Engineering Properties of Volcanic Soils

Propriétés mécaniques des sols volcaniques

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Summary

The authors state that the science of Soil Mechanics cannot always be applied as such to soils that differ from sediments, like those of volcanic origin.

Volcanic soils are made up of unaltered products ejected by volcanoes of mixed type like most of the Italian ones. These soils are accumulated near volcanic centres and they form thick deposits of various shapes. Due to their origin many of the grains have a glassy and spongy texture (pumice and ashes).

The grain size distributions of some volcanic soils, mainly composed of grains of the same type, are given by the authors.

The porosity of volcanic soils is very high because the particles are porous. Oedometric consolidation tests show that $\frac{1}{Cc}$ decreases with the increasing of the initial void ratio e_o, and that the secondary time effect is very pronounced. This behaviour appears to be related to the brittleness of the particles.

The compressive strength measured by triaxial apparatus does not vary when the conditions of the tests or the moisture contents are varied, provided that the void ratio is constant.

Sommaire

Les auteurs établissent que la Mécanique des Sols ne peut pas être appliquée dans tous les cas à des sols différents des sédiments, comme les produits pyroclastiques.

Les sols volcaniques sont constitués par les produits non altérés rejetés par les volcans mixtes comme il arrive pour la plupart des volcans italiens. Les sols en question, accumulés près de centres volcaniques, constituent des dépôts très épais de formes diverses.

A cause de leur origine, ces sols sont formés par des grains à texture vitreuse et spongieuse (comme, par ex., les cendres et les ponces).

Les auteurs donnent les granulométries des sols constitués pour la plupart par des grains d'un seul type. La porosité des sols volcaniques est très élevée parce que les grains sont eux-mêmes poreux. Les essais œdométriques démontrent que $\frac{1}{Cc}$ diminue en même temps que l'indice des vides initial et que l'effet secondaire est très important. Ce comportement dépend probablement de la fragilité des grains. La résistance à la compression dans les essais triaxiaux n'est modifié ni par le changement des conditions d'essai ni par la variation de la teneur en eau, pourvu que la porosité reste constante.

Introduction

The theories and applications of Soil Mechanics mainly deal with the characteristics and the behaviour of sedimentary soils. Sediments, however, represent only one of the types of soil found in nature, as can be seen in Table 1.

Soils of *volcanic* and *metamorphic* origins are widespread in many regions throughout Italy.

The application of the science of Soil Mechanics to these soils is not always permissible because their properties and characteristics differ from those of cohesive and cohesionless sediments that have equal grain size distribution.

The authors confine themselves to soils of volcanic origin. Those of metamorphic origin will be dealt with in subsequent papers [1].

Genesis and geological characteristics of volcanic soils

The term *soils of volcanic origin* refers to cohesionless or semi-cohesive materials that are designated as *loose volcanic tuffs* or *pyroclastic soils* *.

* For clastic volcanic material ejected from craters the term *tephra* has also been proposed [2].

These soils are fairly widespread in Italy. They cover about 4 to 5 per cent of the country and they are found in large areas in the regions of Latium and Campania (Fig. 1). Apart from being used in important engineering works they are the soils upon which the cities of Rome and Naples are built.

Few studies have been made, using the methods of Soil Mechanics, which deal with the characteristics of volcanic soils as a raw material for engineering purposes or as materials for earth constructions like dams.

The authors consider the products of volcanic activity in the Quaternary and Recent Eras, and in particular the unaltered materials that have not undergone exogenic or endogenic alterations. From this point of view these soils differ from soils of volcanic origins that are referred to in the literature [3, 4].

These volcanic soils are formed by the products of volcanoes of mixed type (i. e., volcanoes which alternate explosive phases with phases of effusion of lava) such as those which are active, dormant, or extinct in Italy (volcanoes of the Latium, the Phlegrean Fields, Somma Vesuvio, Etna, etc.).

