotropic ☐ Imbricated (Attitude)

11. GRADING
Blocks / Bombs (> 64mm): rare %
Lapillus (2 ÷ 64mm): 50 %
Coarse ash (0,063- 2 mm): 40 %
Medium to Fine ash (< 0,063 mm): 10 %

12. ANGULARITY
☐ Very angular ☐ Angular ☑ Subangular
☐ Subrounded ☐ Rounded ☐ Very rounded

13. VESICULATION
☐ High ☐ Medium ☑ Low ☐ Absent

14. POROSITY
☑ High ☑ Medium ☐ Low

15. BONDING
☑ True – ☐ Electrostatic / ☑ Welding – ☐ Low ☑ Medium ☐ High
☑ Apparent
☐ Absent

NOTES:
8 = Determination made by visual analysis, are recognizable minerals of leucite.
11 = Granulometry determined by sieving and sedimentation analysis.
14 = Laboratory determination e=1.76 n=0.64
15 = Laboratory determination welding 80 kPa

Figure 10. Compiled data sheet for the deposit of *Pozzolanelle* at Fioranello quarry.

mechanical properties at the scale of the of the laboratory sample, and on the macro-scale, *i.e.*, the structural features at the scale of the *in situ* deposit.

The analysis of thin sections and SEM micrographs permitted to identify the main minerals and a number of features of the grains and of the pores, such as size, shape, and orientation; it also provided evidence that inter-granular pores are partially filled by altered material and secondary minerals, indicating that the bonding is partly diagenetic.

The results of triaxial compression tests on intact samples indicated that the mechanical behaviour of intact *Pozzolanelle* gradually changes from brittle and dilatant to ductile and contractant with increasing confining pressure: as already observed for similar pyroclastic materials, there is no one-to-one relationship between dilatancy and stress ratio, and the condition of zero dilatancy (or critical state) is attained under different values of stress ratio. This behaviour may be explained by a progressive reduction of the friction angle of the material connected to progressive grain crushing; further analyses of thin sections of the material in the proximity of the shear surfaces should provide evidence of grain crushing to help clarify this point.

Finally, the paper provides the compiled technical sheet for the classification of the deposit, according to the descriptive model for volcanic soils proposed by the Authors.

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