Jordan Journal of Civil Engineering, Volume **20**, No. **1**, **2026**
DOI: https://doi.org/10.14525/JJCE.v20i1.07

Jordan Journal of Civil Engineering

Journal homepage: https://jjce.just.edu.jo

Effect of $CaCl_2$ on the Behavior of Lime-Pozzolana-stabilized Marley Soil

Hamid Gadouri [1)*], ***Brahim Meziani*** [1)]

[1)] *Earth Sciences Department, Faculty of Nature and Life Sciences and Earth Sciences, Khemis Miliana University, Road Theniet El-Had Khemis Miliana 44225, Algeria. * Corresponding Author. E-Mail: hamid.gadouri@univ-dbkm.dz*

ARTICLE INFO

Article History:
Received: 9/1/2025
Accepted: 8/9/2025

ABSTRACT

The geotechnical properties of soils are often influenced by chemical compounds and mineral additives. This study investigates the effects of varying calcium chloride ($CaCl_2$) contents (0% to 6% by weight of dry soil) on the Atterberg limits and classification of Marley soil (MS), stabilized with 8% lime (L), 20% natural pozzolana (NP), and their combination (8%L+20%NP). The research also examines the impact of curing time (1 and 30 days) on the plasticity index (PI) and soil classification, both with and without $CaCl_2$. In the absence of $CaCl_2$, the addition of L, alone or combined with NP, significantly reduced the PI of stabilized MS and markedly improved its classification, particularly with the L-NP combination over longer curing periods. In contrast, NP alone caused only a slight decrease in the PI. The inclusion of $CaCl_2$ further reduced the PI in the MS–L and MS–L-NP mixtures. Notably, the transformation in soil classification was more substantial with L and L-NP than with NP alone. A comparative evaluation of the Unified Soil Classification System (USCS) and the British Soil Classification System (BSCS) revealed that the BSCS offered greater precision in classifying stabilized MS, underscoring its suitability for such applications. These findings highlight the significant benefits of incorporating $CaCl_2$, alone or in combination with L or L-NP, in enhancing the PI and the classification of MS. The improvements in both PI and classification are influenced by several factors, including additive type and amount, $CaCl_2$ content, curing period, and the classification system employed.

Keywords: Marley soil (MS), Mineral additives (L and NP), Calcium chloride ($CaCl_2$), Atterberg limits, USCS and BSCS classification systems, Stabilization.

INTRODUCTION

A significant portion of clayey soils, often referred to as problematic soils, is traditionally unsuitable for use as building materials due to their poor quality. Problematic clayey soils, particularly those with high shrink-swell potential, present significant geotechnical challenges in many countries due to deformations that they undergo under loading. They often require prior improvement before being suitable for civil engineering use. For example, in the United States, it has been estimated that the annual cost of damage from expansive soils is \$2.3 billion, primarily due to differential heave from moisture variations in montmorillonite-rich clays (Gromko, 1974). In Algeria, expansive clays in regions such as M'sila frequently damage road pavements and built structures, justifying the need for adapted stabilization techniques (Khemissa et al., 2015). Similar issues are observed in Iraq, where gypseous soils, widespread in many regions, are highly collapsible upon wetting, leading to severe settlement and structural damage, thereby necessitating stabilization or specialized foundation solutions (Seleam, 2006; Fattah et al., 2012). Extensive research has been conducted, as indicated in the literature, with numerous laboratory studies focusing on chemical soil stabilization techniques to enhance the properties of these soils. Various additives have been explored in these studies, including cement, lime, natural pozzolana (NP), volcanic ash, fly ash, silica fume, copper slag, phosphogypsum, ceramic dust, polyvinyl waste, rice husk ash, bagasse ash, olive cake residue, wheat husk, cassava peel ash, eggshell powder, and grain storage dust (Ola, 1977; Al-Rawas, 2004; Hossain et al., 2007; Harichane & Ghrici, 2009; Harichane et al., 2011a; Harichane et al., 2011b; Harichane et al., 2011c; Harichane et al., 2012; Zoubir et al., 2013; Asgari et al., 2015; Al-Swaidani et al., 2016; Harichane et al., 2017). Recent contributions have further enriched the understanding of soil stabilization and improvement techniques. For instance, Islam et al. (2018) demonstrated the effectiveness of fly ash in enhancing the strength development of clay soils, while Alsharie and Alayed (2019) reported significant gains in concrete compressive strength by partially replacing fine silica with stone cutting powder. Stabilization of low plasticity clay soils with crushed limestone was successfully investigated by Salih and Abdalla (2022), and Melese (2022) highlighted the improvement of expansive soil properties through scoria modification. Bayoumy et al. (2024) examined the strength and deformability of cemented clayey sand, whereas Aymen et al. (2024) evaluated consolidation settlement using both observational and conventional approaches with data from Algerian test embankments. More recently, Karkush and Ali (2025) investigated the durability of gypseous soils stabilized with nano-silica under varying environmental conditions. Collectively, these studies underline the diversity of materials and techniques available for improving problematic soils, while emphasizing the need for further research on the role of chloride compounds in lime–pozzolana–stabilized soils.

Furthermore, laboratory studies on problematic soils have demonstrated that chemical soil stabilization techniques have become increasingly valuable in civil engineering applications. These methods offer the advantage of improving soil quality without the need for high-quality materials, resulting in significant reductions in project timelines and transportation costs. However, despite these benefits, the effectiveness of chemical soil stabilization is influenced by several factors, including the mineralogical composition of the stabilized soil (Sivapullaiah et al., 2000; Gadouri et al., 2017c), the type of additive used and its amount (Asgari et al., 2015), the type of sulphates used and their concentration (Kinuthia et al., 1999; Gadouri et al., 2019a), curing conditions such as temperature and curing period (George et al., 1992), and organic matter content (Xu et al., 2008; Afrin, 2017).

However, the presence of sulphates in natural soils poses a common challenge for chemical soil stabilization (Mitchell, 1986). As a result, numerous studies have been published examining the impact of sulphates on key geotechnical properties of stabilized clayey soils. These properties include the Atterberg limits, compaction characteristics, soil classification, unconfined compressive strength, shear strength, California bearing ratio, compressibility, and swelling pressure (Kinuthia et al., 1999; Sivapullaiah et al., 2000; Puppala et al., 2004; Celik & Nalbantoglu, 2013; Hu et al., 2016; Gadouri et al., 2017a, 2017b, 2017c; Gadouri et al., 2018; Gadouri et al., 2019a, 2019b; Gadouri, 2023; Meziani & Gadouri, 2023).

On the other hand, selecting an appropriate system for soil description and classification is essential for accurately characterizing the wide variety of materials used in geotechnical engineering practice. A detailed description of extracted samples or *in-situ* soil provides valuable information about both the physical properties and the condition of the soil. Soil classification, in turn, involves categorizing soils into distinct classes or groups for easier description and analysis. In geotechnical engineering, various classification systems are commonly employed, often based on factors such as grain size or soil plasticity, with the BSCS being one of the widely used methods (BS 5930-15), the USCS (ASTM D2487-06), and the American Association of State Highway and Transportation Officials (AASHTO) system (ASTM D3282-09). In fact, these classification systems can also be utilized to evaluate the impact of mineral additives and chemical compounds on the classification of stabilized soils. According to the literature, the Atterberg limits are among the most commonly used properties for assessing changes in soil classification. This is typically done by plotting the values of the plasticity index and liquid limit on a plasticity chart (Harichane & Ghrici, 2009; Khemissa & Mahamedi, 2014; Gadouri et al., 2018).

In Algeria, large-scale civil engineering projects, including roadway sub-grades, road embankments, trench backfills, landfill liners, and earth dams, are currently underway, and the soils used as building materials require improvement before they can be utilized. Soil classification plays a critical role in geotechnical engineering practice, and it can change following stabilization, especially when mineral additives are used or chemical compounds such as sulphates are present. For instance, Gadouri et al. (2018) examined the impact of sulphates on the soil classification of soil–lime–natural pozzolana mixtures. Their findings indicated that calcium cations (Ca^{2+}, derived from $CaSO_4{\cdot}2H_2O$ and lime) improved the classification of stabilized clayey soils, while the presence of sodium cations (Na^+, derived from Na_2SO_4) had an undesirable effect on soil classification.

The NP is abundantly available in the Beni-Saf region in the western part of Algeria (Ghrici et al., 2007). $CaCl_2$ naturally occurs in brines, evaporite deposits, and certain rock salt formations (Gadouri et al., 2018). While widely used in various industries, its specific role in soil stabilization remains comparatively less explored. Despite the extensive research on soil stabilization, the influence of chloride compounds on the geotechnical properties of MS–L–NP mixtures remains almost unexplored. This study aims to fill this gap by investigating the effects of varying $CaCl_2$ contents on the Atterberg limits. Additionally, it seeks to compare the performance of the USCS and the BSCS in classifying stabilized MS, providing a comprehensive understanding of their suitability for such applications.

EXPERIMENTAL INVESTIGATIONS

Soil Used

The MS, containing 57% $CaCO_3$, used in this study was sourced from Tacheta Zougara (Ain Defla), a town located in the north-west of Algeria. The soil was extracted and transported to the laboratory for further preparation. Several laboratory tests were conducted to identify and classify the soil. The physico-mechanical properties of MS are presented in Table 1.

