Physical and mechanical characteristics of pyroclastic soil for the construction of embankments

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ABSTRACT

In the framework of wider research activity on the physical and mechanical behaviour of volcanic soils, this paper reports the results of some laboratory tests on this type of geomaterial. The background of this research is the need for a construction company to possibly use pyroclastic material excavated along a tunnel profile to build railway embankments included in the design of a new High-Speed Train Line near the city of Naples, Italy. However, according to the standards of the National Italian Railways Company, pyroclastic soils cannot be employed as construction materials unless they are supported by a specific testing program demonstrating their good performance. The pyroclastic soil, which is widespread in the project area, is the product of Mt. Vesuvius volcanic activity. It is a coarse-graded soil that includes a significant percentage of non-plastic fines. They should be placed under compact conditions. The experimental campaign was aimed at identifying some physical characteristics that can synthesize the homogeneity of the pyroclastic deposit in terms of shearing resistance. The preliminary results obtained in terms of grading curves, modified Proctor compaction curves, and stress-strain curves from conventional drained triaxial tests are presented and discussed in this paper. The latter were executed on fully saturated specimens after compacting the soil at the optimum water content and on the dry and wet sides of the Proctor curve. The overall initial outcomes of the experimental campaign indicated that this material has acceptable characteristics and is suitable for the construction of railway embankments.

Keywords: Pyroclastic soil; compaction; triaxial tests.

1. Introduction

This paper presents preliminary results on the mechanical characterization of a pyroclastic soil deposit located near Naples, Italy, for use as a construction material for railway embankments.

The background of this research is the aim of a construction company to take advantage of the excavation activities of a long tunnel using the resulting soil to build railway embankments. The tunnel and embankment constitute key elements in the first route of the new High-Speed Train Line Naples-Bari, which is currently one of the biggest construction projects in Italy.

Pyroclastic soils are widespread in the construction area because of the volcanic activity of Mt. Vesuvius. Several studies have been conducted to investigate hydraulics (Aversa et al. 1998, Pirone et al. 2016) and mechanical behaviour (Picarelli et al. 2007; Parlato and Santucci de Magistris 2007; Papa and Nicotera 2011; Nicotera et al. 2015; d'Onofrio and Alleanza 2022). It emerged that the grain size distribution, void ratio, and structure play a fundamental role in the index and state properties, as well as in the hydro-mechanical response of these materials. Furthermore, the mechanisms of generation and formation of deposits and the distance from the eruptive centre should be accounted for a complete understanding of the pyroclastic soil behaviour (Picarelli et al. 2007). In accordance with the characteristics and history of eruptions, these deposits may be layered, coarse-grained or fine-grained, cemented or loose, fractured or intact. Their structure is extremely variable from deposit to deposit and, in the same deposit, along the vertical and horizontal directions, the hydro-mechanical response to external input may strongly vary from point to point. Pyroclastic soils may pose engineering problems owing to certain special intrinsic features, such as the high porosity and fragility of single porous particles (Picarelli et al. 2020). In addition, pyroclastic soils under typical unsaturated conditions may experience large deformations upon wetting owing to the potential collapse of the soil skeleton (Picarelli et al., 2007), with a progressive flattening of the soil–water characteristic curve and the presence of hysteretic phenomena (Bilotta et al. 2005).

Thus, because of their heterogeneity and the complexities associated with their unsaturated hydro-mechanical behaviour, pyroclastic soils are not commonly used for the construction of earthworks such as road and railway embankments. For the same reasons, the standard technical specifications of the National Italian Railways Company do not allow the use of this type of soil unless a specific mechanical characterization is performed. However, given their wide distribution in the area of interest and their cost-effectiveness, it is worth verifying the possibility of using excavated pyroclastic soils as construction materials for earthworks. Therefore, a comprehensive laboratory investigation is required.

In the paper, an overview of the project that includes the geological description of the area is presented together with the results of the first part of a wider experimental program executed on the pyroclastic material in the framework of the rules used in Italy to design railway embankments.

