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Reuse of Etna volcanic ash for construction of large civil infrastructures

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ABSTRACT: An experimental investigation on the effects induced by lime treatment on the volcanic ash from Mount Etna, Sicily, is developed. The need to valorize pyroclastic materials generated during volcanic eruptions arises from the large amounts of ashes produced during eruptive events and the resulting disposal issues. Lime treatment represents a possible strategy for reusing such materials for the construction of large civil infrastructure. A multiscale approach is carried out to determine physical and mechanical properties of the treated material. The link between the macroscopic evolution of ash properties and the ongoing of the reactions induced by lime are investigated by means of microstructural analysis. A preliminary study on the grain size of the material suitable for the lime treatment is carried out in order to provide a sufficient percentage of fine fraction to increase the ash reactivity in the alkaline environment. The influence of compaction characteristics and curing time on the evolution of the ash properties is considered in the study. Lime treatment induces an increase in unconfined compressive strength, which is relevant for curing times longer than 28 days. Mineralogical investigations showed a gradual development of pozzolanic activity over time with the formation of cementitious compounds starting from 14 days. The maximum reactivity of the ash in the alkaline environment is found between 40 and 60 days of curing, with total consumption of the excess hydrated lime in the system.

KEYWORDS: volcanic ash, lime treatment, mechanical behavior, chemo-physical evolution

1 INTRODUCTION

Lime treatment of soils is an increasingly common method for reusing excavated materials in large-scale civil infrastructure construction. In the context of growing sustainability requirements, major construction projects are expected to maximize the reuse of all materials generated on site, with the aim of minimizing waste production. This strategy contributes to reducing the exploitation of natural resource sites, limiting the use of landfills, and promoting environmental protection. Moreover, it leads to a significant decrease in CO_2 emissions and transportation costs.

In recent years, scientific research has led to a deeper understanding of the chemo-physical evolution induced by lime treatment in fine grained soils, as well as the benefits this process brings in terms of the geotechnical properties of the treated materials. Moreover, the technique has been extended to soils previously not considered suitable for treatment, such as volcanic soils, which are widely distributed in certain areas of central and southern Italy (Cecconi & Russo, 2012; Vitale et al., 2017). Recently, Cecconi & Russo (2024) highlighted, through multiscale experimental investigations, several distinctive features of the chemo-physical evolution and mechanical behavior of lime treated pyroclastic soils, confirming the effectiveness of the technique and its applicability even to pozzolanic soils with medium to coarse grain sizes. Cambi et al. (2016) evidenced that such soils exhibit minimal or no cation exchange activity, whereas Russo et al. (2015) observed the onset of pozzolanic reactions immediately upon the addition of lime. As a result, the microstructural reorganization of the system is characterized by a moderate particles aggregation, due to the limited cation exchange activity, despite a measurable reduction in specific surface area (Cecconi & Russo, 2013). A significant increase in small sized porosity highlights the formation of secondary phases, which are the products of pozzolanic reactions (Guidobaldi et al., 2018). At the volume scale of the sample, lime treated pyroclastic soils exhibit a marked improvement in mechanical response, both in terms of compressibility and shear strength, due to the cementation induced by hydrated secondary phases (Guidobaldi et al., 2017). The phenomenon of structural collapse, i.e., a typical behavior of such soils under partially saturated conditions when the degree of saturation increases under load, is significantly reduced, if not entirely eliminated, indicating the enhanced stability of the soil skeleton due to lime treatment (Cecconi & Russo, 2012).

The paroxysmal phenomena that have characterized Mount Etna volcanic activity in recent years have generated large amounts of debris, raising significant challenges related to their disposal. Thanks to recent dispositions established by Sicilian Region, the pyroclastic material covering public and private areas is now classified as a recoverable material, eligible for processing and reuse as a secondary raw material. As a result, the need to valorize large amounts of volcanic ash has prompted numerous studies aimed at characterizing this material, whose amorphous structure and elemental composition make it particularly attractive for practical applications and promising as a sustainable resource for use in production processes.