Mineral Additives

The lime used (8%L) in this study was a hydrated lime ($Ca(OH)_2$) which was commercially available lime typically used for construction purposes. The physico-chemical properties of this additive are presented in Table 2. In addition, the NP was used as an additive (20%NP) for soil stabilization. It was obtained from Beni–Saf deposit located in the west of Algeria. It was first crushed and then passed through a mill to a specific surface area of 420 m^2/kg which was verified according to ASTM C204-07. The contents of lime and NP adopted in this study were selected on the basis of prior experimental evidence and their proven efficiency in stabilizing expansive clays. Harichane and Ghrici (2009) investigated grey clay soils with lime contents ranging from 0 to 10% and NP contents from 0 to 20%. They identified 8% lime as the optimum dosage, as higher percentages did not yield significant additional improvements in Atterberg limits or strength, while 20% NP was found to provide the most pronounced effect. Moreover, their combination (8%L+20%NP) produced synergistic improvements, including reductions in plasticity and enhanced strength. Comparable findings were reported by Al-Rawas et al. (2005), who showed that 6% lime eliminated swelling potential in expansive Al-Khod soil from Oman, confirming the efficiency of lime as a stabilizer, and by Al-Swaidani et al. (2016), who demonstrated that up to 20% NP combined with lime (≤8%) significantly improved compaction, CBR, and shrinkage properties of Syrian clayey soils. Based on these established ranges, the present study adopted 8% lime and 20% NP to ensure methodological consistency and effective stabilization. The physico-chemical properties of this additive are also given in Table 2.

Table 1. Physico-mechanical properties of the MS

Physico-mechanical properties	**MS**
Particle size <2 mm	96.2
Particle size <0.08 mm	90.7
Particle size <0.002 mm	30.3
Natural water content (%)	13.2
Dry Density (γd_{max}, kN/m^3)	14.4
Liquid Limit (LL, %)	72.9
Plastic Limit (PL, %)	33.5
Plasticity Index (PI, %)	39.4
Classification System (USCS), (-)	CH
Classification System (BSCS), (-)	CV
Optimum Moisture Content (W_{OPN}, %)	27.2
Maximum Dry Density (γd_{max}, kN/m^3)	17.1
Swelling pressure (kPa)	311

Table 2. Physico-chemical properties of L and NP (Gadouri et al., 2017a)

Physical / chemical name	L (%)	NP (%)
Physical form	Dry white powder	Dry brown 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	-	5.34
Specific surface area (m²/kg)	-	420
Pozzolanic activity index (%)	-	79
CaO	> 83.3	9.90
MgO	< 0.5	2.42
Fe_2O_3	< 2.0	9.69
Al_2O_3	< 1.5	17.5
SiO_2	< 2.5	46.4
SO_3	< 0.5	0.83
Na_2O	0.4 - 0.5	3.30
K_2O	-	1.51
CO_2	< 5.0	-
TiO_2	-	2.10
P_2O_3	-	0.80
$CaCO_3$	< 10.0	-

Chemical Compound

Calcium chloride ($CaCl_2$) is a highly soluble salt with strong hygroscopic properties, enabling it to rapidly absorb moisture from its surroundings. In soil stabilization, $CaCl_2$ acts primarily through two mechanisms: (i) moisture control, by attracting and retaining water, which can influence workability during mixing and compaction; and (ii) chemical interaction, particularly in lime- or pozzolana-treated soils, where the chloride ions may modify the ionic environment, accelerating the flocculation of clay particles and potentially influencing the rate of pozzolanic reactions. These effects can reduce the soil's plasticity index (PI) and, in some cases, alter its classification. The magnitude of these benefits depends on the $CaCl_2$ dosage, the curing period, and the nature of the base soil. In this study, calcium chloride ($CaCl_2$) was used as a chemical compound. It was added to all the studied mixtures in deferent amounts (0-6% by weight of dry soil). The dosage range of calcium chloride ($CaCl_2$) was determined by combining solubility considerations and previous research findings. $CaCl_2$ has a high solubility in water (74.5 g/100 mL at 20°C, ≈ 745 g/L), which ensures its uniform distribution in the soil without risk of precipitation at moderate contents. To define a technically effective, yet safe, range, previous studies were considered. Almajed et al. (2023) tested $CaCl_2$ contents between 4% and 8% in expansive Al-Qatif clay and reported significant reductions in swell potential and swelling pressure, though higher contents resulted in strength loss due to excessive salt. Zumrawi and Eltayeb (2016) found that 1%-4% $CaCl_2$ in black cotton soil improved unconfined compressive strength and reduced plasticity, with peak performance around 3%-4%. Afrin (2017) further confirmed that chloride compounds (NaCl, $CaCl_2$, $MgCl_2$) at 4%-12% decreased Atterberg limits and improved compaction. In light of these findings, and considering the high plasticity of Marley clay, a $CaCl_2$ range of 0–6% was selected. This interval encompasses the optimum ranges reported in the literature, avoids the risks associated with excessive chloride, and remains consistent with practical field applications. From a physico-chemical perspective, $CaCl_2$ acts through cation exchange and flocculation of clay particles, mechanisms particularly relevant to highly plastic soils such as Marley clay. By adopting 8%

lime and 20% NP (dosages repeatedly reported as optimal in the literature) and limiting $CaCl_2$ to 0–6%, our methodology balances proven efficacy, soil-specific mineralogical considerations, and long-term performance.

TEST PROCEDURES AND SAMPLE PREPARATION

Atterberg Limits Test

Atterberg's limits of MS samples containing $CaCl_2$ were investigated and performed according to ASTM D4318-00. However, several samples were studied for assessing the effects of $CaCl_2$ on the soil classification of MS–L, MS–NP and MS–L–NP mixtures. Preliminary tests conducted with curing periods of 1 day, 15, 30, and 60 days revealed that most of the stabilization effects occurred within the first 30 days, with negligible variations in Atterberg limits between 30 days and 60 days. Accordingly, 1-day and 30-day curing periods were selected for the main experimental program to capture both immediate and representative long-term effects while ensuring testing efficiency. Table 3 showed a total of 16 combinations based on the MS.

Table 3. A summary of the mix combinations tested for the MS samples with and without $CaCl_2$

Designation	Soil mixture (%)			
	MS	L	NP	$CaCl_2$ (Cl)
P0L0Cl0	100	0	0	0
P0L0Cl2	98	0	0	2
P0L0Cl4	96	0	0	4
P0L0Cl6	94	0	0	6
P0L8Cl0	92	8	0	0
P0L8Cl2	90	8	0	2
P0L8Cl4	88	8	0	4
P0L8Cl6	86	8	0	6
P20L0Cl0	80	0	20	0
P20L0Cl2	78	0	20	2
P20L0Cl4	76	0	20	4
P20L0Cl6	74	0	20	6
P20L8Cl0	72	8	20	0
P20L8Cl2	70	8	20	2
P20L8Cl4	68	8	20	4
P20L8Cl6	66	8	20	6

Soil Classification

The change caused by mineral additives and $CaCl_2$ on the classification of MS was studied basing on both the Unified (ASTM D2487-06) and British (BS 5930-15) Soil Classification Systems).

Sample Preparation

All the samples were prepared without $CaCl_2$ (MS–L, MS–NP, and MS–L–NP mixtures) and with $CaCl_2$ (MS–L–$CaCl_2$, MS–NP–$CaCl_2$, and MS–L–NP–$CaCl_2$ mixtures) in accordance with Gadouri et al. (2018). In the absence of $CaCl_2$, the MS was stabilized using 8%L, 20%NP, and the combination of both (8%L+20%NP), and distilled water was added to all the MS mixtures for the Atterberg limits test. After preparation, each soil–additive mixture was mixed thoroughly for at least 15 minutes before being placed in airtight containers at a controlled temperature of 25°C ± 2°C and a relative humidity of 50% ± 2% for about 1 day and 30 days of curing, to allow moisture distribution, the infiltration of water through the MS mixtures, and the development of cementitious bonds. No mechanical remixing was performed after curing in order to preserve the soil fabric and the cementitious products formed during this period. Thus, the plastic limit tests were performed on the same material prepared for the liquid limit test. However, the plastic limit values were calculated as the average of the water contents from both trials. Both liquid limit and plastic limit tests were conducted at room temperature. On the other hand, in the presence of $CaCl_2$, the samples were mixed in the same way as described above except that different $CaCl_2$ contents (0 to 6% by weight of dry soil) were also added to the MS–L, MS–NP and MS–L–NP mixtures in a dry state. When the distilled water was added to the mixtures the Atterberg limits tests were performed in the same way as described above and after the same curing periods.

EXPERIMENTAL RESULTS AND DISCUSSION

Atterberg's Limits Modification

Figure 1 presents the results of $CaCl_2$ effects on the PI of MS samples stabilized by using L, NP and their combination (L–NP). In all cases, it is quite clear to see that the PI not only changed with the added mineral additives, but also varied with the increase of both $CaCl_2$ content and curing time.

