

Assessing the Effects of Motor Oil, Gypsum, and Sodium Chloride on the Behavior of Lime-improved Grey High Plasticity Clay

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Abstract

This study evaluates the effects of motor oil (MO), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), and sodium chloride (NaCl) as additives on the geotechnical properties of Grey High Plasticity Clay (GS) improved with 0, 4, and 8% lime (L). Each additive was incorporated into GS at 0, 2, and 4% by dry weight. Unconfined compressive strength (UCS) tests were performed on specimens compacted at their optimum moisture content (OMC) and maximum dry density (MDD) after 7, 30, and 120 days of curing. Results indicated that the plasticity index (PI) of GS decreased with the addition of additives, whether used alone or combined with lime. The introduction of any additive into natural or lime-improved GS enhanced soil classification, with gypsum and NaCl exhibiting a more pronounced effect. Additionally, MDD decreased while OMC increased as lime content rose, due to cation exchange reactions leading to clay particle flocculation. However, MDD increased with higher additive contents, whereas OMC decreased with increasing MO and NaCl but rose with gypsum. UCS values improved significantly with any additive, particularly after 120 days of curing. Microstructural analysis *via* scanning electron microscopy (SEM) revealed the formation of cementitious compounds and/or ettringite in GS samples improved with lime alone or in combination with gypsum, contributing to strength enhancement.

Keywords

Grey High Plasticity Clay, lime, motor oil, gypsum, sodium chloride, geotechnical properties

1 Introduction

The rapid expansion of urban infrastructure and population growth have significantly reduced access to high-quality construction sites, often forcing engineers to build on soils with poor geotechnical characteristics. To address this challenge, various soil improvement techniques have been developed to enhance stability and reduce deformation-related risks in construction projects. The selection of an appropriate soil treatment method must consider both economic feasibility and environmental sustainability. Among these methods, chemical stabilization using binders such as cement and lime has been widely practiced for decades [1–3].

Lime stabilization, in particular, is known for its immediate impact on soil consistency, making it a preferred technique for short-term applications [4]. Over longer curing periods, this method enhances mechanical properties by initiating pozzolanic reactions, leading to the formation of cementitious compounds such as calcium silicate

hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), which contribute to strength development [5]. The use of mineral additives in soil stabilization has also gained prominence in civil engineering due to its effectiveness in mitigating swelling-related damage in expansive soils, a common cause of structural deterioration [6]. Additionally, stabilizing problematic soils with mineral additives can significantly reduce transportation costs and construction time.

While soils with high organic content, as indicated by elevated LOI and low MDD values, have been traditionally classified as unsuitable for lime stabilization due to inhibited pozzolanic reactions, recent research underscores the potential for successful treatment through optimized mix designs and chemical additives. Foundational work demonstrates that high-organic-content clays can be stabilized with optimized lime content alone, while contemporary studies reveal that chemical additives like sodium chloride (NaCl) can effectively mitigate the adverse effects

of organic matter, enabling significant long-term strength gains. Specifically, studies report successful stabilization of soft clay with 14% organic content [7], and a seven-fold strength increase in marine clay using NaCl supplementation [8]. This study directly engages with this paradigm, hypothesizing that a composite lime-NaCl system can enhance the engineering properties of contaminated, high-LOI clays, offering a practical strategy for soils traditionally considered unsuitable.

However, in certain soils, the presence of sulfates can adversely affect the stabilization process [9]. Sulfates exist in either soluble form in groundwater (SO_4^{2-} ions) or as solid compounds in sedimentary formations, such as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$), arcanite (K_2SO_4), and thenardite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) [10]. Moreover, the oxidation of pyrite (FeS_2) under specific conditions can lead to the formation of gypsum through a series of chemical reactions [11]. Numerous studies have explored the impact of sulfates on the physico-mechanical behavior of stabilized soils [7, 8, 12–15].

Lime stabilization, whether used alone or in combination with other additives, has demonstrated significant benefits in improving soil properties. This process relies on the cation exchange capacity (CEC) of clay particles, which is influenced by their negatively charged surfaces [10]. These charges create repulsive forces between particles, but when lime (CaO) is introduced in the presence of water, calcium hydroxide [$\text{Ca}(\text{OH})_2$] forms, releasing calcium (Ca^{2+}) and hydroxyl (OH^-) ions. The calcium ions reduce repulsive forces, promoting particle aggregation and flocculation, which enhances soil cohesion [16]. As a result, lime addition reduces the plasticity index (PI) [1], lowers maximum dry density (MDD), and increases optimum moisture content (OMC) [2, 4].

Over time, the rise in calcium concentration from lime or cement increases the soil's pH, facilitating the dissolution of alumina (Al_2O_3) and silica (SiO_2) minerals. These dissolved components subsequently react with lime through pozzolanic reactions, forming additional cementitious products such as C-S-H, C-A-H, and calcium aluminosilicate hydrates (C-A-S-H) [17]. These compounds enhance unconfined compressive strength (UCS) [2] and shear strength [18, 19], while reducing swelling potential [20] and compressibility [21].

Despite these benefits, the presence of sulfates in the soil can significantly disrupt the stabilization process. Sulfates interfere with cation exchange and pozzolanic reactions [22], potentially rendering certain soils unsuitable for treatment. In some cases, the reaction between lime and sulfates leads

to the formation of expansive minerals such as ettringite, which can cause structural damage [23]. The extent of this damage depends on soil composition [7, 8], additive concentration, and environmental conditions [23]. Furthermore, research by Kinuthia et al. [12] suggests that sulfate effects vary based on the associated cation type.

In addition to lime, the use of volcanic materials rich in reactive silica has been explored as an alternative stabilization approach. When used alone or with lime, these materials enhance soil properties by participating in pozzolanic reactions [24]. In Algeria, natural pozzolana is abundant in regions such as Beni-Saf [25] and has been successfully employed in lime-stabilized clayey soils, particularly in the presence of monovalent (Na_2SO_4) and divalent ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) sulfates, to improve plasticity, compaction, UCS, and durability [26].

Despite extensive research on lime stabilization and sulfate interactions, there is limited literature on the influence of motor oil (MO), gypsum, and sodium chloride (NaCl) on the geotechnical behavior of lime-improved clayey soils. This study aims to investigate the effects of these additives on Atterberg limits, compaction characteristics, and UCS, thereby contributing to a better understanding of their role in soil improvement.

2 Experimental study

2.1 Materials used

2.1.1 Grey High Plasticity Clay and distilled water

Throughout this study, the abbreviation GS refers to the Grey High Plasticity Clay, classified as CH according to USCS. This soil was collected from an embankment project site located in Haouche El-Ghaba, near Chelif town in western Algeria (Fig. 1). Its particle size distribution curve (Fig. 2) was determined through dry sieving, following NF P94-056 standard [27]. Additionally, the fraction of GS and lime (L) passing the 80- μm sieve was measured at 85% (Table 1) using a wet sieving method, where distilled



Fig. 1 GS obtained from an embankment project site (Haouche El-Ghaba) near Chelif town in the west of Algeria

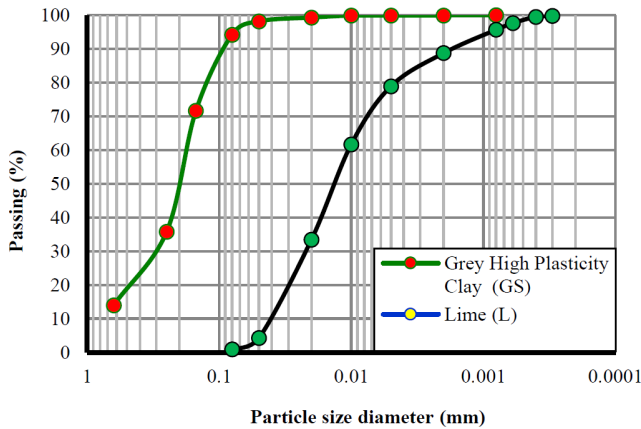


Fig. 2 Particle size distribution curve of the GS studied

Table 1 Physico-mechanical properties of the GS

Physico-mechanical properties	Grey soil (GS) (%)
Depth (m)	4.0
Natural water content (%)	32.90
Specific gravity (-)	2.71
Passing 80 μm sieve (%)	85.0
Liquid limit (LL) (%)	82.8
Plastic limit (PL) (%)	32.2
Plasticity index (PI) (%)	50.6
Classification system (USCS) (-)	CH
Optimum moisture content (W_{OPN}) (%)	28.30
Maximum dry density ($\gamma_{d_{max}}$) (kN/m ³)	13.80
Unconfined compressive strength (UCS) (KPa)	100
Loss on ignition (%)	17.03

water was employed to enhance clay particle dispersion. This approach ensured maximum particle separation, allowing for an accurate assessment of the clay content.