These materials, ejected during the explosive phases, are

Table 1

Lithogenetic classification of soils

Sedimentary	Slope debris. Alluvial deposits Glacial — Eolic — Lacustrine — Marine — Residual soils (e.g. "granites" and "crystalline schists" of Calabria, dolomitic rock flour). Slide debris, soil horizons etc.	Sometimes with formation of new minerals (mostly clay minerals), but without cementation or lithification.
Volcanic	Ejected blocks. Scoriae and scoriaceous lavas. Lapilli up to volcanic sands directly ejected from volcanoes. Pumices (pumiceous lapilli) up to loose volcanic ashes sometimes mixed with other coarser material of the same origin (loose tuffs); only non lithified and unaltered materials are considered here.	In the vicinity of volcanic centres of the mixed or explosive type : e.g. Phlegrean Fields, Vesuvius, Volcanoes of Latium, Roccamonfina, Etna etc.
Metamorphic	Tectonic brecciae up to "clay" (friction clay), without subsequent cementation.	A mixture of crushed material and blocks from the same rock formation; the blocks being jointed and fracred but not crushed. Such soils are common in limestone and dolomitic-limestone regions of the Appennini and in granite and schist regions of Calabria.

thrown into the atmosphere and are deposited around the volcano at distances which depend upon the size of the individual fragments and on the type of eruption, as well as on meteorological conditions at the time of the eruption.

Therefore, a noteworthy difference exists between soils deposited in the immediate vicinity of the craters and soils deposited at distances away from them, which are sometimes very great.

In the former, non uniform coarse grained materials are more frequent, whereas in the latter fine-grained uniform materials predominate.

As regards shape, strike and dip of the geological structures formed by volcanic soils, a distinction must be made between areas near to the eruptive centres and those which are distant from them.

In the region near the centres, several factors contribute to the formation of a complex series of soils of various types which may have different degrees of induration. The materials ejected from volcanoes are deposited on very complex sloping surfaces and hence lens shaped bodies or masses are formed. Moreover, the explosive phases (paroxistic or otherwise) of mixed type volcanic phenomena, which are characterized by the throwing out of loose products, alternate with phases of lava effusion, with phases of quiescense, and with long or short phases of inactivity. Finally, in a volcanic area there may be more than one crater or volcano active at the same time (Fig. 2).

The soils remote from an eruption centre have greater uniformity and homogeneity and they may also be deposited in layers. In every case they blanket the topography of the region at the time of the eruption.

By way of example, Fig. 3 and 4 show some typical soil profiles in Rome and Naples [5, 6].

Constitution, grain size distribution and porosity

The pyroclastic soils, due to their origin, consist of a variety of materials, as illustrated in Table 2. There the distinction between the constituent materials is made on the basis of the modes or conditions of their genesis.

Table 2

Pyroclastic soils classified according to the origin of the constituent materials

Origin	*Type of products*
Products directly derived from the erupting magma which is active at the moment of the eruption (essential ejecta).	*Ejected scoriae* (similar to the scoriae of lava; glassy only on the surface). *Lapilli* mostly consisting of pieces of angular or rounded vesicular lava. *Bombs.* *Vitreous scoriae.* *Pumices* (pumiceous lapilli) formed of frothy glass. *Ashes* (more or less pumiceous and scoriaceous); puzzolanas with very active constituents.
Materials derived from previously solidified volcanic or intrusive rocks of the volcano (accessory ejecta).	Products of the same types as above, torn away from the chimney of the explosion. Pure liquido-magmatic products already solidified and torn away from the roof of the magma chamber or from the chimney (fragments of igneous rocks of deep consolidation intruded among sedimentary beds; fragments of old lavas). Products of endo-morphism.
Alien materials; fragments of rocks from the roof or the walls of the chimney torn away during the explosions (accidental ejecta).	Fragments of rocks whose nature, geological age, facies etc. can be directly recognised. Products of contact-metamorphism up to tachylyte, buchite, fragments of marble, etc.
Materials of the above mentioned types thoroughly mixed.	*Volcanic brecciae.* *Volcanic ashes* (some inert volcanic materials generally referred to as puzzolanas and some actual puzzolanas). *Loose volcanic tuffs.*

Many of these materials have a vitreous texture which is more or less spongy and frothy. They have been formed by the consolidation of fragments of magma, rich in gas, that were thrown into the atmosphere and rapidly cooled. Into

Fig. 1 Distribution of volcanoes in Italy.
Répartition géographique des volcans en Italie.

this category fall the *ashes*, the *pumices*, and the *pumiceous lapilli* *.