Effect of $CaCl_2$ on the PI of Unnstabilized MS and MS–NP Mixture

As illustrated in Figure 1a, the presence of $CaCl_2$ has a slight effect on the plasticity index (PI) of unstabilized MS. After 1 day of curing, the PI decreased slightly from 39.4% to 36.1%, 34.3%, and 32.5% with the addition of 2%, 4%, and 6% $CaCl_2$, respectively. This trend becomes more pronounced after 30 days of curing (Figure 1b), with the PI further decreasing by 4.3%, 5.5%, and 7.9% for the same concentrations of $CaCl_2$.

After 1 day of curing, the addition of 20%NP to MS without $CaCl_2$ resulted in a slight reduction in its PI, decreasing from 39.4% to 38.2%, equivalent to a 1.2% decrease. Similar observations have been reported by other researchers, including Harichane et al. (2010), Zoubir et al. (2013), and Al-Swaidani et al. (2016). When $CaCl_2$ was introduced into the MS–NP mixtures, the PI showed further reductions after 1 day of curing, dropping to 34.1%, 33.3%, and 32.1% with 2%, 4%, and 6% $CaCl_2$, respectively (Figure 1a). After 30 days of curing, this trend became more pronounced, with the PI of NP-stabilized MS decreasing by 5.6%, 5.8%, and 8.9% for 2%, 4%, and 6% $CaCl_2$, respectively (Figure 1b). Consistent with these findings, Gadouri et al. (2017a) observed that when NP was used as a sole additive, varying $CaSO_4$ contents produced a considerable decrease in the PI of all tested grey soil samples.

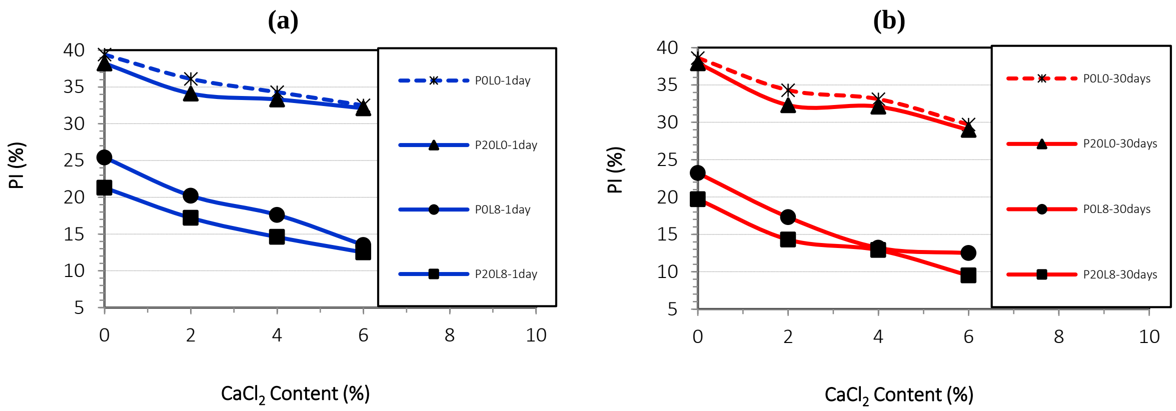


Figure 1. Effect of different $CaCl_2$ contents on the classification of MS stabilized with 8%L, 20%NP and 8%L+20%NP for different curing periods (a) 1 day and (b) 30 days

Effect of $CaCl_2$ on the PI of MS–L Mixture

Conversely, using L as an additive without $CaCl_2$ significantly enhanced the workability of the MS sample by substantially reducing its PI over time, particularly after 30 days of curing (Figure 1). Specifically, after 1 day of curing, the incorporation of L alone reduced the PI from 39.4% to 25.4% (Figure 1a). Brandl (1981) similarly reported a decrease in soil PI from 32.3% to approximately 5% with the addition of 2.5% L. Unlike the results observed with NP, the addition of $CaCl_2$ to L-stabilized MS caused a marked reduction in PI values by 5.2%, 7.8%, and 11.9% for 2%, 4%, and 6% $CaCl_2$ after 1 day of curing, respectively (Figure 1a). These findings align with those reported by Gadouri et al. (2017b). Moreover, Celik and Nalbantoglu (2013) noted that for similar soils stabilized with 5%L, with the presence of monovalent cations (Na^+ from Na_2SO_4), the PI decreased from 32% to 15% in the presence of 2000 ppm Na_2SO_4. However, the PI increased to 34% and 38% with Na_2SO_4 concentrations of 5000 ppm and 10,000 ppm, respectively.

These results indicate that the observed increases and decreases in PI are influenced by the concentration of the chemical compound used, the type of anion present (Cl^- from $CaCl_2$, SO_4^{2-} from Na_2SO_4 or $CaSO_4$), and the curing duration. Kinuthia et al. (1999) attributed these modifications in PI values to the cation exchange process, which directly impacts the viscosity of the clay–water mixture. Furthermore, this process significantly alters the physico-chemical interactions between clay particles. An increase in cation concentration leads to greater separation between clay particles, promoting aggregation and modifying particle size. This re-organization of particles affects pore distribution and subsequently modifies the consistency limits of the stabilized soil.

However, in the case of L-stabilized MS without $CaCl_2$, the PI decreased significantly from 39.4% to 23.2%, after a 30-day curing period. Hussain and Dash (2010) observed that the PI of lime-treated soils tends to decrease over longer curing periods due to the formation of calcium silicate hydrate (C–S–H), which has the capacity to absorb water. Similar trends were reported by Gadouri et al. (2017b) and Al-Swaidani et al. (2016). When L was added to the MS and cured with $CaCl_2$ for 30 days, a further reduction in the PI value was observed compared to the results after just 1 day of curing. Specifically, the PI decreased by 5.9%, 10%, and 10.7% in the presence of 2%, 4%, and 6% $CaCl_2$, respectively (Figure 1b). Notably, for the 6% $CaCl_2$ scenario, the PI of the L-stabilized MS is 3.15 times lower than that of the untreated MS corresponding to 68.3% reduction (12.5% for NP0L8Cl6 *versus* 39.4% for NP0L0Cl0). In the context of our study, the reduction in the PI value of L-stabilized MS was more pronounced than that reported by Li et al. (2016). Their study recorded only a 1% decrease in PI over a curing period of 42 days for L-treated marine clays in the presence of chloride salts.

Effect of $CaCl_2$ on the PI of MS–L–NP Mixture

After 1 day of curing, the combination of L and NP in the absence of $CaCl_2$ significantly reduced the PI value from 39.4% to 21.3%, which was lower than that of L-stabilized MS alone (Figure 1a). For a similar soil type (clayey soil treated with an L–NP mixture), Al-Swaidani et al. (2016) reported a substantial decrease in the PI of stabilized soil from 28.8% to 2.9% using L and NP as a combined treatment. Additionally, significant changes were observed with the introduction of 6% $CaCl_2$, where the PI decreased further from 21.3% to 9.5%. In general, the reduction in the PI of stabilized MS upon the addition of $CaCl_2$ alone can be attributed to the compression of the diffuse double layer, as explained by Locat et al. (1990).

The measured amorphous silica (46.4%) and amorphous alumina (17.5%) contents of the natural pozzolana fall well within the ranges typically associated with high pozzolanic reactivity, as reported in ASTM C618-22 for Class-N natural pozzolans. The predominance of the amorphous phase enhances the dissolution of reactive silica and alumina in alkaline environments generated by lime hydration ($Ca(OH)_2$ release), leading to the formation of secondary calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H). The specific surface area (420 m^2/kg) further increases the dissolution rate and reactive interface, accelerating the pozzolanic reaction kinetics.

The pozzolanic activity index (79% at 28 days, ASTM C311-21) confirms the ability of this material to actively bind calcium hydroxide and contribute to the strength development of stabilized soils. Although the activity index is slightly below the 85% threshold considered “high reactivity” for some industrial pozzolans, the combined high amorphous content and fine particle size suggest that longer curing periods would yield continued strength gains. Therefore, in the present study, the NP is expected to significantly participate in reducing the plasticity index and altering the classification of Marley soil when used in combination with lime and, to a lesser extent, with $CaCl_2$.

Modification in Soil Classification According to USCS and BSCS Systems

Based on the measured LL and PI (where PI=LL–PL) values, fine-grained soils are divided into five (5) and ten (10) classes according to the plasticity charts of the Unified Soil Classification System (USCS) and the British Soil Classification System (BSCS), respectively. In the USCS, silts (M) and clays (C) are separated by the A-line ($PI = 0.73*(LL–20)$), with low plasticity (L) for $LL<50\%$ and high plasticity (H) for $LL\geq50\%$, yielding five categories: ML (low-plasticity silt), MH (high-plasticity silt), CL (low-plasticity clay), CH (high-plasticity clay), and CL–ML (dual classification for soils in the hatched zone near the origin). In the BSCS, the same A-line separates M from C, but each is further divided into five plasticity levels: L (low), I (intermediate), H (high), V (very high), and E (extremely high). This results in ten possible classes: (i) for silts (M): ML (low-plasticity silt), MI (intermediate-plasticity silt), MH (high-plasticity silt), MV (very-high-plasticity silt), and ME (extremely-high-plasticity silt), and (ii) for clays (C): CL (low-plasticity clay), CI (intermediate-plasticity clay), CH (high-plasticity clay), CV (very-high-plasticity clay), and CE (extremely-high-plasticity clay). Based on the Atterberg limits results of MS samples stabilized with L, NP, and their combination (Table 4), the changes caused by the presence of $CaCl_2$ on the classification of all the mixtures were studied by plotting the values of their PI and LL on a plasticity chart (Figures 2, 3, 4, 5 and 6).

