

Abstract

An experimental investigation was undertaken to study the effect of calcium sulphate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) on the behaviour of the grey clay (GS) and red clay (RS) soils stabilized with lime (L), natural pozzolana (NP) and their combination (L-NP). In this study, the geotechnical properties investigated are respectively, the Atterberg limits on samples cured for 1 to 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) on samples cured for 7 to 120 days. The results show that both GS and RS samples can be successfully stabilized with L alone or with L-NP which substantially reduce their plasticity index (PI) and increase their UCS. On the other hand, a negligible effect was reported when the NP is used alone. However, when combining a fraction of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ to samples containing L or L-NP, a further decrease in the PI is observed. In addition, higher UCS values are recorded.

Keywords

Clayey soil, lime (L), natural pozzolana (NP), calcium sulphate, plasticity index (PI), unconfined compressive strength (UCS)

1 Introduction

Civil engineering projects located in areas with inappropriate soils is one of the most frequent problems in the world. Soil stabilization technique has been practiced for several years with the main aim to render the soils capable of meeting the requirements of the specific engineering projects [1]. Hydraulic binders (cement and L) were used as stabilizers in various civil engineering fields. Soils stabilization is a technique that requires the use of hydraulic binders alone or in combination with other mineral additives such as fly ash. Extensive studies have been carried out to study the different effects produced by the use of cement alone or in combination with L [2–4], rice husk ash, [5–7] and fly ash [8, 9] on physico-mechanical properties of soils.

In the absence of sulphates, the reduction in the repulsion forces between the clay particles (due to the L addition) creates a bond between them and forms flocks. This change caused by L reduces the plasticity index and the maximum dry density of the stabilized soil but increases their optimum moisture content [10]. At the later stage, the increase in the concentration of hydroxyl (OH^-) from L raises the pH of the soil, and causes the dissolution of alumina and silica which interact with calcium ions to form cementing products such as calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH). The formation of these compounds is responsible on the increase in unconfined compressive strength (UCS) values of the stabilized soil [11] and their shear strength values [12].

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 on the soil nature, the type and the content of additives [3] and the concentration and the type of cation associated with the sulphate anion [13]. Indeed, the effects caused by the presence of different types of sulphates on the geotechnical properties of soils stabilized with additives have been investigated by several researchers [13–19].

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The combination of volcanic materials with L produces a beneficial effect on the behaviour of the stabilized soil [9]. The NP is found in abundance in areas of Beni-Saf located in the west of Algeria [20]. The NP was used in combination with L to improve the engineering properties of both GS and RS such as the shear strength, the plasticity and the UCS [10, 11, 21, 22]. 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 the same soils (GS and RS) using L, NP and their combination.

2 Materials Used and Identification

2.1 Soils

In the present study, two soils were used, 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. The soil was excavated, placed in plastic bags and transported to the laboratory for preparation and testing. Laboratory tests were carried out to classify each type of soil (Fig. 1a).



Fig. 1 Materials used and their preparation; (a) clayey soils passed to 1mm sieve, (b) NP before and after preparation, (c) hydrated lime usually used for construction purposes and (d) calcium sulphate

The Physico-mechanical properties of both clayey soils are presented in Table 1. The chemico-mineralogical properties of both clayey soils are depicted in Table 2.

2.2 Mineral additives

The NP used in this study was collected from Beni-Saf located in the Western of Algeria. It was ground to the specific surface area of $420\text{m}^2/\text{kg}$ (Fig. 1b). The L used in this study is commercially available L typically used for construction purposes (Fig. 1c). The physico-chemical properties of L and NP are presented in Table 3.

Table 1 Physico-mechanical properties of both clayey soils (After [11])

Physico-mechanical properties	GS	RS
Depth (m)	4.00	5.00
Natural water content (%)	32.90	13.80
Specific Gravity	2.71	2.84
Passing 80 μm sieve (%)	85.00	97.50
Liquid Limit (LL, %)	82.80	46.50
Plastic Limit (PL, %)	32.20	22.70
Plasticity Index (PI, %)	50.60	23.80
Classification System (USCS)	CH	CL
Optimum Moisture Content (W_{OPN} , %)	28.30	15.30
Maximum Dry Density ($\gamma_{\text{d,max}}$, kN/m^3)	13.80	16.90
Unconfined Compressive Strength (UCS, KPa)	100	510
Loss on ignition (%)	17.03	7.13

Table 2 Chemico-mineralogical properties of both clayey soils

Chemical or mineralogical name	Chemical formula	GS (%)	RS (%)
Calcium oxide	CaO	14.43	2.23
Magnesium oxide	MgO	1.99	2.14
Iron oxide	Fe_2O_3	5.56	7.22
Alumina	Al_2O_3	14.15	19.01
Silica	SiO_2	43.67	57.02
Sulfite	SO_3	0.04	0.19
Sodium oxide	Na_2O	0.34	0.93
Potassium oxide	K_2O	1.96	3.17
Titan dioxide	TiO_2	0.65	0.83
Phosphorus	P_2O_5	0.18	0.14
pH	-	9.18	9.05
Calcite	CaCO_3	26.00	4.00
Albite	$\text{NaAlSi}_3\text{O}_8$	-	8.00
Illite	$2\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 24\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	16.00	24.00
Kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	12.00	16.00
Montmorillonite	$\text{Al}_2((\text{Si}_4\text{Al})\text{O}_{10})(\text{OH})_2 \cdot \text{H}_2\text{O}$	20.00	-
Chlorite	$\text{Mg}_2\text{Al}_4\text{O}_{18}\text{Si}_3$	-	9.00
Ferruginous minerals	-	6.00	7.00
Organic matter	-	0.33	-

2.3 Chemical compound

The chemical element used in this study is the calcium sulphate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) produced by Biochem Chemopharma which is a leading international Manufacturer and Supplier of Laboratory Reagents (Fig. 1d). The physico-chemical properties of this element are shown in Table 4.

Table 3 Physico-chemical properties of lime and natural pozzolana (After [11])

Physical or chemical name	L (%)	NP (%)
Physical form	Dry white powder	Dry brown powder
Specific Gravity	2.00	-
Over 90 μm (%)	< 10.00	-
Over 630 μm (%)	0	-
Insoluble material (%)	< 1.00	-
Bulk density (g /L)	600 – 900	-
Loss on ignition	-	5.34
CaO	> 83.30	9.90
MgO	< 0.50	2.42
Fe_2O_3	< 2.00	9.69
Al_2O_3	< 1.50	17.50
SiO_2	< 2.50	46.40
SO_3	< 0.50	0.83
Na_2O	0.40 - 0.50	3.30
K_2O	-	1.51
CO_2	< 5.00	-
TiO_2	-	2.10
P_2O_3	-	0.80
CaCO_3	< 10.00	-

Table 4 Physico-chemical properties of calcium sulphate

Physico-chemical properties	Calcium sulphate
Color	White
Chemical formula	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
Molar weight (g/mol)	172.17
Auay (dried), (%)	99.0
Insoluble matter (%)	0.025
Chloride (Cl, %)	0.002
Nitrate (NO_3 , %)	0.002
Ammonium (NH_4 , %)	0.005
Carbonate (CO_3 , %)	0.05
Heavy metals (Pb, %)	0.001

3 Test Procedures

Laboratory tests on plasticity and UCS were conducted on both selected clayey soils. Several combinations of NP and L were used for their stabilization. These combinations were mixed with or without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. A total of 72 combinations based on GS and RS is shown in Table 5.

3.1 Atterberg Limits Test

Atterberg limits were performed according to ASTM D4318 [23]. The variations in the liquid limit (LL), plastic limit (PL) and plasticity index (PI) of two untreated clayey soils before and after admixtures added were studied.

Table 5 Combinations of both clayey soils studied

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

3.2 Unconfined Compressive Strength Test

The UCS tests were performed according to ASTM D2166 [24] and were conducted on untreated and treated soil samples. The specimens were prepared with or without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ by compaction at the maximum dry unit weight and optimum moisture content deduced of compaction tests.

3.3 Samples Preparation

3.3.1 Soil-L, soil-NP and soil-L-NP mixtures

For both Atterberg limits and UCS tests the air dried soils were initially mixed with the predetermined quantity of NP (0, 10 and 20%), L (0, 4 and 8%) or L-NP in a dry state. On the one hand, the distilled water was added to the soil mixture for the Atterberg limits test. To let the water invades and permeates through the soil mixture, the samples 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 (Fig. 2).



Fig. 2 Determination of the LL after 1 and 30 days of curing; (a) the paste was remixed with each stabilizer for at least 15 min before performing the first test, (b) practice the groove and start the test and (c) determination of the water content (LL) by desiccation at 105 °C during 1 day

The PL tests were performed on material prepared for the liquid limit (LL) test (Fig. 3). The plastic limit (PL) was determined as the average of the two water contents. Both LL and PL tests were conducted at room temperature. The plastic index (PI) value is the difference between the LL and PL.

