E3S Web of Conferences **642**, 03031 (2025) https://doi.org/10.1051/e3sconf/202564203031
EUNSAT2025 + BGE

Synergic effect of hydrated lime and guar gum treatments on the shear strength and retention behaviour of a pyroclastic soil

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Abstract. In the pursuit of sustainable ground improvement methods, numerous studies have examined the geotechnical properties of soil treated with biopolymers, such as guar gum. Only a few works have instead explored the combination of biopolymers with traditional stabilisers like hydrated lime. This study experimentally investigates the synergic effect of guar gum (GG) and hydrated lime (HL) treatment on the shear strength and water retention behaviour of a pyroclastic silty sand. Soil samples were treated with either 2%HL and 1%GG, or 1%HL and 2%GG, where percentages are relative to the dry soil mass. The soil-water retention behaviour was measured using 'small tip' tensiometer probes installed in near-saturated samples exposed to ambient evaporation. Retention data were interpolated using the van Genuchten retention law, which was subsequently used to interpret results from direct shear tests conducted on both near-saturated and unsaturated soil samples. Treated samples exhibit higher water retention capacity and shear strength than the untreated ones, with the 2%HL and 1%GG treatment yielding the best performance. These findings highlight the potential of combining hydrated lime with guar gum to enhance geotechnical properties of soils, offering a sustainable approach to ground improvement.

1 Introduction

Increasing demand for sustainable ground improvement solutions has prompted both the scientific community and industry professionals to explore bio-based materials as soil stabilisers. Among these eco-friendly alternatives, biopolymers, such as guar gum, have emerged as promising substitutes for conventional energy-intensive binders, like cement and lime.

Guar gum is a hydrophilic polysaccharide extracted from the endosperm of a *Cyamposis tetragonoloba* plant. It readily hydrates in cold aqueous solutions, forming strong hydrogen bonds in polar solvents [1]. Owing to the presence of hydroxyl groups and hydrogen ions, guar gum forms highly viscous hydrogels [2,3], which exhibit significant potential for enhancing the geotechnical properties of soils [2,4–6]. However, most existing studies have focused on guar gum as a sole soil stabiliser [5,7–9], while only a few have investigated its combined application with traditional binders [10–12]. As a result, the potential to partially or fully replace these conventional energy-intensive binders remains largely underexplored.

Moreover, the majority of studies on biopolymer-based treatments have focused on fine-grained plastic soils under partially saturated conditions [8,13–15]. In contrast, the treatment of coarse-grained soils with biopolymers remains poorly understood. Additionally, the adverse effects of liquid water on biopolymeric bonds are often overlooked.

To address these knowledge gaps, this study investigates the synergic treatment of a coarse pyroclastic silty sand using combinations of hydrated lime and guar gum under both unsaturated and near-saturated conditions. The soil has been sourced from the shallow layers of loose pyroclastic deposits in the Lattari Mountains in the Campania region (Southern Italy) [16,17], which are prone to flow-like landslides. In this area, as well as in other areas equally subjected to flowslides, ground improvement measures could be beneficial to improve slope stability. Hydrated lime is widely used to enhance the geotechnical properties of soils through flocculation and pozzolanic reactions [18]. However, the production of hydrated lime requires processing of scarce mineral resources at high temperatures, thus negatively impacting on environmental sustainability while increasing greenhouse gas emissions [19,20].

This works aims to reduce the reliance on hydrated lime by synergically incorporating guar gum as a complementary stabiliser. Results from evaporation tests and direct shear tests show that the proposed treatment enhance both water retention capacity and shear strength, highlighting its potential for mitigating shallow flowslides in pyroclastic covers.

2 Materials and Methods

The soil used in this study is a pyroclastic silty sand, collected from a depth of 1 m at the Pagani test site (40°44'23.04" N, 14°37'43.39" E; elevation 126 m) in the Lattari Mountains (Campania, Italy), where volcanic ash layers form a substrate prone to shallow flowslides [16]. Figure 1 shows the grain size distribution of 6 different samples of the tested soil [16, 17]. For the experimental campaign, the natural soil was first sieved through a 4.75 mm sieve to remove larger grains that could introduce spurious local effects during retention and direct shear tests while preserving the original granularity as much as possible.

