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EFFECT OF $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ON THE PHYSICO-MECHANICAL PROPERTIES OF STABILIZED CLAYEY SOILS

K. Harichane¹, H. Gadouri² and M. Ghrici³

¹Department of Civil Engineering
University of Hassiba Ben-Bouali, Chlef
City, 02000 Chlef, Algeria
E-mail: kharichane@yahoo.fr

²Department of Civil Engineering
University of Hassiba Ben-Bouali, Chlef
City, 02000 Chlef, Algeria
E-mail: hamid_gadouri2000@yahoo.fr; web page: <https://gadouriamid.jimdo.com>

³Department of Civil Engineering
University of Hassiba Ben-Bouali, Chlef
City, 02000 Chlef, Algeria
E-mail: m_ghrici@yahoo.fr

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Abstract. *The effects caused by sulphates on the soil stabilization using additives such as lime, cement and fly ash have been reported by several researchers. An experimental investigation was undertaken to study the effects of calcium sulphate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) (0–6% by dry weight of soil) on the behavior of two clayey soils stabilized with lime (L, 0–8%), natural pozzolana (NP, 0–20%) and their combination (L–NP). The engineering properties investigated are respectively, the Atterberg limits on samples cured for 1, 15 and 30 days to assess the diffusion time effect of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (DTC) in the soil paste and the unconfined compressive strength (UCS) after a curing period of 7 to 120 days. In the absence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, the results show that both clayey soils can be successfully stabilized by L alone or in combination with NP, which substantially reduces their plasticity and increases their UCS. However, when combining a fraction of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ to samples containing L or the combination of L–NP, a further decrease in plasticity index (PI) values is observed. In addition, higher UCS values are recorded. In conclusion, the effects of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on both stabilized clayey soils depends on the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content, curing time, type and additive content and mineralogical composition of the stabilized soil.*

1 INTRODUCTION

The chemical stabilization of soils using lime, cement or other additives is not new and remains so far the cheapest technique used in soils stabilization [1, 2]. When no sulphate is present, the cation exchange capacity of the soil depends largely on its particles with negatively charged surfaces. This negative charge develops repulsive forces between the clay particles. However, in the absence of sulphates, the lime hydrates and ionises after its contact with water to form calcium ions and hydroxyl. This change has the effect of reducing the size of the double layer of the clay particles, lowering the repulsive forces between them and, increasing the alkalinity of the solution system [3]. The reduction in the repulsion forces between these particles creates a bond between them and forms flocks. This change caused by lime reduces the plasticity index and the maximum dry density of the stabilized soil but increases their optimum moisture content [3]. On the other hand, it is known that the increase in the concentration of hydroxyl



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(OH) raises the pH of the soil, and causes the dissolution of alumina and silica which interact with calcium ions to form cementitious products such as calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH). These compounds are responsible on the increase in strength (UCS) values of the stabilized soil [5].

However, in the presence of sulphates, the sulphate ions react with calcium, hydroxyl and aluminium compounds to form expansive phases such as ettringite. Furthermore, the magnitude of damage caused by the ettringite depends to the soil nature, the type and the content of additives [6] and the concentration and the type of cation associated with the sulphate anion [7] (Kinuthia et al., 1999). Moreover, the combination of volcanic materials with lime produces a beneficial effect on the behavior of the soil [8]. The NP is found in abundance in areas of Beni-Saf located in the West of Algeria [9]. This latter was used in combination with lime to improve the engineering properties of two clayey soils such as the shear strength, the plasticity and the UCS [4, 5, 10, 11]. However, there is no investigation of the influence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the stabilization of these soils. This work is devoted mainly for study the effect of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the Atterberg limits and UCS of two clayey soils using L and NP.

2 EXPERIMENTAL INVESTIGATION AND TEST PROCEDURES

2.1 Materials used

Two clayey soils stabilized with two additives with or without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ were used in this study, the first is a grey clay soil (GS) which was obtained from an embankment project site, and the second is a red clay soil (RS) which was obtained from a highway project site, and both near Chelif town in the West of Algeria. Laboratory tests were carried out to classify each type of soil. The Physico-mechanical and mineralogical properties of both clayey soils are illustrated in Table 1. However, the NP was collected from Beni-Saf located in the Western of Algeria. It was ground to the specific surface of $420\text{m}^2/\text{kg}$. On the other hand, the lime used is commercially available lime typically used for construction purposes. The physico-chemical properties of these additives are shown in Table 2.

