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Behavior of Natural Pozzolana-Lime-stabilized Clayey Soils Artificially Contaminated by Sulfates

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ABSTRACT

The use of lime in sulfate-bearing clayey soils has historically caused structural damage to infrastructures due to the formation of an expansive ettringite mineral. In this paper, a research was conducted to study the effectiveness of natural pozzolana (NP) for providing better stabilization of sulfate-bearing soils. Compaction and free-swell potential tests were first performed on lime-stabilized grey and red clayey soils (GS and RS) containing different contents of added sodium and calcium sulfates (2, 4 and 6% Na_2SO_4 or $CaSO_4{\cdot}2H_2O$). Then, the same tests were repeated by adding 20%NP. The test results indicated that the presence of 4% and 6% Na_2SO_4 in the soil resulted in an abnormal increase in the swell potential of both lime-stabilized GS and RS. The X-ray diffraction (XRD) results confirmed the growth of the ettringite mineral responsible for this higher swell potential. However, the use of 8% lime with 20%NP in stabilizing sulfate-bearing clayey soils produced significant improvements in the optimum moisture content (OMC) and maximum dry density (MDD), as well as in the swell potential. The addition of 20%NP into the lime-stabilized GS and RS eliminated the harmful effect of Na_2SO_4. In addition, for 120-day curing period, the use of 6% $CaSO_4{\cdot}2H_2O$ was found very effective by reducing the swell potential of NP-lime-stabilized GS and RS from 7.33% to 0.4% and from 2.79% to 0.2%, respectively trips.

KEYWORDS: Clayey soils, Mineral additives, Sulfates, Compaction, Swell potential, Stabilization.

INTRODUCTION

Problematic soils occur in many parts of the world including Algeria and have predominantly montmorillonite clay mineral. They are found to exhibit high swelling upon exposure to water and shrinkage when dried with a consequent reduction in strength and bearing capacity. For example, most of the soils used in the construction of the Algerian highway as building materials are characterized by insufficient geotechnical properties. These soils have been chemically improved to make them able to bear traffic loads (Gadouri et al., 2016). Indeed, chemical stabilization of problematic soils using hydraulic binders was extensively used with the main aim to make them capable of supporting construction loads (Kolias et al., 2005). Many studies have been conducted by several researchers in order to assess the effect of cement, cement kiln dust, unground cement clinker, fly ash, lime and volcanic materials on the physico-mechanical characteristics of clay soils (e.g. Rahman, 1986; Hossain et al., 2007; Harichane et al., 2011b, 2012; Al-Swaidani et al., 2016; Islam et al., 2018; Devendra and Kumar, 2020). However, it should be noted that the production of one metric-ton of cement leads to the emission of about 0.63 metric-ton of CO_2 and requires large amounts of energy (WBCSD, 2016). Cement replacement by using other mineral additives is very important for reducing CO_2 emissions, which are responsible for global warming, floods, significant rising in temperatures, drying up of rivers, rising in sea levels, … etc. Consequently, several researchers have

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recommended the use of volcanic materials in order to minimize both CO_2 emissions and energy consumption (e.g. Hossain et al., 2007; Harichane et al., 2012; Segui et al., 2013; Al-Swaidani et al., 2016; Gadouri et al., 2017). Indeed, the use of lime alone or in combination with volcanic ash was widely utilized as an alternative solution because of its environmental advantages and technical performances (Hossain et al., 2007). For example, the stabilization of cohesive soils with the combination of lime and NP was found to develop significant shear and compressive strengths compared to control soils (Harichane et al., 2011a).

On the other hand, the presence of sulfate ions (SO_4^{2-}) in lime-stabilized soil leads to the formation of ettringite mineral, which is responsible for severe damages observed in road pavements, foundations and infrastructures founded on them (e.g. Mitchell, 1986; Baryla et al., 2000; Puppala et al., 2003, 2006, 2009; Celik and Nalbantoglu, 2013). These damages depend on the type of additive and its amount, the mineralogical composition of the stabilized soil and the type of sulfate and its amount (e.g. Kinuthia et al., 1999; Sivapullaiah et al., 2006; Yilmaz and Civelekoglu, 2009; Segui et al., 2013; Aldaood et al., 2014a, 2014b; Gadouri et al., 2016, 2017).

For any project, compaction and swelling potential are two fundamental parameters that have a significant influence when choosing a suitable material for civil-engineering constructions. Soil compaction is considered as a very important step, which mainly aims to reduce deformation (by increasing Young's modulus), permeability and volume variations and increase the soil bearing capacity (Gadouri et al., 2016). However, clay swelling is generally caused by the variation in moisture content, which induces fractures and cracks in soil foundations and structure walls (Hamza et al., 2022). In fact, expansive clay containing montmorillonite and illite as clay minerals shows a considerable volume change upon small variations in water content considering the environmental changes (Batool et al., 2021; Hamza et al., 2022). Recently, Ebailila et al. (2022) have studied the effective role of different gypsum contents on the long-term performance of lime-stabilized kaolin soil. They have found that the addition of lime to kaolin soil in the absence of gypsum reduced the expansion through both changing of fabric soil and the development of pozzolanic reactions with the curing time. However, the presence of gypsum was found to have a considerable influence by increasing the expansion of the lime-stabilized soil as the gypsum content increased, especially with a more pronounced effect at higher gypsum and lime contents. This behavior was explained by the formation of a high amount of ettringite mineral, which is depending on both lime and gypsum contents (e.g. the swelling of the kaolin soil stabilized with 6% lime was found to increase from 5% up to 30% in the presence of 9% gypsum). This mineral (ettringite) caused a high expansion under the water-soaking condition due to its higher water-absorption capability. A similar study has been conducted by Abdi et al. (2020), where they investigated the effects of sodium and calcium sulfates on the swelling of lime-stabilized kaolinite soil. The obtained results showed that soaking lime-stabilized kaolinite soil samples in sodium -and calcium- sulfate solutions promoted swelling as the result of the formation of ettringite mineral, which is significantly influenced after a longer curing period. According to Gadouri et al. (2019b), Puppala et al. (2019) and Talluri et al. (2020), the calcium stabilizer treatment of clayey soils containing sulfates results in the formation of a highly expansive mineral known as ettringite of secondary formation. Several researchers have used cementitious binders containing a high fraction of ground granulated blast furnace slag (GGBFS) in order to reduce the expansion caused by this expansive mineral. For example, Caselles et al. (2020) have investigated the effect of several binders for stabilizing a silty soil artificially contaminated by 1% gypsum (10g/kg of dry mass of soil). It was observed that stabilization with cementitious binders containing a high cement tricalcium aluminate (C_3A) content led to a volume expansion greater than 5% compared with that of the control soil, while stabilization with binders having a high fraction of GGBFS showed a volume expansion of less than 5%. Similarly, Li et al. (2020) have assessed the effect of GGBFS on suppressing ettringite-induced swelling of gypseous soil by using magnesia-activated. They have found that swelling of MgO-GGBFS-stabilized soil was much lower than that of cement-stabilized soil, while X-ray diffraction results (XRD) showed that no ettringite was formed in MgO-GGBFS-stabilized soil, which was mainly responsible for the lesser swelling compared with that of the cement-stabilized soil after soaking.

In Algeria, large volumes of soil with insufficient properties can be improved to be used for several engineering projects, which are currently under construction, such as road pavements and earth dams. However, soil classification is very important for geotechnical-engineering projects, because it provides important information about the properties of the soil grains themselves. The NP was found in abundance in areas of Beni-Saf located in the west of Algeria (Ghrici et al., 2007). This work aims to investigate the effect of adding sodium and calcium sulfates (Na_2SO_4 and $CaSO_4{\cdot}2H_2O$) with different contents (0-6%) on the compaction and swell potential properties of grey and red clayey soils (GS and RS) stabilized with 8% lime, 20%NP and their combination at different curing periods. Also, the mechanism of particle-particle chemical adhesion developed in soil-lime-NP and soil-lime-NP-sulfate mixtures will be discussed.

MATERIALS' EXTRACTION AND CHARACTERIZATION

Materials' Extraction

Grey soil (GS) and red soil (RS) used in this study were obtained from an embankment project site and a highway project site, respectively (Chelif town located in the west of Algeria). However, the NP used as an additive was obtained from Beni-Saf deposit located in the west of Algeria. These materials were extracted and transported to laboratory research for preparation and testing.

Clayey Soils

A series of laboratory tests were carried out for the identification and classification of both clayey soils (Fig. 1 (a) and (b)). The physico-mechanical and chemico-mineralogical properties of both clayey soils are depicted in Tables 1 and 2, respectively. As shown in Table 1 and based on the USCS, both the GS and RS were classified as CH and CL classes' soils, respectively.