The experimental campaign is aimed at identifying some physical characteristics of the investigated soil that can assess the homogeneity of the pyroclastic deposit in terms of mechanical behaviour.
Therefore, the preliminary results obtained in terms of grading curves and derived parameters, a series of modified Proctor compaction curves, and a series of conventional drained triaxial tests are reported and discussed in the paper.

The main outcomes of this research are to present some of the geotechnical features of this material and to give some suggestions for organizing a rational experimental campaign to characterize a wide deposit of soil to be used as construction material of railway embankments.

2. The High-speed line

The Naples-Cancello line is part of the new High-Speed-High-Capacity (HS/HC) Naples-Bari line, which brings high-speed trains to southern Italy (Fig. 1). It is an important part of the European program for sustainable transport, the Transport European Network (TEN-T) corridor, which aims to shift almost 50% of freight traffic currently on road to rail by 2050, triple the high-speed rail network, connect major seaports to rail, and reduce transport emissions by 60%. The project consists of building a variant of the current Naples-Cancello line, for an overall length of 15.5 km, at a train speed of 130 km/h, with two new stops, one new station, and a new Multi-station Computerized Central Apparatus with a central control post in Naples. This work greatly contributes to the development of the entire South of Italy, allowing it to better integrate itself in socio-economic terms both within Italy and Europe.

Figure 1. High-Speed-High-Capacity Naples-Bari line.

The geological formations outcropping in the area of interest can be classified into (i) Quaternary deposits consisting of sandy silts and silty sands, sometimes clayey, of a prevalently pyroclastic nature, containing stone inclusions; and (ii) volcanic deposits consisting of tuff, cinerite deposits, juvenile scoriae, and lithic clasts, generally in welded lithoid facies. The former are generally present at the base of the reliefs with thicknesses of up to 10-15 metres, while in the neighbouring flat areas, they have thicknesses of a few meters. The latter are products of the volcanic activity of a burning cloud (Ignimbrite Campana), whose deposition resulted in the filling of ancient depressions and reshaping of the valleys of ancient watercourses. As far as the tuff is concerned, there are mainly two sub-units in the area: lithoid yellow tuff with frequent scoria and pumice inclusions, characterized by relatively high shear strengths, and altered gray tuff that is poorly cemented with scoria and pumice inclusions, usually very fractured and/or altered, with variable but also rather low strength characteristics.

3. Experimental program

The purpose of this experimental study was to assess the possibility of using the excavated soil of volcanic origin to build railway embankments, based on a comparison between the design recommendations and the evaluation of the physical and mechanical properties of such materials by laboratory tests.

The assessment of the suitability of the soil for the construction of the embankment body cannot disregard compliance with the standards of the National Italian Railways Company, which are summarised below:

- soils from earthworks, foundations or tunnel excavations that belong to groups A1, A2-4, A2-5, A2-6, A2-7, A3 and A4 (UNI 11531-1/2014) must be used
- soils of A3 group (UNI 11531-1/2014) with a non-uniformity coefficient less than or equal to 7 cannot be used
- The use of pyroclastic soils must be explicitly authorised by the works management
- For the formation of the body of the embankments, rock fragments not larger than 125 mm (UNI 11531-1/2014) may be used to form layers with a maximum thickness of 50 cm
- the uniformity coefficient of the materials used shall be greater than or equal to 15
- The material must be laid with a water content close to the optimum, with a standard deviation of ±2%.

Therefore, the adopted experimental strategy consisted of identifying the soils that, in accordance with the standards set out above, could be used for railway embankments, but also to identify possible homogeneity in the material excavated along the tunnel section (2 km long) that could allow the creation of a unique soil mixture to be used in all embankments.

The adopted procedure involved a preliminary selection of the sampling sites along the tunnel profile based on the available stratigraphic section, followed by grain size distribution analysis and determination of physical properties such as the specific unit weight of the grains γs and the organic content OC for each sample. The material was excavated in a limited part of the entire tunnel profile for a length of approximately 500 m, always in the shallow part of the soil deposit where uncemented pyroclastic materials are present.