The mineralogical composition of GS was analyzed through X-ray diffraction (XRD), with the results presented

in Fig. 3. The excavated soil sample was carefully packed in plastic bags and transported to the laboratory for further preparation and testing. A series of classification tests were conducted to evaluate its physico-mechanical and chemo-mineralogical characteristics, as detailed in Tables 1 and 2. In this study, distilled water was specifically used for Atterberg limits tests to ensure consistency in results.

2.1.2 Lime (L)

The lime used in this study was added to the GS with 0, 4 and 8% by weight of dry soil, which is commercially available lime typically used for construction purposes, especially for road structures. It is a very fine lime which can pass through an 80-μm sieve opening. The activity level of the lime used was 96%. The physico-chemical properties of these additives are presented in Table 3.

2.1.3 Motor oil (MO)

In this study, the MO was used as a contaminant element. The predetermined amounts of this element were mixed (concentrations used are 0, 2 and 4% by weight of dry soil) with water and then added to both the natural GS and lime-improved GS mixes. The physico-chemical properties of the MO used are shown in Table 4.

2.1.4 Gypsum

According to FAO [28], gypsum in Algeria occupies 7966.3 km² which represent 3.3% of the surface of the country and 12.2% of the total surface of gypsum in the world. Overall, the presence of gypsum in Algeria is reported in many regions such as Oran, Mostaganem, Saïda, Tiaret, Ksar-Chellala, Djelfa, M'Sila, the borders of chotts and Zahrez,

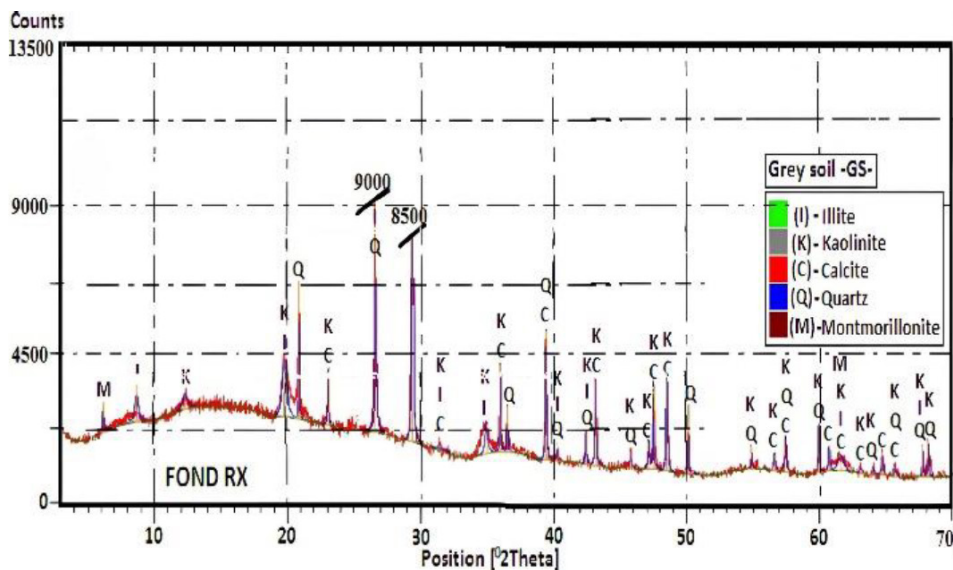


Fig. 3 Mineralogical composition of the GS based on X-ray diffraction analysis

Table 2 Chemico-mineralogical properties of the GS

Chemico-mineralogical properties	Chemical formula	Grey soil (GS) (%)
Calcium oxide	CaO	14.43
Magnesium oxide	MgO	1.99
Iron oxide	Fe ₂ O ₃	5.56
Alumina	Al ₂ O ₃	14.15
Silica	SiO ₂	43.67
Sulfite	SO ₃	0.04
Sodium oxide	Na ₂ O	0.34
Potassium oxide	K ₂ O	1.96
Titan dioxide	TiO ₂	0.65
Phosphorus	P ₂ O ₅	0.18
pH	–	9.18
Calcite	CaCO ₃	26.0
Albite	NaAlSi ₃ O ₈	–
Illite	2K ₂ O · Al ₂ O ₃ · 24SiO ₂ · 2H ₂ O	16.0
Kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄	12.0
Montmorillonite	Al ₂ ((Si ₄ Al)O ₁₀)(OH) ₂ · H ₂ O	20.0
Chlorite	Mg ₂ Al ₄ O ₁₈ Si ₃	–
Ferruginous minerals	–	6.0
Organic matter	–	0.33

Table 3 Physico-chemical properties of the lime used

Physical / chemical name	Chemical formula	Lime (L) (%)
Physical form	–	Dry white powder
Specific gravity	–	2.0
Over 90 μm (%)	–	< 10.0
Over 630 μm (%)	–	0
Insoluble material (%)	–	< 1.0
Bulk density (g/L)	–	600–900
Loss on ignition	–	–
Calcium oxide	CaO	> 83.3
Magnesium oxide	MgO	< 0.5
Iron oxide	Fe ₂ O ₃	< 2.0
Alumina	Al ₂ O ₃	< 1.5
Silica	SiO ₂	< 2.5
Sulfite	SO ₃	< 0.5
Sodium oxide	Na ₂ O	0.4–0.5
Potassium oxide	K ₂ O	–
Carbon dioxide	CO ₂	< 5.0
Titan dioxide	TiO ₂	–
Phosphorus	P ₂ O ₃	–
Calcium carbonates	CaCO ₃	< 10.0

Bousaâda, Hodna, Mechria, El-Bayadh, Khenchla, Batna, Adrar, Ouargla, Ain-Sefra, Biskra, Touggourt, Timmons and El-Golea. However, the gypsum used in this study (obtained from Ksar-Chellala), commercially available gypsum typically used for construction purposes, is very fine gypsum

Table 4 Summary of the motor oil (MO) used in the study

Properties	MO
Color	Shaded color
Physical state	Liquid
Specific gravity (–)	2.71
Flash point (°C)	42
Fire point (°C)	203
Viscosity (mm ² /s at 40 °C)	75.5
Density (g/cm ³)	0.77

which can pass through an 80-μm sieve opening, and with a purity of more than 99%. The physico-chemical properties of this element are depicted in Table 5.

2.1.5 Sodium chloride

The chemical element used in this study is NaCl which is commercially available NaCl in powder form. The physico-chemical properties of this element are depicted in Table 5.

2.2 Experimental program

Laboratory tests on plasticity, compaction and UCS were conducted on the selected GS. Several combinations of MO, gypsum, NaCl, and lime were used for its improvement. According to the experimental program shown in Table 6 [29, 30], there are a total of 18 combinations performed based on the GS for each test. However, Atterberg's limits, compaction and UCS tests were performed according to ASTM D4318-00 [31], ASTM D698-00 [32] and ASTM D2166-00 [33] standards, respectively.