Physico-Mechanical and Mineralogical Properties	GS	RS	Physico-Mechanical and Mineralogical Properties	GS	RS
Color	Grey	Red	Optimum water content (%)	28.3	15.3
Natural water content (%)	32.9	13.8	Maximum dry density (kN/m^3)	13.8	16.9
Specific Gravity	2.71	2.84	UCS (KPa)	100	510
Passing 80 μm sieve (%)	85.0	97.5	Loss an ignition (%)	17.0	7.13
Liquid limit (%)	82.8	46.5	Calcite (%)	26.0	4.00
Plastic limit (%)	32.2	22.7	Illite (%)	16.0	24.0
Plasticity index (%)	50.6	23.8	Kaolinite (%)	12.0	16.0
Classification (USCS)	CH	CL	Montmorillonite (%)	20.0	0.00

Table 1 : Physico-mechanical and mineralogical properties of both grey and red clayey soils

Chemical Name	L (%)	NP (%)	Chemical Name	L (%)	NP (%)
CaO	> 83.3	9.90	TiO ₂	-	2.10
MgO	< 0.50	2.42	P ₂ O ₅	-	0.80
Fe ₂ O ₃	< 2.00	9.69	CaCO ₃	< 10	-
Al ₂ O ₃	< 1.50	17.5	Specific Gravity	2	-
SiO ₂	< 2.50	46.4	Over 90 μm (%)	< 10	-
SO ₃	< 0.50	0.83	Over 630 μm (%)	0	-
Na ₂ O	0.40 - 0.50	3.30	Insoluble material (%)	< 1	-
K ₂ O	-	1.51	Bulk density (g/L)	600 – 900	-
CO ₂	< 5	-	Loss on ignition	-	5.34

Table 2 : Physico-mechanical properties of both lime and natural pozzolana



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Moreover, the chemical element used is the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. A total of 72 combinations based on GS and RS was studied and presented in Table 3.

Mix	Proportions (%)			Mix	Proportions (%)				Mix	Proportions (%)			
	Soil	NP	Ca		Soil	NP	L	Ca		Soil	NP	L	Ca
P0L0C0	100	0	0	P10L0C2	88	10	0	2	P20L4C4	72	20	4	4
P0L4C0	96	0	0	P20L0C2	78	20	0	2	P10L8C4	78	10	8	4
P0L8C0	92	0	0	P10L4C2	84	10	4	2	P20L8C4	68	20	8	4
P10L0C0	90	10	0	P20L4C2	74	20	4	2	P0L0C6	94	0	0	6
P20L0C0	80	20	0	P10L8C2	80	10	8	2	P0L4C6	90	0	4	6
P10L4C0	86	10	0	P20L8C2	70	20	8	2	P0L8C6	86	0	8	6
P20L4C0	76	20	0	P0L0C4	96	0	0	4	P10L0C6	84	10	0	6
P10L8C0	82	10	0	P0L4C4	92	0	4	4	P20L0C6	74	20	0	6
P20L8C0	72	20	0	P0L8C4	88	0	8	4	P10L4C6	80	10	4	6
P0L0C2	98	0	2	P10L0C4	86	10	0	4	P20L4C6	70	20	4	6
P0L4C2	94	0	2	P20L0C4	76	20	0	4	P10L8C6	76	10	8	6
P0L8C2	90	0	2	P10L4C4	82	10	4	4	P20L8C6	66	20	8	6

Table 3 : Combinations of clayey soils samples studied

2.2 Atterberg limits test

Atterberg's limits were performed according to ASTM D4318. Variations in the PI of both untreated clayey soils before and after admixtures added were then studied. The air dried soils were initially mixed with the predetermined quantity of NP, L or L-NP in a dry state. Distilled water was added to the soil mixture. To let the water invades and permeates through the soil mixture, the samples with and without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ are preserved in the airtight container for about 1, 15 and 30 days of curing prior to testing. After curing, the paste obtained was remixed again with each stabilizer thoroughly for at least 15 min before performing the first test. The plastic limit (PL) tests were performed on material prepared for the liquid limit (LL) test. The PL was determined as the average of the two water contents. The PI value is the difference between LL and PL.