Different soil mixtures were prepared using samples with similar grain size distributions. Modified Proctor compaction tests and conventional drained triaxial tests were performed on the different mixtures, as follows:

- CU01: material from a head that had been properly sorted and mixed in situ
- Mix 1: a laboratory mixture of PZI2-C1, PZI3-C1, PZL1-C1 and PZL1-C2 samples

- Mix 2: a laboratory mixture of PZL2-3, PZL2-5 and PZH3-5 samples from the same borehole of the mix 1 samples
- Mix CT: a mixture of soils from the site of interest prepared by a commercial laboratory in Catania (Italy).

Conventional consolidated drained triaxial tests were performed on the soil compacted to the modified optimum water content and dry density. The soil, reconstituted in the laboratory, was previously compacted in the Proctor mould, reduced to the dimensions of the specimen to be tested through a cylindrical cutter and then completely saturated after the set-up in the triaxial apparatus. This procedure allows the results of triaxial tests to be analysed in effective stresses, without having to consider the mechanics of partially saturated soil. Drained tests were carried out adopting an axial displacement rate of 0.05 mm/min that is compatible with the high permeability of these soils. To analyse the sensibility of the tested soil to the compaction conditions, following the strategy described by Vinale et al. (2001) and Santucci de Magistris and Tatsuoka (2004), triaxial tests were also carried out on specimens prepared on the dry and wet sides of the modified Proctor compaction curve. Also in this case, the specimens were completely saturated before triaxial tests were carried out.

4. Experimental results

A series of classification analyses were performed on the pyroclastic soils from the area of interest. A summary of some of the parameters of the grain size distribution curves, obtained by interpolating the data of each individual grain size curve with a Hill function, is shown in Table 1. The specific unit weight of the grains γ_s has an average value of 24.83 kN/m^3. All materials were non-plastic and characterized by an organic content *OC* ranging between 2 and 9% (see Table 2). No specific threshold values of organic content were prescribed for Italian railway embankments. The soils have a uniformity coefficient U_c greater than 15 and a fine fraction *F* (d< 0.063 mm) varying between 15 and 55 All the grain size distribution curves are plotted in Fig. 2 together with those relevant to the four identified mixtures. The soil is fairly homogeneous in the area of investigation, with particle size distributions falling within a relatively small grain size range.

As stated above, Modified Proctor compaction tests were carried out on each mixture following ASTM D1557-12(2021). the resulting compaction curves have limited variability, the optimum water content varies between 22 and 24% and the optimum dry density is between 13.6 and 14.3 kN/m^3 (Fig. 3). Given the similarity between the compaction curves of mixtures 1 and 2 they can be considered to be the same soil, for practical purposes. To verify the effect of compaction on grain breakage, and thus on the grain size distribution of the original material, a comparison of the grain size curves before and after compaction is shown in Fig. 4 for Mix 2. Grain size analyses after compaction were carried out on soils compacted at three different water contents (i.e. dry side, optimum and wet side of the compaction curve).

Table 1. Physical properties and parameters of some grain size analysis: U_C uniformity coefficient, C_C curvature coefficient, *F* fine fraction, *GI* group index, γ_s unit weight of the grains and *OC* organic content

	U_c	C_c	F	GI	γ_s	OC
	-	-	(%)	-	kN/m^3	%
PZI2-C1	13.72	1.11	44.57	1.915	25.24	7.25
PZI2-C3	17.63	1.30	4.64	0.000	24.51	-
PZI3-C1	25.04	1.15	35.98	0.196	24.91	9.64
PZL1-C1	25.38	1.14	35.82	0.165	24.90	7.40
PZL1-C2	21.98	1.10	40.25	1.049	24.46	4.17
PZL1-C3	15.11	1.06	54.40	3.880	24.04	6.12
PZI1Bis-3	6.57	1.08	15.89	0.000	26.57	2.64
PZI1Bis-5	136.81	1.56	19.44	0.000	25.32	6.56
PZL2-3	38.56	1.22	33.13	0.000	24.20	4.56
PZL2-5	14.49	1.08	39.28	0.855	24.43	4.49
PZH3-5	39.48	1.16	35.01	0.001	24.08	4.34
SI1-9	39.48	1.16	35.01	0.001	25.67	1.37
SI1-13	56.36	1.11	46.10	2.220	25.51	0.74
CU01	76.87	1.22	38.88	0.777	24.64	5.01
Mix 1	21.20	1.13	35.26	0.052	24.97	7.45
Mix 2	22.34	1.14	35.63	0.126	24.53	-
Mix CT	19.65	1.10	51.04	3.207	24.10	4.89