Some particles do not have a vitreous texture; others are vitreous only on their surfaces. Among these types are the *scoriae* which are constituted by fragments of scoriaceous lava, the *lapilli* that consist of small fragments of lava, crystals or fragments of crystals, fragments of non-volcanic rock, etc.

It is often found that two or more of the simple types given in Table 2, are mixed in the same deposit.

External agents (like running water and wind) and gravity may remove these loose products and redeposit them away from the place in which they were originally laid down.

Hence these products are often remoulded and sorted, and they can be found mixed with materials of different natures and origins. Mixing, however, may also occur at the time of the deposition of the ejected materials on the ground or in the water.

* It is to be remembered that many volcanic soils have *puzzolanic properties*. Namely, they have an immediate and intense chemical activity thanks to which they can, among other things, react with lime in a moist environment to give hydraulic mortars. From this point of view, volcanic soils have been well known since ancient times [7, 8].

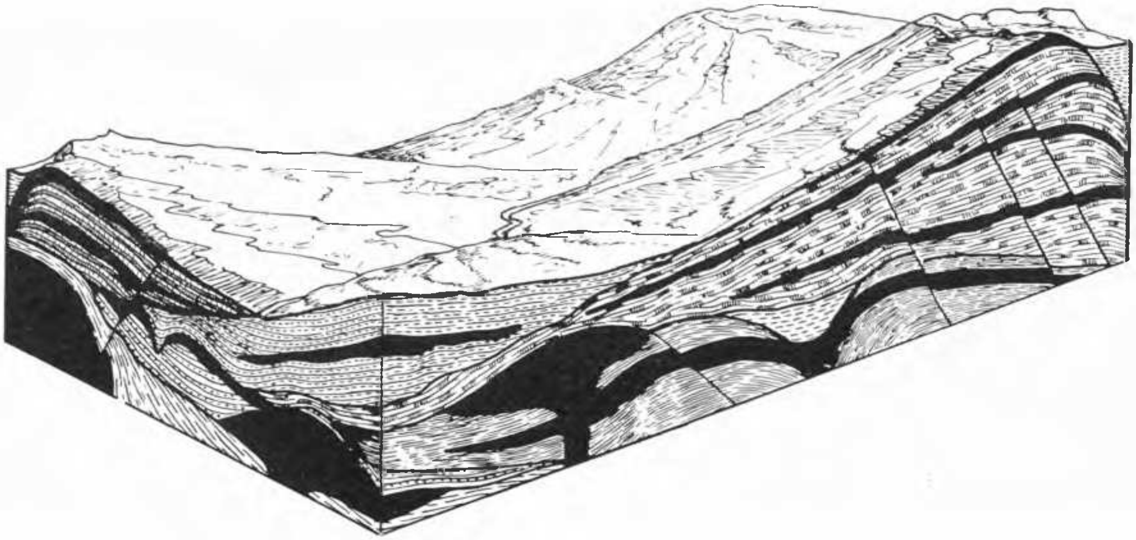

Fig. 2 Block-diagram showing the complex soil profiles in a volcanic region. The solid black areas show lava. The other symbols indicate various types of pyroclastic materials.

Bloc diagramme d'une région volcanique. En noir sont indiquées les laves. Les autres symboles indiquent des produits volcaniques de types différents.

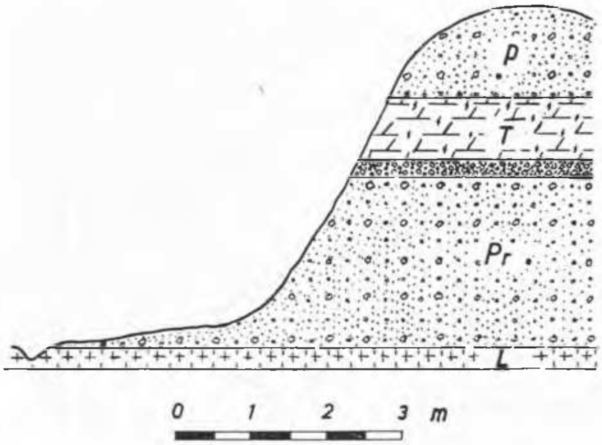

Fig. 3 A typical soil profile in Rome :
L = Lava
Pr = *Pozzolana rossa;* cohesionless volcanic soil made up of lapilli and ashes
T = *Tufo lionato;* volcanic tuff
p = *Pozzolanella;* cohesionless volcanic soil.