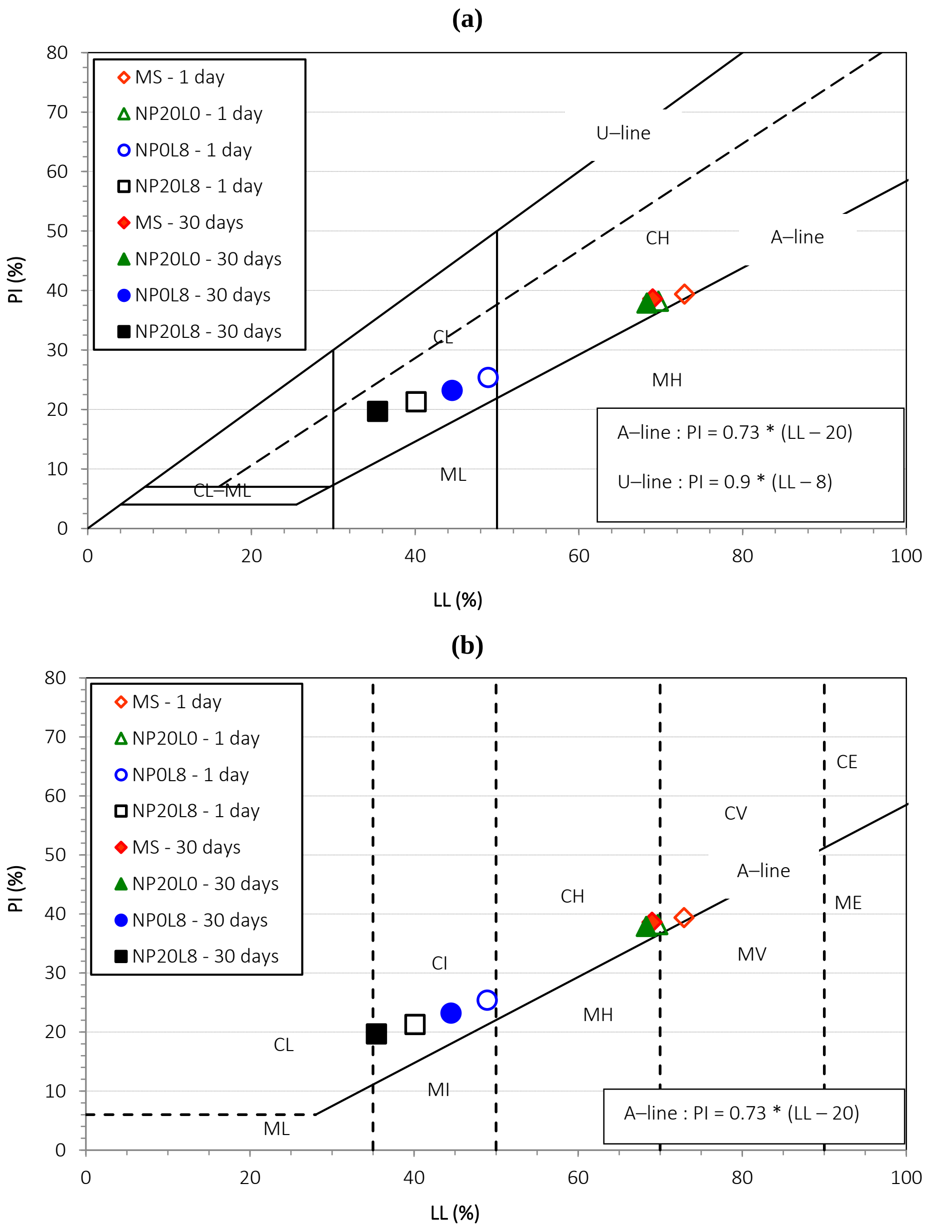


Figure 2. Effect of 20%NP, 8%L and their combination on the classification of MS after curing for 1 day and 30 days, (a) USCS classification system and (b) BSCS classification system

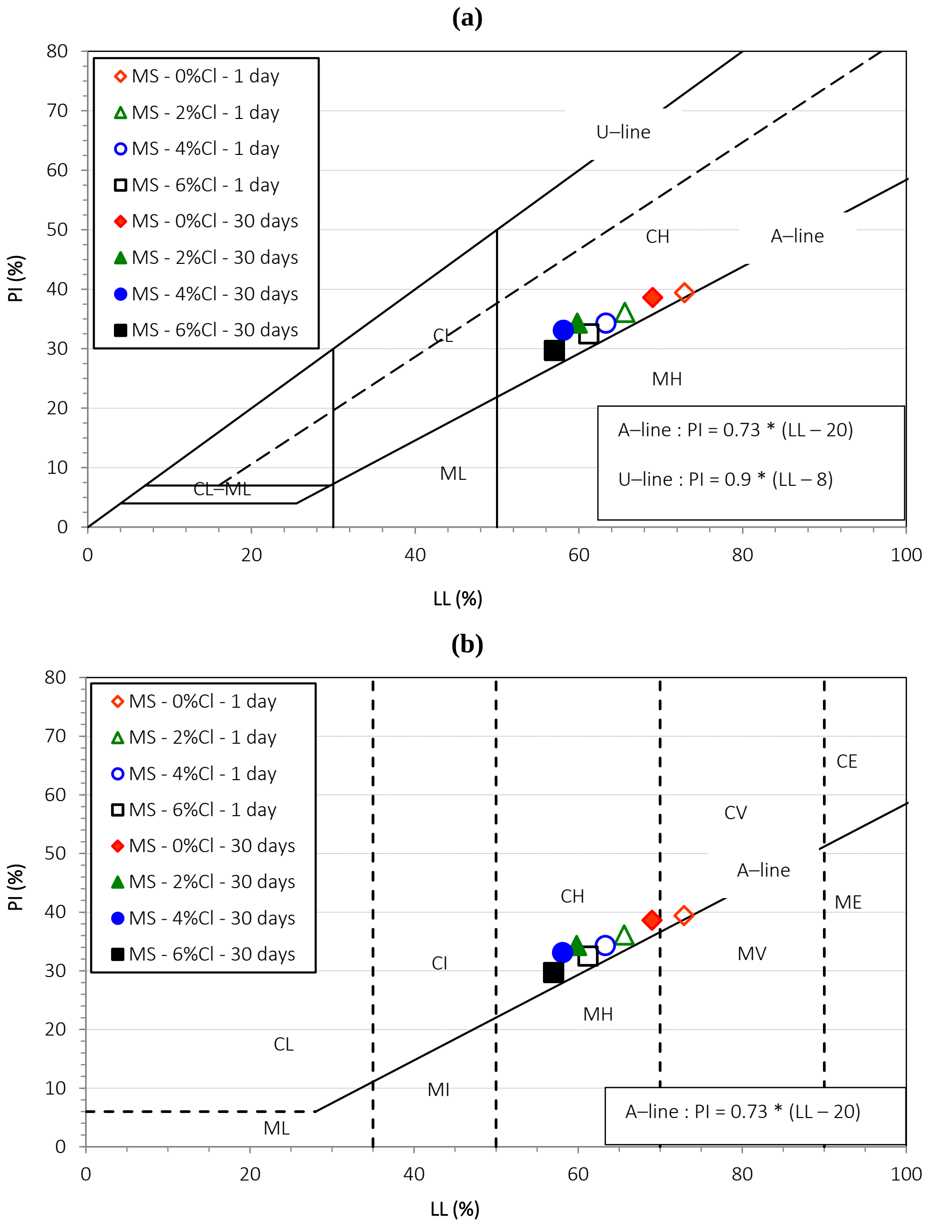


Figure 3. Effect of different $CaCl_2$ contents on the classification of unsterilized MS after curing for 1 day and 30 days, (a) USCS classification system and (b) BSCS classification system

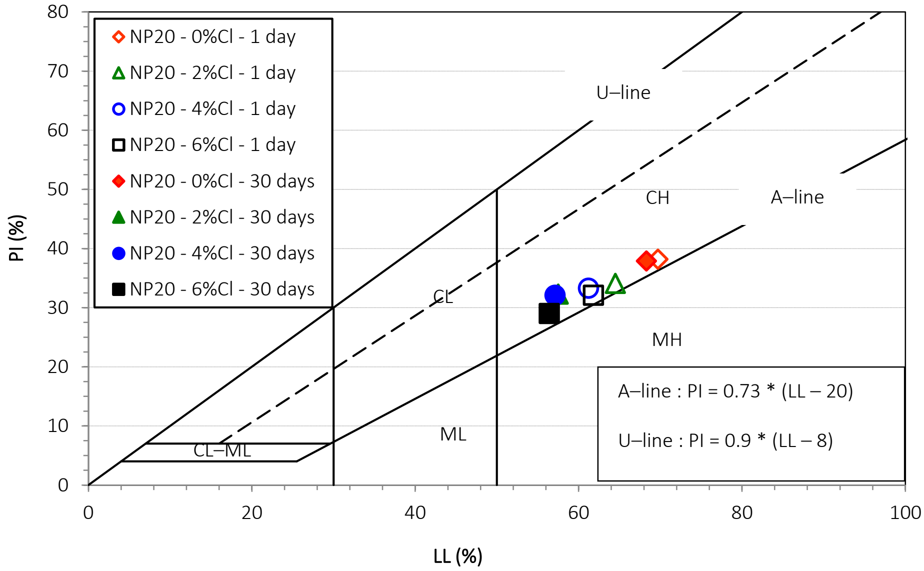
Effect of NP, L and Their Combination on the Classification of MS

As shown in Figure 2, the unstabilized and stabilized MS samples are classified by plotting the values of their PI and LL on both plasticity charts (USCS and BSCS) to assess the effect of using NP, L, and their combination on the classification of MS after 1-day and 30-day curing periods. For any curing period, and according to both the USCS and BSCS, it can be seen that the unstabilized MS was classified as a CH class, because the point (LL, PI) representing the MS class was to the right of the LL = 50% line and above the A-line.