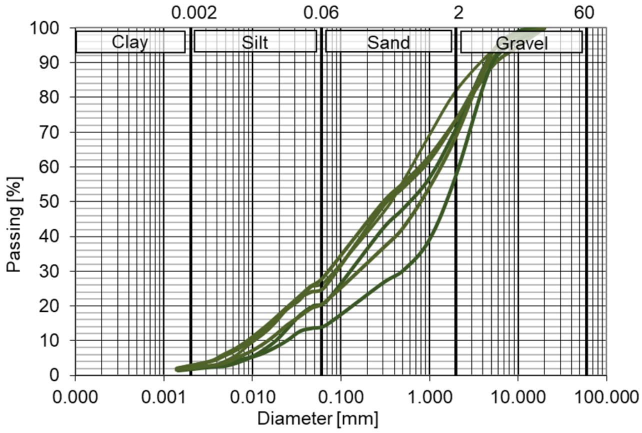

Fig. 1. Grain size distribution of the pyroclastic soil used in this study **[21]** .

The soil was first dried at 105 °C for at least 24 hours and then compacted into samples, which were tested either untreated or treated with a synergistic combination of hydrated lime (HL) and guar gum (GG). HL was supplied by the Italian company Grigolin SpA, while GG was purchased from the German company KoRo Handels GmbH.

Soil samples were treated with either 2% HL and 1% GG (2%HL–1%GG) or 1% HL and 2% GG (1%HL–2%GG), where percentages are intended as relative to the dry soil mass. The total stabiliser content was capped at 3%, which is typical for ground improvement applications.

HL was dry mixed with the soil in the specified proportions, while GG was incorporated using a wet mixing technique. Specifically, the soil-HL dry mix was moistened by adding 20% of a GG solution in demineralised water, at concentrations of 0.05 kg/l for the 2%HL–1%GG samples and 0.1 kg/l for the 1%HL–2%GG samples. Untreated samples (0%HL–0%GG) were also prepared by mixing the soil with 20% of demineralised water. A moisture content of 20% was chosen, for both treated and untreated samples, to ensure workability during sample preparation. After mixing, the moist material was sealed in plastic bags and stored for 7 days to facilitate moisture equalisation. Then, the moist mixes were statically compacted at a target dry density, ρ_d, of approximately 1050 kg/m^3, matching the in-situ density of the pyroclastic cover at 1 m depth [16,17].

Table 1 summarises the main properties of all samples after compaction and before testing, including specific gravity G_s, void ratio e, porosity n, degree of saturation S_r and volumetric water content θ. The specific gravity G_s of the treated samples in Table 1 is the weighted average of the specific gravities of soil, HL and GG, which are 2.70, 2.48 and 1.25, respectively [16,22,23].

Table 1. Properties of compacted samples.

	0%HL-0%GG	2%HL-1%GG	1%HL-2%GG
HL content (%)	0	2	1
GG content (%)	0	1	2
Liquid content (%)	20		
ρ_d (kg/m^3)	1057	1043	1055
G_s (-)	2.60	2.58	2.57
e (-)	1.46	1.48	1.44
n (-)	0.594	0.597	0.590
S_r (-)	0.36	0.35	0.36
θ (-)	0.21	0.21	0.21