Succession des sols volcaniques dans les environs de Rome :
Lr = lave
Pr = *Pozzolana rossa;* sol volcanique incohérent formé par des lapilli et des cendres
T = *Tufo lionato;* tuf volcanique
p = *Pozzolanella;* sol volcanique incohérent.

On the other hand, the volcanic material may undergo alterations such as chemical and mineralogical changes.

The unaltered constituents of volcanic soils are distinguishable not only by their origins and their chemical and mineralogical constituents (mainly silicate, individualized or still vitreous), but also by their grain size distributions.

From the point of view of grain size distribution the authors have considered typical soils which frequently occur in large quantities, and which are composed essentially of one of the simple types of materials of Table 2, such as the ashes and the pumiceous lapilli.

In Fig. 5 the grain size distributions of the types of soils which have been studied can be seen.

The *ashes* are constituted by grains having maximum diameters between 2 mm and 0·2 mm, and minimum diameters being between 0·02 mm and 0·002 mm. The grain size distributions of the *pumices* (or pumiceous lapilli) are usually in the range between 20 mm and 0·2 mm with predominance of the fraction having diameters around 2 mm.

It should be noted that, in the case of the authors, the fraction $< 2\,\mu$ of the volcanic soils is not of the clay type, but of the same chemical and mineralogical nature as the other grains. Also the form and the state of the fine particles resemble to those of the coarse ones. The fraction $< 2\,\mu$ often has more pronounced puzzolanic properties.

Therefore the criteria of appreciation and classification of sedimentary soils, which are based essentially on grain size distribution, are not easily adaptable to volcanic soils. As for Atterberg Limits, their determination is not possible; and even if they could be obtained they would have no significance in relation to the criteria used with sedimentary soils.

In view of their origin and nature, the grains of volcanic soils are of irregular form and have rough surfaces. They also have high porosity, and only a limited number of the pores * are in communication with one another. This is particularly true in the case of vitreous particles (from the pumiceous lapilli to the extremely fine ashes). In the others (scoriae, rock fragments, scoriaceous fragments, etc.) the pores may not be present or they may be limited only to the particle surfaces [7, 9].

The authors concentrate their studies on the highly porous type of grains formed from volcanic glass with dimensions ranging from one micron to several centimetres.

The elements with diameters greater than about 1 mm (pumices) have irregular shapes and a typically spongy texture, varying from fibrous to thready (Fig. 6). Their outer surfaces are characterized by pores having widely varying forms, dimensions and depths. All these pores will be called *external pores*.

* In the following text the voids in the individual grains are defined as "pores". The term "interstices" is used to denote the voids between one grain and another grain.