Table 1. Physico-mechanical properties of both clayey soils

Physico-mechanical Properties	GS	RS
Depth (m)	4.0	5.0
Natural water content (%)	32.90	13.8
Specific Gravity (-)	2.71	2.84
Passing 80 µm Sieve (%)	85.0	97.5
Liquid Limit (LL, %)	82.8	46.5
Plastic Limit (PL, %)	32.2	22.7
Plasticity Index (PI, %)	50.6	23.8
Classification System (USCS), (-)	CH	CL
Optimum Moisture Content (W_{OPN}, %)	28.30	15.3
Maximum Dry Density (γd_{max}, kN/m^3)	13.80	16.9
Unconfined Compressive Strength (UCS, kPa)	100	510
Loss on Ignition (%)	17.03	7.13

Table 2. Chemico-mineralogical properties of both clayey soils

Chemical / 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

Sulfites	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	$CaCO_3$	26.0	4.0
Albite	$NaAlSi_3O_8$	-	8.0
Illite	$2K_2O.Al_2O_3.24SiO_2.2H_2O$	16.0	24.0
Kaolinite	$Al_2Si_2O_5\ (OH)_4$	12.0	16.0
Montmorillonite	$Al_2\ (\ (Si_4Al)O_{10})$	20.0	-
Chlorite	$Mg_2Al_4O_{18}Si_3$	-	9.0
Other Minerals	-	6.0	7.0
Organic Matter	-	0.33	-

Lime and Natural Pozzolana

In this study, the NP rock was ground to the specific surface area of 420 m^2/kg (Fig. 1 (c)). However, the lime used was a hydrated lime ($Ca\ (OH)_2$) commercially available and typically used for construction purposes (Fig. 1 (d)). The physico-chemical properties of these additives are presented in Table 3.

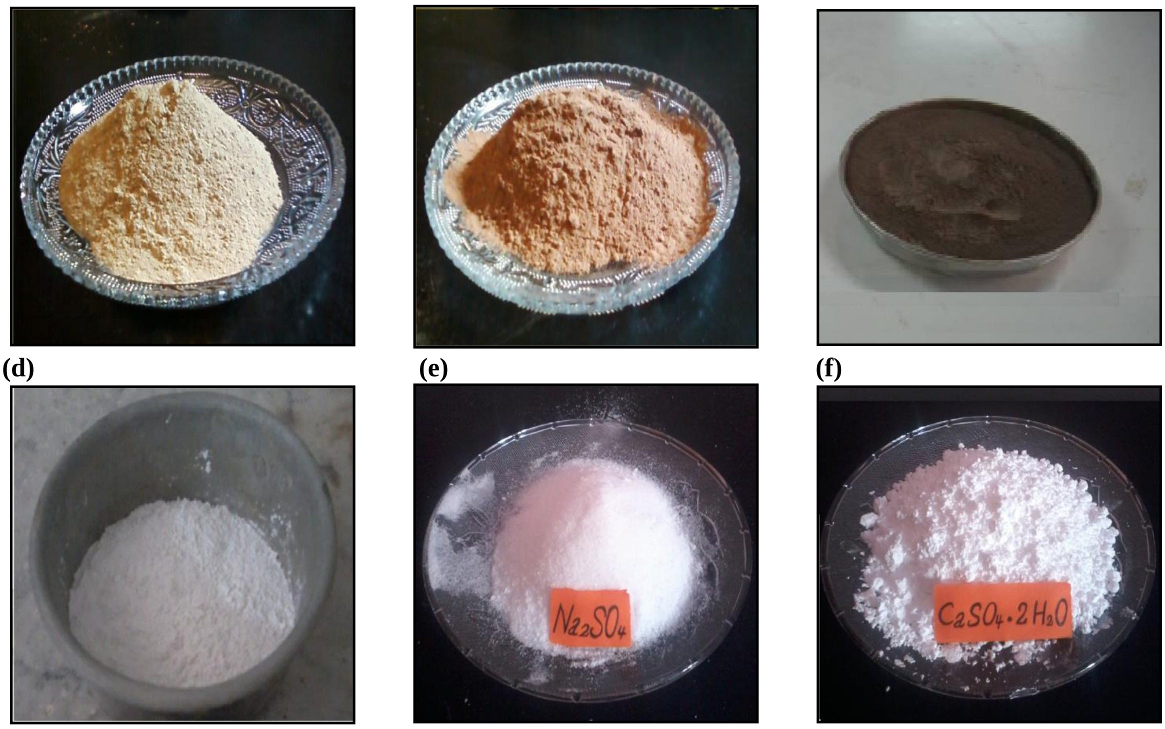

Figure (1): Materials used (a) GS sample (b) RS sample (c) NP powder (d) Hydrated lime (e) Sodium sulfates and (f) Calcium sulfates

Sulfates

Two chemical compounds were used in the study; the first is a sodium-sulfate (Na_2SO_4) (Fig. 1 (e)) and the second is a calcium-sulfate dihydrate ($CaSO_4 \cdot 2H_2O$) (Fig. 1 (f)). These sulfates were produced by Biochem Chemopharma as a leading international manufacturer and supplier of laboratory reagents. The physico-chemical properties of these sulfates are shown in Table 4.

Table 3. Physico-chemical properties of both lime and natural pozzolana

Physical / Chemical Name	Lime (%)	NP (%)
Physical Form	Dry white powder	Dry brown
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
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	-

Table 4. Physico-chemical properties of both sodium and calcium sulfates used

Physico-chemical Properties	Calcium Sulfates (%)	Sodium Sulfates (%)
Physical Form	Dry white powder	Dry white powder
Chemical Formula	$CaSO_4{\cdot}2H_2O$	Na_2SO_4
Molar Weight (g/mol)	172.2	142
Purity (dried)	99	99.5
pH (50g/L, 25°C)	-	5 to 8
Insoluble Matter	0.03	0.01
Chloride (Cl)	0.002	0.001
Nitrate (NO3)	0.002	-
Ammonium (NH4)	0.01	-
Carbonate (CO3)	0.1	-
Heavy Metals (Pb)	0.001	-
Iron (Fe)	0.001	0.001
Calcium (Ca)	-	0.01
Phosphorus (PO_4)	-	0.001

TEST PROCEDURES

Compaction Test

Based on the ASTM D698 (2000), a series of compaction tests were conducted on both unstabilized and stabilized clayey soils. The variations in OMC and MDD values of these samples were studied before and after admixture addition. A total of 63 combinations of soil-lime, soil-NP and soil-lime-NP mixtures based on both clayey soils were tested, as shown in Table 5.

Table 5. A summary of the mix combinations tested for both clayey soils samples with and without sulfates

Mixture	SM (%)				Mixture	SM (%)			
	S	NP	L	Ca		S	NP	L	Na
P0L0*	100	0	0	0	P0L0N2*	98	0	0	2
P0L4	96	0	4	0	P0L4N2	94	0	4	2
P0L8*	92	0	8	0	P0L8N2*	90	0	8	2
P10L0	90	10	0	0	P10L0N2	88	10	0	2
P20L0*	80	20	0	0	P20L0N2*	78	20	0	2
P10L4	86	10	4	0	P10L4N2	84	10	4	2
P20L4	76	20	4	0	P20L4N2	74	20	4	2
P10L8	82	10	8	0	P10L8N2	80	10	8	2
P20L8*	72	20	8	0	P20L8N2*	70	20	8	2
P0L0C2*	98	0	0	2	P0L0N4*	96	0	0	4
P0L4C2	94	0	4	2	P0L4N4	92	0	4	4
P0L8C2*	90	0	8	2	P0L8N4*	88	0	8	4
P10L0C2	88	10	0	2	P10L0N4	86	10	0	4
P20L0C2*	78	20	0	2	P20L0N4*	76	20	0	4
P10L4C2	84	10	4	2	P10L4N4	82	10	4	4
P20L4C2	74	20	4	2	P20L4N4	72	20	4	4
P10L8C2	80	10	8	2	P10L8N4	78	10	8	4
P20L8C2*	70	20	8	2	P20L8N4*	68	20	8	4
P0L0C4*	96	0	0	4	P0L0N6*	94	0	0	6
P0L4C4	92	0	4	4	P0L4N6	90	0	4	6
P0L8C4*	88	0	8	4	P0L8N6*	86	0	8	6
P10L0C4	86	10	0	4	P10L0N6	84	10	0	6
P20L0C4*	76	20	0	4	P20L0N6*	74	20	0	6
P10L4C4	82	10	4	4	P10L4N6	80	10	4	6
P20L4C4	72	20	4	4	P20L4N6	70	20	4	6
P10L8C4	78	10	8	4	P10L8N6	76	10	8	6
P20L8C4*	68	20	8	4	P20L8N6*	66	20	8	6
P0L0C6*	94	0	0	6	SM: Soil mixture; S: Soil; Ca: $CaSO_4.2H_2O$; Na: Na_2SO_4; L: Lime; NP: Natural pozzolana. * Mixtures submitted to one-dimensional free-swell test, considered as optimum values.				
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					

One-dimensional Free-swell Test

The free-swell tests were performed according to ASTM D 4546 (2008). However, they were performed using a standard one-dimensional oedometer machine in order to assess the effect of sodium and calcium sulfates on the free-swell potential of the clayey soils stabilized by lime, NP and their combination. A total of 84 combinations of soil-8%lime, soil-20%NP and soil-8%lime-20%NP mixtures based on clayey soils were tested after curing for 1, 30 and 120 days (Table 5).