2.3 Unconfined compressive strength (UCS) test

The UCS tests were performed according to ASTM D2166 and were conducted on untreated and treated soils samples. The specimens were prepared with or without sulphates $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ by compaction at the maximum dry unit weight and optimum moisture content deduced of compaction tests. After compaction and demolding, the samples were then stored in plastic boxes at the temperature of 25°C and relative humidity of 50% to prevent possible loss in moisture. Furthermore, after 7, 30, 60 and 120 days of curing the samples are tested. The tests of all samples were repeated on three identical specimens and the peak stress accepted was an average of three tests carried out on each sample type.

3 RESULTS AND DISCUSSION

3.1 Plasticity index

The addition of L to two clayey soils improves their workability due to the significant reduction in their PI. The PI of two clayey soils decreases with increasing L content and curing period. It is apparent that an addition of 8%L is sufficient to decrease the PI of the GS from 50.5 to 15.6 and 13.9% after curing for 1 and 30 days, respectively (Figure 1a). Whereas, for the RS stabilized with the same content of L the PI decreases from 23.7 to only 19.6 and 16.9% after curing for 1 and 30 days, respectively (Figure 2a). Similar observations were reported by Okagbue and Yakubu [12]. The addition of NP to two clayey soils reduces their PI and consequently enhances slightly their workability as compared with L alone. It is clear to observe that with 20%NP the PI of the GS decreases from 50.5



to only 43.1 and 42.4% after curing for 1 and 30 days, respectively (Figure 1a). However, with the same content of NP as an additive the PI of the RS decreases from 23.8% to only 18.9 and 18.4% after curing for 1 and 30 days, respectively. Similar trends were observed by Eberemu [13].