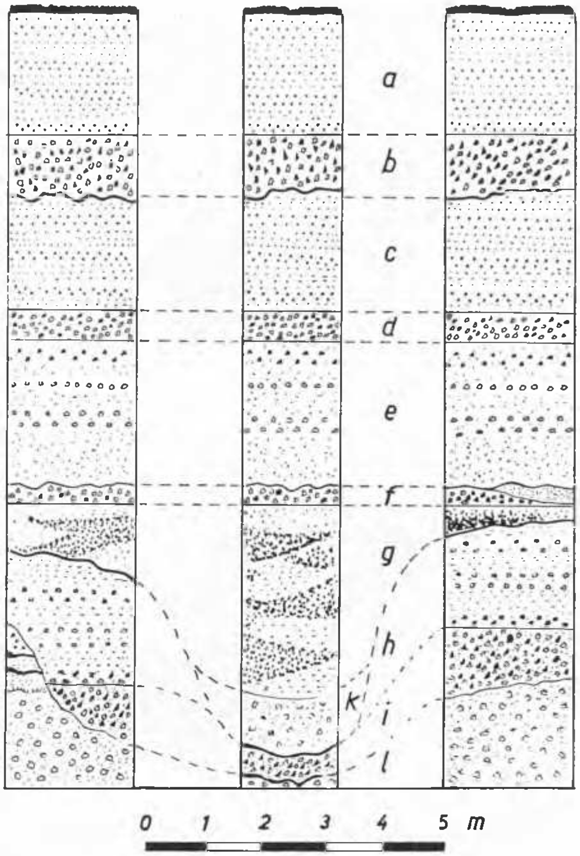

Fig. 4 A typical soil profile in the city of Naples :
(a) ashes ;
(b) pumices and lapideous lapilli ;
(c) very fine, uniform grained ashes ;
(d) pumices ;
(e) pumices and very fine ashes ;
(f) fine pumices mixed with rounded lapilli ;
(g) lens-shaped layers of uniform grained volcanic sands, thin interlayers of ashes ;
(h) volcanic sand mixed with rounded pumices ;
(i) pumices and lapilli ;
(l) fine ashes mixed with small pumices ; the top of this layer has been eroded before the deposition of the overlying soils.

Succession des sols volcaniques dans la région de Naples :
(a) cendres ;
(b) ponces et lapilli ;
(c) cendres à granulométrie très fine et uniforme ;
(d) ponces ;
(e) ponces et cendres à granulométrie très fine ;
(f) petites ponces et lapilli arrondis ;
(g) lentilles de sable volcanique à granulométrie uniforme avec des couches minces de cendres ;
(h) sable volcanique avec ponces arrondies ;
(i) ponces et lapilli ;
(l) cendres à granulométrie fine avec des petites ponces ; la face supérieure de cette couche a été érodée avant que se déposent les autres sols.

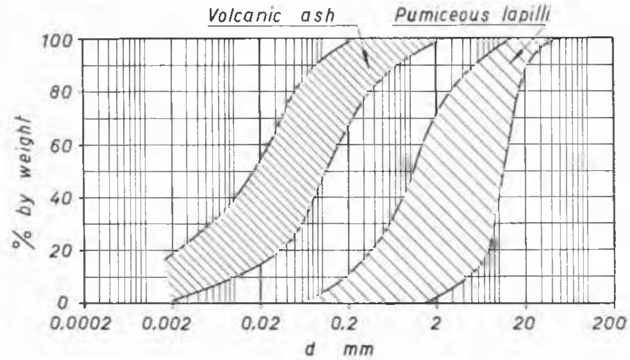

Fig. 5 Grain size distribution of volcanic soils constituted by ashes or by pumices.
Granulométrie de sols volcaniques formés par des cendres ou par des ponces.

Fig. 6 Photograph of some pumices. The external pores of the grains can be easily recognized.
Photographie des ponces. On peut reconnaître les vides externes des grains.

Some pores are completely enclosed within the grains and do not communicate with the atmosphere. They will be called *internal pores*. These voids can still contain water and gases.

In order to define these characteristics we will consider the idealized shape of a grain. This shape (Fig. 7) is determined by a regular surface that is a tangent to the smooth areas of the grain surface and that passes through the edges of the most pronounced surface pores.

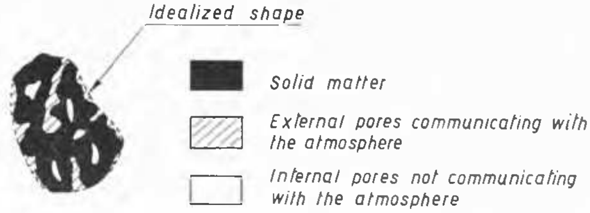

Fig. 7 Idealized section through a grain of pumice.
Section idéale d'un grain de ponce.

The particle is then defined by this idealized shape and its volume V is occupied by :

Solid matter (V_s).

External pores communicating with the atmosphere (V_a).

Internal pores not communicating with the atmosphere (V_i).

Correspondingly three different porosities of the grains can be defined, as follows :

Total grain porosity $m = \frac{V_a + V_i}{V}$

External grain porosity $m_a = \frac{V_a}{V}$

Internal grain porosity $m_i = \frac{V_i}{V}$

It has been found that the total grain porosity varies between 70 and 80 per cent and that the internal grain porosity reaches values from a few per cents up to 10 per cent.