The clayey soils were compacted at a strain rate of 1 mm/min using a rigid static press with 71 mm in diameter and 20 mm in height. However, the clayey soils stabilized with and without sulfates were subjected to 1, 30 and 120 days of curing at 20°C. Once the curing period was over, the compacted clayey soil samples in the oedometer rings were placed in a consolidation cell between two dried porous stones and the vertical displacement of the soil was measured by fixing a sensitive comparator on top of the consolidation cell.

An initial reading was taken to estimate the swell potential just after applying an initial vertical pressure equal to 2.75 kPa. Subsequently, the soil samples stabilized with and without sulfates were soaked with distilled water and let swell under the same vertical pressure (2.75 kPa) at a constant laboratory temperature (25°C ± 2°C). The final reading of the dial gauge (as the highest reading) was used to calculate the free-swell potential together with the initial height of the unstabilized and stabilized clayey soil samples. Dial-gauge readings were recorded at 0, 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60, 120 and 1440 min. The measurement of the expansion of the specimens continued until equilibrium was reached. In fact, the time necessary to reach the maximum value of vertical displacement (the final reading of the dial gauge) depends on the curing time and the content of both sulfates and additives used. In order to allow for any residual swelling of the soil samples, the swell test should be continued until the dial-gauge reading had stabilized for at least 1 day.

SAMPLE PREPARATION

Soil-Lime, Soil-NP and Soil-Lime-NP Mixtures

Prepared samples for both compaction and free-swell tests were stabilized using 8% lime, 20%NP and their combination (8%L+20%NP). The pre-determined quantity of NP and lime were initially mixed with the selected soils in a dry state to obtain different soil-lime, soil-NP and soil-lime-NP mixtures. These mixtures were sieved through 1 mm sieve mesh openings, where each mixture was weighed and placed into a glass container. In addition, the calculated water was also added to each mixture and let stand for 1 hour prior to sample preparation. However, several specimens (71 mm in diameter and 20 mm in height) containing different sulfate contents were performed at MDD and OMC and then submitted to free-swell tests at different curing periods. Indeed, free-swell tests were repeated on two identical samples and the accepted OMC and MDD values were an average of two tests carried out on each sample type.

Soil-Lime-Sulfate, Soil-NP-Sulfate and Soil-Lime-NP-Sulfate Mixtures

All samples used for compaction and free-swell tests were prepared following the same method as explained above with the addition of pre-determined quantity of sodium and calcium sulfates. A static press was used for performing the tests on the specimens after the same time (1 hour) and with the same way as presented above.

RESULTS AND DISCUSSION

Effect of Lime and NP on the Compaction Properties

The results of the effects of both sodium and calcium sulfates on the compaction characteristics of clayey soils stabilized with different contents of lime, NP and their combination are depicted in Table 6 (Gadouri et al., 2019b). However, in the following sections, we will only discuss the results of the effect of sodium and calcium sulfates on the compaction characteristics of clayey soils stabilized with 8%L, 20%NP and 8%L+20%NP, which are considered as optimum values.

Figure 2 shows the modifications in OMC and MDD values of soil-lime, soil-NP and soil-lime-NP mixtures. For the tested clayey soils, there is a considerable decrease in OMC and a significant increase in MDD values of soil-NP mixture as compared with untreated soils. A similar trend was observed by Al-Swaidani et al. (2016). However, with 8%L as an additive, the OMC of both GS and RS samples increased from 28.3% and 15.3% up to 31.1% and 17.4%, respectively. On the other hand, with the same content of lime, the MDD of both GS and RS decreased from 13.8 kN/m^3 and 16.9 kN/m^3 to 12.9 kN/m^3 and 16.2 kN/m^3, respectively. A similar behavior was reported by several researchers when they used lime as an additive for stabilizing fine-grained soils (e.g. Rahman, 1986; George et al., 1992; Bell, 1996; Hossain et al., 2007; Celik and Nalbantoglu, 2013; Jha and Sivapullaiah, 2015; Al-Swaidani et al., 2016). According to Kinuthia et al. (1999), the agglomeration of clay particles due to lime addition lowered the MDD (due to an increase in pore volume) and accommodated more water during the compaction process, consequently raising the OMC of the stabilized soil.

When the combined treatment of 8%L+20%NP was used for stabilizing the RS, a further increase in OMC and a negligible change in MDD values were recorded. However, with the same combination (8%L+20%NP) used for stabilizing the GS, a negligible change in both OMC and MDD values was observed. In all cases, the variance in OMC and MDD values was found to be more pronounced with the GS than with the RS. This is probably due to the behavior of the GS, which presents a different chemico-mineralogical composition as compared to that of the RS.

Table 6. A summary of compaction characteristics' values of both unstabilized and stabilized clayey soil samples with and without sulfates

Mixture	Compaction Characteristics OMC (%) & MDD (kN/m^3)				Mixture	Compaction Characteristics OMC (%) & MDD (kN/m^3)			
	GS		RS			GS		RS	
	OMC	MDD	OMC	MDD		OMC	MDD	OMC	MDD
P0L0	28.30	13.80	15.30	16.90	P10L4C6	33.65	11.90	34.33	15.52
P0L4	30.40	13.20	17.81	16.40	P20L4C6	36.40	12.23	27.32	15.33
P0L8	31.10	12.90	17.39	16.20	P10L8C6	36.91	11.93	26.20	15.17
P10L0	27.61	14.00	14.30	17.12	P20L8C6	35.63	12.10	27.25	15.00
P20L0	25.80	14.30	13.80	17.10	P0L0N2	28.40	13.75	15.25	16.96
P10L4	26.82	13.30	16.61	16.51	P0L4N2	32.30	13.02	20.10	15.95
P20L4	29.00	13.58	18.70	16.39	P0L8N2	33.10	12.70	20.87	15.70
P10L8	29.81	13.30	17.72	16.10	P10L0N2	31.10	13.92	14.35	17.20
P20L8	28.20	13.61	18.20	16.00	P20L0N2	28.50	14.21	13.71	17.25
P0L0C2	30.15	13.63	17.24	16.19	P10L4N2	28.20	13.00	20.70	16.27
P0L4C2	33.20	12.70	20.15	15.60	P20L4N2	31.10	13.32	22.80	16.20
P0L8C2	34.53	12.51	21.20	15.31	P10L8N2	32.05	13.02	21.04	15.87
P10L0C2	29.15	13.87	16.32	16.30	P20L8N2	30.41	13.35	22.36	15.80
P20L0C2	28.35	14.00	15.85	16.50	P0L0N4	28.23	13.81	15.35	16.93
P10L4C2	31.50	12.85	22.50	16.12	P0L4N4	33.10	12.63	20.85	15.40
P20L4C2	33.10	13.20	24.90	16.00	P0L8N4	34.15	12.30	21.53	15.13
P10L8C2	34.10	12.90	23.70	15.75	P10L0N4	31.50	14.08	14.45	17.24
P20L8C2	32.71	13.15	24.31	15.60	P20L0N4	29.07	14.41	13.90	17.30
P0L0C4	32.10	13.17	19.10	15.30	P10L4N4	30.00	12.75	22.20	15.97
P0L4C4	34.25	12.40	22.10	15.23	P20L4N4	32.90	13.05	24.15	15.95
P0L8C4	35.71	12.00	23.40	14.93	P10L8N4	33.72	12.70	22.50	15.60
P10L0C4	31.20	12.35	18.15	15.95	P20L8N4	32.10	13.00	23.91	15.50
P20L0C4	30.51	13.61	17.40	16.10	P0L0N6	28.50	13.95	15.40	16.87
P10L4C4	32.70	12.10	33.70	15.80	P0L4N6	35.25	12.35	22.70	15.12
P20L4C4	35.10	12.45	26.70	15.65	P0L8N6	35.90	12.08	23.54	14.83
P10L8C4	35.60	12.10	25.60	15.45	P10L0N6	32.05	14.02	14.50	17.15
P20L8C4	34.45	12.36	26.35	15.33	P20L0N6	29.30	14.32	14.03	17.19
P0L0C6	34.50	12.71	21.65	14.91	P10L4N6	31.60	12.43	23.15	15.62
P0L4C6	35.85	12.05	24.22	14.90	P20L4N6	34.50	12.70	25.20	15.67
P0L8C6	37.33	11.70	25.00	14.39	P10L8N6	35.00	12.35	23.40	15.32
P10L0C6	32.50	12.00	20.20	15.05	P20L8N6	33.60	12.60	24.81	15.25
P20L0C6	31.90	13.07	19.10	15.70					