On the other hand, the calculated water was added to the soil mixture for the UCS test. The samples are preserved in the airtight container for about 1 hour of curing prior to the preparation of specimens by static compaction using static press. Indeed, the obtained specimens were prepared by compaction at the maximum dry unit weight and optimum moisture content deduced of compaction tests. The specimens were stored in plastic boxes to prevent possible loss of moisture which they were kept in the laboratory at the temperature of 25°C and the relative humidity of 50% (Fig. 4). Furthermore, after 7 to 120 days of curing the specimens are tested (Fig. 5). 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.

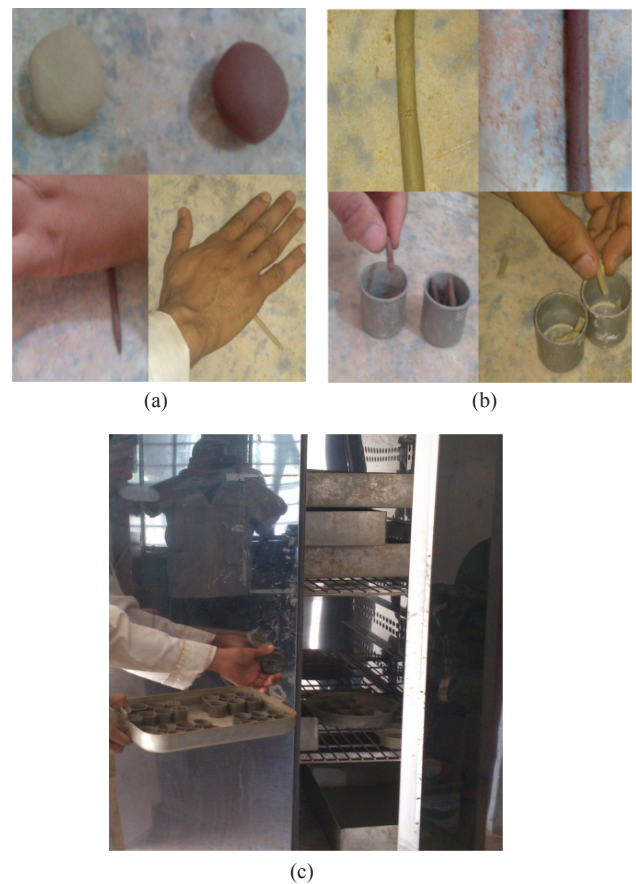


Fig. 3 Determination of the PL after 1 and 30 days of curing, (a) the roll of the soil was performed and the test must be stopped when the roll of the soil tested was cracked at 3 mm in diameter, (b) sample collection and (c) determination of the water content (PL) by desiccation at 105 °C during 1 day

3.3.2 Soil-L-sulphate, soil-NP-sulphate and soil-L-NP-sulphate mixtures

For both Atterberg limits and UCS tests the samples were mixed in the same way as presented above except that different contents of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ powder (0-6% by weight of dry soil) were also added into the soil-L, soil-NP and soil-L-NP mixtures in a dry state. In addition, when the water (distilled water is necessary for Atterberg limits) was added to the mixtures the Atterberg limits and UCS tests were performed after the same curing periods in the same way as presented above.

4 Results and Discussion

4.1 Atterberg Limits

4.1.1 Variation of liquid limit in the absence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

Tables 6 and 7 show that the LL of both GS and RS samples decreases with increasing L content but increases with curing period whereby the LL of the GS appears to be still constant with time. e.g., Table 6 shows that the addition of 8%L to the GS the LL decreases from 82.8% to 62.1 and 61% after curing for 1 and 30 days, respectively. The decrease in LL can be assigned to the cation exchange brought about in the soil by the divalent calcium ions from L [8].

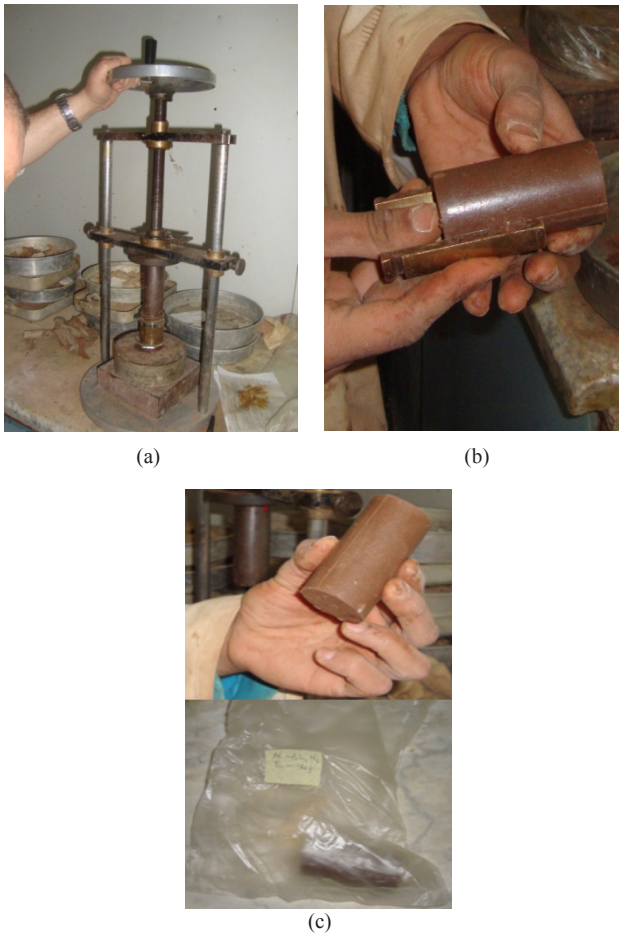


Fig. 4 Preparation of specimens by static compaction, (a) compaction of the sample at the maximum dry unit weight and optimum moisture content deduced of compaction tests, (b) demolding of the sample and (c) preservation of the compacted specimen in plastic boxes to prevent possible loss of moisture during 7 and 120 days of curing

From Table 7, the addition of 8%L to the RS increases the LL from 46.5% up to 54.9 and 59.6% after curing for 1 and 30 days, respectively. For the same class soil, Yong and Ouhadi [25] observed that with 10%L as an additive the LL increases from 49.6% up to 56.5 and 75% after curing for 1 and 30 days, respectively. A similar observation was reported by Asgari et al. [4]. On the other hand, for a similar class soil, Afès and Didier [2] found that with 6%L as an additive the LL reduces from 47.7% to 42.7 and 42.4% after curing for 7 and 30 days,

respectively. The increases and decreases in Atterberg's limits depend on the mineralogical composition of soil where the Table 3 shows that the RS and GS have 0 and 20% of montmorillonitic clay, respectively. Attoh-Okine [26] reported that decreases in the LL are observed for soils with montmorillonitic clay but increases are observed for soils with kaolinitic clay. In addition, Goswami and Singh [8] indicated that the particle arrangement and the presence of divalent cations promote flocculation and increase the LL of kaolinitic soils. Thus, the different complexes cation exchange in each of these soils (GS and RS) is reflected by the difference in their LL behavior.

Tables 6 and 7 show that the LL of both GS and RS samples decreases with increasing NP content but appears to be still constant with curing period whereby GS has the best results. e.g., the addition of 20%L to the GS decreases the LL from 82.8% to 67.3 and 66.7% after curing for 1 and 30 days, respectively. It should be noted that the addition of NP to both GS and RS samples shows a slight decrease in the LL compared with the addition of L alone. This is probably due to the low free L content in the NP. However, for the RS stabilized with 20%NP, the LL reduces from 46.5% to 39.3 and 41.2% after curing for 1 and 30 days, respectively (Table 7). For the same class soil, Sivrikaya et al. [27] observed that the LL decreases from 28% to 25% for the addition of 20% of ground granulated blast-furnace slag-A. In contrast, for the same class soil, the use of 20% rice husk ash, Basha et al. [6] and Rahman [5] reported that the LL increases from 49.8% up to 54.3% and from 36.8% up to 47%, respectively.