Table 5 Physico-chemical properties of chemical compounds used

Physico-chemical properties	Gypsum (%)	Sodium chloride (%)
Physical form	Dry white powder	Dry white powder
Chemical formula	CaSO ₄ · 2H ₂ O	NaCl
Molar weight (g/mol)	172.2	58.44
Solubility in water (g/L at 25°C)	2.04	360
Density (g/cm ³)	2.32	2.17
Assay (dried)	99	99
Insoluble matter	0.03	0.01
Chloride (Cl)	0.002	–
Nitrate (NO ₃)	0.002	0.001
Calcium (Ca)	–	0.003
Phosphorus (PO ₄)	0.001	–
Ammonium (NH ₄)	0.01	0.003
Carbonate (CO ₃)	0.1	0.08
Heavy metals (Pb)	0.001	0.001

Table 6 Summary of the mix combinations tested for the GS

Designation	Proportion of each element (%)				
	GS	Lime	MO	Gypsum	NaCl
GS+0%L [29, 30]	100	0	0	0	0
GS+4%L [29, 30]	96	4	0	0	0
GS+8%L [29, 30]	92	8	0	0	0
GS+2%MO	98	0	2	0	0
GS+2%MO+4%L	96	4	2	0	0
GS+2%MO+8%L	90	8	2	0	0
GS+4%MO	96	0	4	0	0
GS+4%MO+4%L	92	4	4	0	0
GS+4%MO+8%L	88	8	4	0	0
GS+2%Gypsum	98	0	0	2	0
GS+2%Gypsum+4%L	94	4	0	2	0
GS+2%Gypsum+8%L	90	8	0	2	0
GS+4%Gypsum	96	0	0	4	0
GS+4%Gypsum+4%L	92	4	0	4	0
GS+4%Gypsum+8%L	88	8	0	4	0
GS+2%NaCl	98	0	0	0	2
GS+2%NaCl+4%L	94	4	0	0	2
GS+2%NaCl+8%L	90	8	0	0	2
GS+4%NaCl	96	0	0	0	4
GS+4%NaCl+4%L	92	4	0	0	4
GS+4%NaCl+8%L	88	8	0	0	4

The variations in LL, PL, PI, soil classification, MDD, OMC and UCS of the unimproved and lime-improved GS samples with and without MO, NaCl and gypsum were studied. It should be noted that the specimens (with and without MO, gypsum and NaCl) were performed by compaction at the MDD and OMC results obtained from compaction tests. In addition, the obtained results of lime effects on Atterberg's limits and UCS [29] and compaction [30] of the GS will be used to make a comparison study with the new findings of the present research.

2.3 Tests procedures and specimens preparation

2.3.1 Atterberg's limits tests

For the Atterberg's limits tests [31], the air-dried GS was initially mixed (in a dry state) with the predetermined quantity of lime (0, 4 and 8%), MO (in a wet state), NaCl and gypsum (in a dry state). Then, the distilled water was added to the soil mixtures for the Atterberg's limits tests. To let the water invades and permeates through the soil mixtures, all the samples are preserved in the airtight container for about 1 day of curing prior to testing. After curing, the obtained paste was remixed again with each stabilizer thoroughly for at least 15 min before performing the first test. However, the PL tests were performed on material prepared

for the LL tests. The PL was determined as the average of the two water contents. Both the LL and PL tests were conducted at room temperature. The PI value is the difference between the LL and PL obtained for each combination.

2.3.2 Compaction tests

Proctor standard compaction test was applied to determine MDD and the OMC of the GS [32]. The soil mixtures, with and without additives (lime, MO, gypsum and NaCl), were thoroughly mixed for 1 h prior to compaction. The first series of compaction tests were aimed to determine the compaction properties of the unimproved GS. Secondly, tests were carried out to determine the proctor compaction properties of the GS upon improvement with varying amounts of lime in combination with MO, gypsum and NaCl added with different amounts.

2.3.3 UCS tests

UCS tests were conducted on the GS where the WEng-Ltd-5Ton-CM apparatus with a manual data recording system (Wykeham Farrance Eng-Ltd, 5-ton compression machine) was used for UCS tests. The air-dried GS was initially mixed with the predetermined quantity of MO (in a wet state), NaCl and gypsum (in a dry state), and then the calculated water was added to the soil mixture. The samples are preserved in the airtight container for about 1 h of curing prior to the preparation of specimens by static compaction using the static press. That said, the obtained specimens were prepared by compaction at the MDD and OMC deduced from compaction tests. All the specimens prepared with and without MO, gypsum and NaCl were stored in plastic boxes to prevent possible loss of moisture while they were kept in the laboratory at the temperature of 25 °C and relative humidity of 50%. Also, all the prepared specimens have a diameter of $D = 3.8$ cm and $h = 7.6$ cm of length. However, the UCS tests were performed on several specimens after 7, 30 and 120 days curing periods according to ASTM D2166-00 [33]. The UCS tests of all the samples were repeated on three identical specimens. In fact, the accepted UCS was an average of three tests carried out on each sample type. On the other hand, it is known that the SEM gives the magnified images of the size, composition, crystallography, shape, and other physico-chemical characteristics of a specimen. In fact, physico-chemical analyses (in addition to physico-mechanical experiments) are important to observe the reactions occurring between soil and additives used as a result of soil enhancement. However, the PHILIPS S50 SEM model was used in this study to

observe the modification in the structure of the improved GS samples. Indeed, SEM observations were done on the same unimproved and lime-improved GS samples with and without MO, gypsum and NaCl after performing UCS tests at 30- and 120-days curing period. SEM images were taken at 400× magnification. For this, all the GS samples were mounted on metal stubs and coated with gold-palladium alloy at 200 nm thickness in a low-pressure argon atmosphere, which dried them. In addition, the GS samples (volume 1 cm³) were injected by epoxy fix resin, polished, gold-coated and then scanned by a low-resolution SEM (PHILIPS S50 SEM model). Several digital images at different magnifications were made in order to observe the formation of cementitious materials and ettringite. It should be noted that all the GS samples were prepared in the same manner.

3 Results and discussion

3.1 Atterberg's limits

Fig. 4 illustrates the impact of MO, gypsum, and NaCl on the Atterberg limits of both untreated and lime-improved GS samples. The results indicate that the liquid limit (LL) and plastic limit (PL) of the lime-improved GS tend to increase with higher MO content, whereas they decrease with the addition of gypsum and NaCl.

Previous studies have shown that an increase in NaCl (Na⁺ ions) or CaCl₂ (Ca²⁺ ions) concentration reduces the repulsive forces between particles, facilitating their movement and significantly lowering the LL of the examined bentonite [34]. The observed rise in plasticity with MO addition could be attributed to its lubricating properties, which enhance particle mobility and rolling, thereby promoting plastic behavior. Additionally, the introduction of an electrolyte solution (NaCl dissolved in water) may alter the cation exchange capacity through adsorption processes. The increased ion concentration reduces repulsive forces and enhances effective stress, leading to the flocculation of clay particles and, consequently, a reduction in the plasticity of the improved GS.

The incorporation of lime into soils enhances their workability by significantly reducing the plasticity index (PI). For both untreated and lime-improved GS samples, a decline in PI values was also noted with increasing MO, gypsum, and NaCl content. The initial increase in PI can be attributed to the presence of lime, which introduces pozzolanic compounds that demand additional water for complete hydration. Conversely, the subsequent reduction in PI is likely due to the flocculation and agglomeration of

clay particles, which occur as a result of ion exchange at the particle surfaces [32].