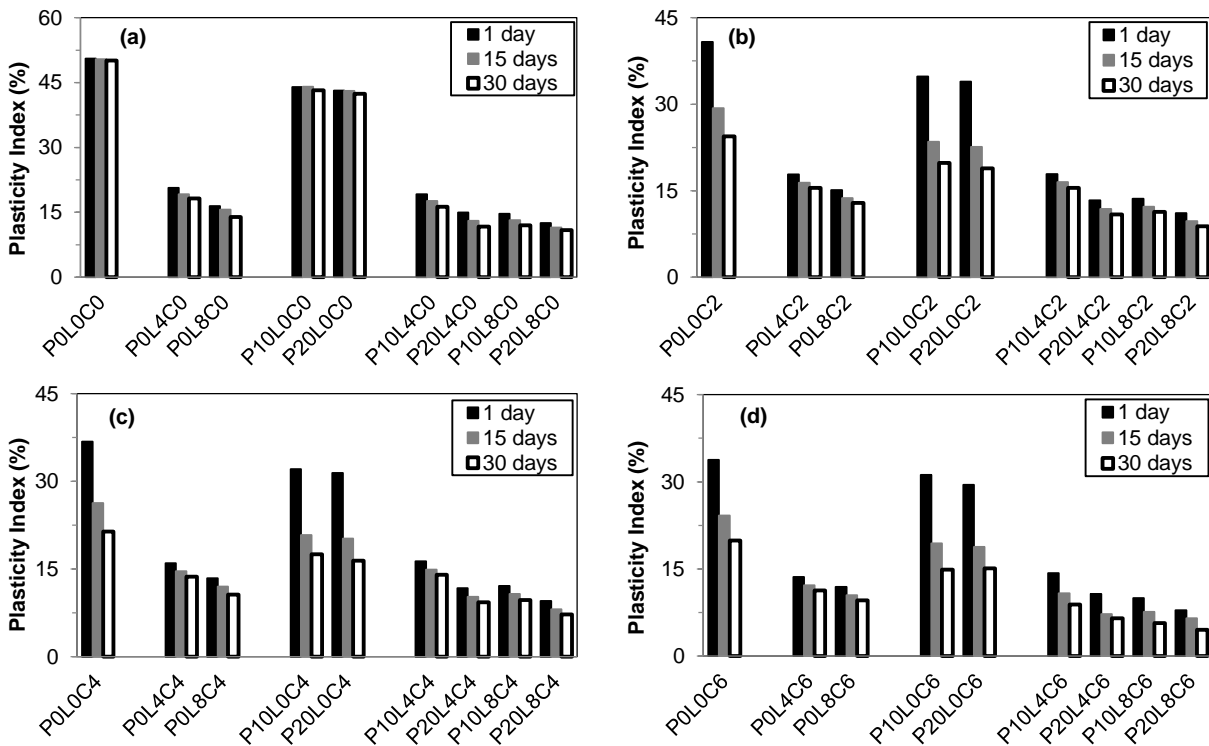


Figure 1. Effect of different content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the PI of the stabilized GS

The better results of PI are achieved when the combination L-NP is used. It is obvious to see that the combination L-NP has a significant effect on the PI of the GS than of the RS. In addition, there is a significant decrease in PI with increasing L-NP content and curing period. For example, for the GS stabilized with a combination of 20%NP+8%L the PI decreases from 50.5% to 12.5 and 10.9% after curing for 1 and 30 days, respectively (Figure 1a). However, for the RS stabilized with the same combination the PI decreases from 23.8% to 14.8 and 11.1% after curing for 1 and 30 days, respectively (Figure 2a). In all cases, the high reduction in PI is observed for samples stabilized with a combination of L-NP compared with L or NP alone. This behavior can be explained by the complementary roles played by the L and NP where the beneficial effects of one can compensate for the disadvantages that could present another.

The addition of L alone with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ decreases considerably the PI of two clayey soils particularly with increasing L content, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and DTC. In contrast, the PI of both stabilized clayey soils increases with increasing L content, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and DTC. Kinuthia et al. [7] reported that the interaction between two particles of clay soil is considerably affected by the cation exchange process because the increase in cation concentration results an increase in the distance between these clay particles, promotes the increasing of the clay particles size and affect the pores distribution due to the particles arrangement; this lead to the change in the Atterberg limits of soils.