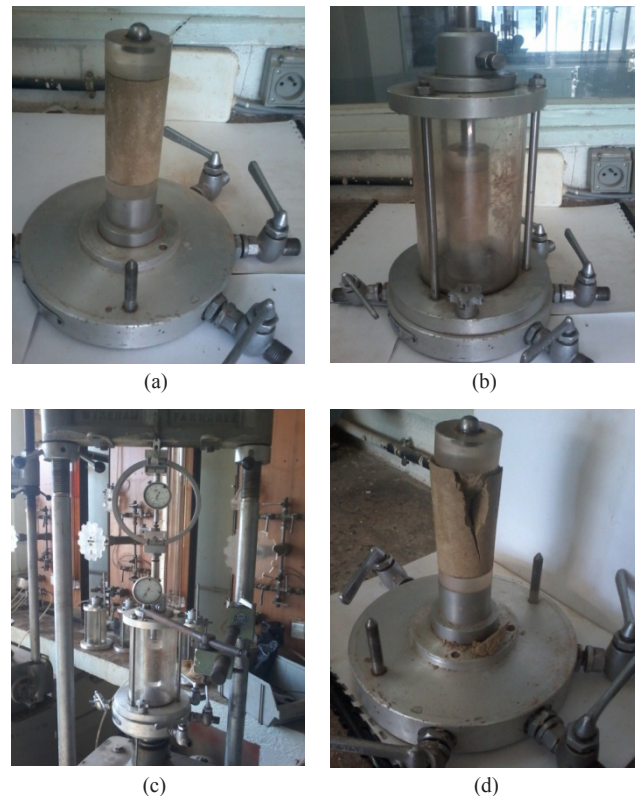


Fig. 5 Procedure of the UCS test, (a) specimen for submit the UCS test, (b) installation of the specimen in the cell, (c) installation of the cell in the static press and start the UCS test and (d) specimen state after the test

Table 6 Effect of different content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the LL and PL of stabilized GS at different curing period

AL* (%)	Ca** (%)	DTC (day)	Sample mixture (%)								
			P0L0	P0L4	P0L8	P10L0	P20L0	P10L4	P10L8	P20L4	P20L8
LL	0	1	82.8	64.5	62.1	69.4	67.3	65.2	63.9	63.0	62.2
		15	82.5	63.7	61.4	70.5	68.1	63.8	62.3	63.2	61.2
		30	83.2	63.0	61.0	68.2	66.7	62.8	61.2	62.1	61.0
	2	1	73.5	63.8	61.4	60.6	58.4	64.4	62.2	63.2	61.5
		15	65.3	62.9	60.5	51.6	49.4	63.5	61.3	62.2	60.6
		30	62.7	62.4	60.0	49.1	46.9	63.0	60.9	61.8	60.2
	4	1	70.4	62.6	60.3	58.2	56.1	63.3	61.2	62.0	60.4
		15	63.2	61.7	59.4	49.2	47.1	62.4	60.7	61.1	59.7
		30	60.6	61.2	58.4	46.7	44.7	61.9	59.8	60.6	59.0
	6	1	68.1	61.3	59.5	57.9	54.7	62.2	60.1	60.9	59.6
		15	60.8	60.4	58.5	48.2	46.2	61.2	59.1	60.0	58.6
		30	57.8	59.9	58.1	45.0	43.7	60.8	58.7	59.5	58.2
PL	0	1	32.2	45.5	45.7	25.5	24.2	46.0	49.2	48.0	49.8
		15	32.1	44.5	45.8	26.5	25.0	46.2	49.3	50.0	49.7
		30	33.1	44.8	47.1	25.0	24.3	46.5	49.5	50.1	50.1
	2	1	32.7	46.0	46.3	25.8	24.5	46.6	48.6	49.9	50.4
		15	36.0	46.5	46.7	28.1	26.7	47.0	49.1	50.4	50.9
		30	38.3	46.9	47.2	29.3	28.0	47.5	49.6	50.9	51.4
	4	1	33.6	46.6	46.9	26.1	24.7	47.0	49.1	50.4	50.9
		15	36.9	47.1	47.3	28.4	27.0	47.5	49.6	50.8	51.4
		30	39.3	47.6	47.8	29.2	28.2	48.0	50.1	51.3	51.9
	6	1	34.3	47.7	47.6	26.7	25.2	47.9	50.0	50.3	51.7
		15	36.6	48.2	48.1	28.8	27.4	50.4	51.5	52.8	52.2
		30	37.9	48.6	48.5	30.1	28.7	51.8	53.0	53.0	53.7

*Atterberg Limits, ** $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

It should be noted that the stabilization of both clayey soils with a combination of L-NP shows the same decrease in LL values compared to that of the L alone. With 10%NP+4%L as an additive the LL of the RS increases from 46.5% up to 56.4 and 61.8% after curing for 1 and 30 days, respectively (Table 7). Whereas, for the same class soil, with a combination of 12%FA+3%L, Ansary et al. [28] found that the LL of the soil-B decreases from 44% to 32.3%.

4.1.2 Variation of liquid limit in the presence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

In all cases the LL, PL and PI of two stabilized clayey soils vary with the variation of the type and additive content, type and sulphate content and DTC (Tables 6 and 7 and Figs. 6 and 7). Indeed, the workability of both untreated and treated soil samples containing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ is improved due to the significant reduction of their PI. Yilmaz and Civelekoglu [29] reported that with gypsum as an additive the PI of the bentonite soil decreases from 186.9% to 139.5 and 121.9% for the addition of 2.5 and 7.5% of gypsum, respectively.

With L as an additive the LL of both GS and RS samples containing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ decreases considerably with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content, L content and DTC. e.g., the addition

of 8%L to the GS on curing for 1 day, the LL decreases from 62.1% to 61.4, 60.3 and 59.5% respectively with 2, 4 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Table 6). For a similar class soil, Kinuthia et al. [13] reported that the LL decreases from 73% to 71, 69 and 67% respectively with 1, 2 and 3% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ for 6%L addition. On the other hand, for the same class soil, Sivapullaiah et al. [15] observed that the LL increases from 68% up to 70, 73 and 76% respectively with 0.5, 1 and 3% CaSO_4 for 6%L addition due to the chemical interaction between soil, L and CaSO_4 . However, for the RS stabilized with 8%L on curing for 1 day, the LL decreases from 54.9% to 54.2, 53.7 and 52% respectively with 2, 4 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Table 7).

Tables 6 and 7 show that with NP as an additive the LL of both GS and RS samples decreases considerably with increasing NP content, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and DTC. Indeed, the highest values of LL are achieved when the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content is greater than 2%. However, there is a negligible change in the LL values of NP-treated GS samples on curing with 2% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ as compared with the samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. In general, for any content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and DTC the differences in LL values between L and NP as additives are more pronounced with the RS than with the GS. This is can be explained by the behaviour of the RS which has a low PI. This is can be explained by

Table 7 Effect of different content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the LL and PL of stabilized RS at different curing period

AL*(%)	Ca** (%)	DTC (day)	Sample mixture (%)								
			P0L0	P0L4	P0L8	P10L0	P20L0	P10L4	P10L8	P20L4	P20L8
LL	0	1	46.5	57.4	54.9	44.0	39.3	56.4	56.4	55.1	54.9
		15	45.5	59.6	57.8	45.1	40.5	58.3	56.7	58.1	57.0
		30	46.0	61.5	59.6	44.8	41.2	61.8	58.2	60.5	58.1
	2	1	46.0	57.0	54.2	43.3	39.1	55.9	54.9	55.3	54.3
		15	44.3	55.5	53.2	41.5	37.9	54.2	53.3	54.3	52.3
		30	44.0	55.3	53.0	41.3	37.7	54.5	53.2	54.5	52.7
	4	1	44.8	55.8	53.7	42.0	38.5	54.9	54.0	54.8	53.7
		15	42.1	53.6	51.7	40.4	37.0	53.4	52.1	52.8	51.9
		30	41.7	53.7	51.5	40.1	36.7	53.0	51.8	52.6	51.4
	6	1	39.9	54.0	52.0	37.4	35.8	53.3	52.0	52.9	51.7
		15	36.3	51.2	49.2	32.7	30.3	50.4	48.6	49.0	48.0
		30	35.9	50.8	48.8	31.4	29.7	49.0	48.2	48.6	47.8
PL	0	1	22.7	34.8	35.3	20.5	20.4	36.2	39.7	38.3	40.6
		15	21.5	38.5	39.5	21.8	21.5	39.5	40.5	43.0	44.3
		30	23.0	41.5	42.7	21.5	22.8	44.2	44.2	46.7	47.0
	2	1	23.0	35.0	35.3	20.7	20.7	36.8	38.6	40.2	40.8
		15	23.6	35.7	36.2	21.0	21.1	37.5	39.4	41.2	42.0
		30	24.7	36.6	36.3	21.4	21.3	38.6	40.7	42.3	43.2
	4	1	23.5	36.1	36.4	21.4	21.8	37.6	39.5	41.0	41.2
		15	24.2	36.8	36.9	21.9	22.7	38.7	40.7	42.0	42.4
		30	25.6	37.9	38.8	22.9	23.6	39.7	41.9	42.9	44.2
	6	1	24.1	37.2	37.1	21.8	21.6	38.5	40.7	42.2	42.0
		15	24.5	37.8	37.7	22.1	21.9	39.7	41.3	42.3	42.4
		30	26.7	40.1	39.0	23.2	23.1	40.4	42.7	44.1	43.7

*Atterberg Limits, ** $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

the behaviour of the RS which has a low PI.