The observed decrease in PI following chemical treatment can be explained by the compression of the double-layer thickness caused by cation exchange, primarily involving potassium, calcium, and ferric ions [35–38]. Among the tested additives, gypsum had the most pronounced effect in lowering PI, compared to MO or NaCl. Furthermore, regardless of concentration, MO, gypsum, and NaCl, whether applied individually or in combination with lime, led to a significant reduction in the PI of GS samples when compared to those treated solely with lime, except for samples improved with 4% lime in the presence of 2% and 4% MO.

It has been established that the cation exchange process plays a crucial role in clay particle interactions. An increase in cation concentration (Na⁺ from NaCl and Ca²⁺ from gypsum) enhances particle separation, leading to changes in clay particle size and pore distribution, which ultimately affects the soil's consistency limits. Consequently, the modifications in PI can be attributed to this cation exchange process, which influences the viscosity of the clay-water mixture [12]. Additionally, research by Yilmaz and Civelekoglu [39] has shown that the PI of gypsum-improved bentonite decreased from 186.9% to 139.5% and 120.8% with the addition of 2.5% and 10% gypsum, respectively. This behavior is explained by the replacement of monovalent ions with calcium ions from gypsum, which significantly reduces the double-layer thickness, leading to a decrease in the LL and, subsequently, a reduction in PI for the improved soil.

3.2 Soil classification

According to ASTM D2487-06 [40], the A-line on the plasticity chart serves as a boundary distinguishing silts (denoted as M) from clays (denoted as C). Additionally, soils with a liquid limit (LL) above 50% are classified as high plasticity (H), while those with an LL below this threshold are categorized as low plasticity (L).

Furthermore, when the Atterberg limits fall within the hatched zone near the origin of the plasticity chart, the soil is assigned a dual classification as low-plasticity clay-silt (CL–ML). As illustrated in Fig. 5, the classification of both untreated and lime-improved GS samples, with and without MO, gypsum, and NaCl, was determined by plotting their PI and LL values on the plasticity chart. This process allows for the reassessment of their classification based on the Unified Soil Classification System (USCS).

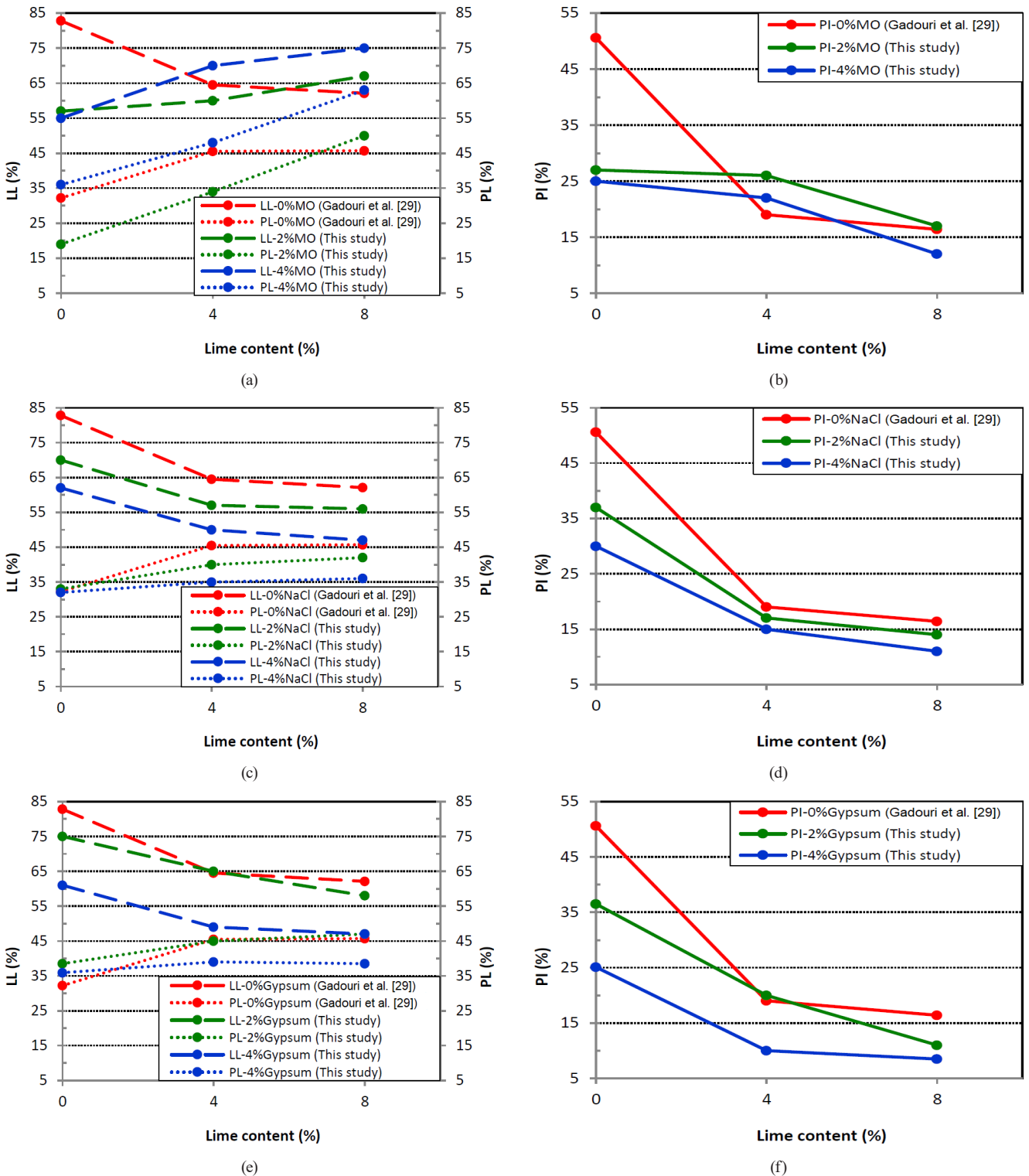


Fig. 4 Effects of different additives on the plasticity of lime-improved GS: (a) Effect of MO on the LL and PL; (b) Effect of MO on the PI; (c) Effect of NaCl on the LL and PL; (d) Effect of NaCl on the PI; (e) Effect of gypsum on the LL and PL; (f) Effect of gypsum on the PI

The natural GS sample was identified as a high-plasticity clay (CH) since its (LL, PI) coordinates were positioned above the A-line and to the right of the LL = 50% threshold. However, with the addition of lime, this classification shifted, placing the LL sample below the A-line and reclassifying it as a high-plasticity silt (MH). Similarly,

introducing MO – whether into untreated or lime-improved GS – led to a significant modification, with all samples being categorized as high-plasticity silt (MH).

A comparable classification (MH) was also observed when gypsum or NaCl was combined with 4% lime, producing results similar to those obtained with MO.