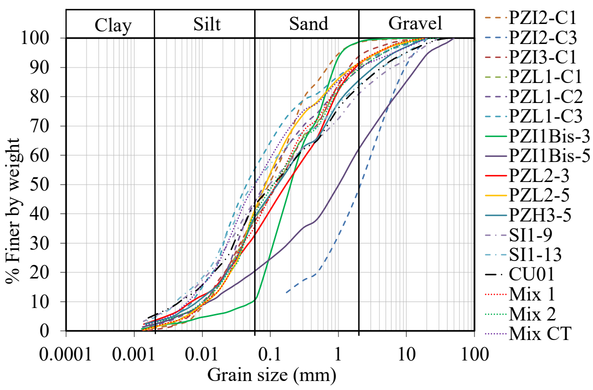

Figure 2. Grain size distributions of the tested pyroclastic soils.

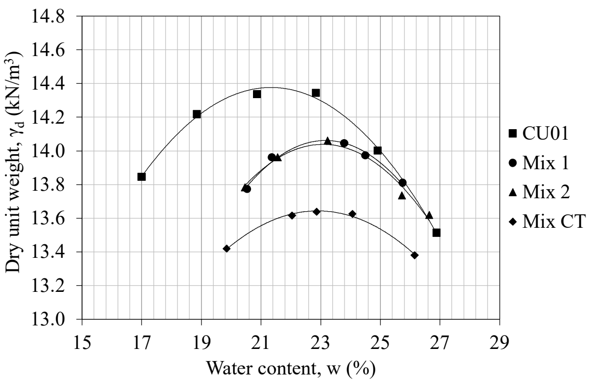

Figure 3. Modified Proctor compaction curves.

The soil undergoes a slight reduction in particle size, the grain size distributions shifting slightly to the left, showing almost no influence of the initial water content on grain breakage.

It should be noted that the compaction tests were all carried out on soil passing through 5 mm diameter, as prescribed by ASTM standards.

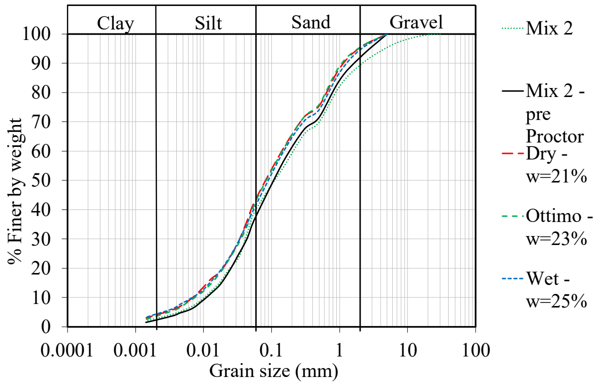

Figure 4. Grain size distributions of the tested pyroclastic soils.

The mechanical behaviour of the compacted soil mixtures was preliminary analysed by carrying out a set of six drained triaxial tests on Mix 1. All the specimens were prepared to the modified Proctor optimum and saturated in the triaxial cell. In addition to the confining stresses considered appropriate for soil that may constitute the body of a railway embankment (i.e., 50, 100 and 150 kPa) higher confining stresses (i.e., 200, 300 and 400 kPa) were also applied to analyse the soil response in a large stress range. The results, reported in the $q:\varepsilon_a$ plane (see Fig. 5), show that the soil exhibits the typical behaviour of dense sand. The well-known influence of the effective confining stresses on the mechanical response, a clear difference between the peak and constant volume strength conditions, dilatancy until the formation of a failure surface within the specimen, and stiffness dependency on the effective confining stress were observed. By interpreting the experimental results in terms of effective cohesion c' and internal friction angle φ', it is observed that through a preliminary interpretation of the results, at constant volume the soil has φ'=33° while at the peak it is found to have c'=75 kPa and φ'=41°.