In general, the greatest decrease in LL values is achieved when the L and NP are combined. However, with a combination of L-NP as additives, both stabilized GS and RS samples containing any content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ show a slight decrease in LL values compared with samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. e.g., with 20%NP+8%L as an additive the LL of the GS samples containing 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ decreases from 62.2 and 61% to 59.6 and 58.2% after 1 and 30 days of curing, respectively (Table 6). For the same combination and the same content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, the PL of the RS decreases from 54.9 and 58.1% to 51.7 and 47.8% after curing for 1 and 30 days, respectively (Table 7). The decrease in LL values with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and DTC is more pronounced in the RS than in the GS.

4.1.3 Variation of plastic limit in the absence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

For both stabilized GS and RS samples the PL increases with increasing L content and curing period. e.g., with 8%L as an additive the PL of the GS increases from 32.2% up to 43.8 and 44.8% after curing for 1 and 30 days, respectively (Table 6). A similar behaviour was observed by Rahman [5].

However, the addition of 8%L to the RS increases the PL from 22.7% up to 35.3 and 42.7% after curing for 1 and 30 days, respectively (Table 7). For a similar class soil, Afès and Didier [2] reported that the use of 6%L the PL increases from 24% up to 32.4 and 34% after curing for 7 and 30 days, respectively. Similar observations for similar class soil were reported by several researchers [4, 25, 26]. It is known that the use of L leads to the flocculation of clay particles which causes an immediate increase in PL.

In all cases there is a negligible decrease in the PL of NP-treated both GS and RS samples compared to L alone. With 10%NP as an additive the PL of the GS decreases from 32.2% to 25.5 and 25% after curing for 1 and 30 days, respectively (Table 6). However, The addition of 10%NP to the RS decreases the PL from 22.7% to 20.5 and 21.5% after 1 and 30 days of curing, respectively (Table 7). Dissimilar behaviours were observed by [5, 6]. It is suggested that the decrease in the PL of both GS and RS samples is probably due to the replacement of coarser soil particles by finer NP particles.

In all cases there is a considerable increase in the PL of both clayey soils with increasing L-NP content and curing period (Tables 6 and 7). In general, for the combination L-NP, the PL shows a highest increase as compared to L alone. The addition

of 20%NP+8%L to the GS increases the PL from 32.2% up to 49.8 and 50.1% after curing for 1 and 30 days, respectively. With 20%NP+8%L as an additive the PL of the RS increases from 22.7% up to 40.6 and 47% after curing for 1 and 30 days, respectively. For the same class soil, with a combination of 18%FA+3%L, Ansary et al. [28] observed that the PL of the soil-B increases from 25% up to 35.8%.

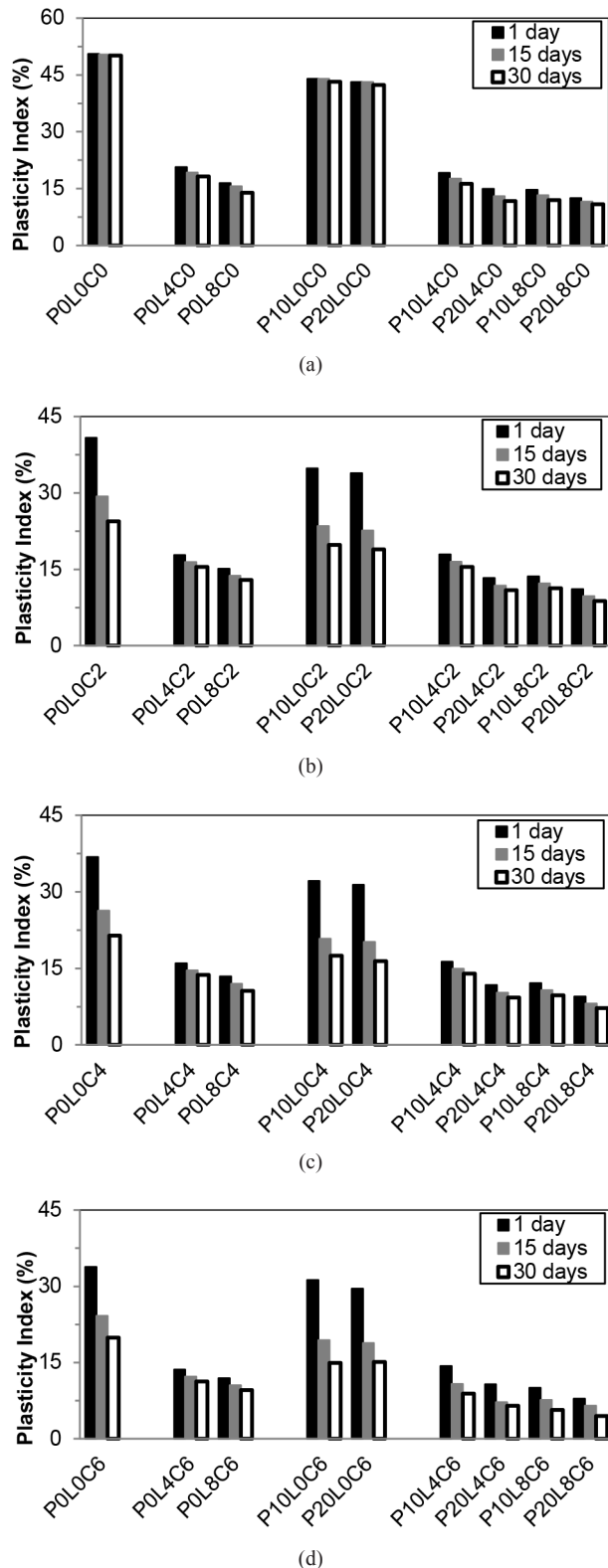


Fig 6 Effect of different content of CaSO₄.2H₂O on the PI of the stabilized GS

4.1.4 Variation of plastic limit in the presence of CaSO₄.2H₂O

In all cases the PL of L-treated both GS and RS samples increases with increasing CaSO₄.2H₂O content, L content and TDC. e.g., with 8%L as an additive the PL of the GS sample containing 6% CaSO₄.2H₂O increases from 45.7 and 47.1% up to 47.6 and 48.5% after curing for 1 and 30 days, respectively (Table 6). However, for the RS sample stabilized with 8%L in the presence of 6% CaSO₄.2H₂O the PL increases from 35.5% up to 37.1% after 1 day of curing but decreases from 42.7% to 39% after curing for 30 days (Table 7).

With any content of NP as an additive the PL of the RS increases slightly with increasing CaSO₄.2H₂O content and DTC, whereas the PL of the GS increases with DTC but appears to be still constant with increasing CaSO₄.2H₂O content. Generally, the effects produced by the CaSO₄.2H₂O on the PL of NP-treated both GS and RS samples are negligible as compared with L alone or in combination with NP.

It is clear to see that the PL of L-NP-treated both GS and RS samples increases with increasing L-NP content, CaSO₄.2H₂O content and DTC (Tables 6 and 7). Indeed, the addition of L-NP to the GS samples containing CaSO₄.2H₂O shows an increase in the PL as compared with samples without CaSO₄.2H₂O. Whereas, the PL values of the RS samples treated with L-NP without CaSO₄.2H₂O are very higher as compared with samples containing CaSO₄.2H₂O.

4.1.5 Variation of the plasticity index in the absence of CaSO₄.2H₂O

The changes in the PI of both GS and RS samples stabilized with L, NP and L-NP without sulphates are depicted in Figs. 6a and 7a. The addition of L to both GS and RS samples improves their workability due to the significant reduction in their PI. The PI of both GS and RS samples decreases with increasing L content and curing period whereby the decrease is more pronounced in the GS than the in RS. 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 (Fig. 6a). 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 (Fig. 7a). For the same class soil, Afès and Didier [2] reported that with 6%L as an additive the PI decreases from 23.7% to 10.3 and 8.4% after curing for 7 and 30 days, respectively. Similar observations were reported by [26, 28].

The addition of NP to both GS and RS samples reduces slightly their PI 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 (Fig. 6a). 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. For the same class soil, Yadu and Tripathi [30] and Sivrikaya et al. [27] reported

that the PI decreases from 17 and 9% to 13 and 4% for the addition of 12% and 20% of granulated blast furnace slag and ground granulated blast furnace slag-A, respectively. Similar trends were observed by Eberemu [31] and Rahman [5] where they have used bagasse ash and rice husk ash respectively. In contrast, Degirmenci et al. [32] were found that the PI increased with increasing FA content due to its small size particles with high surface area compared with that of the NP.