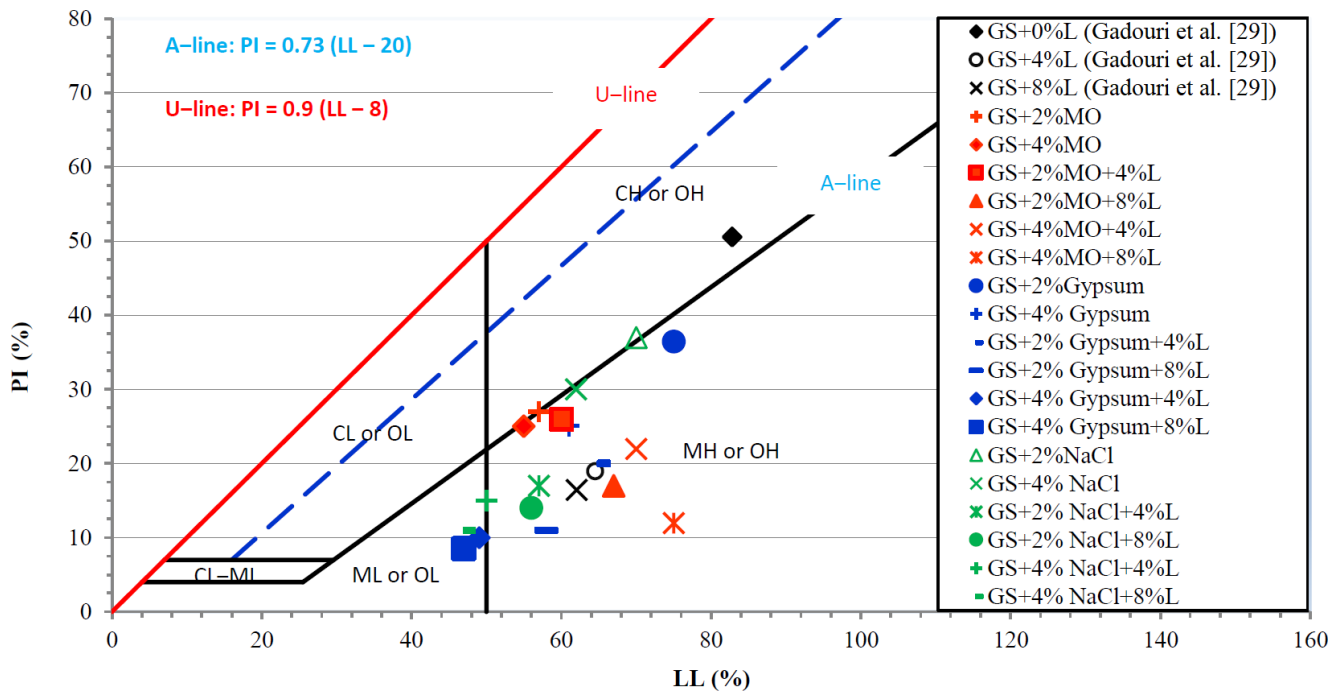


Fig. 5 Effects of different additives (MO, NaCl and gypsum) on the classification of lime-improved GS

However, in samples treated with 8% lime in combination with 4% gypsum or 4% NaCl, the classification shifted further. The representative point fell below the A-line and to the left of the $LL = 50\%$ boundary, leading to a reclassification as low-plasticity silt (ML).

Notably, the impact of gypsum and NaCl on GS classification was more pronounced than that of MO. As highlighted by Gadouri et al. [41], this transformation is attributed to flocculation, which occurs due to the electrochemical interaction between calcium ions (Ca^{2+} from lime or gypsum) and clay particles. This reaction leads to an immediate alteration in the soil's consistency limits, ultimately affecting its classification.

3.3 Compaction

Fig. 6 presents the variations in maximum dry density (MDD) and optimum moisture content (OMC) for both untreated and lime-improved GS samples, with and without MO, gypsum, and NaCl. It is evident that as the lime content increased, MDD decreased while OMC increased. This reduction in MDD and corresponding rise in OMC can be attributed to the cation exchange reaction, which promotes flocculation of the soil's clay fractions [12].

However, regardless of whether the GS samples were untreated or lime-improved, MDD showed a progressive increase with higher MO, gypsum, and NaCl content. Notably, this increase was more significant when gypsum

and NaCl were used compared to MO. Conversely, OMC exhibited a decreasing trend with increasing MO and NaCl content but showed an upward trend when gypsum was added.

The continuous increase in MDD observed with the addition of MO can be attributed to its lubricating properties, which facilitate compaction while reducing the amount of water required to achieve maximum density. This increase may also result from cation exchange reactions, as well as the fact that MO, being a fluid, occupies the voids within the soil matrix. The corresponding decrease in OMC with higher MO content can be explained by the lubricating nature of MO, which enhances the slippage of soil particles, allowing for greater densification at lower water content [38].

Regarding the presence of NaCl, its addition to the pore fluid of improved GS samples reduces the thickness of the diffuse double layer, leading to a denser packing of clay particles and, consequently, an increase in dry density. Additionally, as NaCl concentration rises, the solid volume fraction increases, thereby reducing the volume of water required.

Similarly, the increase in MDD with higher gypsum content can be attributed to a reduction in the void ratio. Gypsum particles, which are smaller than $80\ \mu m$ in diameter, effectively fill the pore spaces between soil grains, enhancing compactness and, as a result, increasing the MDD of the GS samples.

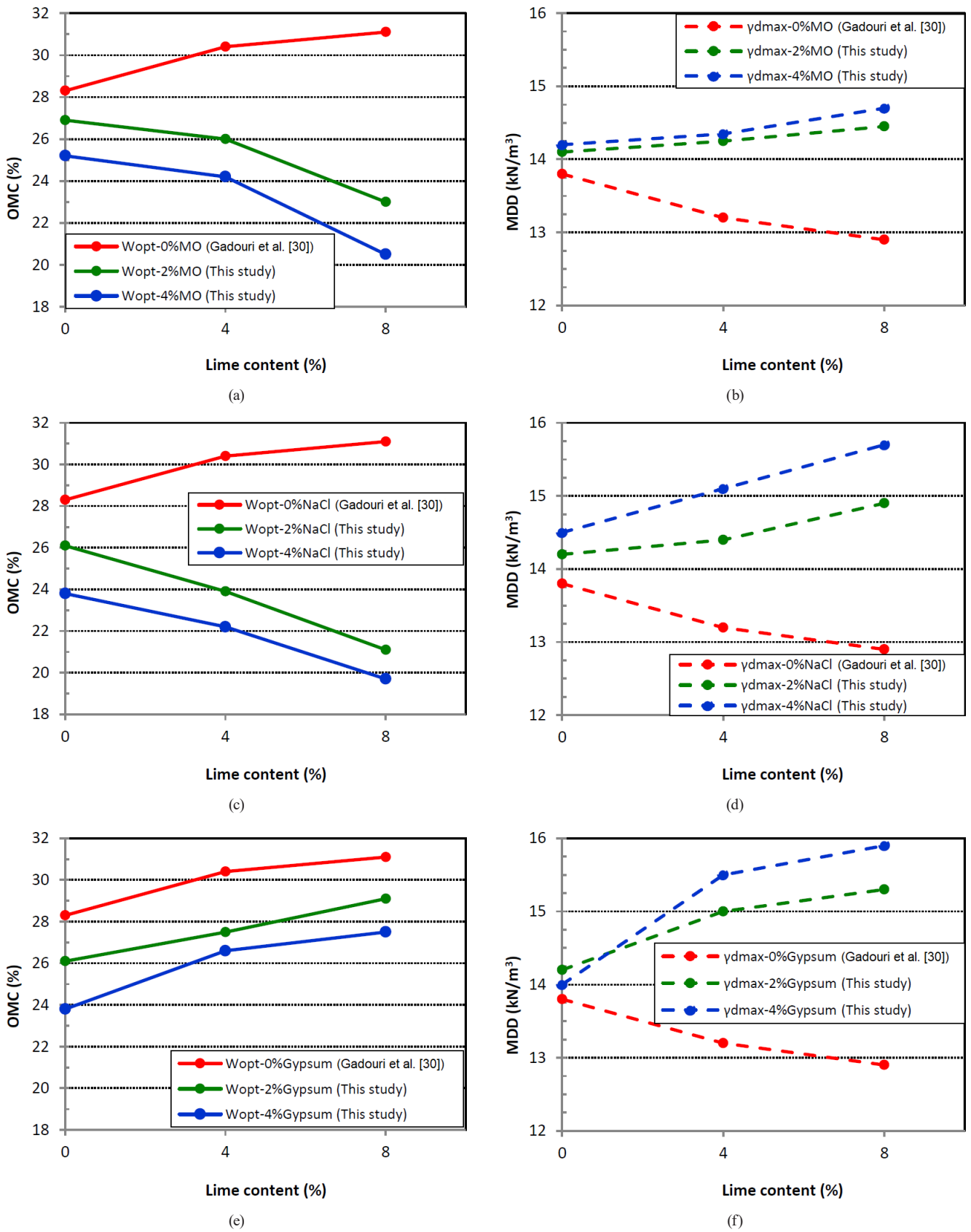


Fig. 6 Effects of different additives on the compaction parameters of lime-improved GS: (a) Effect of MO on the OMC; (b) Effect of MO on the MDD; (c) Effect of NaCl on the OMC; (d) Effect of NaCl on the MDD ; (e) Effect of gypsum on the OMC; (f) Effect of gypsum on the MDD