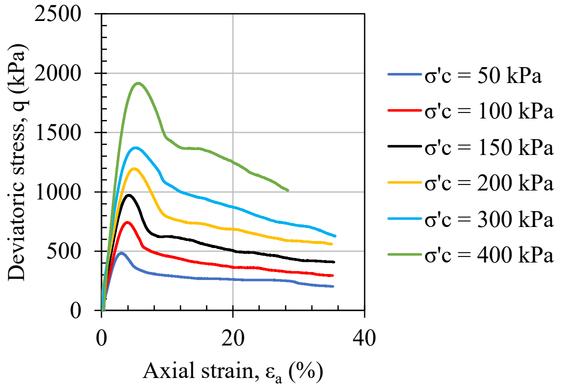

Figure 5. Consolidated drained triaxial test results on saturated specimens of mix 1.

The behaviour observed for Mix 1 was confirmed by the results of triaxial tests carried out on specimens of Mix 2 compacted at the optimum water content, as shown in Fig. 6a. As a first approximation, the shear strength can be summarized in a unified manner for the two mixtures through φ'=34° at constant volume and c'=90 kPa and φ'=41° at the peak state. In addition, the mechanical response of the CT mix, consisting of soils taken from different sites along the tunnel section, appeared to indicate homogeneity (Fig. 6a). In all datasets presented, a strong post-peak strength drop related to shear band formation was observed, dependent, among other factors, on the applied stress level. Overall, a value of φ'=35° at constant volume and c'=97 kPa and φ'=41° at the peak state can be assumed for the three mixtures (Fig. 6b).

Similar conventional drained triaxial compression tests were performed on the CU01 mix. In this case, the soil constituting the mixture was obtained directly from the pile of soil stored during the excavation. Tests on specimens compacted at modified Proctor optimum dry density and 95% of optimum dry density on the dry and wet side of the compaction curve were performed. From the experimental results shown in Fig. 7, dilatancy was exhibited by the tested pyroclastic soils, both in q-ε_a (Fig. 7a) and p'-e planes (Fig. 7b). However, a higher ductility of the material prepared at an initial wet water content was observed compared to the dry and optimum compacted specimens, which exhibited a higher peak strength, and the ultimate strength appeared to depend only on the effective confining stress state and not on the initial water content.

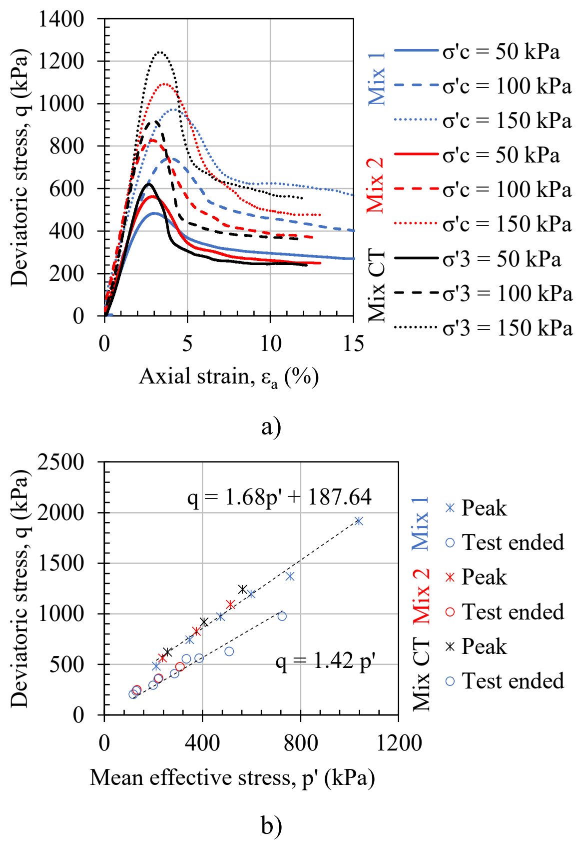

Figure 6. Consolidated drained triaxial tests: comparison between mix 1, mix 2 and mix CT in terms of a) stress-strain curves and b) strength envelopes.