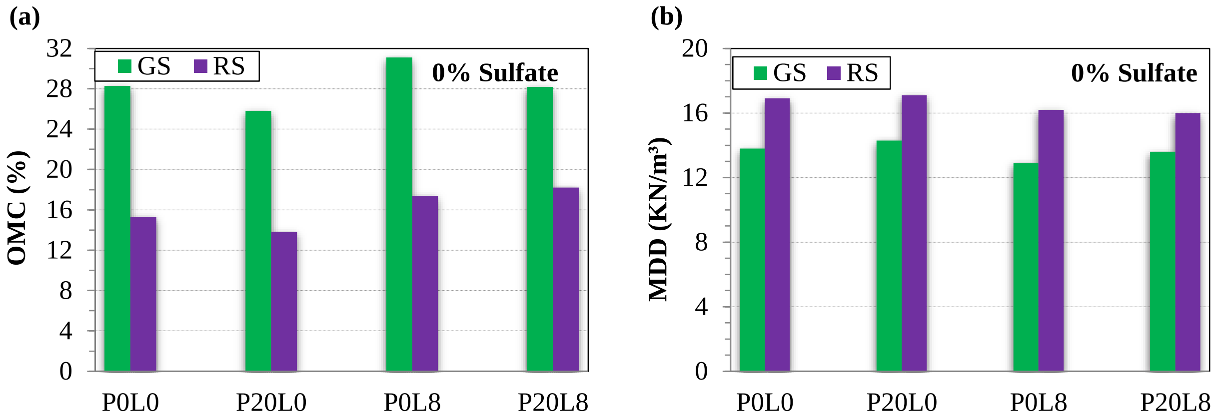

Figure (2): Effect of 8%L, 20%NP and their combination (8%L+20%NP) on compaction characteristics of both clayey soil samples (a) OMC and (b) MDD

Effect of Sulfates on the Compaction Properties of Unstabilized Clayey Soils

Table 7 presents the results of both OMC and MDD variations of the unstabilized clayey soils assessed under different sulfate contents. The two unstabilized clayey soils showed a negligible change in OMC and MDD values upon the addition of various sodium-sulfate contents. It is obvious to observe that sodium sulfate has a negligible influence on the OMC and MDD of both control soils. In contrast, for both clayey soils, the OMC considerably increased with increasing calcium-sulfate content, but the MDD decreased with its increase. According to Aldaood et al. (2014a), the reduction in the MDD value is due to the lower density value of calcium-sulfate particles as compared with those of both clayey-soil particles. However, the increase in the OMC value with added calcium sulfates can be explained by the large specific surface area of calcium sulfates which has the capacity to absorb a large amount of water as compared with that of both clayey soil particles.

Table 7. Changes in the compaction characteristics' values of the unstabilized clayey soil samples performed with and without sulfates

Sulfate Type	Soil Type	Mixture	Compaction Characteristics	
			OMC (%)	MDD (KN/m^3)
Without sulfate	GS	P0L0	28.30	13.80
	RS	P0L0	15.30	16.90
Sodium sulfate (Na_2SO_4)	GS	P0L0N2	28.40	13.75
		P0L0N4	28.23	13.81
		P0L0N6	28.50	13.95
	RS	P0L0N2	15.25	16.96
		P0L0N4	15.35	16.93
		P0L0N6	15.40	16.87
Calcium sulfate ($CaSO_4 \cdot 2H_2O$)	GS	P0L0C2	30.15	13.63
		P0L0C4	32.10	13.17
		P0L0C6	34.50	12.71
	RS	P0L0C2	17.24	16.19
		P0L0C4	19.10	15.30
		P0L0C6	21.65	14.91

Effect of Sulfates on the Compaction Properties of Stabilized Clayey Soils

Figures 3 and 4 illustrate the results of the effects of sodium and calcium sulfates on the compaction characteristics of soil-lime, soil-NP and soil-lime-NP mixtures. With 20%NP used as an additive, the OMC of both clayey soils considerably increased with increasing both sodium-and calcium-sulfate contents except for the case of the RS containing sodium sulfates. However, with the same additive (20%NP), the MDD of both clayey soils significantly decreased with increasing sodium -and calcium-sulfate contents, but the MDD of the RS remained constant. In all cases, the variance (increases and decreases) of compaction characteristics of the soil-NP mixture was found to be more pronounced with calcium sulfates than with sodium sulfates. Kinuthia et al. (1999) reported that the presence of sodium sulfates has a slight effect on both the OMC and MDD of lime-treated kaolinite as compared to that found in the presence of calcium sulfates.

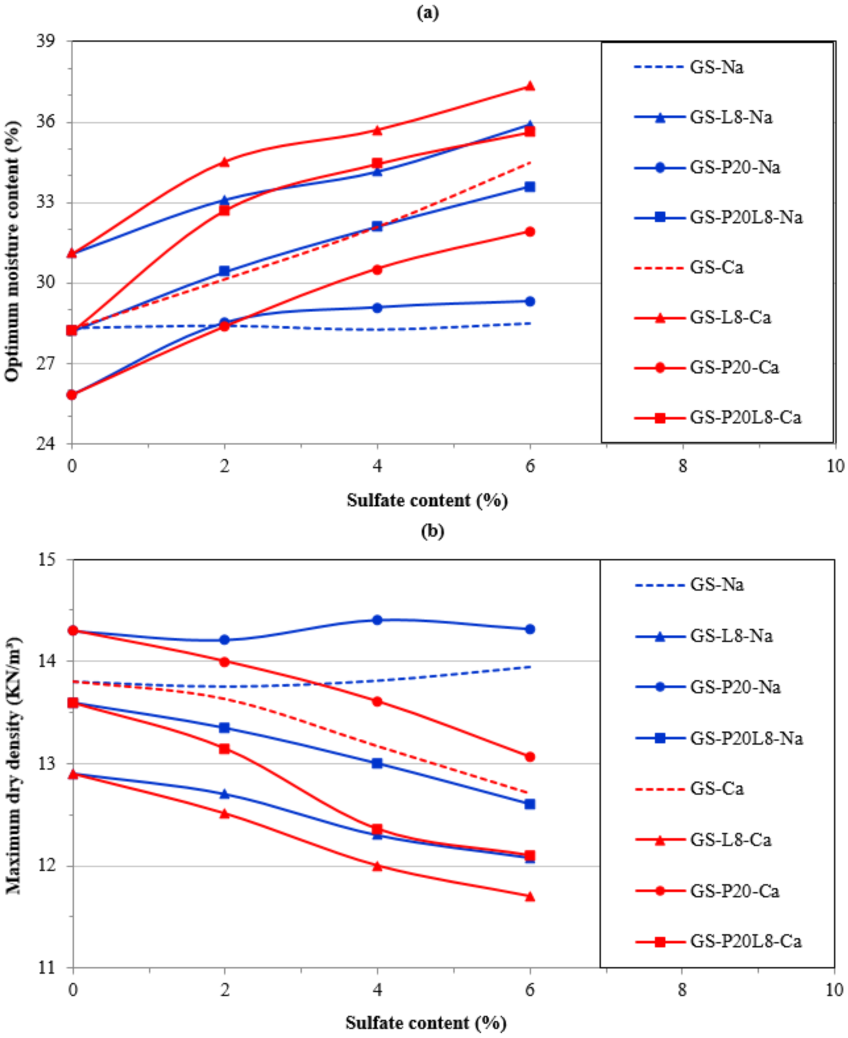

Figure (3): Effect of different sodium -and calcium-sulfate contents on compaction characteristics of GS stabilized with 8%L, 20%NP and their combination (8%L+20%NP) (a) OMC and (b) MDD

Furthermore, in the case of soil-lime and soil-lime-NP mixtures, there is a decrease in MDD and an increase in OMC values with sodium- and calcium-sulfate addition. Similarly, Vipulanandan and Mohammed (2015) have found that the OMC of a low plastic soil increased from 17% up to 21% when the calcium-sulfate concentration was increased from 0% up to 4%, whereas the MDD decreased from 15.2 kN/m^3 to 14.4 kN/m^3 and this behavior could be attributed to the changes observed in the soil mineralogy. On the other hand, this behavior can be explained by the tendency of lime to absorb more water content in order to complete its hydration, consequently leading to an increase in the OMC value, as reported by Aldaood et al. (2014a). In addition, Di-Sante et al. (2015) have reported that the reduction in the MDD of the lime-stabilized highly expansive clayey soil is attributed to the formation of coarser aggregates due to the pozzolanic reactions, which already occurred during the mellowing period. In fact, these coarser aggregates show higher resistance to compaction and hence produce larger macropores and thus, the stabilized soil becomes less dense as compared to the untreated soil. For both clayey soils, the sensitivity of both OMC and MDD to the sulfate effect was found to be more pronounced with calcium sulfates than with sodium sulfates. In addition, it was also found to be more pronounced with calcium-sulfate content than with sodium-sulfate content. This behavior confirms that the sensitivity of the amorphous silica (SiO_2 from soil and/or NP) to the effect of cation type was more pronounced with the divalent cations (Ca^{2+}) than with the monovalent ones (Na^+).