This study investigates the short and long term effects induced by lime on volcanic ash from Mount Etna, collected near Zafferana Etnea (CT) following the February 2021 eruption. The experimental activity focused on the analysis of the physical and mechanical properties of both natural and lime treated pyroclastic material as a function of curing time, as well as on the assessment of ash reactivity in the alkaline environment through microstructural investigations. The multiscale approach adopted in the experimental work enabled the assessment of the microstructural and mechanical changes of the treated ash as a function of the chemo-physical evolution of the system.

2 MATERIALS AND METHODS

2.1 *Materials*

The volcanic ash from Mount Etna used in the experimental work is sampled near Zafferana Etnea (CT), a town located on the southeastern side of Mount Etna, following the paroxysmal cycle that occurred between February 22 and 28, 2021. From a mineralogical point of view, the pyroclastic material is mainly composed of clinopyroxenes and plagioclase (primary phases), along with high amounts of an amorphous phase, consisting of volcanic glass derived from the fragmentation of the erupted magma (Figure 1a). From a chemical standpoint, the volcanic ash is composed of silicon (SiO_2 = 47.20 wt%) and aluminum (Al_2O_3 = 17.07 wt%), and rich in Fe, Mg, and Ca (Fe_2O_3 = 11.30 wt%; MgO = 5.29 wt%; CaO = 10.98 wt%). In terms of particle size distribution, the raw material collected on site (PE) is classified as sand with gravel (Figure 1b).

The lime used in the study is supplied by Unicalce S.p.A. and consists of calcium oxide (CaO) with a purity exceeding 90%.

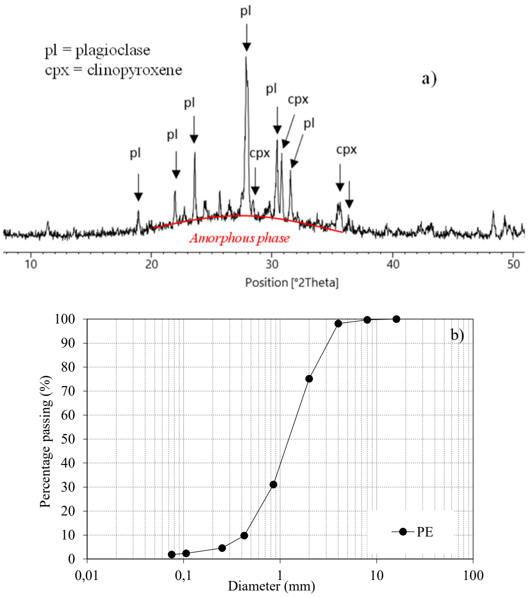

Figure 1. Volcanic ash (PE): a) X-ray diffraction pattern; b) grain size distribution curve.

2.2 *Initial Consumption of Lime (ICL)*

The minimum lime content required for treatment is determined based on the Initial Consumption of Lime (ICL), evaluated by means of pH measurements according to the ASTM D6276. In this procedure, a series of samples are prepared by progressively adding increasing amounts of lime (CaO) to the material, followed by mixing with distilled water to form a suspension. The pH of each mixture is then measured after a one hour equilibration period. Figure 2 shows pH trend as a function of CaO content. The lime percentage that yields a pH value of 12.4, corresponding to a solution saturated with calcium ions, represents the minimum amount required to ensure optimal conditions for the development of lime-induced reactions. In this study, the selected lime content was 3%.

2.3 *Sample preparation*

A preliminary study on the particle size distribution of the material is carried out to ensure an adequate fine fraction, aimed at increasing the specific surface area and enhancing reactivity in the presence of lime. For this purpose, a portion of the raw material is ground to obtain a particle size fraction smaller than 75 μm (PE_d < 0.075 mm), and the samples are prepared by mixing 70% of the fine fraction with 30% of the original raw material (PE_70-30) (Figure 3).