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. e.g., 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 (Fig. 2a and b). 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 (Fig. 7a). Ansary et al. [28] reported that for a similar class soil, the PI decreases from 19% to 2.3% for the addition of 6%FA+3%L. 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 behaviour 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.

4.1.6 Variation of the plasticity index in the presence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

Figs. 2b-d and 3b-d show the changes in the PI of both GS and RS samples stabilized with NP, L and L-NP in the presence of varying contents of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. The addition of L alone to both GS and RS samples on curing with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ decreases considerably the PI particularly with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content, L content and DTC. e.g., after 30 days of DTC, the PI of the GS stabilized with the same content of L decreases from 16.4% to 12.9, 10.6 and 9.6% respectively with 2, 4 and 6% of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Fig. 6b, c and d). For the same DTC, the PI of the RS stabilized with 8%L decreases from 19.6% to 16.7, 12.7 and 9.8% in the presence of 2, 4 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, respectively (Fig. 7b, c and d). Kinuthia et al. [13] 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, this promotes the increase of the clay particles size and affects the pores distribution due to the particles arrangement which leads to the change in the consistency limits of soils. Indeed, the modification in the PI is the result of cation exchange processes which affect the viscosity of the clay-water mix.

The PI of two stabilized clayey soils decreases with increasing NP content, DTC and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content whereby RS has the best results. e.g., after 1 day of DTC, the PI of the

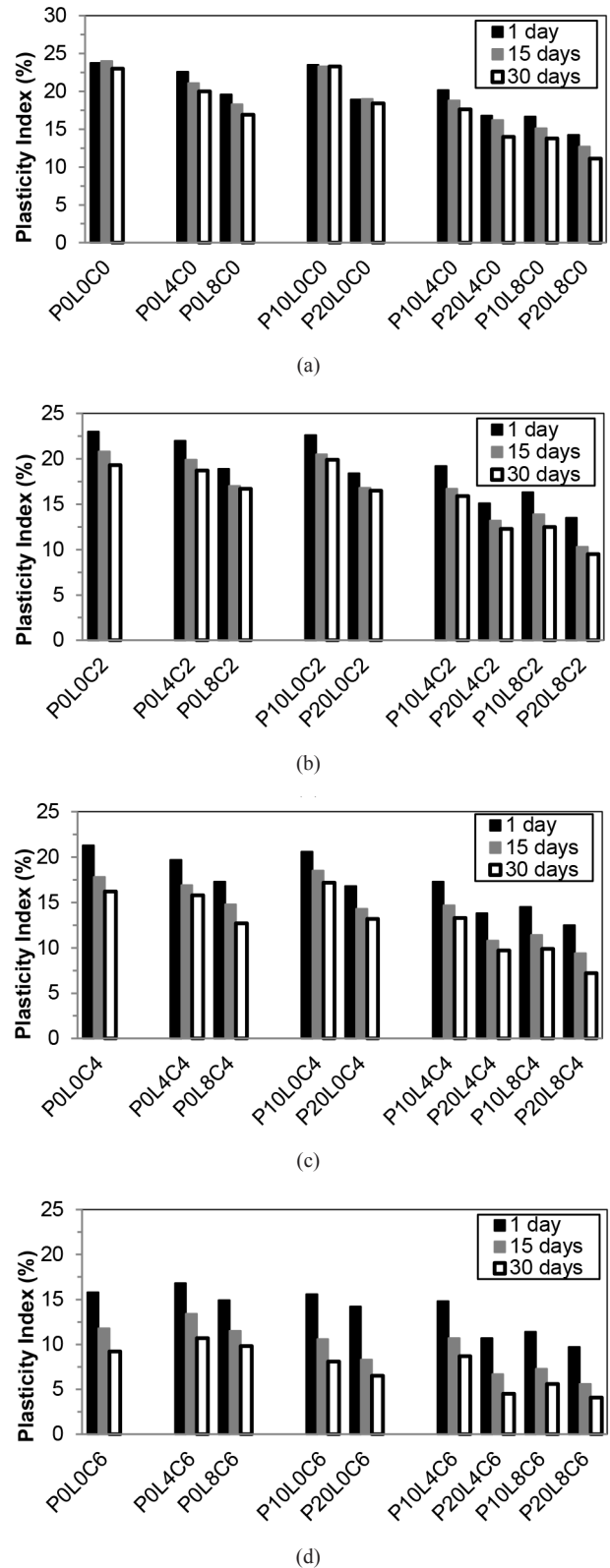


Fig. 7 Effect of different content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the PI of the stabilized RS

GS stabilized with 20%NP decreases from 50.5% to 33.9 and 29.5% respectively with 2 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Fig. 6b and d). Whereas, for the same content of NP and the same DTC, the PI of the RS decreases from 23.8% to 18.4 and 14.2% respectively with 2 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Fig. 7b and d). In addition, with 20%NP as an additive and after 30 days of DTC, the PI

of the GS decreases from 50.5% to 18.9 and 15.1% respectively with 2 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Fig. 6b and d). Whereas, for the same content of NP and the same DTC, the PI of the RS decreases from 23.8% to 16.5 and 6.5% respectively with 2 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Fig. 7b and d). It should be noted that the addition of NP to both GS and RS 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 as compared with untreated and treated soil samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. According to Yilmaz and Civelekoglu [29], the PI of the bentonite stabilized with gypsum decreases from 186.9% to 139.5 and 120.8% for the addition of 2.5 and 10% of gypsum, respectively. This is due to the replacement of monovalent ions by calcium ions (from $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) which provokes a reduction in diffuse double layer thickness and leads to the decrease in LL, consequently, the decrease in the PI. For comparison, it is clear to see that after curing for 30 days the RS samples containing 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ alone or mixed with 20%NP produces high PI values as compared with samples stabilized with 8%L alone or mixed with 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

Furthermore, 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 $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. Moreover, there is a significant decrease in the PI of both GS and RS samples with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and DTC (Figs. 6b-d and 7b-d). e.g., for the GS stabilized with 10%NP+4%L on curing for 1 day of DTC, the PI decreases from 19.2% to 17.9, 16.3 and 14.3% respectively with 2, 4 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Fig. 6b, c and d). Whereas for the same soil and after 30 days of DTC, the PI decreases from 16.3% to 15.5, 14 and 8.9% respectively with 2, 4 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Fig. 6b, c and d). In addition, the decrease in the PI of both GS and RS samples with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and DTC is considerably important when the content of L-NP increases. e.g., for the GS stabilized with 20%NP+8%L on curing for 1 day of DTC, the PI decreases from 12.5% to 11.1, 9.5 and 7.9% respectively with 2, 4 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Fig. 6b, c and d). Whereas for the same soil and after 30 days of DTC, the PI decreases from 10.9% to 8.8, 7.2 and 4.5% respectively with 2, 4 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Fig. 6b, c and d). In general, the PI values of L-NP-treated both GS and RS samples containing any content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ are very higher compared with samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

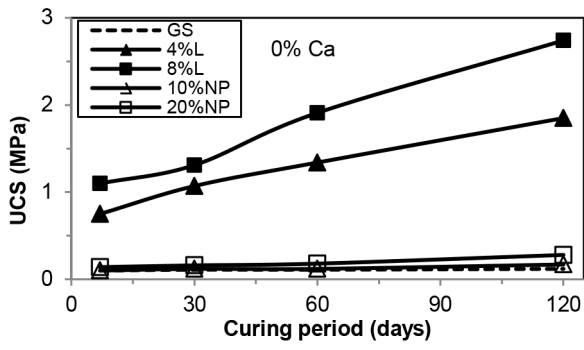
Generally, the improvement in the consistency limits of two stabilized clayey soils depends on the type and the content of additive added, the content of sulphate used, the DTC and the mineralogical composition of stabilized soil.

4.2 Unconfined Compressive Strength

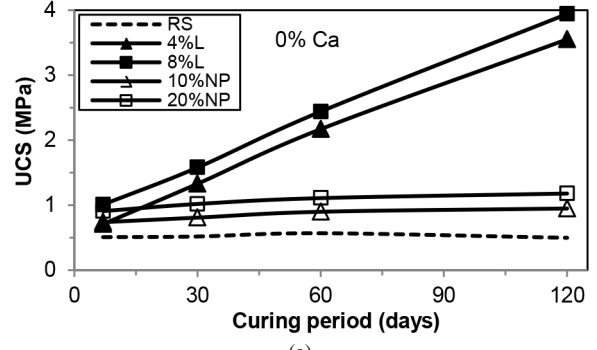
4.2.1 Variation of the unconfined compressive strength in the absence of sulphates

Figures 8-10 depict the results of the effect of L, NP and their combinations on the UCS of both GS and RS samples stabilized with or without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. According to Figs. 8a and 9a, the addition of L alone to both GS and RS samples binds their particles and produces a significant increase in the UCS which increases with increasing L content and curing period. A similar behaviour was observed by McCarthy et al. [33]. In addition, Asgari et al. [4] reported that the UCS of the soil obtained from northwestern of Arak city increases curing period and L content up to 3% but decreases after this content. 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 [22]. However, there is a negligible increase in UCS values of both GS and RS samples when the NP is used alone due to its low reactivity with the clay particles. Therefore, it is not possible to use the NP alone for the stabilization of these clayey soils. The differences in the UCS between L and NP as additives are more pronounced with the RS than with the GS. This behaviour is probably due to the mineralogical composition and high plasticity index value of the GS as compared with that of the RS.