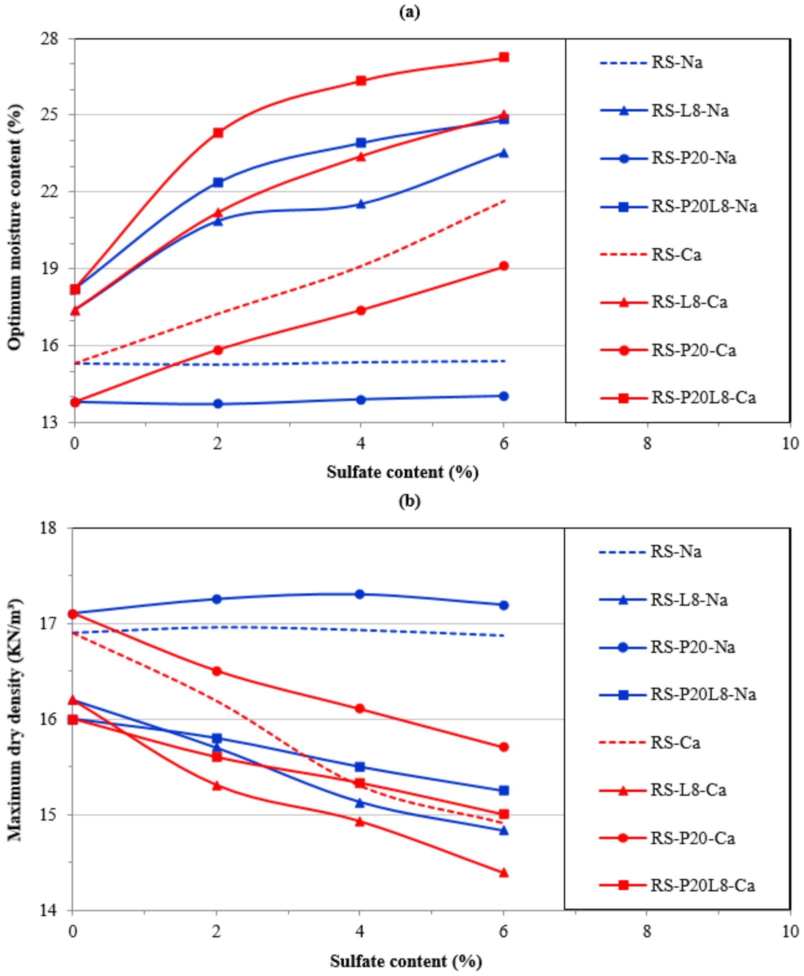

Figure (4): Effect of different sodium -and calcium-sulfate contents on compaction characteristics of RS stabilized with 8%L, 20%NP and their combination (8%L+20%NP) (a) OMC and (b) MDD

For GS, the sensitivity of the OMC to the sulfate effect was found to be more pronounced with the 8%lime added alone than with the combined treatment of 8%lime+20%NP. This is because the use of lime in the presence of calcium sulfates was found to have a high tendency to absorb a large amount of water as compared to the use of lime alone due to its high specific surface area. In contrast, in the case of RS, the sensitivity of the OMC to the sulfate effect was found to have a converse behavior as compared to that of GS. This is probably due to the behavior of RS with its low plasticity index, which leads to the low cation-exchange capacity and consequently to a slight water absorption. In fact, Kinuthia et al. (1999) have reported that the divalent sulfate metals (calcium and magnesium sulfates) raised the OMC and lowered the MDD by a larger magnitude as compared to those containing monovalent cations (sodium and potassium sulfates).

Effect of Lime and NP on the Swell Potential

Figure 5 shows the modifications in swell-potential values caused by adding 8%L, 20%NP and their combination (8%L+20%NP). This figure indicates that both unstabilized GS and RS samples developed swell-potential values of 7.11% and 2.7% after curing for 1 day, respectively, but they became 7.33% and 2.79% after a 30-day curing period, respectively. A little change was observed in swell-potential values when using NP alone as an additive for stabilizing the two clayey soils. A similar trend was observed by Al-Rawas et al. (2005), where they found that the swell potential of an expansive soil decreased from 9.39% to 6.1% and 6%, respectively, with the addition of 6% and 12% artificial pozzolan (known as Sarooj). However, it is quite clear to observe that the addition of 8% lime into GS and RS results in a reduction of the swell potential, especially when combining 8% lime and 20%NP. A similar behavior was observed by Al-Rawas et al. (2005), where they found that the swell potential of an expansive soil decreased from 9.39% to 2.7% and 0%, respectively with the addition of 3% and 9% artificial pozzolan. Indeed, there is a considerable decrease in the swell-potential values when lime is added alone as compared to that of unstabilized clayey soils. In addition, for both clayey soils, the decrease in the swell-potential values was found to be more important when using the combination of 8% lime and 20%NP, especially after a longer curing period (120 days). For example, after a 1-day curing period, the swell potential of the GS samples decreased from 7.11% to 6.11% and 4.29%, respectively with the addition of 8%L and 8%L+20%NP. For the same soil sample cured for 120 days, a further decrease in swell-potential values was recorded (from 7.33% to 4.81 and 3.10% respectively, with the addition of 8%L and 8%L+20%NP) (Figure 5 (b)). This can be explained by the formation of new mineral phases during the pozzolanic reactions caused by the addition of 8% lime alone or mixed with 20%NP, as shown in Figures 5 and 6. These two figures present the XRD patterns of both GS and RS samples stabilized with 8%L, 20%NP and 8%L+20%NP after curing for 60 days in the presence of 4% sodium and calcium sulfates. It is obvious to observe that before stabilization, the XRD analysis showed that the main components of GS are quartz, montmorillonite, illite, kaolinite and calcite clay minerals, while calcite is the predominant clay mineral (Fig. 6 (j)). However, illite, kaolinite and quartz (predominant) clay minerals are the main components of RS (Fig. 7 (j)). When adding 8% lime alone or in combination with 20%NP into the GS and RS samples, the XRD analysis showed the formation of calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) compounds, which are responsible for the changes observed in their mineralogical composition and consequently, a reduction in their swell potential was observed (Figs. 6 (g, h) and 7 (g, h)). However, with 20%NP added alone (as a stabilizer) to both clayey soils, the formation of cementitious compounds (C–S–H and C–A–H) was not revealed by XRD patterns (Figs. 6 (i) and 7 (i)). This can be explained by the low pH developed by adding NP, which can’t react with the clay minerals in the absence of lime or other pozzolanic reaction activators (Gadouri el al., 2019a). In addition, the decrease in the swell-potential values was found to be more pronounced with GS than with RS. This is probably due to the behavior of GS, which presents a different chemico-mineralogical composition as compared to that of RS (Gadouri el al., 2019a). In general, the above results indicate that adding lime alone or in combination with NP acts as a very good stabilizing agent, which is valuable in reducing the swell potential of the two clayey soils.