Evaporation tests were performed on cylindrical specimens (10.7 cm height, 4.4 cm diameter) using a 'small tip' tensiometer probe (Soilmoisture Equipment, 2100F) to measure matric suction. This tensiometer probe features a porous ceramic tip that is placed in contact with the soil sample and connected to a water reservoir with a manometer measuring suction, as shown in Figure 2. Before testing, the porous ceramic tip and the connecting pipe were carefully saturated. The ceramic tip was then inserted at the bottom of a cylindrical plexiglass mould, where the soil samples were statically compacted at a dry density of 1050 kg/m^3 and subsequently flooded from the top surface. The samples did not attain, however, full saturation due to air bubbles trapped within the soil pores, limiting the maximum degree of saturation to approximately 82%. After flooding, the top of the mould was covered with a double plastic film for 24 hours to facilitate moisture equalisation within the sample. The sample was left uncovered during the day to enable pore water evaporation and, hence, the development of suction. Thereafter, it was covered during the night to promote water homogenisation. This process ensured that both matric suction and sample mass could be measured under equilibrium conditions each morning. The procedure was repeated for several consecutive days until cavitation of the tensiometer probe.

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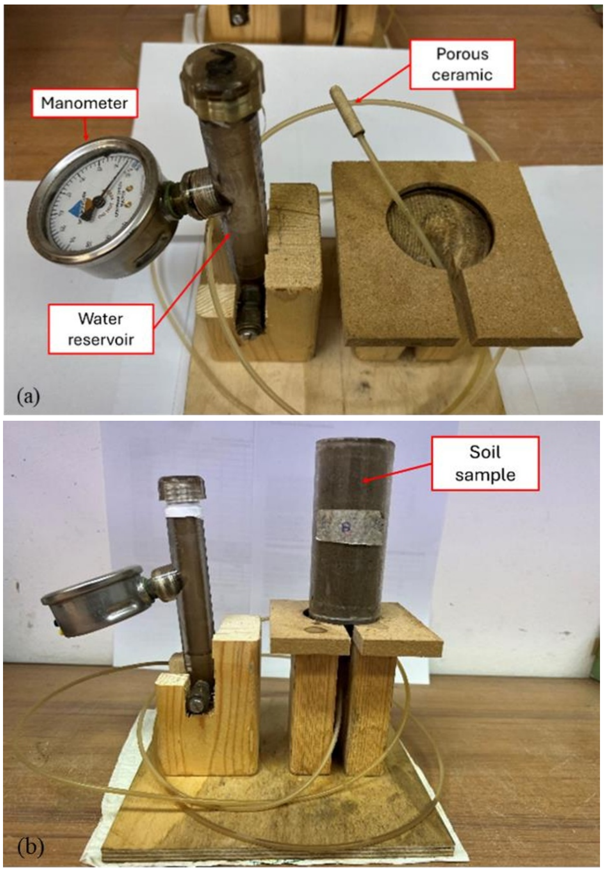

Fig. 2. Small tip tensiometer probe (a) and experimental set-up to measure the soil-water retention during evaporation tests (b).

Direct shear tests were also conducted both under unsaturated conditions on the as-compacted samples and under near-saturated conditions after flooding the shear box. As in the evaporation tests, full saturation was not attained due to trapped air within the soil pores, with samples reaching a maximum degree of saturation of about 82%. Before shearing, samples were consolidated under variable vertical stresses, σ_v from 15 kPa to 40 kPa to replicate in-situ conditions at the sampling depth. In agreement with [24], the horizontal displacement rate during shearing, v_H was defined as:

$$v_H = 125/t_{100} \leq 25\ \mu m/min \tag{1}$$

where t_{100} is the time in minutes at the end of the primary consolidation as illustrated in Figure 3. All samples exhibited a v_H exceeding the upper limit of Equation 1 and hence a constant shearing rate of 25 µm/min was used in all cases.

The results from the direct shear tests were interpreted according to the extended Mohr-Coulomb strength criterion, which applies to both saturated and unsaturated soils, as detailed in the following sections.