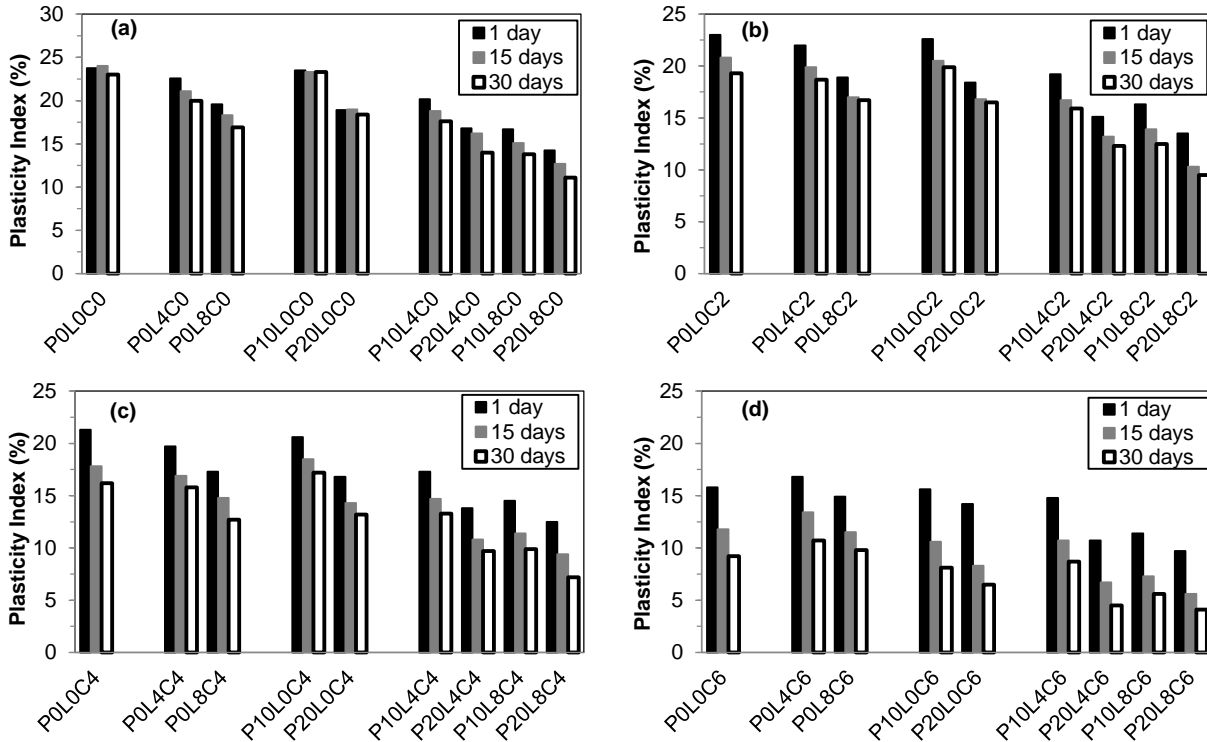


Figure 2. Effect of different content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the PI of the stabilized RS

The PI of two stabilized clayey soils decreases with increasing NP content, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period whereby RS has the best results. It should be noted that the addition of NP to two clayey soils samples on curing with any content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ shows a much better decrease in the PI compared to the untreated and treated soil samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. According to Yilmaz and Civelekoglu [14], the replacement of monovalent ions by calcium ions from $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ provokes a reduction in diffuse double layer thickness leading to decrease in LL, consequently, the decrease of PI.

The best results of PI are achieved for two clayey soil samples stabilized with a combination of L-NP on curing with various content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. The effect of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the PI of both clayey soils samples is similar. In addition, there is a significant decrease in the PI of two clayey soils samples with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period (Figures 1b-d and 2b-d). In addition, the decrease in the PI of two clayey soils samples with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period is considerably important when the content of L-NP increases. In general, the PI values of L-NP-treated two clayey soils samples containing any content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ are very higher compared with samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

3.2 Unconfined compressive strength

Figures 3-5 depict the results of the effect of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of both clayey soils stabilized with L, NP and their combinations. According to Figures 3a and 4a, the addition of L alone to two clayey soils binds their particles and produces a significant increase in the UCS which increases with increasing L content and curing period. A similar behavior was observed by Asgari et al. [2]. The increase in strength is due to the formation of cementing compounds binding the soil particles which is the result of the L reaction with the clay particles [11]. However, there is a negligible increase in UCS values of two clayey soils when the NP is used alone due to its low reactivity with the clay particles. The differences in the UCS between L and NP as additives are more pronounced



with the RS than with the GS. This behavior is probably due to the mineralogical composition and high plasticity index value of the GS as compared with that of the RS.