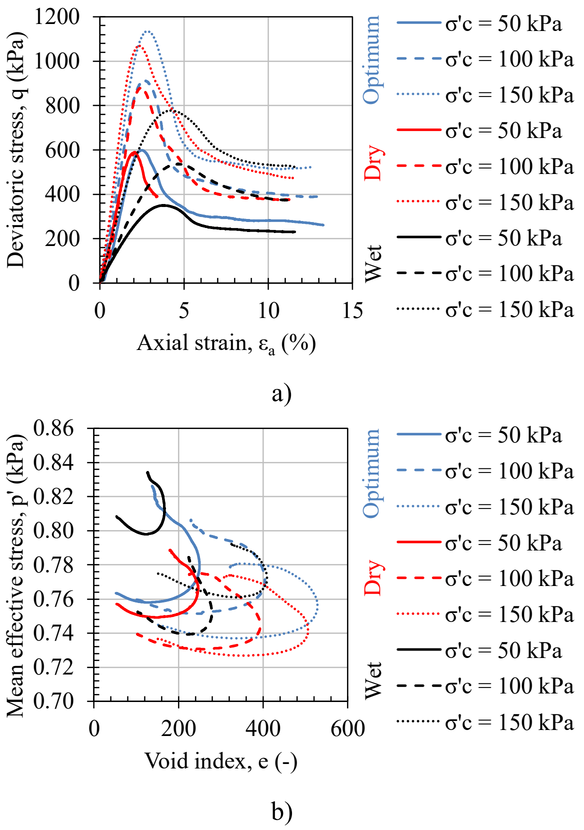

Figure 7. Consolidated drained triaxial tests results on saturated specimens of CU01 mixture at different initial water content: a) q-ε_a and b) p'-e planes.

The stiffness of the soil tends to decrease as the Proctor water content increases and the peak shear strength is reached at increasing strain levels as the Proctor water content increases.

This is more evident if the stress-strain curves obtained on the mixture CU01 are represented in a dimensionless stress-strain plan (Fig. 8), by normalising both deviatoric stresses and axial strain with respect to the relevant values measured at the peak.

As reported in Fig. 8, a 70% reduction in strength was measured for the specimen prepared at the wet side of optimum while a 50% decrease is observed for the specimens prepared at the optimum and dry water contents.

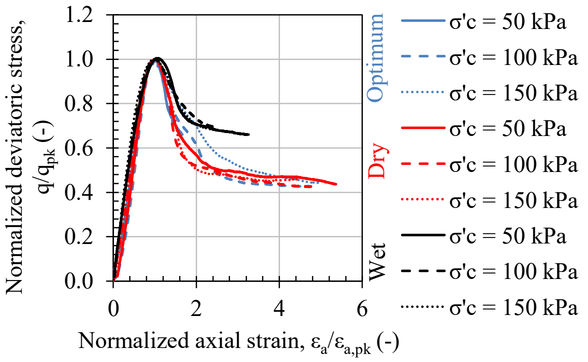

Figure 8. CU01: CID triaxial tests at three different effective confining stresses (50, 100, 150 kPa) and at three different initial conditions (optimum, dry, wet) - deviatoric stress normalized with respect to its peak value vs axial strain normalized to its value at peak.