After 1 day of curing, and according to the USCS, the classification of unstabilized MS did not change upon adding NP, but shifted to the left of the 50% line. However, it transformed into the CL class when L or the L–NP combination was added (Figure 2a). Similarly, Gadouri et al. (2018) reported that the grey soil class moved below the A-line and transitioned to the MH class when treated with L alone or in combination with NP. Conversely, no soil class transformation occurred when only NP was used. In contrast, Al-Swaidani et al.

(2016) observed different results, where the classification of stabilized soil changed from the CH class to the MH class when NP alone was applied.

(a)



(b)

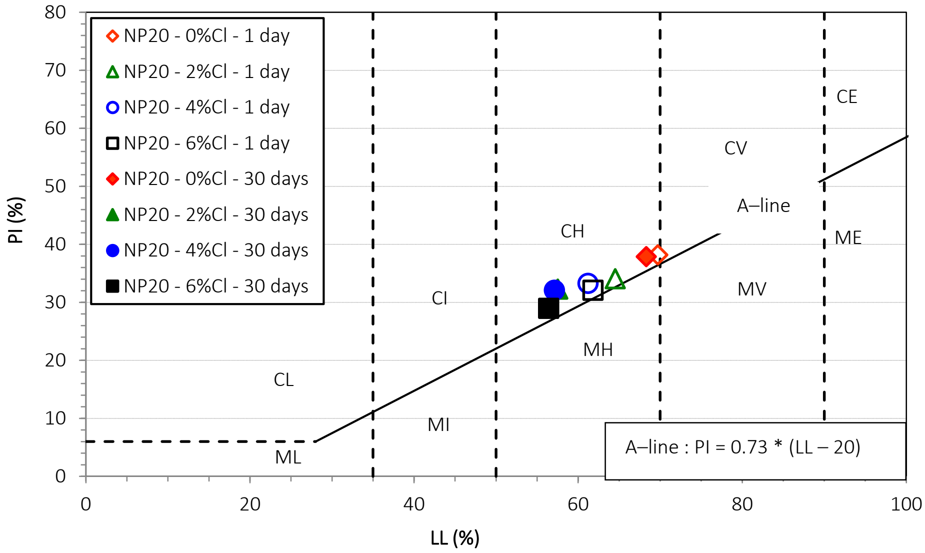


Figure 4. Effect of different $CaCl_2$ contents on the classification of MS–NP mixture after curing for 1 day and 30 days, (a) USCS classification system and (b) BSCS classification system

Additionally, after 1 day of curing, and according to the BSCS, the unstabilized MS class transformed from CV to CH upon adding NP. However, when L or the L–NP combination was added, the soil shifted to the left of the 50% line and changed to the CI class (Figure 2b). On the other hand, according to both the USCS and BSCS, no soil class transformation was observed after 30 days of curing when NP or L was added to the MS. The only exception was the L–NP combination, where the soil class was positioned precisely on the 35% line.

Effect of $CaCl_2$ on the Classification of Unstabilized MS

It can be seen that the addition of $CaCl_2$ alone to the high-plasticity clayey soils caused a slight improvement in its classification. In fact, for any curing period, the unstabilized MS samples (classified as a CH class) containing any $CaCl_2$ content were classified as a CL and CI classes according to the USCS (Figure 3a) and BSCS (Figure 3b), respectively. However, according to the BSCS, the MS sample cured with 6% $CaCl_2$ for 30 days can be also classified as HL class, because it is near to the A-line.

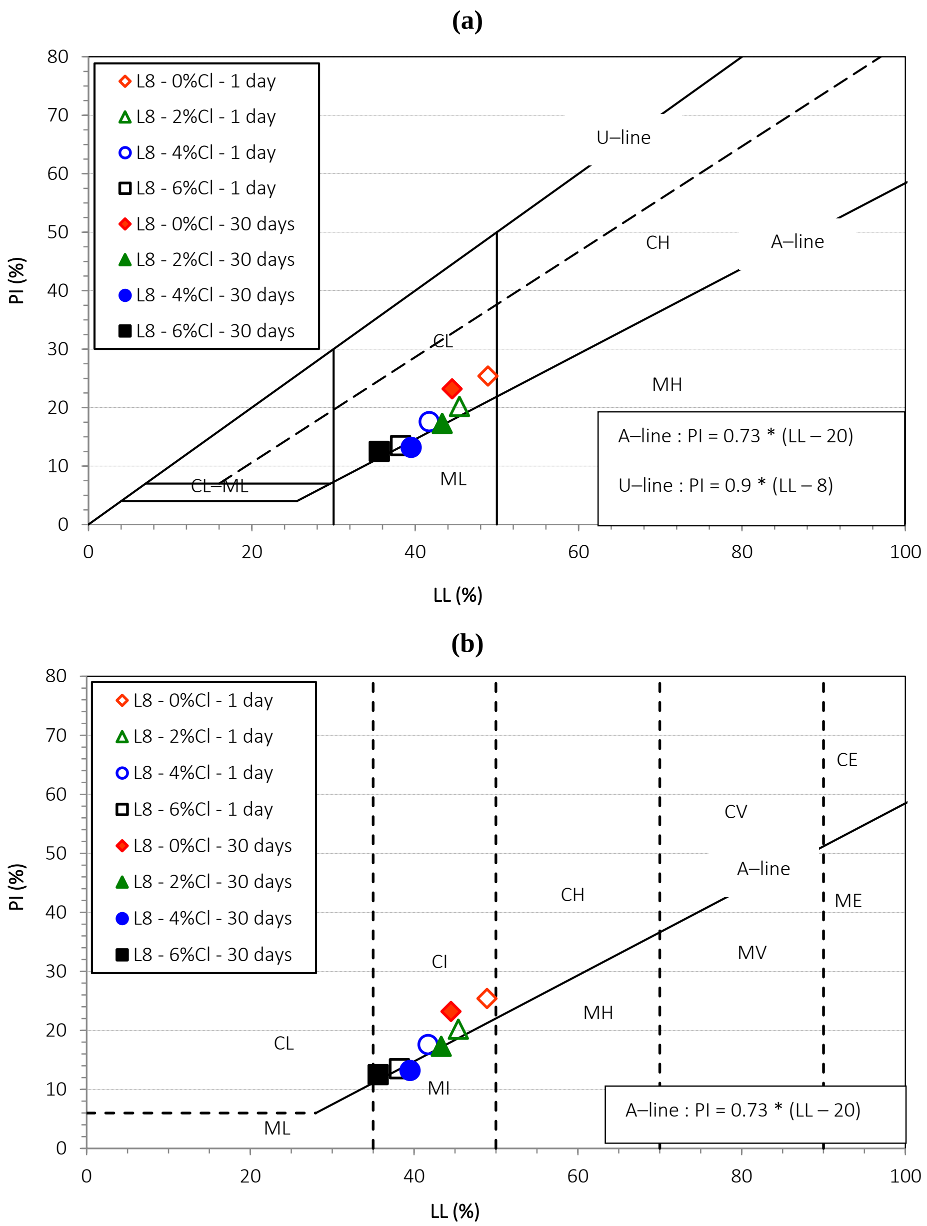


Figure 5. Effect of different $CaCl_2$ contents on the classification of MS–L mixture after curing for 1 day and 30 days, (a) USCS classification system and (b) BSCS classification system

Effect of $CaCl_2$ on the Classification of MS–NP Mixture

According to the USCS and for any curing time, no soil class transformation was observed when adding $CaCl_2$ to the MS–NP mixture (Figure 4a). On the other hand, according to the BSCS, it is obvious to observe that the presence of 2, 4, and 6% $CaCl_2$ transformed the classification of MS–NP mixture from CV to CI class after curing for 1 day and 30 days (Figure 4b). In addition, based on the BSCS and for 30 days curing time, the MS–NP mixture containing any $CaCl_2$ content can be also classified as HL class, because it is near to the A-line.