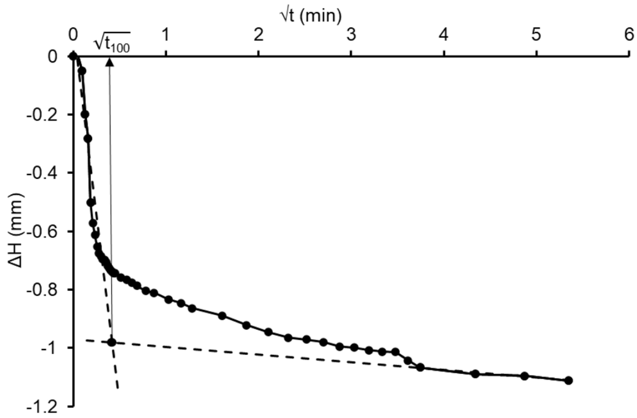

Fig. 3. Determination of t_{100} from the consolidation curve of the saturated 1% HL-2% GG sample under a vertical effective stress of 40 kPa (NF P94-071-1, 1994).

3 Results and discussion

3.1 Evaporation tests

Figures 4(a) and (b) presents the retention data of both untreated and treated samples in terms of degree of saturation S_r and volumetric water content θ, respectively. The matric suction s and the gravimetric water content w are measured during the evaporation tests. Instead, the degree of saturation S_r and volumetric water content θ are computed from the gravimetric water content w as:

$$S_r = wG_s/e \tag{2a}$$
$$\theta = S_r(e/1+e) \tag{2b}$$

where e is the void ratio and G_s is the specific gravity of Table 1. The values of S_r and θ are determined by assuming that the void ratio e remained constant during evaporation and equal to the compaction value in Table 1, which is reasonable for the tested soil [25]. The experimental retention curves were then interpolated using the following relationship:

$$\begin{aligned} S_r &= S_{r,e}(S_{r,max} - S_{r,res}) + S_{r,res} \\ &= (S_{r,max} - S_{r,res})/(1+(\alpha s)^n)^m + S_{r,res} \end{aligned} \tag{3}$$

where $S_{r,max}$ and $S_{r,res}$ are the maximum and residual degree of saturation, respectively, while the effective degree of saturation $S_{r,e}$ is calculated by the van Genuchten equation [26] varying between one and zero as suction increases from zero to infinity. The maximum degree of saturation $S_{r,max}$ is the value at the start of the test, while the residual degree of saturation $S_{r,res}$ is calculated from the void ratio in Table 1 assuming a residual volumetric water content of 0.12 [17,25]. For simplicity and consistency, it is assumed that HL and GG treatments do not affect the maximum and residual degrees of saturation.

Figures 4(a) and (b) show the Van Genuchten curves fitted to the experimental data for both untreated and treated samples. These curves were calibrated by simultaneously adjusting the two independent parameters α and n, while the parameter m was set as $1 - (1/n)$. Table 2 summarises the Van Genuchten parameters for all sample compositions.

Results show that treated samples retain more water than untreated ones, consistent with previous studies on HL- and GG-treated silty soils [18,27]. The 2%HL–1%GG sample exhibited the highest water retention capacity. This is attributed to the HL treatment reducing macro- and micro-pores size and void interconnectivity [28]. Additionally, GG is a hydrophilic biopolymer and naturally retains large volumes of water within hydrogel bonds [9,29]. Soil water retention is particularly enhanced in the intermediate section of the retention curve, while differences with the untreated samples diminish towards extreme saturation levels, justifying the assumption of common values of maximum and residual degrees of saturation. Nevertheless, increasing GG content beyond 1% reduces retention gains, likely due to chemical interactions between the two binders. Analysing these interactions is however beyond the scope of this study.