While the unit weight of solid matter ($G = \frac{P}{V_s}$, where P is the weight of the pulverized and oven dried grain) reaches, in the case of Phlegrean pumices (Naples), average values of about 2·5 gr per cub cm,* their apparent unit weight $\left(G_2 = \frac{P}{V}\right)$ is less than one. A unit weight, $G_1 = \frac{P}{V - V_a}$, which takes into account the external grain porosity only, can also be defined.

The fragments of volcanic glass with dimensions less than about 1 mm (volcanic ash) (Fig. 8) often have sharp edges, and their total grain porosity may be very much less than that of pumices because of the smaller particle sizes. For these materials the internal pores, when there are any, have a proportionately greater importance.

Physico-mechanical properties

The *in situ* unit dry weight γ_d of volcanic soils varies between wide limits. In the case of soils consisting mainly of coarse pumices, the values of γ_d may be less than 1 ton per cub. m while for volcanic ash one obtains values of γ_d greater than 1 ton per cub. m but never very high.

When the porosity of a volcanic soil as a whole is determined by the usual methods, it must be remembered that the results include not only the voids among the grains (interstices) but also the pores within the grains (Fig. 9). The coefficient which represents the looseness of the material is clearly not n, but n_2 which takes into account only the interstices between the particles.

In the case of soils consisting of pumices one can find, for instance, values for n equal to 0·80 whereas n_2 may have values of only small percentages.

For volcanic ashes n assumes values usually between 0·50 and 0·60.

Due to the high values of the porosity, n, these soils are able to absorb very large volumes of water. It is obvious however that only that part of the water, often a very small part, which occupies the interstices will influence the mechanical properties of these soils. For this reason, the standards of classification and the rules for execution based on the moisture contents, which are valid for the usual soils, cannot be used here.

At the same time it should be remembered that, if reference is made not only to the interstices between the grains but also to the external and internal pores of the grains, the degree of saturation of volcanic soils is always less than unity.

* That is to say, values more or less corresponding to those of alkali-trachytes.

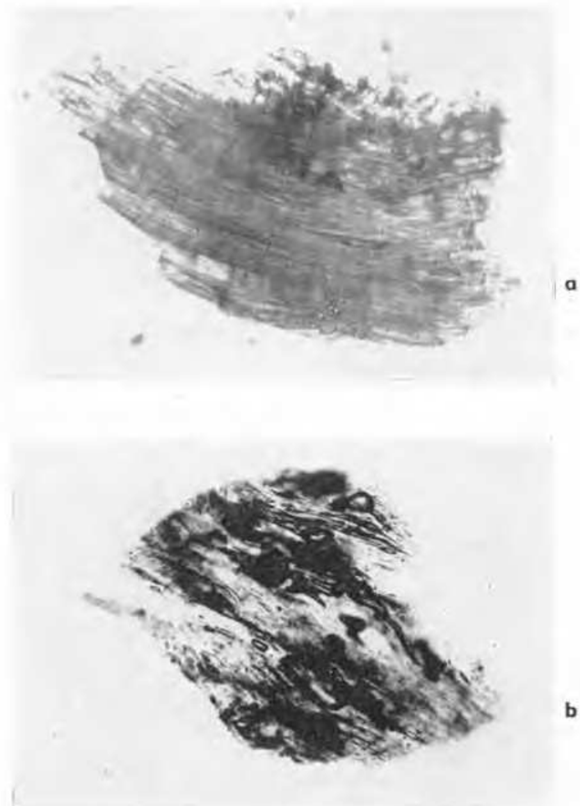

Fig. 8 Grains of volcanic ash (micro-pumice Enl. × 100). In (a) the internal pores of elongated form simulating a fibrous texture can be seen ; in (b) a more pronounced spongy texture is evident.

Grains de cendre (micro-ponces ; × 100). En (a) les vides internes, de forme allongée ressemblant à une texture fibreuse, peuvent être reconnus ; en (b) une texture spongieuse est mise en évidence.