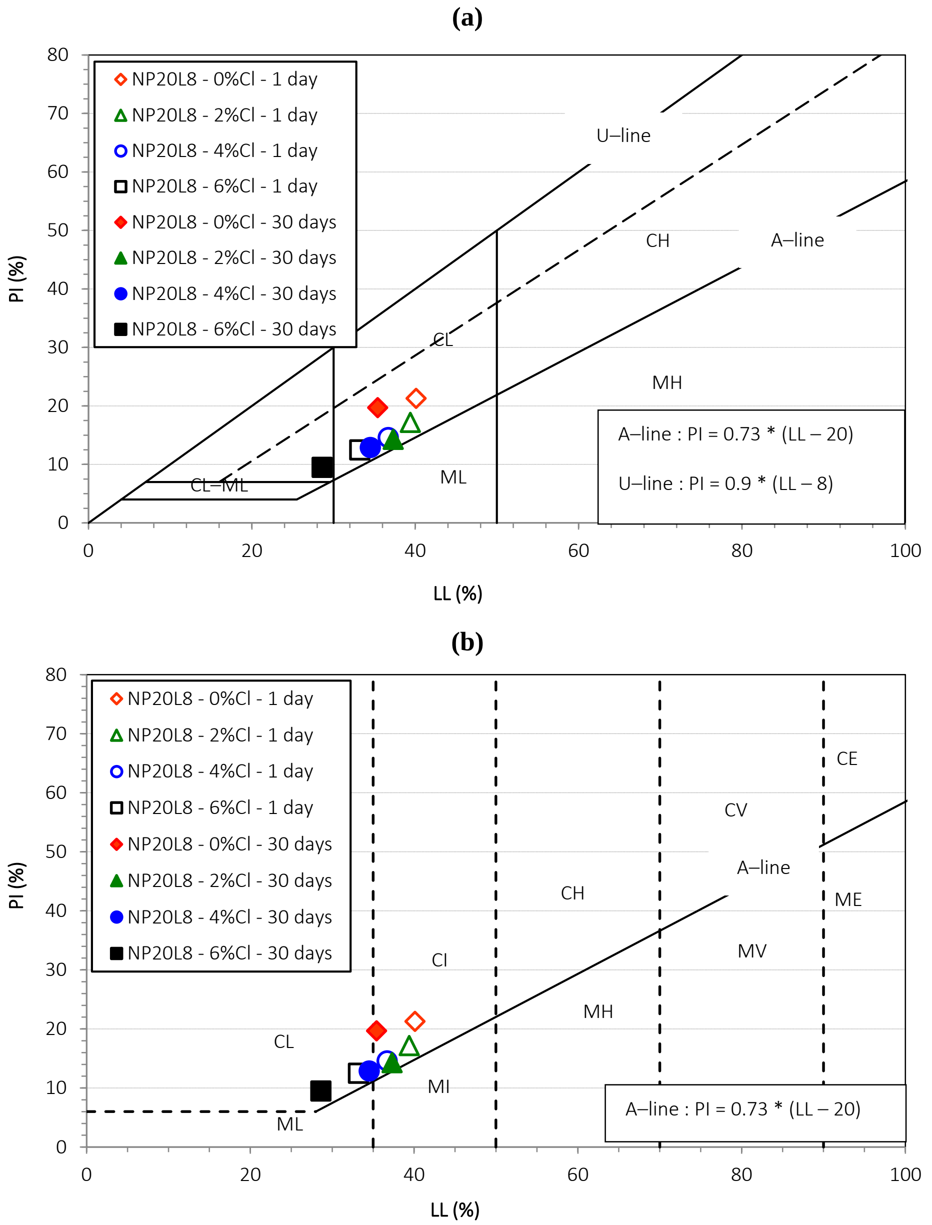


Figure 6. Effect of different $CaCl_2$ contents on the classification of MS–NP–L mixture after curing for 1 day and 30 days, (a) USCS classification system and (b) BSCS classification system

Effect of $CaCl_2$ on the Classification of MS–L and MS–L–NP Mixtures

For any curing period, and according to both the USCS and BSCS, it is evident that a considerable change in soil classes occurred for the MS–L mixture containing any amount of $CaCl_2$ compared to the same mixture (MS–L) without $CaCl_2$. Indeed, according to the USCS, the L-stabilized MS samples with and without $CaCl_2$ were classified as CL and ML classes after 1-day and 30-day curing periods, respectively (Figure 5a).

However, according to the BSCS, the same mixtures (MS–L and MS–L–$CaCl_2$) were classified as CI and MI classes after 1-day and 30-day curing periods, respectively (Figure 5b). On the other hand, for a shorter curing period (1 day), it is clear that a considerable transformation in soil classes was recorded for the MS–L–NP–$CaCl_2$ mixture compared to the same mixture (MS–L–NP) without $CaCl_2$. However, for a longer curing period (30 days) and for all $CaCl_2$ contents, the L–NP–stabilized MS sample, classified as ML (according to the USCS; Figure 6a) and MI (according to the BSCS; Figure 6b), was transformed to CI and MI soil classes.

Table 4. Effect of different $CaCl_2$ contents on both LL and PI of stabilized MS for 1 day and 30 days curing period

Atterberg's limits (%)	$CaCl_2$ (%)	Curing period (days)	Sample mixture (%)			
			NP0L0	NP20L0	NP0L8	NP20L8
Liquid limit (LL)	0	1	72.9	69.7	48.9	40.1
		30	69.0	68.3	44.5	35.4
	2	1	65.6	64.5	45.4	39.4
		30	59.8	57.5	43.3	37.3
	4	1	63.3	61.2	41.7	36.7
		30	58.1	57.1	39.5	34.5
	6	1	61.2	61.8	38.2	33.2
		30	57.0	56.4	35.6	28.6
Plasticity index (PI)	0	1	39.4	38.2	25.4	21.3
		30	38.6	37.9	23.2	19.7
	2	1	36.1	34.1	20.2	17.2
		30	34.3	32.3	17.3	14.3
	4	1	34.3	33.3	17.6	14.6
		30	33.1	32.1	13.2	12.9
	6	1	32.5	32.1	13.5	12.5
		30	29.7	29.0	12.5	09.5

Comparison of BSCS and USCS Precision

The observation that the British Soil Classification System (BSCS) offers greater precision compared to the Unified Soil Classification System (USCS) stems from the BSCS's more detailed sub-division of plasticity categories-ten intervals *versus* five in the USCS. This finer gradation enables the detection and reporting of marginal, yet meaningful, changes in Atterberg limits that may occur during soil stabilization treatments. For example, small reductions in plasticity index that might leave a soil in the same category under USCS could result in a shift to a lower category under BSCS, thereby reflecting performance improvements that the USCS might overlook.

While this increased resolution does not directly improve soil behavior, it enhances the ability of engineers to quantify and communicate incremental stabilization effects, particularly in research contexts or quality-control applications where tracking small changes is critical. In the context of this study, BSCS classification shifts corresponded more closely with the measured changes in Atterberg limits, providing a more nuanced interpretation of the stabilization process. Therefore, the choice of classification system can influence the perceived effectiveness of an additive and should be considered when reporting laboratory results or developing field specifications.

ENHANCEMENT MECHANISM ON THE CLASSIFICATION OF STABILIZED MS

When $CaCl_2$ was absent, the addition of L alone or in combination with NP to the MS samples produced an immediate change in their physical properties due to the cation exchange capacity. According to Gadouri et al. (2018), clay particles' surface is negatively charged which can increase the repulsive forces between them. In addition, the calcium hydroxide [$Ca(OH)_2$] hydrated in the contact of water (H_2O) and produced calcium (Ca^{2+}) and hydroxyl (OH^-), as shown in Eq. (1).

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^- \quad (1)$$

Both ions (Ca^{2+} and OH^- from L addition) were attracted to the surface of clay particles which decreased the repulsive forces by flocculation and then increased the adhesion between clay particles to form flocs by agglomeration (Locat et al., 1990). In fact, the immediate change in Atterberg's limits was explained by the electric reaction between clay particles and Ca^{2+} cations as the results of clay particles' flocculation (Gadouri et al., 2017b), which modified the soil classification (George et al. 1992; Harichane & Ghrici, 2009). However, the dissolution of $CaCl_2$ in the contact of H_2O produced Ca^{2+} and Cl^- ions, as shown in Eq. (2).

$$CaCl_2 \rightarrow Ca^{2+} + 2Cl^- \quad (2)$$

In addition, $CaCl_2$ acts as a setting accelerator in cement and geopolymer systems. It enhances the reaction kinetics, promoting faster hydration of silica and alumina. Under alkaline conditions provided by calcium hydroxide, silica (SiO_2) and alumina (Al_2O_3) from stabilized soil react to form calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H).

In conclusion, the presence of $CaCl_2$ in both the unstabilized MS sample and the MS–NP mixture considerably decreased their PI values and consequently improved their classification. This effect can be explained by the decrease in particle–particle separation. In contrast, the negatively charged surfaces of clay particles have a strong tendency to attract divalent cations such as Ca^{2+} released from $CaCl_2$ dissolution, leading to particle flocculation and a reduction in diffuse double layer thickness. However, it is suggested that chloride ions (Cl^-), being anions, are repelled by the clay surfaces and remain in the pore fluid, where they probably contribute to the ionic strength, but do not directly adsorb onto clay particles.

PRACTICAL IMPLICATIONS

The findings of this study have several practical implications for the field application of $CaCl_2$ in the stabilization of Marley soil and similar problematic fine-grained soils. The observed reductions in plasticity index and favorable shifts in soil classification suggest that $CaCl_2$, when used in combination with lime and natural pozzolana, can enhance workability, reduce shrink-swell potential, and potentially improve bearing capacity *in situ*. This is particularly relevant for arid and semi-arid regions, such as northern Algeria, where seasonal moisture fluctuations can significantly affect sub-grade performance.