Effect of Sulfates on the Swell Potential of Unstabilized Clayey Soils

The results of the swell-potential variation of both unstabilized clayey soils assessed under different sulfate contents are depicted in Table 8. It is quite clear to see that both unstabilized clayey soils showed a negligible change in swell-potential values upon the addition of any sodium-sulfate content. In contrast, for both clayey soils, the swell potential was found to decrease considerably with increasing calcium-sulfate content, especially with increasing the curing period. These results are in accordance with those obtained by Aldaood et al. (2014a), where they have found that after curing for only 2 days, the swell potential of the gypseous soil decreased from 0.95% to 0.5, 0.3 and 0.2%, respectively, with the addition of 5%, 15% and 25% of gypsum. The same investigators have recorded that the decrease in swell-potential values of the soil samples can be explained by the addition of gypsum (known as a non-expansive material) and the reduction of the clay content in the soil matrix. In addition, a similar trend was reported by Yilmaz and Civelekoglu (2009), where they found that the decrease in the swell-potential value of the bentonite soil was found to be much higher when the addition of gypsum was larger and the reduction in the swell-potential value was found to reach almost 70% for soil samples containing 25% of gypsum.

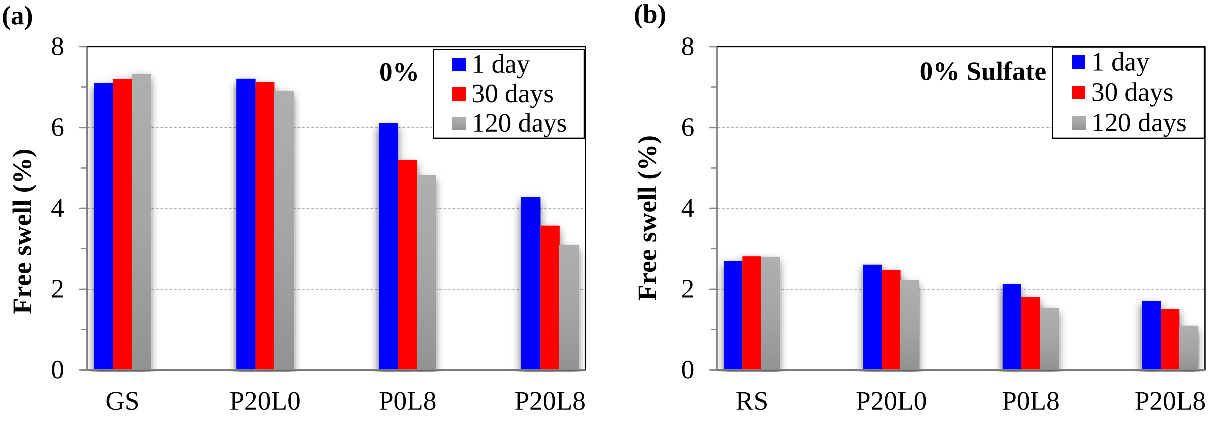

Figure (5): Effect of 8%L, 20%NP and their combination (8%L+20%NP) on the swell potentials of both clayey-soil samples (a) GS and (b) RS

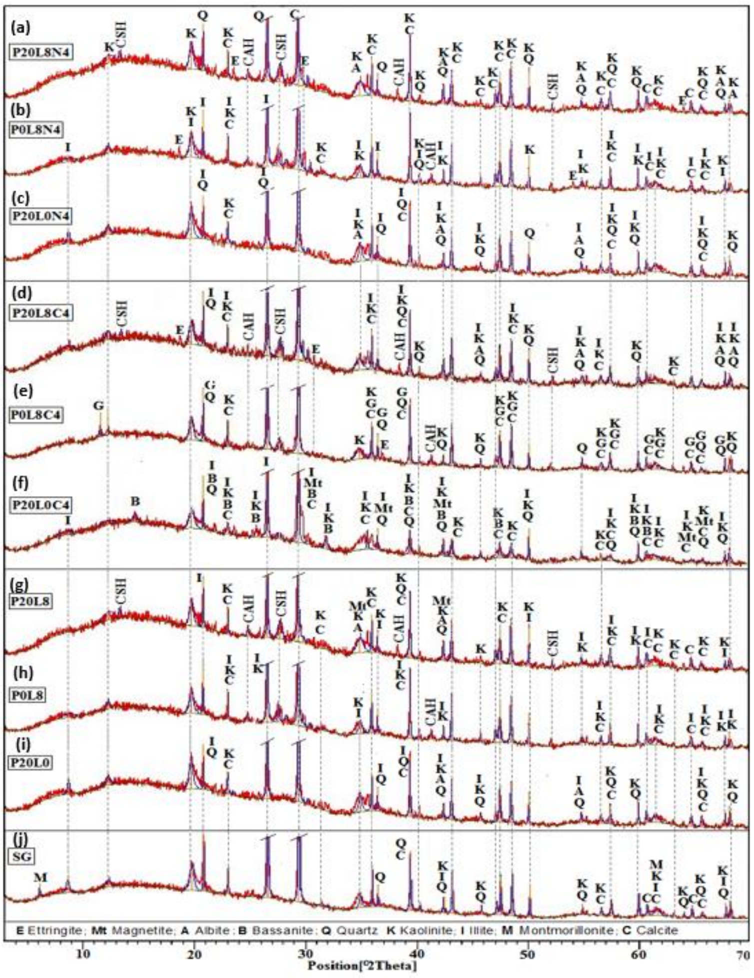

Figure (6): XRD patterns of GS samples stabilized with 8%L, 20%NP and 8%L+20%NP in the presence of 4% of Na_2SO_4 and $CaSO_4 \cdot 2H_2O$ after a 60-day curing period

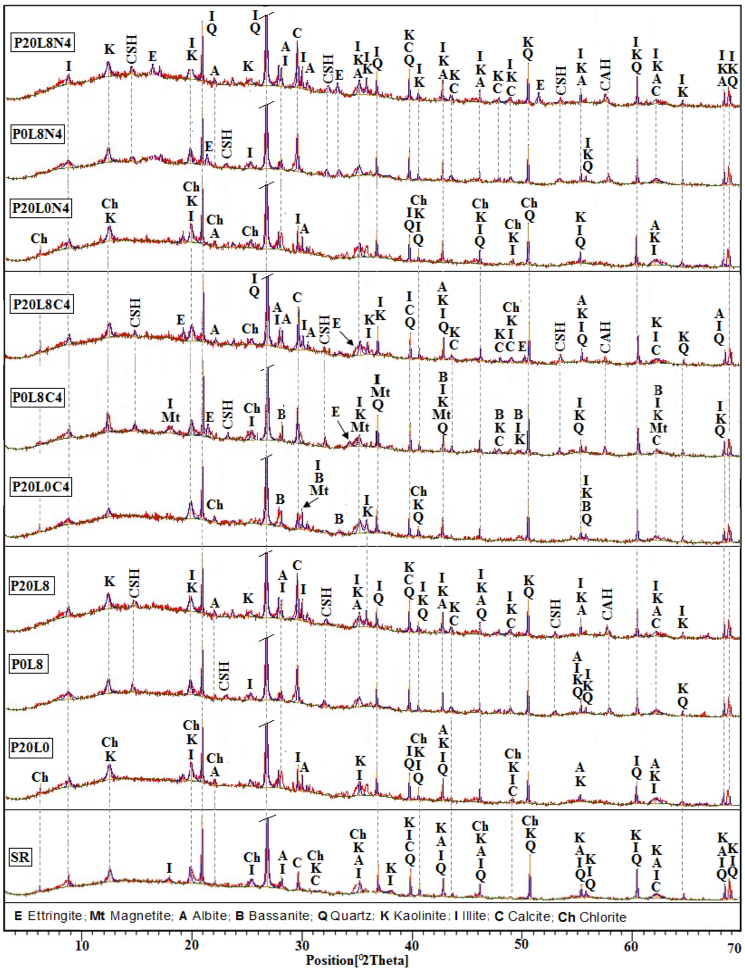

Figure (7): XRD patterns of RS samples stabilized with 8%L, 20%NP and 8%L+20%NP in the presence of 4% of Na_2SO_4 and $CaSO_4·2H_2O$ after a 60-day curing period

Table 8. Changes in the swell-potential values of the unstabilized clayey-soil samples tested with and without sulfates at different curing periods

Sulfate Type	Soil Type	Mixture	Swell Potential (%)		
			1 day	30 days	120 days
Without sulfates	GS	P0L0	7.11	7.20	7.33
	RS	P0L0	2.70	2.81	2.79
Sodium sulfates (Na_2SO_4)	GS	P0L0N2	7.05	7.15	7.25
		P0L0N4	7.11	7.20	7.30
		P0L0N6	7.13	7.22	7.37
	RS	P0L0N2	2.70	2.81	2.79
		P0L0N4	2.68	2.85	2.81
		P0L0N6	2.73	2.83	2.79
Calcium sulfates ($CaSO_4·2H_2O$)	GS	P0L0C2	6.70	6.23	6.11
		P0L0C4	6.51	6.00	5.63
		P0L0C6	6.21	5.70	5.15
	RS	P0L0C2	2.61	2.40	2.31
		P0L0C4	2.40	2.25	2.10
		P0L0C6	2.23	2.11	2.01