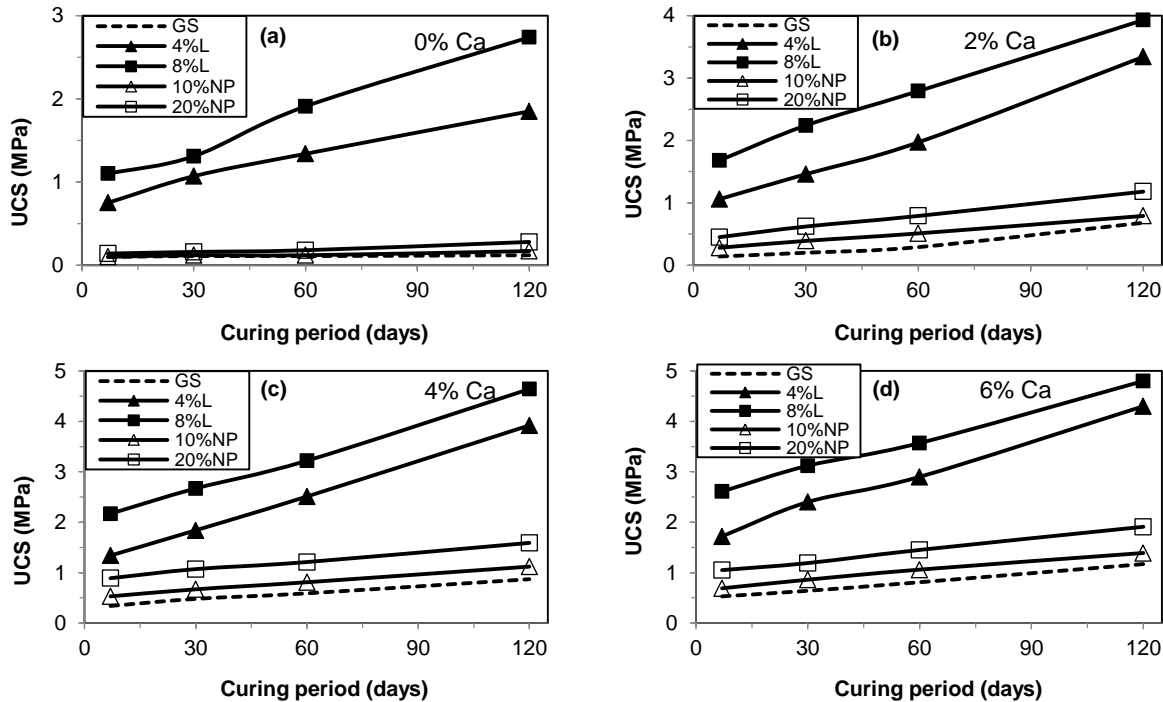


Figure 3. Effect of different content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of the GS stabilized with L and NP alone

The results of the effect produced by the combination L-NP without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of two clayey soils are depicted in Figure 5a. It can be seen that the better results of the UCS are achieved when the combination L-NP is used. However, the UCS of both stabilized clayey soils increases considerably with curing period and L-NP content. For example, the UCS of the GS stabilized with a combination of 20%NP+4%L increases from 0.1 MPa up to 1.3 and 3 MPa after curing for 7 and 120 days, respectively. For the RS stabilized with a combination of 20%NP+4%L the UCS increases from 0.5 MPa up to 2.2 and 7 MPa after curing for 7 and 120 days, respectively. Similar observations for similar soils were reported by McCarthy et al. [15].

Furthermore, it is obvious to observe that the combination L-NP has a much better effect on the UCS of the RS than of the GS, particularly, at later stage. For example, after curing for 120 days the UCS of both GS and RS stabilized with a combination of 20%NP+8%L represented an increase of 47 and 16 times respectively compared with both untreated soils. Similar observations were reported by Hossain et al. [8]. The dissolution of alumina and silica from soil and/or NP depends strongly on the L content which produces more cementitious products responsible to the increase in the UCS of two clayey soils. In all cases, high UCS values are observed for samples stabilized with a combination of L-NP compared to those stabilized with L or NP alone. Generally, the better increase produced by the L alone or by a combination of L-NP on the UCS of both clayey soils can be explained by the pozzolanic reactions which form new cementing compounds and bind the soil particles together [10].

The results of the effect of L, NP and their combination in the presence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of two stabilized clayey soils are depicted in Figures 3b-d and 4b-d. In all cases the UCS values of two clayey soils samples stabilized with L, NP and L-NP in the presence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ are higher than those of samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. Indeed, there is a significant increase in UCS of both untreated clayey soils samples with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period whereby RS has the best results. A similar trend was observed by Yilmaz



and Civelekoglu [14]. It is obvious to see that there is a much better increase in UCS values of NP-treated two clayey soils samples with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period whereby RS has the greatest values. The same trend was observed by Aldaood et al. [16] where they reported that the increase in strength of L-treated gypseous soils due to the finer grained of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ which increases the compactness of the matrix and consequently the UCS of soil samples. Whereas, the slight UCS values obtained for the NP-treated two clayey soils samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ can be explained by the presence of cracks in these samples which due to the high specific surface area of NP.