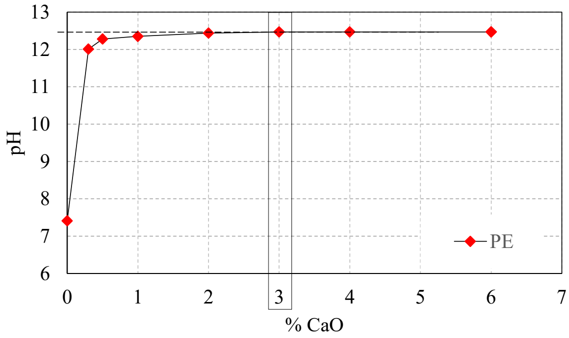

Figure 2. pH measurements as function of CaO content.

The treated samples are prepared by adding 3% by weight of quicklime powder and allowing the lime to hydrate for 24 hours prior to compaction. The samples are then cured for 24 hours, 7, 14, 28, 40, 60, and 90 days. The optimum water content and maximum dry density values for raw and lime treated samples are determined using Harvard compaction test. This method was selected due to the limited amount of material available, which did not allow the execution of standard Proctor-type compaction tests. Although not standardized, the Harvard compaction procedure is widely used in the literature for small sample volumes and provides reliable results for comparative purposes (e.g., Santos et al., 2019). In this study, the material is compacted in a cylindrical mold in three layers, each subjected to a fixed number of blows to achieve uniform compaction. The moisture content was adjusted to the desired value prior to testing. The resulting optimum water content and maximum dry density values are reported in Table 1.

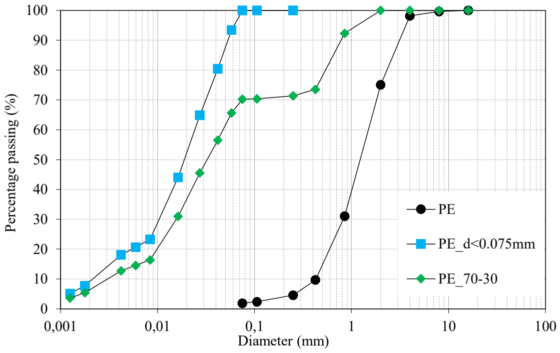

Figure 3. Grain size curves of the raw ash (PE), of the particle size fraction with diameter < 75 μm (PE_d<0.075mm), and of the mixture for lime treatment (PE_70-30).

Table 1. Compaction characteristics of samples.

ID	w_{opt} (%)	γ_{dmax} (g/cm^3)
PE_70-30	*16*	1.77
3CaO_PE	*17.5*	1.78

2.4 *Experimental procedures*

Uniaxial Compressive Strength tests (UCS) are performed on cylindrical specimens with a Wykeham Farrance device, at a maximum load of 5 kN and a displacement rate of 1.00 mm/min.

Ultrasonic wave velocities (UV) are recorded according to UNI EN 14579 using a BOVIAR DSP UTD 1004 Ultrasonic device, with a pair of 55 kHz transducers in direct arrangement. An adequate acoustic coupling between samples and transducers is achieved by placing a thin film of hydro soluble gel (GIMA, Italy).

The reactivity of the ash–water–lime system is investigated by means of X-ray diffraction (XRD). XRD analyses are performed using a Bruker AXS D8 Advance diffractometer with a Cu X-ray tube ($\lambda = 0.154$ nm).

Microstructural investigations are carried out through Scanning Electron Microscopy (SEM). Sample surfaces are examined using Zeiss Merlin VP Compact and JEOL JSM-5310 microscopes, both equipped with an Oxford Instruments microanalysis unit featuring an INCA X-Max solid-state detector.

3 RESULTS

Mechanical behaviour of raw and lime treated samples at increasing curing times (i.e., 7, 28, 40, 60, and 90 days) is reported in Figure 4. The stress-strain curve of the treated sample after 7 days of curing is quite similar to the untreated specimen, showing only a slight increase in unconfined compressive strength.