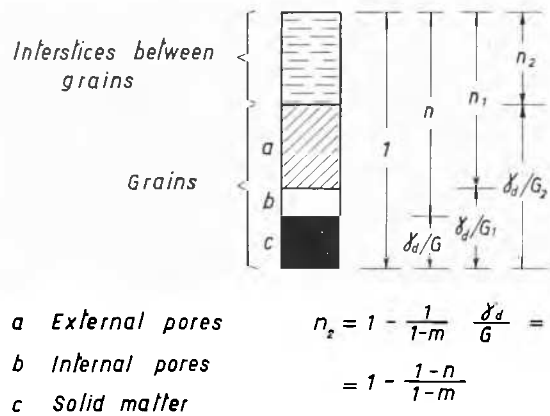

Fig. 9 Diagram illustrating the porosities of a volcanic soil.

Diagramme expliquant la porosité des sols volcaniques.

Indeed, even if the water fills all the interstices, it cannot penetrate into the internal pores nor can it displace the air in the external pores which are often very minute, except with extreme difficulty and under special conditions.

Œdometric consolidation tests have proved that volcanic soils consolidate according to the semi-logarithmic law valid for other soils.

$$\text{The compression index } C_c = \frac{e_0 - e}{\log_{10} \dfrac{p_0 + p}{p_0}}$$

of volcanic ashes depends on the initial soil porosity.

The tests show the existence of a linear relationship between $\frac{1}{C_c}$ and the initial void ratio, e_0 (Fig. 10).

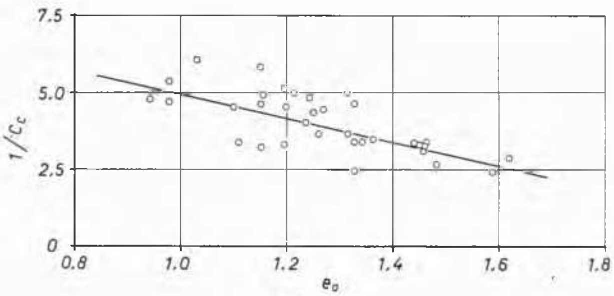

Fig. 10

The rate of consolidation is characterized by a primary consolidation which is negligible compared with the secondary one. The decrease of the void ratio, e, can therefore be expressed by an equation of the following type :

$$\Delta e = a + b \log \frac{t}{t_0}$$

where a is the decrease of e after the time t_0.

Within the explored range of values of p, that is up to 10 kg per sq. cm, the values of the coefficient b for a given soil increase when the applied pressure, p, is increased. They also depend on the type of volcanic material. We can for the moment state that b is greater in pumices than in ashes.

The shape of the consolidation curves and the variations of the coefficient b are clearly related to the brittleness of the grains and/or of their external parts [10, 11].

If volcanic soils that normally lie above the water table are gradually flooded, they begin to settle even if the acting pressure remains constant. Laboratory tests have shown that these settlements can reach values of some percentage of the soil thickness. The value of the settlement depends on the value of the active pressure, and it becomes smaller as the pressure increases.

The compressive strength in a triaxial test does not change appreciably with variations in the method of stress application. The procedure generally used by the authors is to apply the pressure σ_3 with the drainage valves open, and then after several hours to apply the deviator stress $(\sigma_1 - \sigma_3)$, with the drainage valves closed.

In the case of volcanic ashes it has been found that when the moisture content varies, with no change in the soil porosity, there are no appreciable variations in compressive strength.

The results thereby obtained in the triaxial compression test give values of the friction angle, φ, between 30° and 40° and values of apparent cohesion, c, which are either negligible or very small.

The significance of these results in relation to the behaviour of the materials *in situ*, and especially in relation to the fact that many unusually high and nearly vertical slopes exist in volcanic soils, is the object of current research by the authors.

Volcanic soils are satisfactorily employed in the construction of embankments. Under the action of field compacting equipment or in the laboratory under the action of the hammer in Proctor's test, the grains break up to a certain extent with consequent changes in grain size distributions and in the other properties of the soil. The measured values of the optimum moisture content are usually very high. Both these characteristics are easily explained when it is remembered what has been said about the constitution, form, and porosity of the grains, and the condition of their surfaces.

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