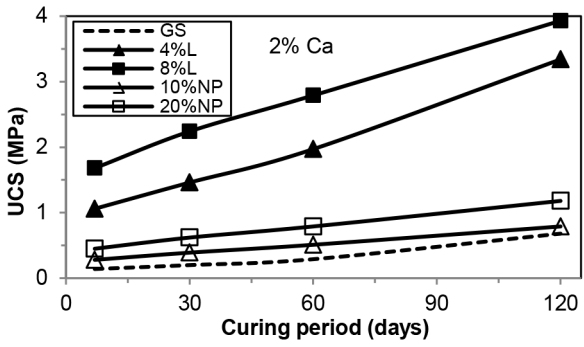
The results of the effect produced by the combination L-NP without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of both GS and RS samples are depicted in Fig. 10a. It can be seen that the better results of the UCS are achieved when the combination L-NP is used. However, the UCS of both stabilized clayey soils increases considerably with curing period and L-NP content. E.g., 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 a similar class soil, McCarthy et al. [33] reported that the UCS of oxford clay treated with a combination of 18%FA+3%L increases from 0.4 MPa up to 1 and 1.8 MPa after curing for 7 and 90 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. For a similar class soil, McCarthy et al. [33] reported that the UCS of Lias clay treated with a combination of 18%FA+3%L increases from 0.4 MPa up to 1.1 and 2.1 MPa after curing for 7 and 90 days, respectively.



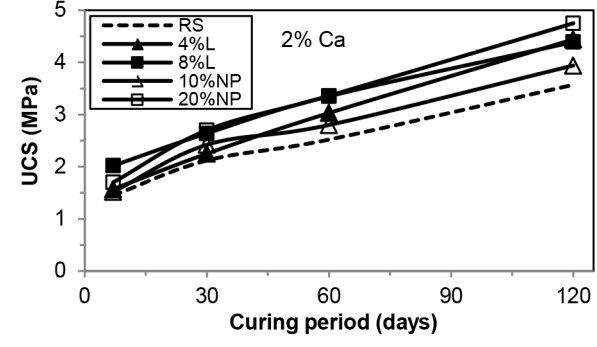
(a)



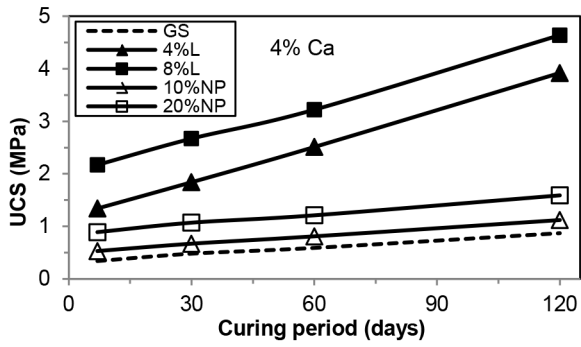
(a)



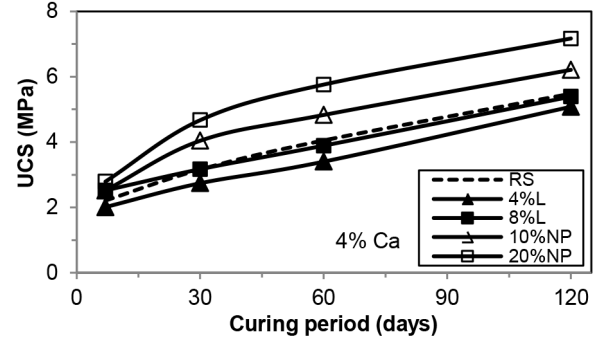
(b)



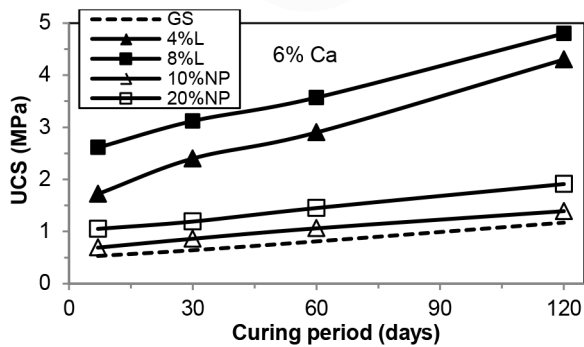
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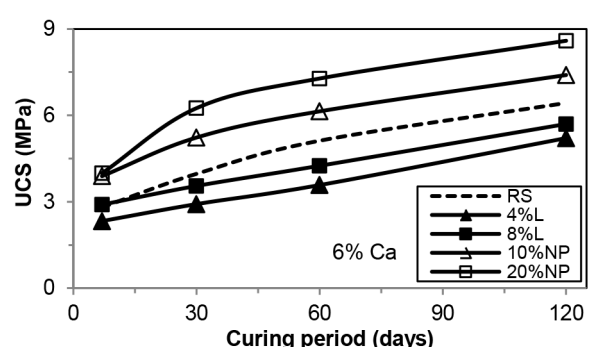
(c)



(c)



(d)



(d)

Fig. 8 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

Fig. 9 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

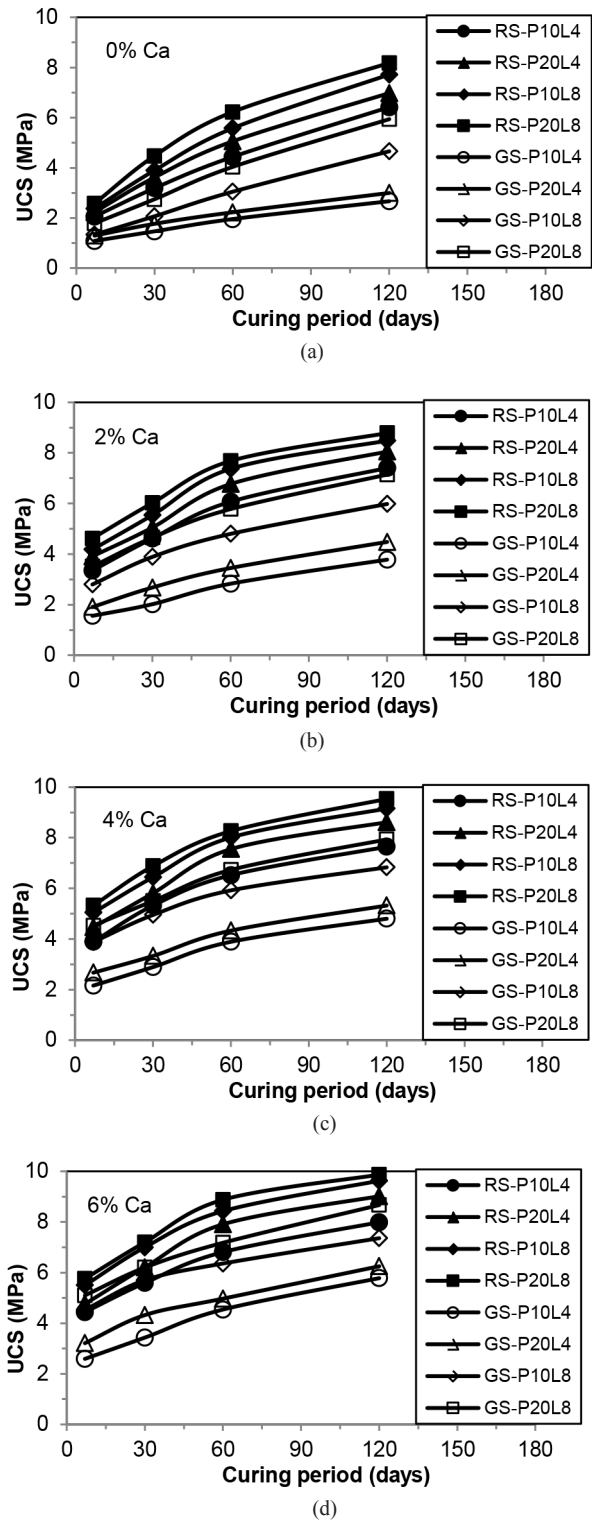


Fig. 10 Effect of different content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of two soils stabilized with L-NP

However, 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. e.g., 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. [9] where they found that the combination of 10% volcanic ash and 4% L for both S1

and S2 soils represented an increase of 21 and 10 times respectively compared with both untreated soils. The dissolution of alumina and silica from soil and/or NP depends strongly on the L content which produces more cementitious products responsible on the increase in the UCS of both GS and RS samples. 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. The same behaviour is observed by Koliass et al. [1]. 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 [21].