From an environmental standpoint, the high solubility of $CaCl_2$ raises the possibility of leaching, especially under conditions of high rainfall or fluctuating groundwater levels. While such leaching could lead to a gradual reduction in the stabilizing effect, it might also increase chloride concentrations in surrounding water bodies or soils, warranting careful assessment in environmentally sensitive areas. To mitigate these risks, field trials should incorporate leachate monitoring and consider integrating complementary stabilizers with lower mobility.

In terms of cost-effectiveness, $CaCl_2$ is widely available and relatively inexpensive compared to other chemical stabilizers, and its ease of application, requiring only dissolution in water before mixing, reduces labor and equipment requirements. However, its long-term performance under traffic loading and varying climatic conditions remains to be validated. Pilot-scale field applications and life-cycle cost analyses are therefore recommended to confirm the economic and engineering benefits identified in the laboratory.

On the other hand, the observed changes in soil classification, such as shifts from CH (high plasticity clay) to CL (low plasticity clay) or MH (high plasticity silt) to MI (intermediate plasticity silt), have important engineering implications for the performance of stabilized sub-grades and foundations. In practical terms, reducing plasticity generally leads to a lower swell potential and diminished shrinkage upon drying, which translates into improved volumetric stability. This is particularly critical for pavements and lightly loaded structures in expansive soil regions, where differential movement can induce cracking and serviceability issues.

From a geotechnical design perspective, a transition from CH to CL often correlates with an increase in allowable bearing capacity, as lower-plasticity clays tend to exhibit higher shear strength and reduced compressibility. Similarly, MI soils compared to MH soils are less susceptible to moisture-induced strength loss, making them more suitable for applications where seasonal moisture variations are expected. While direct bearing capacity tests were not part of the present study, the classification improvements observed here are consistent with performance gains reported in earlier stabilization studies (e.g. Bell, 1996; Consoli et al., 2011). These correlations suggest that the combined use of lime, NP, and $CaCl_2$ not only modifies the plasticity behavior, but also has the potential to enhance the mechanical performance and long-term serviceability of stabilized soils in the field.

CONCLUSIONS

The impact of $CaCl_2$ on the plasticity index (PI) and classification of MS–L, MS–NP, and MS–L–NP mixtures has been thoroughly assessed. Based on the findings, several key conclusions can be drawn:

- Effect of NP and $CaCl_2$ on MS Classification and Plasticity: NP alone produced only marginal changes in PI and classification; the observed improvements are primarily attributable to $CaCl_2$, particularly in L-stabilized mixes. This suggests that NP alone is insufficient to significantly enhance MS classification or effectively reduce PI under these conditions.
- Transformation of Soil Classification with L and NP Additives: The introduction of 8% L, both alone and in combination with 20% NP without $CaCl_2$, successfully transformed MS from a CH to a CL class (according to the USCS) and from CV to CH and CI classes (according to the BSCS). Additionally, the addition of L and L–NP greatly improved the workability of the stabilized MS, mainly by lowering the PI, with more pronounced improvements observed after extended curing periods.
- Role of $CaCl_2$ in Soil Stabilization and Classification: The use of $CaCl_2$ alone, or in combination with NP, slightly improved the PI and classification of both unstabilized and NP-stabilized MS, regardless of the curing period. This indicates that $CaCl_2$ has limited effectiveness for soil stabilization in geotechnical applications, such as road pavements. However, for L-stabilized MS, 6% $CaCl_2$ content over an extended curing period markedly decreased the PI of L-stabilized MS, which in some cases resulted in a change in soil classification, depending on the classification system used. Therefore, the use of 6% $CaCl_2$ in L-stabilized MS should be carefully considered for soil stabilization in geotechnical projects. Moreover, the effect of $CaCl_2$ on soil classification was more pronounced when combined with L or NP than when NP was used alone. The BSCS provided a more accurate classification than the USCS, highlighting its potential as a more reliable method for evaluating stabilized soils, especially in projects requiring high precision.

NOTATIONS

MS	Marley Soil
CH	Clay of High Plasticity
CL	Clay of Low Plasticity
L	Lime
NP	Natural Pozzolana
$CaCl_2$	Calcium Chloride
LL	Liquid Limit
PL	Plastic Limit
PI	Plasticity Index
ASTM	American Society for Testing and Materials
USCS	Unified Soil Classification System
BSCS	British Soil Classification System
C–S–H	Calcium Silicates Hydrates
C–A–H	Calcium Aluminates Hydrates

Conflict of Interests

The authors declare that there is no conflict of interests in relation to this article.

Finding

This research was funded by the General Directorate for Scientific Research and Technological Development (DGRSDT) of the Algerian Ministry of Higher Education and Scientific Research.

Data Availability

Data will be made available upon reasonable request.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

REFERENCES

Afrin, H. (2017). A review on different types of soil stabilization techniques. *International Journal of Transportation Engineering and Technology, 3*(2), 19-24.

Afrin, H. (2017). Stabilization of clayey soils using chloride components. *American Journal of Civil Engineering, 5*(6), 365-370. https://doi.org/10.11648/j.ajce.20170506.18

Almajed, A., Dafalla, M., & Shaker, A.A. (2023). The combined effect of calcium chloride and cement on expansive soil materials. *Applied Sciences, 13*(8), 4811. https://doi.org/10.3390/app13084811

Al-Rawas, A.A. (2004). Characterisation of incinerator ash treated expansive soils. *Proceedings of the ICE - Ground Improvement, 8*(3), 127-135. https://doi.org/10.1680/grim.2004.8.3.127

Al-Rawas, A.A., Hago, A.W., & Al-Sarmi, H. (2005). Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman. *Building and Environment*, *40*(5), 681-687. https://doi.org/10.1016/j.buildenv.2004.08.028

Alsharie, H., & Alayed, O. (2019). The effect of replacing fine silica with stone cuttings' powder on the compressive strength of concrete: A case study in Jordan. *Jordan Journal of Civil Engineering*, *13*(1), 124-135.

Al-Swaidani, A., Hammoud, I., & Meziab, A. (2016). Effect of adding natural pozzolana on geotechnical properties of lime-stabilized clayey soil. *Journal of Rock Mechanics and Geotechnical Engineering*, *8*(5), 714-725. https://doi.org/10.1016/j.jrmge.2016.05.005

Asgari, M.R., Dezfuli, A.B., & Bayat, M. (2015). Experimental study on stabilization of a low plasticity clayey soil with cement/lime. *Arabian Journal of Geosciences*, *8*(3), 1439-1452. https://doi.org/10.1007/s12517-014-1265-0

ASTM International. (2000). *ASTM D4318-00: Standard test methods for liquid limit, plastic limit and plasticity index of soils*. ASTM International.

ASTM International. (2006). *ASTM D2487-06: Standard practice for classification of soils for engineering purposes (Unified Soil Classification System)*. ASTM International.

ASTM International. (2007). *ASTM C204-07: Standard test method for fineness of hydraulic cement by air-permeability apparatus*. ASTM International.

ASTM International. (2009). *ASTM D3282-09: Standard practice for classification of soils and soil-aggregate mixtures for highway construction purposes*. ASTM International.

ASTM International. (2021). *ASTM C311-21: Standard test methods for sampling and testing fly ash or natural pozzolans for use in portland-cement concrete*. ASTM International.

ASTM International. (2022). *ASTM C618-22: Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*. ASTM International.

Aymen, D.M., Benamghar, A., & Boudjellal, M. (2024). Consolidation settlement by observational and conventional methods utilizing results of test embankments from Algeria. *Jordan Journal of Civil Engineering*, *18*(3), 361-371. https://doi.org/10.14525/JJCE.v18i3.01

Bayoumy, M., El Sawwaf, M., & Elsawwaf, A. (2024). Strength and deformability characteristics of cemented clayey sand. *Jordan Journal of Civil Engineering*, *18*(4), 623-636. https://doi.org/10.14525/JJCE. v18i4.08

Brandl, H. (1981). Alteration of soil parameters by stabilization with lime. In *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering*, *3*, 587-594, Stockholm.

British Standards Institution. (2015). *BS 5930-15: Code of practice for site investigations*. British Standards Institution.