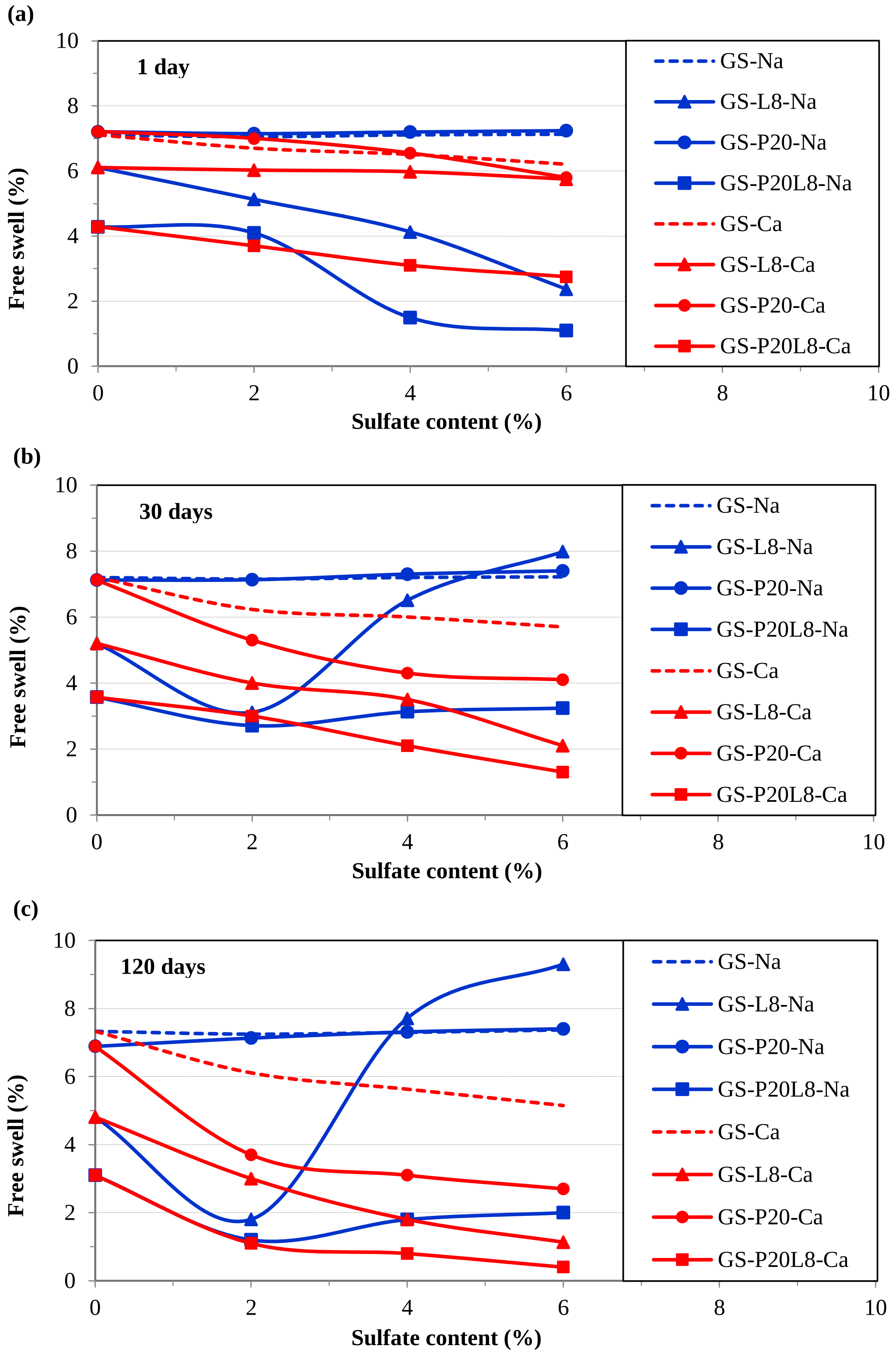

Figure (8): Effect of different sodium-and calcium-sulfate contents on the swell potential of GS samples stabilized with 8%L, 20%NP and their combination (8%L+20%NP) at different curing periods (a) 1 day (b) 7 days and (c) 120 days

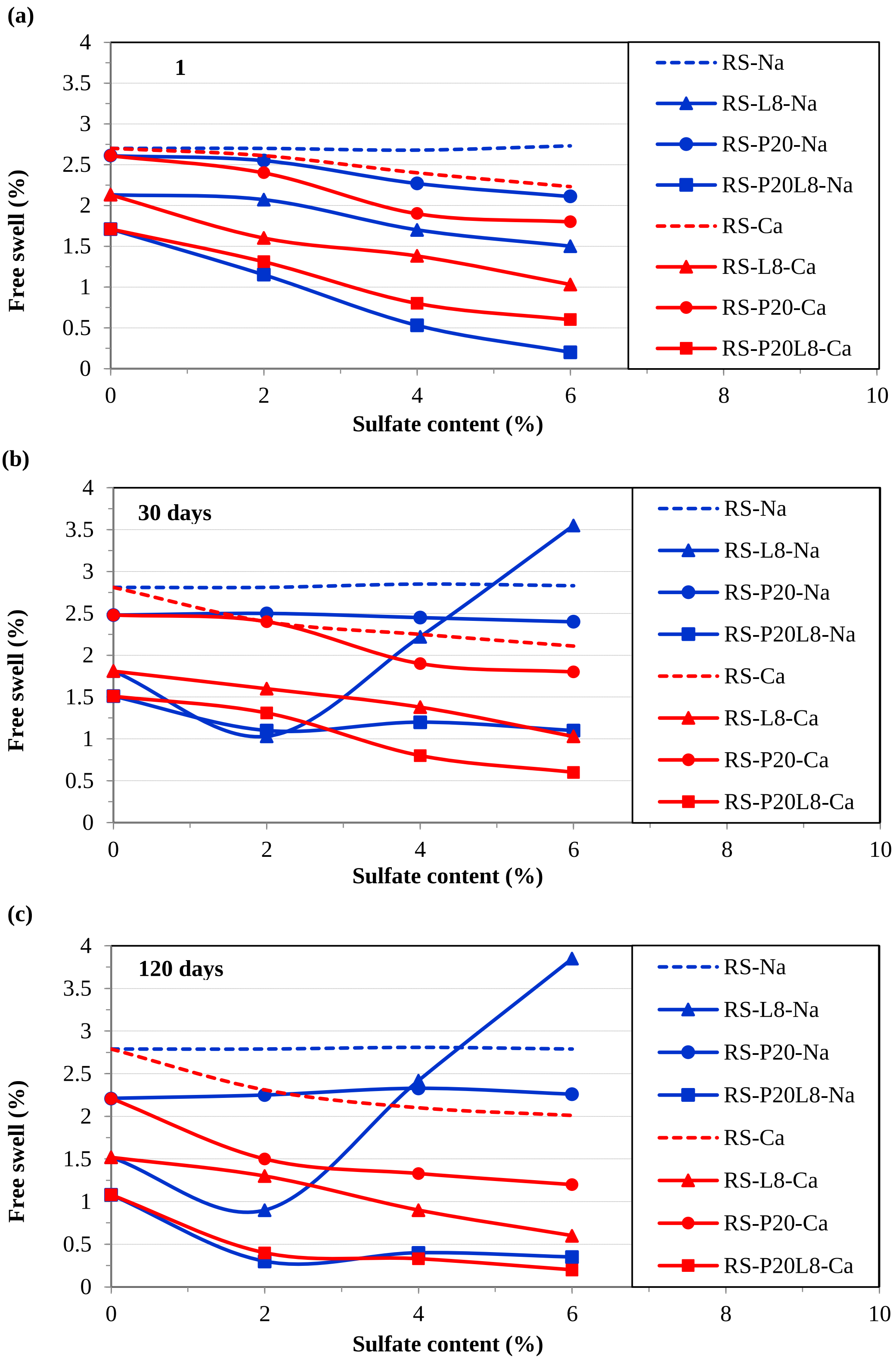

Figure (9): Effect of different sodium-and calcium-sulfate contents on the swell potential of RS samples stabilized with 8%L, 20%NP and their combination (8%L+20%NP) at different curing periods (a) 1 day (b) 7 days and (c) 120 days

Effect of Sulfates on the Swell-potential of Stabilized Clayey Soils

The results of the swell-potential variation of both stabilized clayey soils assessed under different sulfate contents at different curing periods are shown in Figures 8 and 9. In the case of the presence of calcium sulfates at any curing period, test results indicated that the swell potential of both GS and RS samples stabilized with 8%L, 20%NP and the combination 8%L+20%NP starts to decrease significantly with increasing both calcium-sulfate content and curing period. Decreasing in swell-potential values was found to be more pronounced with the addition of 8%L+20%NP than with the addition of 8%L or 20%NP alone. As shown in Figs. 6 (d, e) and 7 (d, e), the significant decrease in the swell potential of both clayey soils can be explained by the formation of both primary ettringite (known as a non-expansive mineral) and cementing agents (C–S–H and C–A–H), which strongly bend the clay particles together and consequently reduce their swell potential. According to Gadouri et al. (2019b), the ettringite of primary formation is a product resulting from the chemical reaction between cementing agents (C–A–H and C–S–H) and calcium sulfates due to the pozzolanic reactions between calcium ions (Ca^{2+} from lime hydration) and silica/alumina (from soil and/or NP addition). This type of ettringite mineral doesn't cause swelling, because it was crystallized in the free spaces of the material before hardening. In fact, this crystal has several beneficial effects on the stabilized soil by decreasing its porosity and permeability and increasing its strength and consequently; that reduction of its swell potential can be observed.