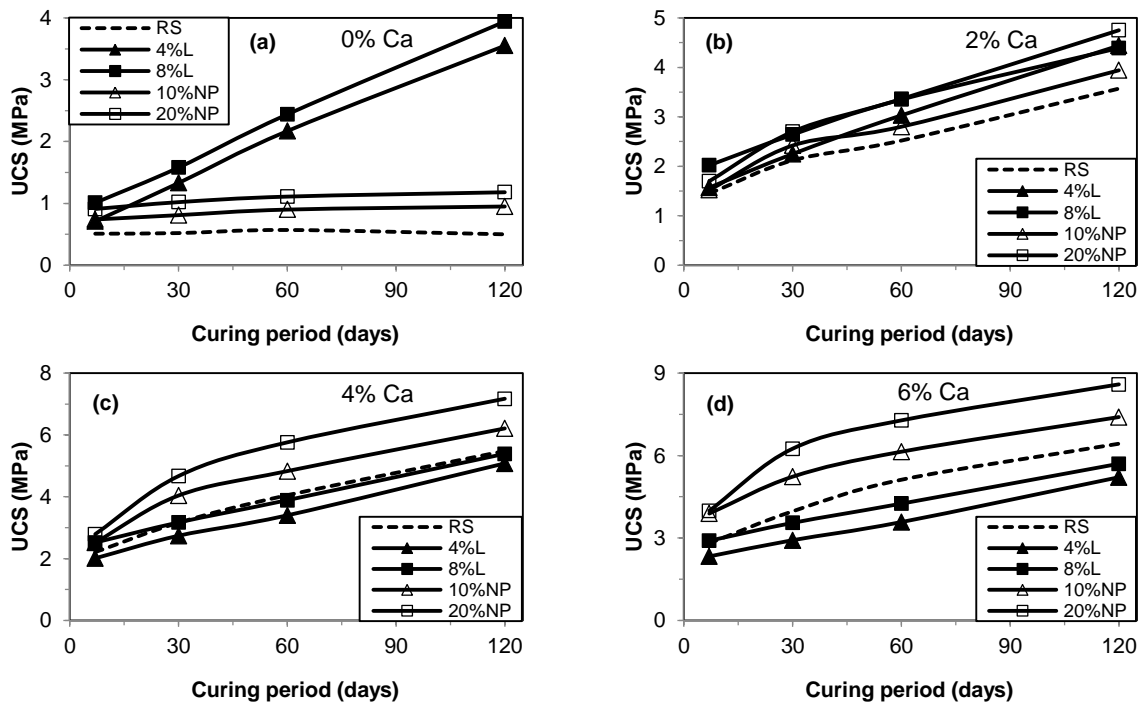


Figure 4. Effect of different content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of the RS stabilized with L and NP alone

However, the addition of L alone to two clayey soils samples on curing with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ increases the UCS with curing period. Furthermore, at early stage there is a high increase in UCS of L-treated two clayey soils samples with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and L content compared with samples cured without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. The little increase in the UCS of L-treated RS as compared with the NP-treated the same soil is due to the fact that the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ has the capacity to reduce the solubility of hydrated L [17]. Furthermore, in all cases the increase in UCS values with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period is more pronounced in the RS than in the GS. This leading us to suggest that the increase in UCS values could be due to the behavior of the RS with the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ interaction.

However, the UCS of two clayey soils stabilized with a combination of L-NP increases sharply with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content, L-NP content and curing period whereby RS has the best results (Figure 5b-d). Generally, the early increase in the UCS of two clayey soils can be explained by the presence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ which accelerates the chemical reaction between soil and L to form ettringite by the reaction of SO_4^{2-} with the CSH and CAH from pozzolanic reactions [16].