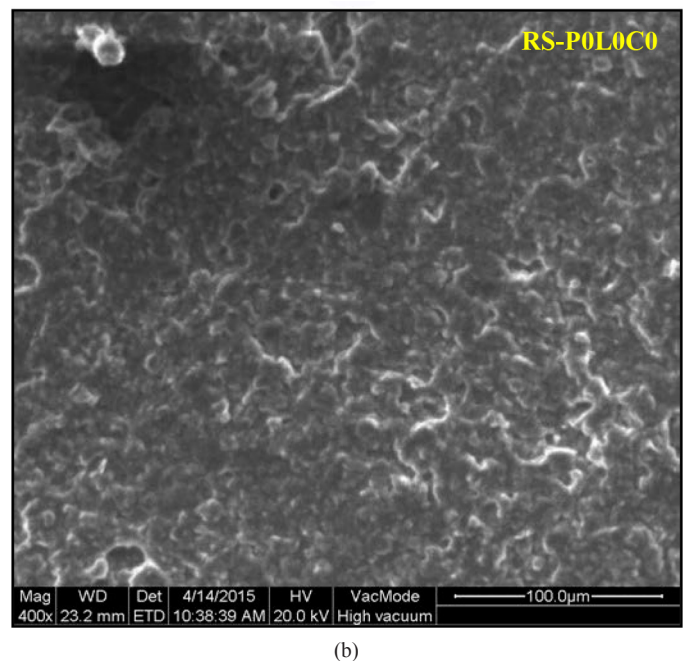
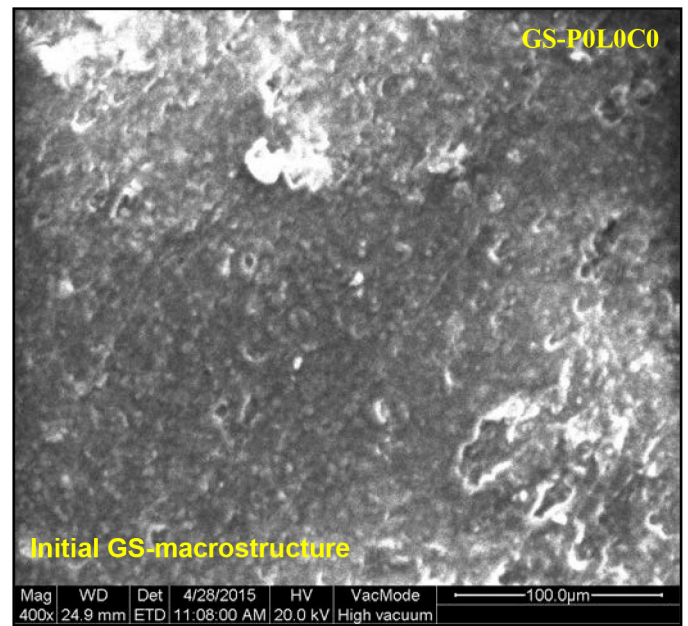
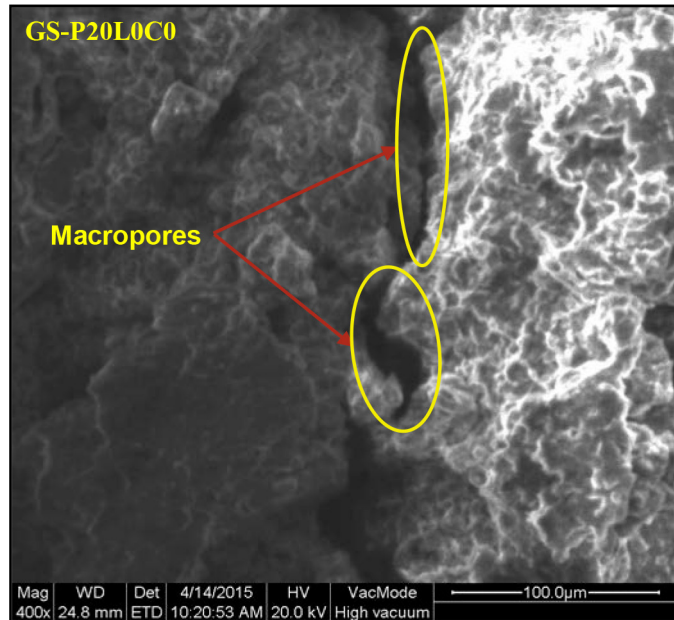


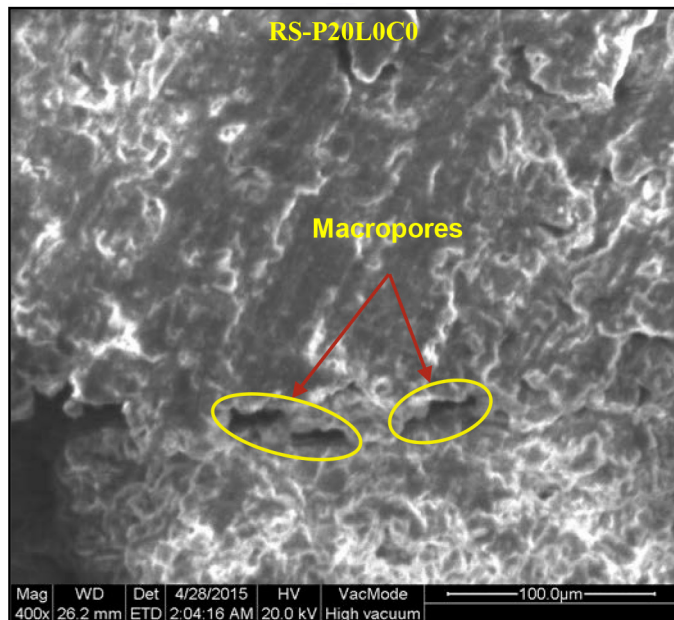
Fig. 11 SEM images show the initial microstructure of both untreated GS and RS samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ after 60 days of curing

4.2.2 Variation of the unconfined compressive strength in the presence of sulphates

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 both stabilized GS and RS samples are depicted in Figs. 8b-d and 9b-d. In all cases the UCS values of both GS and RS 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 $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.



(a)

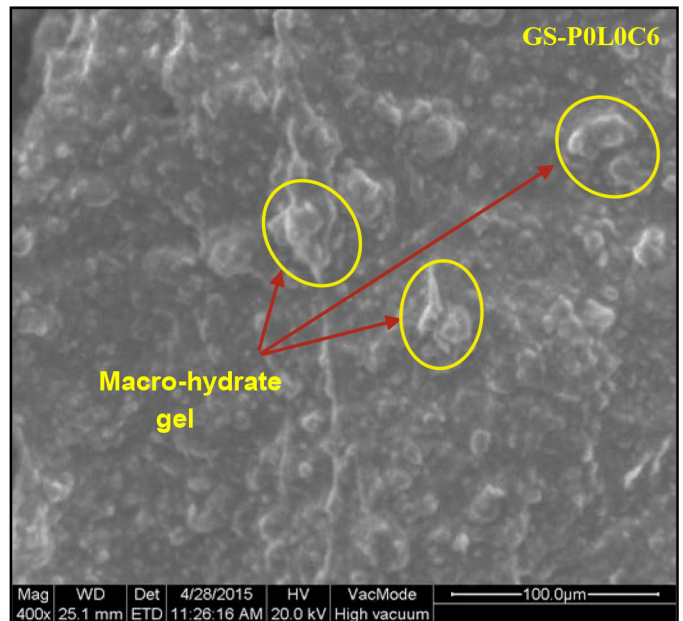


(b)

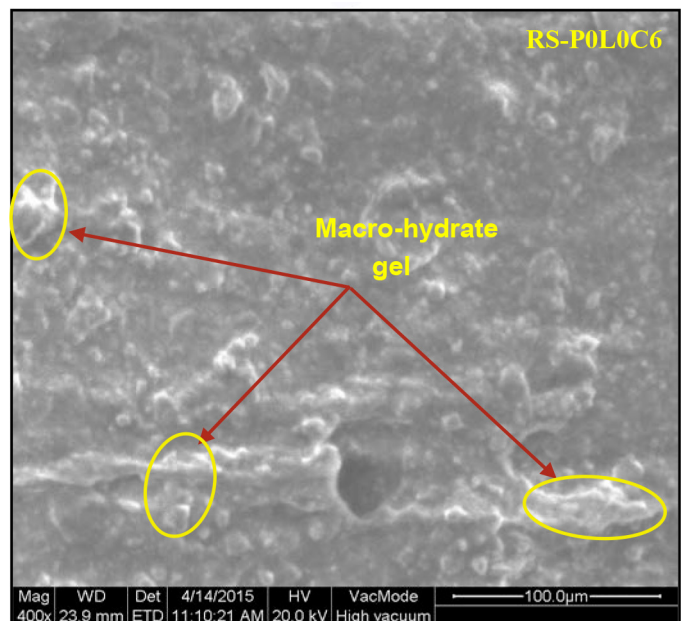
Fig. 12 SEM images show the evolution of the microstructure of NP-treated both GS and RS samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ after 60 days of curing