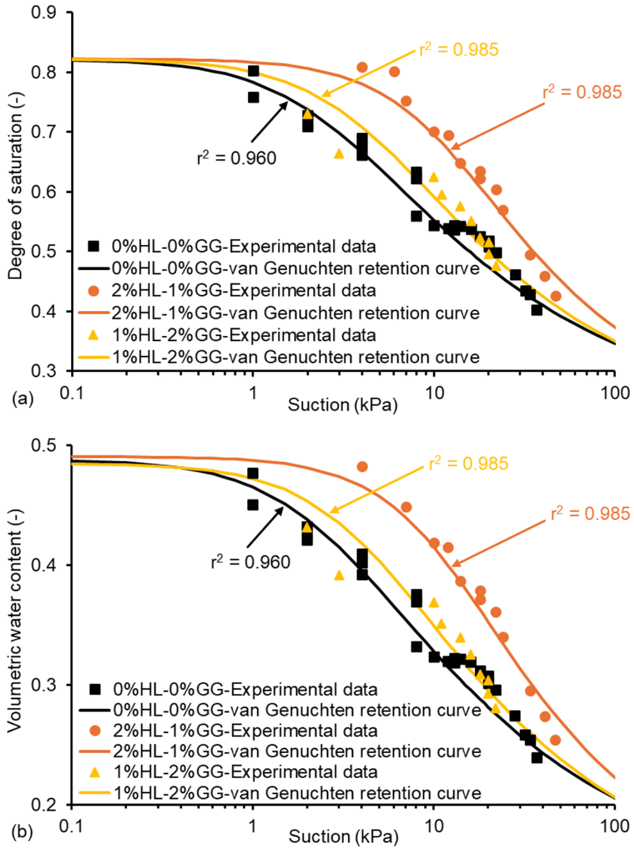

Fig. 4. Soil-water retention curves in terms of the degree of saturation (a) and volumetric water content (b).

Table 2. Soil-water retention parameters for all sample compositions.

Sample composition	$S_{r,max}$ (-)	$S_{r,res}$ (-)	α (1/kPa)	n (-)	m (-)
0%HL-0%GG	0.82	0.20	0.372	1.400	0.286
2%HL-1%GG			0.092	1.570	0.363
1%HL-2%GG			0.234	1.450	0.310

3.2 Direct shear tests

All samples exhibited strain hardening behaviour, with shear stress increasing monotonically as horizontal displacement grew. The strength τ was therefore taken as the maximum value measured at the end of shearing, corresponding to a horizontal displacement of about 6.7 mm (i.e. ~10% of the sample diameter), in agreement with [24]. The measured values of shear strength are plotted in Figure 5 for both near-saturated and unsaturated tests conducted on each material composition, along with the corresponding extended Mohr-Coulomb interpolation:

$$\tau = c' + \sigma_v'' \tan \varphi' \quad (4)$$

where c' and φ' are the soil effective cohesion and angle of shearing resistance, respectively, while σ_v'' is the Bishop vertical stress [30]. The Bishop vertical stress is here formulated in terms of the effective degree of saturation $S_{r,e}$, [31] as:

$$\begin{aligned}\sigma_v'' &= (\sigma_v - u_a) + S_{r,e}(u_a - u_w) \\ &= (\sigma_v - u_a) + S_{r,e}s \end{aligned} \quad (5)$$

where σ_v, is the total vertical stress, u_a is the pore air pressure and u_w is the pore water pressure. Equation 5 reduces to the Terzaghi effective when $S_{r,e}$ equals one (i.e., $S_r = S_{r,max} = 0.82$). The effective degree of saturation $S_{r,e}$ in Equation 5 is calculated using the experimental degree of saturation S_r, along with the values of $S_{r,max}$ and $S_{r,res}$ from Table 2. This value of $S_{r,e}$ is then inserted into the calibrated Van Genuchten retention curve (Figure 4) to determine the corresponding matric suction s.

At the end of the direct shear tests, samples exhibited slight variations in porosity, i.e. less than 2% compared to the as-compacted value in Table 1. This minor change is considered to have a negligible effect on the retention behaviour of the soil, justifying the use of the retention curves in Figure 4 for determining soil suction in Equation 5. Table 3 summarises the values of the effective cohesion and angle of shearing resistance for all sample compositions tested in this work. The effective friction angle of the untreated soil is consistent with the values reported in the literature for pyroclastic soils in the Campania Region (35°–38°) [17]. However, inspection of Figure 5 indicates that the experimental data tend to deviate from the linear envelope at low vertical stresses, suggesting that a curvilinear failure criterion would be more representative. The adoption of a more sophisticated failure criterion is considered beyond the scope of this study and future research should address this aspect.