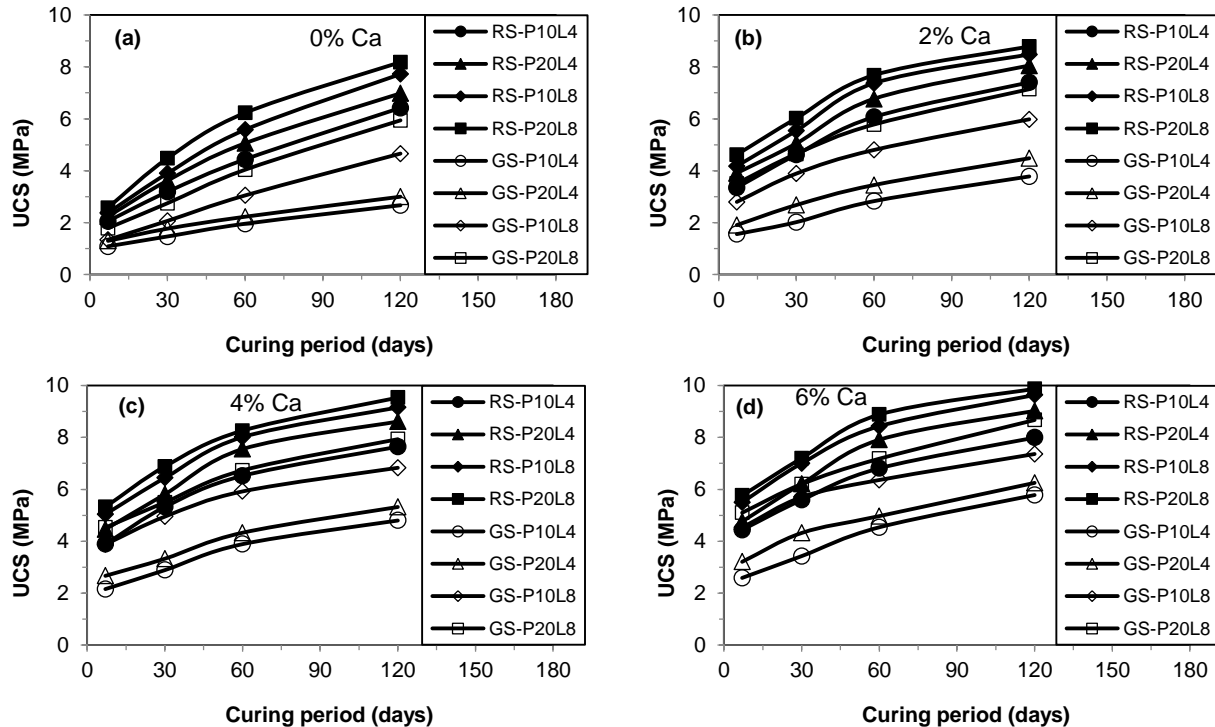


Figure 5. Effect of different content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of two soils stabilized with L-NP

4 CONCLUSIONS

Soil stabilisation with L alone or in combination with NP in the presence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ is a way to decrease the PI and increase the UCS of both clayey soils. Based on the test results, the following conclusions can be drawn:

The addition of L to two clayey soils produces a significant reduction in the PI which decreases with increasing L content. The use of NP without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ reduces slightly the PI of two clayey soils. The combination of L-NP without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ decreases significantly the PI of two clayey soils more than the use of L alone. Thus, the use of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ as an additive reduces considerably the PI of two clayey soils. The degree of reduction depends largely to the mineralogical composition of the soil, the type and the amount of mineral additives, the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and the curing period.

The stabilization with L alone without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ increases considerably the UCS of both clayey soils. This increase depends of the amount of L added and the curing time. However, a negligible influence on the UCS of both clayey soils containing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ is achieved when the NP is used alone. But, when the L and NP is combined without Na_2SO_4 , the UCS of both clayey soils becomes very high and, increases with increasing curing time and content of additives added.

The high early values of UCS developed by both clayey soils with curing time can be attributed to the acceleration of the pozzolanic reaction due to the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ added.

The $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ has negligible effect on the UCS of both clayey soils stabilized with lime alone whereas the mineralogical nature of clay soil plays an important role in the chemical reaction with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

The progressive increase in the UCS of both clayey soils, particularly the RS, can be explained by the formation of ettringite favored by the presence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ in the Soil-L-NP system. Indeed, the increase in the values of UCS is particularly important when the amount of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ increases.

Economically, the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ is cheaper and technically it can be used alone for clayey soil as a stabilizer and



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accelerator for pozzolanic reactions. Moreover, their effect becomes very high when it is mixed with NP alone.

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