The increasing ductility and the decreasing dilatancy observed in the specimen prepared with increasing Proctor water content can be ascribed to the different structures induced by the Proctor compaction at different water contents. As a matter of fact, compaction on the dry side of optimum produces a soil structure characterised by visible aggregates of particles and inter-aggregates pores, while wet of optimum samples appear more homogeneous. These differences in structure can affect the soil pre-failure behaviour (Vinale et al. 2001). An overall interpretation of the shear strength of the pyroclastic soils tested, based on data from an interpretation of each triaxial test through the deviatoric stress *q* and the mean effective stress *p'* at the peak and the end of the test, separating the data from the dry and optimum specimens from that of the wet soil is shown in Fig. 9. Data of specimens prepared with a mixture of Mix 1 and Mix 2, at a dry density of 95% of the optimum value, on the dry and wet sides of the compaction curve respectively, are also shown. A slight curvature of the failure envelope at higher stresses and a lower peak strength were observed in the case of specimens prepared at an initial water content greater than the optimum value (Fig. 9a). At higher strains (Fig. 9b), toward the critical state condition, the soils appear to exhibit a unique strength independent of preparation conditions and saturation path and mainly related to the lithological nature of the soil.

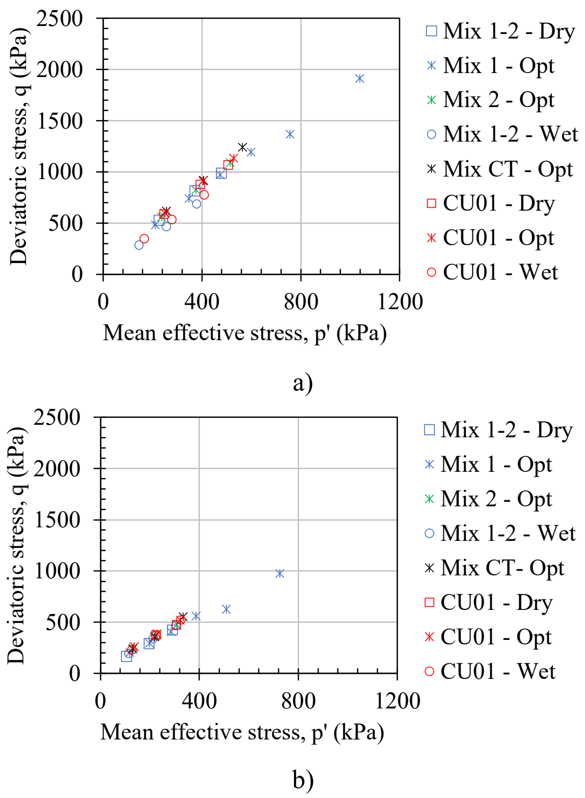

Figure 9. Deviatoric stress vs mean effective stress at a) peak and b) end of the test.

5. Concluding remarks

To assess the usability of pyroclastic soils for the construction of railway embankments as part of the construction work of the High-Speed-High-Capacity

Naples-Bari line, Naples-Cancello section, a comprehensive experimental campaign of mechanical characterization was carried out. The pyroclastic soils retrieved from different sites along the route of interest were subjected to identification, Modified Proctor compaction, and conventional drained triaxial tests.

The tested soils were fairly homogeneous and belonged to the category of relatively non-uniform silty sands or sandy silts, with no plasticity and non-zero organic content.

These soils can be effectively compacted, as shown by the laboratory compaction curves, which are relatively uniform and consistent with the measured physical and grain size characteristics. Furthermore, it was verified that the compaction using the modified Proctor technique does not result in a substantial change in the grain size distribution of the original soil.

A certain homogeneity of pyroclastic soil behaviour and some expected influence of material preparation water content on both stiffness and peak shear strength emerged. Significantly higher peak strength for materials prepared at the dry and optimum water content of the modified Proctor test were observed. The stress-strain behaviour analysis together with the congruence and uniformity of the experimental data suggest using the excavated pyroclastic soil in the construction of the embankments of the Naples-Cancello High-Speed line. To confirm this, the triaxial tests were carried out on the saturated specimens, but it is well known that the compacted soils are placed in a partially saturated condition and therefore can generally rely on a reserve of stiffness and strength related to suction. This study was limited to an analysis of the strength parameters of pyroclastic materials. It should be highlighted that further engineering parameters, including the stiffness and durability of these materials, should be studied to assess their effectiveness as construction materials for the bodies of railway embankments.

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