3.4 Unconfined compressive strength

The strength of both untreated and lime-improved GS samples, with and without MO, gypsum, and NaCl, was evaluated after compaction at their respective OMC and MDD (Fig. 7). Additionally, the microstructural characteristics of the lime-improved GS samples were analysed using SEM observations. The primary objective of this microstructural study was to examine changes induced by the addition of lime, MO, gypsum, and NaCl, as well as to

identify the formation of ettringite minerals and cementitious compounds responsible for strength variations, as illustrated in Figs. 8 and 9.

The results clearly demonstrate that the presence of gypsum and NaCl positively influences the strength of both untreated and lime-improved GS samples.

SEM images reveal significant microstructural modifications in GS samples containing gypsum (Fig. 8 (c) to (f)) and NaCl (Fig. 9 (c) to (f)) when compared to the initial

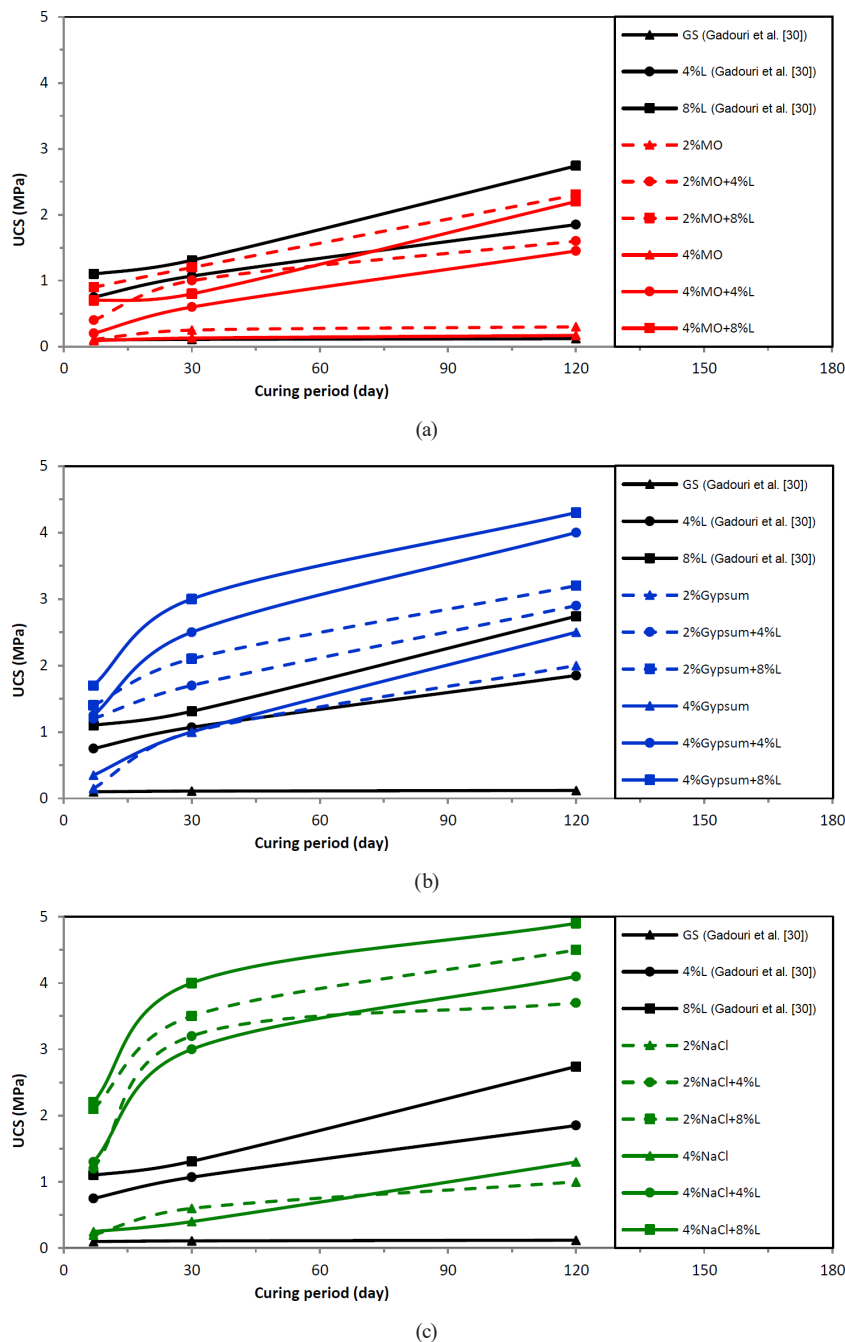


Fig. 7 Effects of different additives on the UCS of lime-improved GS: (a) Effect of MO on the UCS; (b) Effect of NaCl on the UCS; (c) Effect of gypsum on the UCS