An improvement in the mechanical response of the treated ash, in terms of both stiffness and strength, is evident after 14 days of curing and become more significant after 40 days from lime addition, with the average shear strength increasing from 120 kPa to 710 kPa (Figure 4a).

Samples tested after 60 and 90 days of curing exhibit UCS values far higher than those observed for shorter curing times, as shown in Figure 4b, where the scale is adjusted accordingly. Peak values of 3780 kPa and approximately 4130 kPa are recorded for the 60 day and 90 day cured samples, respectively.

An experimental relationship between Unconfined Compressive Strength (UCS) and Ultrasonic Velocity (UV) values is reported in Figure 5. The correlation is obtained using the average maximum strength values from multiple UCS tests, whenever more than one test was performed, to account for experimental variability and improve the reliability of the results. Ultrasonic velocity is a physical parameter directly correlated with the mechanical performance of the material, and it tends to increase as the unconfined compressive strength increases. X Ray diffraction patterns of raw and lime treated samples at increasing curing time are shown in Figure 6. New reflections attributed to the presence of unconsumed portlandite are detected in the lime treated samples up to a curing time of 28 days. The intensities of these peaks decrease with increasing curing time, until their disappearance after 60 days of curing. These observations are consistent with the ongoing of pozzolanic reactions: portlandite dissociates in solution, providing calcium ions (Ca^{2+}) that react with silicon and aluminum, which in turn dissolve from the glassy phase of the ash in a highly alkaline environment. The stable cementitious compounds cannot be detected by X-rays due to their amorphous nature. Conversely, the typical crystalline phases of the ash (i.e., plagioclase and clinopyroxenes) are not altered by the treatment, remain stable in a strongly alkaline environment. The formation of hydrated compounds is also confirmed by SEM observations.

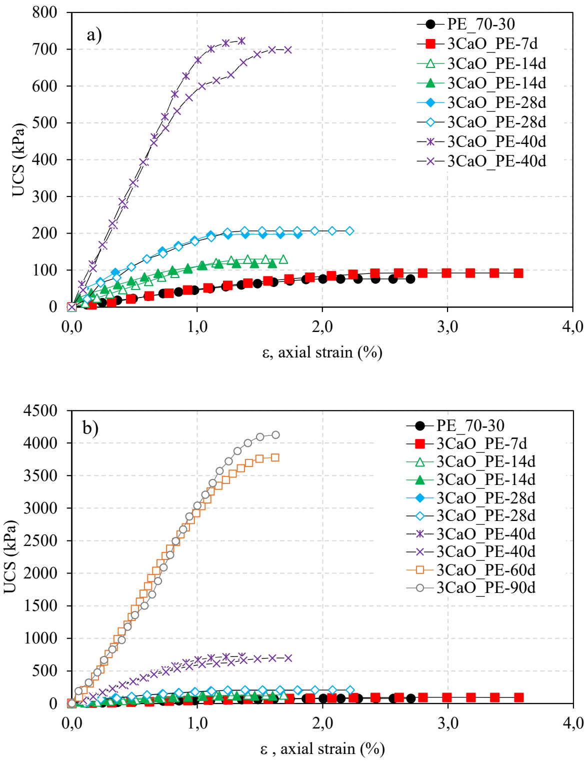

Figure 4. Stress strain curves of raw and treated samples at increasing curing times: a) up to 40 days of curing; b) up to 90 days of curing.

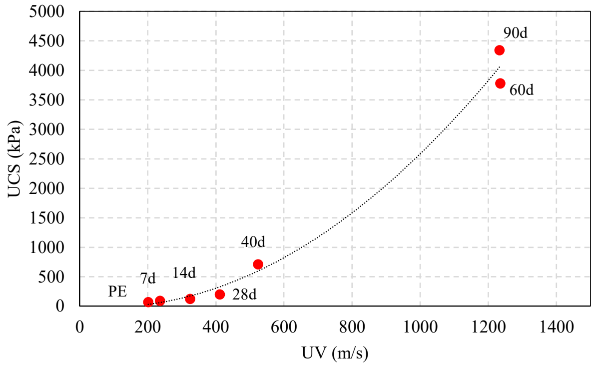

Figure 5. UCS vs. UV values at increasing curing time.

