Abstract

The paper presents the results of a multi-scale study performed throughout the recent two years aimed at investigating the mechanical behaviour of an ignimbrite belonging to the Orvieto-Bagnoregio formation, and outcropping at the site of Orvieto. The study is preparatory for a more thorough research - which is currently in progress – on the effects of lime stabilization on the chemical-physical properties and the mechanical response of the same examined Orvieto soil.

1. Motivation of the study

In this paper, we illustrate the results obtained from an extended experimental investigation on a pyroclastic coarse-grained soil retrieved from the site of Orvieto (Terni, Central Italy). The experimental programme has been performed in three main research-laboratories, in Italy (University of Perugia, University of Cassino and Southern Lazio) and in France (University of Nantes, IMN). It consisted of chemical, physical, mechanical tests at different scales, in order to gain a knowledge of the main constituents of the raw soil, its microstructural features, compressibility and shear strength properties. The study, which was faced and developed by researchers working in different fields (geologists, geotechnical engineers, geochemists), can be considered necessary and preparatory for the second step and main goal of the research on this pyroclastic soil, which focuses on the link between the mechanical improvement induced by lime addition and the chemo-mineralogical evolution of the system through a multi-scale analysis of the treated material. The availability of secondary phases induced by lime addition has been found to be the main responsible for the observed mechanical improvement, showing the effectiveness of the treatment and the key role of zeolites in the chemo-physical evolution of the system: this topic, dealt with through a broad experimental work, and still in progress, is the object of a companion paper presented to this IARG2017.

2. The deposit of pozzolane in Orvieto

The investigated soil belongs to a thick ignimbrite deposit, known as the Orvieto-Bagnoregio Ignimbrite, located in the Northern part of the Roman Magmatic Province (Central Italy), in the Vulsini district (Cappelletti et al, 1999). This district is characterized by a volcanic activity associated with four main eruptive centres (Nappi et al., 1998; Peccerillo, 2005), dominated by pyroclastic fall deposits covering an area of about 2200 km². The four main centres show a similar pattern: a
strombolian and effusive activity at the beginning, followed by a caldera-forming eruption with ignimbrite associate-deposits, and finally an eruptive phase marked by magmatic and hydromagmatic events. The pyroclastic soil was originated by the Bolsena eruptive centre, from 0.49 to 0.32 My, and mainly consists of pyroclastic products generating thick ignimbrite deposits, which superimposed Pleistocene sediments, often made of stiff clays. The average thickness of the deposits is about 10 m, but it is much thicker in the distal outcrops (Cappelletti et al., 1999), reaching its maximum (about 60 m) in the Orvieto cliff. Intense erosion processes lead to the formation of small plateaux surrounded by steep cliffs, such as the city of Orvieto. The ignimbrite consists of a rock-like facies (tuff) and a slightly coherent facies (pozzolana). At the foot of the cliff, a few meters thick layer of red tuff is observed. The tuff is affected by systematic vertical jointing extending also in the lower more consistent layer of pozzolana. In the weaker upper layer of pozzolana, joints are widely-spaced, irregular and not evident. The investigated material, here denoted as OR soil (identified as PWD4 by Gentili et al., 2014) belongs to the pozzolana facies and it is one of the most enriched in zeolites, mainly Chabasite (Fig. 3b). For a technical classification of the rock mass, taking into due consideration the geological complexity of such pyroclastic materials, whose heterogeneity depends on several factors, such as viscosity, temperature, chemical interaction, eruption energy, distance from the magma chamber, post-depositional processes, we have used the descriptive model for volcanic soils (Cecconi et al., 2010) based on a operationally tested data sheet. This provides 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 the pozzolanic OR soil is a welded pyroclastic rock with a massive structure and quite homogeneous at the scale of the deposit, presenting limited local variations in grading. The pyroclasts are more than 90% juvenile, with 65% matrix and 25% clasts. The material falls in the lapilli-ash field of Fischer's chart, consisting of lapilli (25%) coarse ashes (35%) and medium to fine ashes (40%), while blocks and bombs are totally absent. Clast shape is sub angular.
3. Structural features an mechanical properties

3.1 Micro scale analyses

The OR soil was retrieved in blocks and crumbled in a mortar until passing the sieve 450 μm and oven-dried for 24 hours at 60°C. Chemical, mineralogical and physical properties of the raw material are described in Guidobaldi et al. 2017a. The OR-soil is characterized by a relevant presence of Ca-Chabazite and Iron-enriched altered amorphous phase, both clearly identified by SEM observations (Figure 2a,b,c).