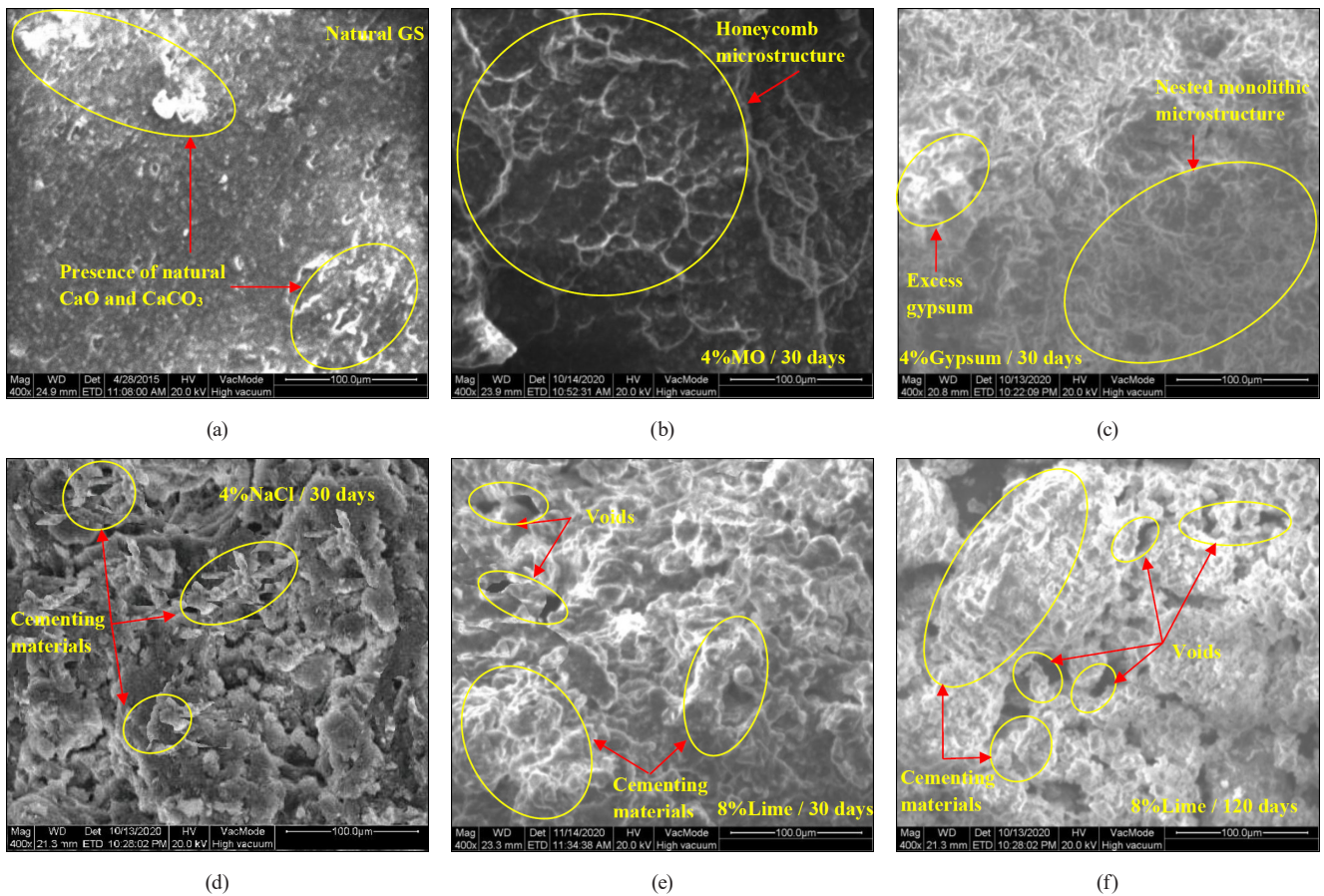


Fig. 8 SEM images show the modification in microstructure of the GS samples: (a) Microstructure of the GS; (b) Unimproved GS containing 4%MO; (c) Unimproved GS containing 4%Gypsum; (d) Unimproved GS containing 4%NaCl; (e) GS improved with 8%Lime for 30 days curing; (f) GS improved with 8%Lime for 120 days curing

GS microstructure (Fig. 8 (a)). In contrast to the original soil structure, the addition of lime results in soil particles becoming less distinct due to the encapsulation of pozzolanic reaction products, leading to a reduction in visible voids between particles.

Overall, the findings align with the strength evolution observed in lime-improved GS samples, both with and without MO, gypsum, and NaCl, after curing for 30 and 120 days. The presence of voids in GS samples treated with lime alone or in combination with gypsum and NaCl is attributed to clay particle flocculation caused by cation exchange (Fig. 8 (e) and (f) and Fig. 9 (c) to (e)). In the case of untreated GS, an increase in gypsum and NaCl content led to a significant rise in UCS values over time, particularly after prolonged curing (120 days). This strength enhancement was more pronounced with gypsum than with NaCl. However, at higher NaCl concentrations (4% NaCl), UCS values increased further, surpassing those of samples without salt. A similar trend was previously observed by Davoudi and Kabir [42].

In the presence of MO, UCS exhibited a slight increase with rising lime content and curing time but showed

a significant decline as MO concentration increased. SEM images revealed a honeycomb-like microstructure when 4% MO was used alone (Fig. 8 (b)). However, the formation of cementitious compounds was observed when 4% MO was combined with 8% lime at any curing stage (Fig. 9 (a) and (b)).

On the other hand, when gypsum was added, UCS values at an early stage (7 days) were recorded as 0.1, 0.15, and 0.35 MPa for samples containing 0%, 2%, and 4% gypsum, respectively. After a 120-day curing period, the same samples developed UCS values of 0.12, 2, and 2.5 MPa for 0%, 2%, and 4% gypsum, respectively. The strength enhancement in unimproved soil samples containing gypsum can be attributed to the fine-grained nature of gypsum, which improves matrix compactness and, consequently, soil strength [15, 32]. Additionally, previous studies by Holm et al. [43] and Kujala and Nieminen [44] indicate that gypsum enhances soil strength by altering the hydration process of calcium silicate, which predominantly occurs during the early stages of hydration.

The introduction of gypsum as an additive releases sulfate ions (SO_4^{2-}), which react with alumina (Al_2O_3),

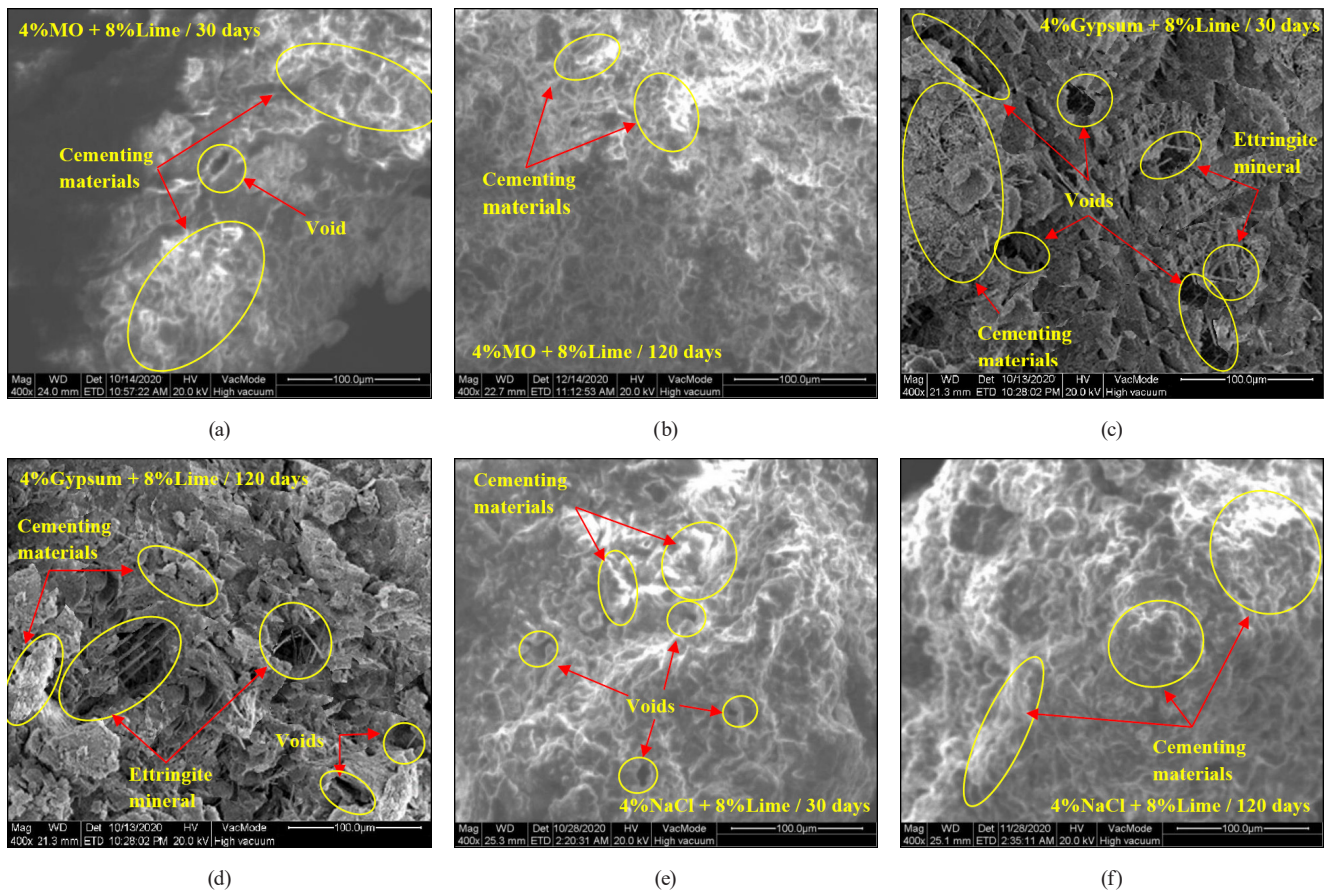


Fig. 9 SEM images show the change in microstructure of the GS samples: (a) GS containing 4%MO+8%Lime for 30 days curing; (b) GS containing 4%MO+8%Lime for 120 days curing; (c) GS containing 4%Gypsum+8%Lime for 30 days curing; (d) GS containing 4%Gypsum+8%Lime for 120 days curing; (e) GS containing 4%NaCl+8%Lime for 30 days curing; (f) GS containing 4%NaCl+8%Lime for 120 days curing

a primary soil component. Asgari et al. [45] reported that soil strength increased with lime addition up to 3% but declined beyond this threshold due to the formation of cementitious compounds, particularly calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which bond soil particles through lime-clay reactions [2]. Similarly, Gadouri et al. [29] observed a gradual increase in the strength of high-plasticity clay soils, which was attributed to ettringite formation due to the presence of calcium sulfate in the improved system, particularly at high gypsum concentrations. This behavior was confirmed by SEM images, where ettringite formation was distinctly visible after 30 and 120 days of curing (Fig. 9 (c) and (d)).