The combination of HL and GG led to an increase in soil shear strength compared to the untreated soils, within the stress range examined in this study. The 2%HL–1%GG sample exhibited the highest shear strength, with effective cohesion increasing from 0.0 kPa (untreated) to 8.9 kPa, though the friction angle experienced a slight reduction from 36° to 34°. The cohesion gain stems from pozzolanic reactions forming cementitious compounds [32,33], and guar gum hydrogels forming an adhesive matrix via hydrogen bonding [4,34]. However, these hydrogels also reduce the friction angle by coating soil particles and diminishing the intergranular sliding resistance [35,36].

Replacing a larger part of HL with GG led to a reduction of shear strength, though the 1%HL–2%GG sample still outperformed the untreated soil. The friction angle of the 1%HL–2%GG sample remained consistent with that of the 2%HL–1%GG sample, while the effective cohesion slightly decreased to 7.9 kPa.

This finding contrasts with studies reporting a more pronounced increase of cohesion at higher GG content [6,36]. This discrepancy likely stems from the 'near-saturated' conditions imposed during direct shear tests. Prolonged exposure to liquid water weakens hydrogen bonds and reduces the viscosity of the guar gum hydrogel [1]. Conversely, HL treatment is less affected by wet conditions, preserving higher cohesion compared to the untreated soil.

Overall, results highlight the potential of the proposed treatment for stabilising flowslides in shallow pyroclastic covers, as even a modest increase of cohesion, on the order of few kilopascals, can significantly contribute to the mitigation of shallow landslides. However, the slight reduction in the friction angle suggests a reduced effectiveness at greater depths, where the frictional component of soil strength tends to govern slope stability.

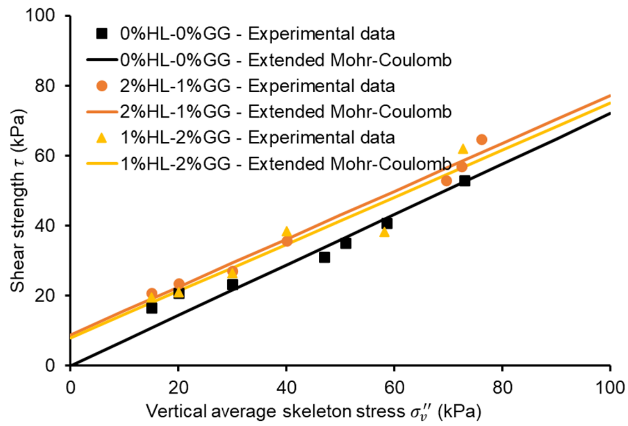

Fig. 5. Variation of shear strength with vertical average skeleton stress for the three sample compositions.

Table 3. Shear strength parameters for all sample compositions.

Sample composition	***c'* (kPa)**	***φ'* (°)**
0%HL-0%GG	0.0	36
2%HL-1%GG	8.9	34
1%HL-2%GG	7.9	34

4 Conclusions

This paper presented some results from an experimental programme of evaporation and direct shear tests on both untreated and treated pyroclastic soil samples. The treatment combined a conventional chemical binder, hydrated lime, with the biopolymer guar gum in varying proportions. The main findings are summarised as follows:

- Treated samples exhibited higher water retention capacity than untreated ones within the relatively low suction range of 0 – 60 kPa explored in this study, with the 2%HL–1%GG sample showing the greatest value.
- Treated samples exhibited greater shear strength than untreated ones across the relatively low vertical stress range of 15 – 45 kPa explored in this study.
- Samples with the highest HL content exhibited the highest shear strength, which slightly decreased as the GG content increased.

These results underscore the potential of the proposed treatment as an effective ground improvement measure for mitigating shallow flowslide risks. Future research should include micro-scale analysis (e.g. scanning electron microscopy) and extend this investigation from the laboratory scale to real-world slope applications.

The contribution from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005) through funding of the last author in the framework of the RETURN Extended Partnership is gratefully acknowledged.

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