![Figure 2. Micrographs at different magnification factors: a) clasts configuration; b) Chabazite crystals surrounded by altered amorphous phase, c) glassy amorphous phase (after Guidobaldi et al., 2017b)]
The prominent presence of Chabazite (46.3%), is furtherly confirmed by all the used investigation techniques. X-Ray powder diffraction also allowed the identification of minor phases such as: Sanidine (18.1%), Augite (5.7%), K-Feldspar, Analcime and Biotite; the estimated amorphous phase equals 15.2%. (see Fig. 3). Also, Micro-X Ray Fluorescence (μ-XRF), Thermogravimetric Analysis (TGA), Infra-Red (FTIR) spectroscopy, 29Si Nuclear Magnetic Resonance Spectroscopy (29Si NMR) analyses were performed to get a full comprehension of the microstructural and chemo-mineralogical features of the raw OR soil. All these cited tests were performed at Institut des Matériaux Jean Rouxel (IMN), Université de Nantes. Chemical analyses were performed by means of μ-XRF technique. The bulk chemical composition is reported in Table 1. The presence of significant amounts of CaO, K₂O and FeO, and the silicon to aluminum ratio equal to 3.66 is consistent with relevant amount zeolites, in particular Chabazite.

Mercury Intrusion Porosimetry on the raw material was carried at University of Cassino by means of the Micromeritics AutoPore III, provided with a vacuum pump for the degassing of pores, a low pressure unit and high pressure unit (max Hg pressure respectively 206.85 kPa and 206.85 MPa) permitted to detect pore diameters from 0.07 μm to 300 μm. In particular, MIP of raw OR soil samples allowed the identification of three main classes of pores, with most frequent diameters respectively
equal to 0.01, 1.0 and 5.0 µm (see Figure 3). The first two classes are mainly composed of inter-
particles voids while the main contribution to the smaller pore population is mainly given by the
intrinsic porosity of the altered Iron-enriched amorphous phase (Guidobaldi et al., 2017b).

3.2 Laboratory sample scale

At the scale of the laboratory sample, the OR raw soil presents a partial saturation, \( S_r = 47\% \) and the
initial average water content is of about 15%. The material used for sample preparation can be
classified as a silty sand with \( D_{\text{max}} = 0.425\text{mm} \) (Fig. 4). The physical properties of OR soil in its
natural state are shown in Table 1a, while Table 1b summarizes the initial physical properties of the
investigated samples before testing.

### Table 1a. Physical properties of natural OR deposit

<table>
<thead>
<tr>
<th>( w ) (%)</th>
<th>( G_s ) (-)</th>
<th>( S_r ) (%)</th>
<th>( \gamma ) (kN/m(^3))</th>
<th>( \gamma_d ) (kN/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>2.43</td>
<td>47</td>
<td>15.8</td>
<td>13.7</td>
</tr>
</tbody>
</table>

### Table 1b. Initial physical properties of OR samples.

<table>
<thead>
<tr>
<th>( w ) (%)</th>
<th>( \gamma_d ) (kN/m(^3))</th>
<th>( S_r )</th>
<th>( n )</th>
<th>( e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>13.0±1.2</td>
<td>60.7±12.9</td>
<td>0.47±0.05</td>
<td>0.88±0.18</td>
</tr>
</tbody>
</table>

Samples preparation were reconstituted in three layers, each compacted through 10 consecutive mallet
blows (mass 850g) dropping from a height of 0.4 m. The laboratory investigation on the mechanical
behaviour of raw and treated OR soil consisted of direct shear tests (Guidobaldi et al., 2017a),
unconfined compression tests and oedometer tests. Some results from oedometer tests are herein
presented. The evolution of the mechanical behaviour of treated samples over curing time will be dealt
with in the companion paper on lime-stabilised Orvieto soil, based on the chemo-physical evolution of
the system, with particular attention to the role of zeolites. The oedometer apparatus is a standard one.
Vertical stress was conventionally applied in successive steps (\( \Delta \sigma_v/\sigma_v = 1 \)). As the 90% of the
measured axial strain systematically takes place in less than one minute, stress increments were
applied each 30 minutes. Tests were performed in unsaturated conditions; however, no suction
measurements were performed before and during the tests. The 1D compressibility curves of raw samples of OR soil samples are reported in Figure 5 in terms of axial strain $\varepsilon_a$ vs. vertical stress, $\sigma_v$. The initial voids ratio of raw samples is in the range $e_0 = 0.86 \div 0.88$, which is rather low, but comparable to the typical values estimated for other pyroclastic soils in Central Italy (Cecconi et al., 2011). The initial response of not-treated samples on first loading (< 100 kPa) is moderately stiff. In the range of vertical stress in excess of about 200 kPa, large volumetric strains occur but the maximum stress level accomplished upon loading appears to be still too low from reaching a single normal compression line. The initial response on first loading is characterized by very gradual yield as the vertical stress increases, with significant volume changes even before major yield. The influence of curing time is very clear; the effect is mainly due to the development of stable bonds between aggregates deriving from the products of pozzolanic reactions (see Cambi et al., 2017).

![Figure 5. Compressibility curves from oedometer tests](image)

### Bibliografia


Cecconi M., Cambi C., Guidobaldi G., Pane V., Russo G., Vitale E., Deneele D.