A significant increase in UCS values was noted when soil samples were improved with different lime contents in the presence of varying concentrations of gypsum and NaCl. Furthermore, samples containing a combination of lime with either gypsum or NaCl exhibited higher UCS values compared to those improved with lime alone. The presence of excess sodium ions (Na^+) from NaCl

addition has been reported to enhance pozzolanic compound formation (mainly C-S-H and C-A-H), which contributes to soil silica dissolution. In solution, sodium ions (Na^+) are believed to compress the diffuse water layer, enhancing particle-particle interaction and promoting flocculation, which in turn facilitates the development of cementing agents through chemical reactions [42].

Conversely, as MO concentration increased, UCS values of GS improved with varying lime contents decreased. However, UCS values exhibited an overall increase with curing time. The strength improvement over the curing period observed in this study can be attributed to the extent of the reaction between lime and soil minerals, which is time-dependent. Ochepe and Joseph [46] reported that the presence of spent petroleum oil led to a decrease in UCS values of treated soil, with reductions averaging 46%, 23%, and 13% after 7, 14, and 28 days, respectively, compared to uncontaminated soil. This reduction in strength due to petroleum oil contamination can be explained by the penetration of the oil into the improved soil matrix,

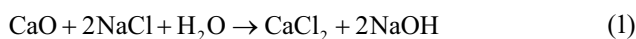
potentially disrupting the integrity of the calcium silicate gel through reactions with hydrocarbon compounds, leading to lower strength development.

Moreover, for any given curing period, samples improved with the combined NaCl + L treatment exhibited higher UCS values compared to those improved with MO + L or gypsum + L combinations.

For instance, after a 120-day curing period, all samples improved with 8% lime recorded UCS values of 0.17 MPa, 4.3 MPa, and 4.9 MPa for 4% MO, 4% gypsum, and 4% NaCl, respectively. Notably, samples containing lime alone exhibited higher UCS values compared to those containing MO alone or in combination with lime.

According to the literature, gypsum accelerates the chemical reaction between soil and lime, leading to the formation of ettringite through the reaction of sulfate ions (SO_4^{2-}) with cementitious materials (C-S-H and C-A-H) produced from pozzolanic reactions. These cementitious materials, along with ettringite formation, significantly contribute to the strength development of clayey soils [15, 32].

Additionally, the reaction between lime (naturally present in the grey soil at 14.43% or introduced *via* CaO from lime addition) and NaCl in the presence of H_2O results in the production of sodium hydroxide (NaOH), creating a highly alkaline solution with a pH value significantly higher than that of $\text{Ca}(\text{OH})_2$ (Eq. (1)). According to Shi and Day [47], the pH in the presence of NaOH can reach values as high as 13, which can further enhance the stabilization process.



As a result, the elevated pH level (induced by the presence of NaOH following the reaction) promotes the dissolution of a substantial quantity of alumina (Al_2O_3) and silica (SiO_2) within the soil matrix. These dissolved compounds subsequently react with the remaining lime, leading to the formation of increased amounts of cementitious products. This process is primarily responsible for the significant enhancement in compressive strength, particularly at the early curing stage (7 days).

4 Conclusions

This research investigates the impact of MO, gypsum, and NaCl on Atterberg limits, soil classification, compaction, UCS, and microstructural changes in GS improved with varying lime contents. The key findings are summarized as follows:

- Atterberg limits and soil classification: the addition of MO increased LL and PL, whereas gypsum and NaCl caused a decrease. The rise in Na^+ concentration (from

NaCl) reduced repulsive forces, enabling easier particle movement and leading to a reduction in LL values. Conversely, MO's lubricating effect enhanced plastic behavior. The PI of both unimproved and lime-improved GS samples decreased with increasing MO, gypsum, and NaCl content due to lime-induced pozzolanic reactions requiring additional hydration water. This decline in PI is also attributed to the agglomeration and flocculation of clay particles due to ion exchange. Moreover, the addition of these stabilizers modified the soil classification, particularly in the presence of gypsum and NaCl, which altered particle distribution and pore structure.

- Compaction characteristics: MDD decreased while OMC increased with rising lime content due to cation exchange-induced flocculation of clay particles. However, MDD progressively increased with higher MO, gypsum, and NaCl concentrations. In contrast, OMC decreased with increasing MO and NaCl but increased with gypsum content. The increase in MDD due to gypsum addition is explained by a reduced void ratio as fine gypsum particles filled the soil pores. NaCl reduced diffuse double-layer thickness, enhancing particle packing. MO, with its lubricating properties, facilitated particle movement, resulting in higher densities at lower water content.
- Unconfined compressive strength (UCS): gypsum and NaCl positively influenced UCS in both unimproved and lime-improved GS samples. Increased gypsum and NaCl concentrations led to substantial UCS gains, particularly after prolonged curing, with a more pronounced effect from gypsum. SEM images confirmed significant microstructural changes in natural and improved GS containing gypsum or NaCl. However, while UCS increased with higher lime content and curing time, it significantly decreased with rising MO concentration. Gypsum-containing GS samples exhibited superior UCS due to finer gypsum particles enhancing matrix compactness. Additionally, ettringite formation, stimulated by calcium sulfate presence, contributed to strength gains, as confirmed by SEM observations after 30 and 120 days.
- Cementitious reactions and Strength development: the marked UCS increase in GS improved with lime in combination with gypsum or NaCl is attributed to excess sodium ions promoting pozzolanic compound formation. These ions compressed the diffuse water layer, enhancing particle contact, flocculation, and

cementing agent formation. Conversely, increasing MO concentration reduced UCS due to oil penetration into the improved soil structure and potential interactions between hydrocarbon compounds and calcium silicate gel, affecting its stability.

- Role of gypsum and NaCl in strength gain: gypsum accelerated soil-lime reactions, forming ettringite through sulfate (SO_4^{2-}) interaction with pozzolanic products (C-S-H and C-A-H). These cementitious materials, alongside ettringite, significantly contributed to strength gains. Furthermore, the reaction between natural lime (from GS) and NaCl in the presence of water produced sodium hydroxide (NaOH), creating a higher alkaline environment than calcium hydroxide [$\text{Ca}(\text{OH})_2$]. This elevated pH facilitated alumina and silica dissolution, which reacted with residual lime to form substantial cementitious products, driving early-stage strength gains.

Regarding research perspectives, further investigations are recommended to explore:

- The long-term effects of interactions between MO and cementitious products.
- The durability of soils improved with gypsum and NaCl under freeze-thaw cycles and aggressive environments.
- The optimization of MO, gypsum, and NaCl proportions to balance mechanical and chemical improvement benefits.

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