Figure 7 shows the SEM images of the raw ash and lime treated sample after 7, 14, and 60 days of curing. The volcanic ash is characterized by particles of varying shapes and sizes; the glassy phase consists of some larger grains and aggregates of small particles (Figure 7a). After 7 days of curing, the surface of the sample is not altered by the addition of lime (Figure 7b). The formation of hydrated compounds is clearly detected starting from 14 days after lime addition (Figure 7c). As curing time increases (i.e., 60 days), the sample shows a surface characterized by a fibrous texture of hydrated gel phases, which are responsible for the development of cementitious bonds between particles and, consequently, for the significant improvement in the mechanical performance of the treated material (Figure 7d).

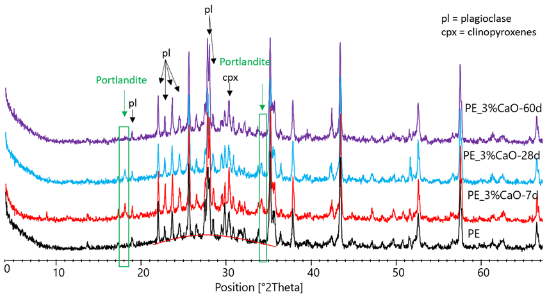

Figure 6. X Ray diffraction patterns of raw and lime treated samples at increasing curing time.

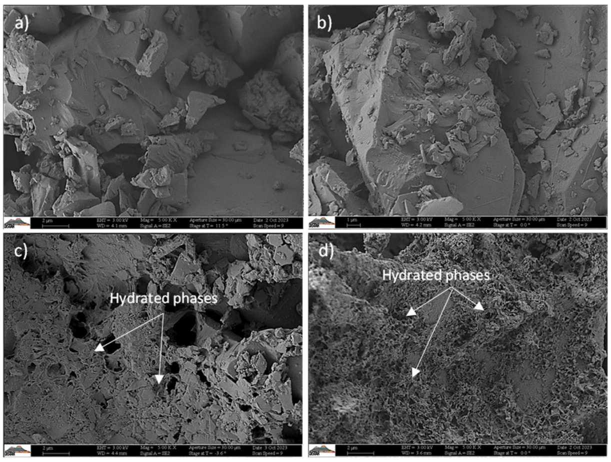

Figure 7. SEM observations: a) raw ash; lime treated ash: b) 7 days of curing; c) 14 days of curing; d) 60 days of curing.

4 CONCLUSIONS

The experimental study provides insights into the short and long term effects of lime addition on the mechanical performance and chemo-physical evolution of volcanic ash from Mount Etna. The research activity, based on a multiscale approach, highlights that lime addition does not significantly alter the mechanical response of the treated pyroclastic material within the first 7 days of curing. In the short term, no precipitation of newly formed mineralogical phases is observed after the treatment. Moreover, due to the lack of clay minerals, no microstructural reorganization related to ion exchange or flocculation processes occurs. Conversely, a significant improvement in mechanical behavior is observed between 40 and 60 days of curing, as a result of the bonding effect induced by the pozzolanic reactions. Cementitious compounds are clearly detected in the SEM images, forming a fibrous gel matrix in which the particles become progressively embedded. After 60 days of curing, the increase in shear strength shows a reduced dependency on curing time. This is consistent with the mineralogical evolution of the treated ash, which shows that beyond 60 days, no excess portlandite remains in the system to sustain further precipitation of hydrated phases from ongoing pozzolanic reactions. These preliminary results indicate that this improvement technique could potentially represent a viable solution to the environmental issues affecting the Sicilian region. A subsequent phase of the experimental activity will be focused on the implementation of the designed treatment on test sites to assess the effectiveness of the laboratory study.

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