Celik, E., & Nalbantoglu, Z. (2013). Effects of ground granulated blastfurnace slag (GGBS) on the swelling properties of lime-stabilized sulfate-bearing soils. *Engineering Geology*, *163*, 20-25. https://doi.org/10.1016/j.enggeo.2013.06.006

Consoli, N.C., Rosa, D.A., Cruz, R.C., & Dalla Rosa, A. (2011). Water content, porosity and cement content as parameters controlling strength of artificially cemented silty soil. *Engineering Geology*, *122*(3-4), 328-333. https://doi.org/10.1016/j.enggeo.2011.05.017

Fattah, M.Y., Al-Musawi, H.H.M., & Salman, F.A. (2012). Treatment of collapsibility of gypseous soils by dynamic compaction. *Geotechnical and Geological Engineering*, *30*(6), 1369-1387. https://doi.org/10.1007/s10706-012-9552-z

Gadouri, H. (2023). Behavior of natural pozzolana-lime-stabilized clayey soils artificially contaminated by sulfates. *Jordan Journal of Civil Engineering*, *17*(4), 635-655. https://doi.org/10.14525/JJCE.v17i4.07

Gadouri, H., Harichane, K., & Ghrici, M. (2017a). Effect of calcium sulphate on the geotechnical properties of stabilized clayey soils. *Periodica Polytechnica Civil Engineering*, *61*(2), 256-271. https://doi.org/10.3311/PPci.9597

Gadouri, H., Harichane, K., & Ghrici, M. (2017b). Effects of Na_2SO_4 on the geotechnical properties of clayey soils stabilised with mineral additives. *International Journal of Geotechnical Engineering*, 1-13. https://doi.org/10.1080/19386362.2016.1238562

Gadouri, H., Harichane, K., & Ghrici, M. (2017c). Effect of sodium sulphate on the shear strength of clayey soils stabilised with additives. *Arabian Journal of Geosciences*. https://doi.org/10.1007/s12517-017-3016-y

Gadouri, H., Harichane, K., & Ghrici, M. (2018). Assessment of sulphates effect on the classification of soil-lime-natural pozzolana mixtures based on the Unified Soil Classification System (USCS). *International Journal of Geotechnical Engineering*, 1-9. https://doi.org/10.1080/19386362.2016.1275429

Gadouri, H., Harichane, K., & Ghrici, M. (2019a). A comparison study between $CaSO_4{\cdot}2H_2O$ and Na_2SO_4 effects on geotechnical properties of clayey soils stabilised with mineral additives to recommend adequate mixtures as materials for road pavements. *International Journal of Geotechnical Engineering*, 1-22. https://doi.org/10.1080/19386362.2017.1320850

Gadouri, H., Harichane, K., & Ghrici, M. (2019b). Assessment of sulphates effect on pH and pozzolanic reactions of soil-lime-natural pozzolana mixtures. *International Journal of Pavement Engineering*, 1-14. https://doi.org/10.1080/10298436.2017.1337119

George, S.Z., Ponniah, D.A., & Little, J.A. (1992). Effect of temperature on lime-soil stabilization. *Construction and Building Materials, 6*, 247-252.

Ghrici, M., Kenai, S., & Said-Mansour, M. (2007). Mechanical properties and durability of mortar and concrete containing natural pozzolana and limestone blended cements. *Cement and Concrete Composites, 29*(7), 542-549. https://doi.org/10.1016/j.cemconcomp.2007.04.009

Gromko, G.J. (1974). Review of expansive soils. *Journal of Geotechnical and Geoenvironmental Engineering, 100*(6), 667-687. https://doi.org/10.1061/AJGEB6.0000059

Harichane, K., & Ghrici, M. (2009, May 30). Effect of combination of lime and natural pozzolana on the plasticity of soft clayey soils. *2nd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering*, Near East University, Nicosia.

Harichane, K., Ghrici, M., & Kenai, S. (2011a). Effect of curing period on shear strength of cohesive soils stabilized with combination of lime and natural pozzolana. *International Journal of Civil Engineering, 9*(2), 90-96.

Harichane, K., Ghrici, M., & Kenai, S. (2012). Effect of the combination of lime and natural pozzolana on the compaction and strength of soft clayey soils: A preliminary study. *Environmental Earth Sciences, 66*(8), 2197-2205. https://doi.org/10.1007/s12665-011-1444-8

Harichane, K., Ghrici, M., & Kenai, S. (2017). Stabilization of Algerian clayey soils with natural pozzolana and lime. *Periodica Polytechnica Civil Engineering.* https://doi.org/10.3311/PPci.9229

Harichane, K., Ghrici, M., & Missoum, H. (2011c). Influence of natural pozzolana and lime additives on the temporal variation of soil compaction and shear strength. *Frontiers of Earth Science, 5*(2), 162-169. https://doi.org/10.1007/s11707-011-0160-y

Harichane, K., Ghrici, M., Kenai, S., & Grine, K. (2011b). Use of natural pozzolana and lime for stabilization of cohesive soils. *Geotechnical and Geological Engineering, 29*(5), 759-769. https://doi.org/10.1007/s10706-011-9423-5

Harichane, K., Ghrici, M., Khebizi, W., & Missoum, H. (2010). Effect of the combination of lime and natural pozzolana on the durability of clayey soils. *Electronic Journal of Geotechnical Engineering, 15*, 1194-1210.

Hossain, K.M.A., Lachemi, M., & Easa, S. (2007). Stabilized soils for construction applications incorporating natural resources of Papua New Guinea. *Resources, Conservation and Recycling, 51*(4), 711-731. https://doi.org/10.14525/JJCE.v17i4.07

Hu, Z., Jia, Z., Gao, L., & Yuan, Z. (2016). The effects of sulfate on the strength of lime-fly ash stabilized soil. *Electronic Journal of Geotechnical Engineering, 21*(10), 3669-3676.

Hussain, M., & Dash, S.K. (2010). Influence of lime on plasticity behaviour of soils. In *Proceedings of Indian Geotechnical Conference GEOtrendz* (pp. 16-18). Bombay, India.

Islam, S., Hoque, N., Uddin, M., & Chowdhury, M. (2018). Strength development in clay soil stabilized with fly ash. *Jordan Journal of Civil Engineering, 12*(2), 188-201.

Karkush, M., & Ali, S.D. (2025). Durability of gypseous soil stabilized with nano-silica under environmental conditions. *Jordan Journal of Civil Engineering, 19*(1), 164-178. https://doi.org/10.14525/JJCE.v19i1.12

Khemissa, M., & Mahamedi, A. (2014). Cement and lime mixture stabilization of an expansive overconsolidated clay. *Applied Clay Science, 95*, 104-110. https://doi.org/10.1016/j.clay.2014.03.017

Khemissa, M., Mahamedi, A., & Mekki, L. (2015). Problematic soil mechanics in the Algerian arid and semi-arid regions: Case of M'sila expansive clays. *Journal of Applied Engineering Science and Technology, 1*(2), 37-41. https://doi.org/10.69717/jaest.v1.i2.32

Kinuthia, J. M., Wild, S., & Jones, G.I. (1999). Effects of monovalent and divalent metal sulphates on consistency and compaction of lime-stabilised kaolinite. *Applied Clay Science, 14*(1), 27-45. https://doi.org/10.1016/S0169-1317(98)00035-8

Li, M., Chai, S., Du, H., & Wang, C. (2016). Effect of chlorine salt on the physical and mechanical properties of inshore saline soil treated with lime. *Soils and Foundations, 56*(3), 327-335. https://doi.org/10.1016/j.sandf.2016.06.007

Locat, J., Berube, M.A., & Choquette, M. (1990). Laboratory investigations on the lime stabilization of sensitive clays: Shear strength development. *Canadian Geotechnical Journal*, *27*(3), 294-304. https://doi.org/10.1139/t90-042

Melese, D.T. (2022). Improvement of engineering properties of expansive soil modified with scoria. *Jordan Journal of Civil Engineering, 16*(2), 211-218.

Meziani, B., & Gadouri, H. (2023). Swelling suppressing by using polypropylene fibre as reinforcement in natural pozzolana-lime-stabilised expansive grey clayey soil artificially contaminated by sulphates. *Multiscale and Multidisciplinary Modeling, Experiments and Design*, *6*(4), 477-504.

Mitchell, J. K. (1986). Practical problems from surprising soil behaviour. *Journal of Geotechnical Engineering, 112*(3), 274-279. https://doi.org/10.1061/(ASCE)0733-9410(1986)112:3(274)

Ola, S.A. (1977). The potentials of lime stabilization of lateritic soils. *Engineering Geology, 11*(4), 305-317. https://doi.org/10.1016/0013-7952(77)90011-X

Puppala, A.J., Griffin, J.A., Hoyos, L.R., & Chmotid, S. (2004). Studies on sulfate-resistant cement stabilization methods to address sulfate-induced soil heave. *Journal of Geotechnical and Geoenvironmental Engineering, 130*(4), 391-402.

Salih, N., & Abdalla, T. (2022). Stabilization of low plasticity clay soil utilizing crushed limestone. *Jordan Journal of Civil Engineering, 16*(2), 219-228.

Seleam, S.N. (2006). Evaluation of collapsibility of gypseous soils in Iraq. *Journal of Engineering, 12*(3), 712-726. https://doi.org/10.31026/j.eng.2006.03.21

Sivapullaiah, P.V., Sridharan, A., & Ramesh, H.N. (2000). Strength behaviour of lime-treated soils in the presence of sulphate. *Canadian Geotechnical Journal, 37*(6), 1358-1367.

Swami, B.L. (2002). Feasibility study of marble dust in highway sector. *Highway Research Bulletin, 67*, 27-36.

Xu, R., Guo, Y., & Liu, Z. (2008). Mechanical properties of stabilized artificial organic soil. *Frontiers of Architecture and Civil Engineering in China, 2*(2), 161-165.

Zoubir, W., Harichane, K., & Ghrici, M. (2013). Effect of lime and natural pozzolana on dredged sludge engineering properties. *Electronic Journal of Geotechnical Engineering, 18*(C), 589-600.

Zumrawi, M.M., & Eltayeb, K.A. (2016). Laboratory investigation of expansive soil stabilized with calcium chloride. *International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering, 10*(2), 199-203.