Indeed, there is a significant increase in UCS of both untreated GS and RS samples with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period whereby RS has the best results. Yilmaz and Civilekoglu [29] observed that with gypsum as an additive the UCS

of the bentonite soil increases from 58.7KPa up to 73.1 and 79.6KPa for the addition of 2.5 and 7.5% of gypsum, respectively. It is obvious to see that there is a much better increase in UCS values of NP-treated both GS and RS samples with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period whereby RS has the greatest values. E.g., with 20%NP as an additive, after 7 days of curing the UCS of the GS increases from 0.2 MPa up to 0.5 and 1.1 MPa respectively with 2 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. But, for the same content of NP and curing period the UCS of the RS increases from 0.9 MPa up to 1.7 and 4 MPa respectively with 2 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. However, with 20%NP as an additive, after 120 days of curing the UCS of the GS increases from 0.3 MPa up to only 1.2 and 1.9 MPa respectively with 2 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.



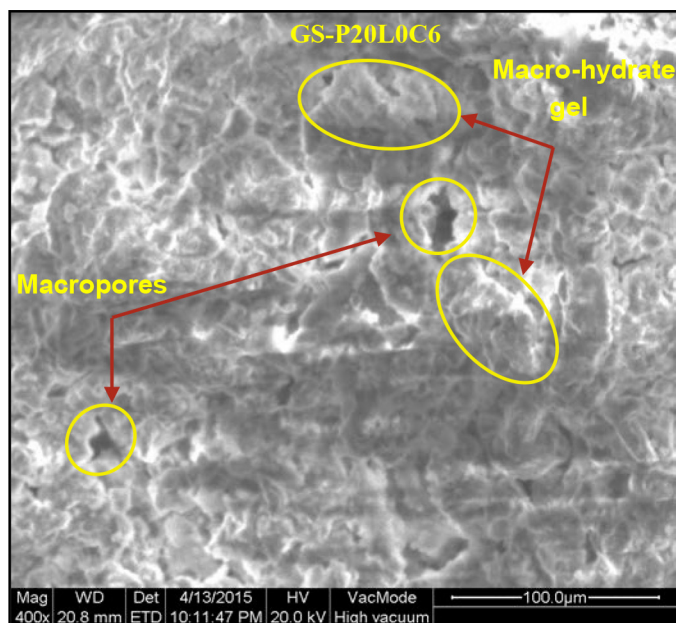
(a)



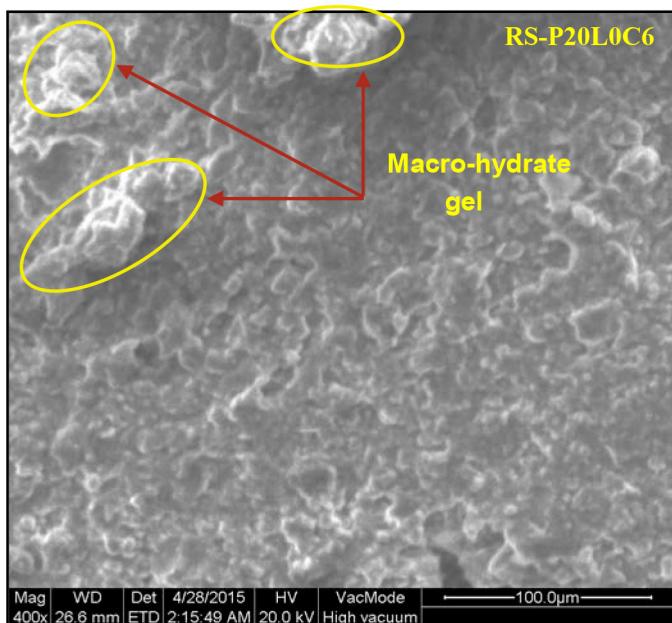
(b)

Fig. 13 SEM images show the evolution of the microstructure of both untreated GS and RS samples in the presence of 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ after 60 days of curing

Whereas, for the same content of NP and curing period the UCS of the RS increases from 1.2 MPa up to 4.8 and 8.6 MPa respectively with 2 and 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. However, the scanning electronic microscope (SEM) images show that the presence of 6% of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ improves significantly the compactness of both untreated and NP-treated both GS and RS samples after curing for 60 days as compared with samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Figs. 11-14). It is clear to see that there is a formation of macro-hydrates gel (CSH and/or CAH) in both GS and RS samples responsible on the much better change in their microstructure and the gain of strength (Figs. 13 and 14).



(a)



(b)

Fig. 14 SEM images show the evolution of the microstructure of NP-treated both GS and RS samples in the presence of 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ after 60 days of curing

Further, Aldaood et al. [18] 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 both GS and RS samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ can be explained by the presence of macropores in these samples which due to the high specific surface area of NP (Fig. 12a and c).

However, the addition of L alone to both GS and RS samples on curing with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ increases the UCS with curing period. The increase in the UCS with time can be attributed to the hydration rate due to the short time reactions between soil, L and gypsum to form CSH and/or CAH and ettringite [19]. In addition, Hunter [14] reported that the hydroxyl OH^- retained from L hydration combines with montmorillonite to form aluminum compounds and then reacts with sulphates to form the ettringite mineral. However, at early stage there is a high increase in UCS of L-treated both GS and RS samples with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and L content compared with samples cured without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. In contrast, at later stage the UCS of L-treated both GS and RS samples increases slightly with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and L content. The same behaviour was obtained by Segui et al. [16]. It is clear to see that with any content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ there is a high difference in UCS values between the NP-treated GS samples and L-treated the same soil samples. In contrast, with 2% of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and for any curing periods, both untreated and NP-treated RS samples appear to develop the same UCS values compared with the L-treated the same soil with the same content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. In addition, after 30 days of curing with 4 and 6% of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ the UCS values of both untreated and NP-treated RS samples are very higher compared with those of L-treated the same soil with the same contents of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. e.g., on curing with 4 and 6% of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ the RS stabilized with 20%NP develop respectively UCS values of 7.2 and 8.6 MPa after curing for 120 days. Whereas, for the same contents of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ the RS stabilized with 8%L develop respectively UCS values of 5.4 and 5.7 MPa after the same curing period. 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 (Shi and Day, 2000) [34]. 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 behaviour of the RS with the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ interaction.

However, the UCS of both GS and RS samples 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 (Fig. 10). E.g., with 2% of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ both GS and RS stabilized with the combination 10%NP+4%L develop an UCS value of 3.8 and 7.4 MPa after curing for 120

days, respectively. But with the same content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and curing period the UCS of both GS and RS stabilized with 20%NP+8%L becomes 7.1 and 8.8 MPa, respectively.

However, on curing with 6% of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ both GS and RS stabilized with the combination 10%NP+4%L develop an UCS of 5.8 and 8 MPa after curing for 120 days, respectively. Whereas, for the same content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and curing period the UCS of two GS and RS stabilized with 20%NP+8%L becomes 8.7 and 9.9 MPa, respectively. Generally, the early increase in the UCS of both GS and RS samples 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 [18].

5 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 away to decrease the PI and increase the UCS of both clayey soils. Based on the test results, the following conclusions can be drawn:

1. The addition of L to both GS and RS samples 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 both GS and RS samples. The combination of L-NP without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ decreases significantly the PI of both GS and RS samples more than the use of L alone.
2. The use of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ as an additive reduces considerably the PI of both GS and RS samples. The degree of reduction depends largely on 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.
3. The stabilization with L alone without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ increases considerably the UCS of both GS and RS samples. This increase depends on the amount of L added and the curing period. However, a negligible influence on the UCS of both GS and RS samples containing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ is observed when the NP is used alone.
4. The high early values of UCS developed by both GS and RS samples with curing period can be attributed to the acceleration of the pozzolanic reaction due to the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ added.
5. The $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ has a marginal influence on the UCS of both GS and RS samples stabilized with lime alone.
6. The mineralogical composition of the clayey soil plays an important role in the chemical reaction with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.
7. The progressive increase in the UCS of both GS and RS, particularly the RS, can be explained by the formation of ettringite due to the presence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ in the Soil-L-NP system. Indeed, the increase in UCS values is particularly important when the amount of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ increases.

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

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