In the case of the presence of sodium sulfates at any curing period, it can be seen that the sodium sulfates added with any content presented a marginal effect on the swell potential of both NP-stabilized clayey soils. However, for a shorter curing period (1 day) (Figs. 8 (a) and 10 (a)), the presence of sodium sulfates in the GS and RS samples stabilized with 8%L, 20%NP and the combination 8%L+20%N had a similar effect as that of calcium sulfates, where the swell potential started to decrease considerably when sodium-sulfate content increased. In addition, the sensitivity of the swell potential to the sulfate effect was found to be more pronounced with the presence of sodium sulfates than with the presence of calcium sulfates. On the other hand, as shown in Figs. 8 (c-d) and 9 (c-d), for 30-and 120-day curing periods, the swell potential of both lime-stabilized clayey soil samples considerably decreased to 2% with sodium sulfates, but then significantly increased beyond this value. According to Celik and Nalbantoglu (2013), the significant increase in the swell potential of the lime-stabilized soils with different sulfate concentrations can be explained by the formation of the ettringite mineral, which is highly expansive. The reactions between calcium from lime, reactive alumina in soil and sulfate ions (SO_4^{-2}) in the soil solution formed the ettringite minerals, which caused an increase in the swelling of the lime-stabilized soil. On the other hand, the high swelling can be attributed to the optimum compaction moisture content and low seating pressure applied during the swell tests (Puppala et al., 2005). Furthermore, the same behavior was observed when using 8%L+20%NP, because the swell potential was found to decrease significantly to 2% with sodium sulfates, but then marginally increased beyond this value. It should be noted that when 20%NP was added into both lime-stabilized clayey soils at different sodium-sulfate contents, instead of an increase in the swell potential, a negligible increase was obtained. This behavior indicates that, in the presence of 20%NP, the adverse effect of sodium sulfates on both lime-stabilized clayey soils was suppressed and the swelling of both lime-stabilized clayey soils was prevented. For example, in the presence of 20%NP, the swell potential of the lime-stabilized GS on curing with 6% sodium sulfates decreased from 7.98% to 3.24% and from 9.3% to 2%, respectively, after curing for 30 and 120 days. Thus, in the case of lime-stabilized RS with the same sodium-sulfate content, the swell potential was found to decrease from 3.55% to 1.1% and from 3.85% to 0.35%, respectively, with 30- and 120-day curing periods.

As shown in Figs. 6 (a, b) and 7 (a, b), the significant decrease in the swell potential of both clayey soil samples containing 2% sodium sulfates can be explained by the formation of high contents of cementing agents (C–S–H and C–A–H) due to the high pH value from NaOH as compared to the pH value from $Ca(OH)_2$ (the detailed role of pH is given below). However, the significant increase in the swell potential of both lime-stabilized clayey soils containing 4% and 6% sodium-sulfate contents can be attributed to the formation of the ettringite of secondary formation, which is highly expansive. The ettringite of secondary formation is a product resulting from the chemical reaction between cementing agents (C–A–H and C–S–H) and sodium sulfates. However, this crystal generates a higher internal swelling, which is mainly attributed to the crystallization pressures, increasing the porosity of the soil (consequently the permeability), decreasing the free-water content during ettringite nucleation, absorbing a lot of water molecules (consequently producing a high expansion), improving the compressive strength at an early stage (densifying the structure), but deteriorating the specimens at a later stage (Gadouri et al., 2019b).

Effects of Additives and Sulfates on Compaction Characteristics and Swell Potential

The addition of lime alone or mixed with 20%NP (without sulfates) into the two clayey soils immediately modified their physical properties due to the cation-exchange process. Electrically, the external surface of the clay particles is negatively charged, which develops high repulsive forces between them. With the introduction of lime into the soil environment, $Ca\,(OH)_2$ is dissolved in water and Ca^{2+} and $(OH)^-$ are freed, as shown in Eq. (1). Cation exchange occurs between cations linked to the clay layers and Ca^{2+}; Ca^{2+} becomes the only inter-lamellar cation. Clay particles are surrounded by a diffuse hydrous layer, which is modified by the ion exchange of calcium. This modifies the density of the electrical charge around the clay particles and attracts them closer to each other to form flocks (flocculation). This implies stronger attraction forces between layers and stacking of a greater number of layers (Locat et al., 1990). These reactions change the clay texture, giving thicker particles, reducing plasticity and increasing the soil strength (George et al., 1992; Harichane and Ghrici, 2009; Rahman, 1986; Gadouri et al., 2016). On the other hand, the dissolution of both sodium and calcium sulfates in the presence of water produced calcium and sodium cations, as shown in Eqs. (2) and (3). However, the reaction between sodium sulfates and lime in the presence of water led to the formation of sodium hydroxide, which developed a higher alkaline solution as compared to that developed by calcium hydroxide, as shown in Eq. (4) (Roy, 1986).

$$\mathrm{Ca\,(OH)_2 \rightarrow Ca^{2+} + 2OH^-} \qquad (1)$$

(Ionization of calcium hydroxide in the presence of water)

$$\mathrm{Na_2SO_4 \rightarrow 2Na^+ + SO_4^{2-}} \qquad (2)$$

(Dissolution of sodium sulfates)

$$\mathrm{CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O} \qquad (3)$$

(Dissolution of calcium sulfates)

$$\mathrm{Ca\,(OH)_2 + Na_2SO_4 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O + 2NaOH} \qquad (4)$$

(Formation of sodium hydroxide and pH value rises up to 13)

The incorporation of calcium sulfates into the stabilized GS and RS samples decreased the particle-particle separation as the result of calcium cations' exchange between clay particles and calcium sulfates. However, the presence of sodium sulfates with any content has the tendency to increase the particle-particle separation resulting from sodium cations' exchange between clay particles and sodium sulfates (Gadouri et al., 2019b).

Based on the obtained results, it can be concluded that the rate of sulfate diffusion in the paste of both stabilized clayey soils is not the same. However, the sulfate diffusion was found to depend not only on the size of clay particles and their amounts, the type of clay minerals and the cation-exchange capacity, but also depends on the curing period.

Mechanism of Particle-particle Chemical Adhesion in Soil-lime-NP and Soil-lime-NP-Sulfate Mixtures

The contact of water ($2H_2O$) with the hydrated lime [$Ca\,(OH)_2$] increased the pH value of the solution (Eq. (1)). The acceleration of pozzolanic reactions rate leads to the acceleration of NP dissolution, which forms monosilicate [$SiO\,(OH)_3$]$^-$ and aluminate [$Al\,(OH)_4$] compounds. According to Shi and Day (2000), when calcium cations (Ca^{2+}) contact these compounds, the adhesion materials such as calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H) can be formed as follows (Eqs. (5) and (6)):

$$\mathrm{Y[SiO\,(OH)_3]^- + XCa^{2+} + (Z - X - Y)H_2O + (2X - Y)OH^- \rightarrow C_X - S_Y - H_Z} \qquad (5)$$

(Formation of calcium silicate hydrates)

$$2[\mathrm{Al\,(OH)_4}]^- + 4\mathrm{Ca}^{2+} + 6\mathrm{H_2O} + 6\mathrm{OH}^- \rightarrow \mathrm{C_4AH_{13}} \quad (6)$$

(Formation of calcium aluminate hydrates)

The role of these compounds (C–S–H and C–A–H) in the soil-lime-NP mixtures is to produce a layer of stable protective film that envelops the soil particles, bends the soil particles together, seals the voids (by decreasing the void index), reduces the water permeability and improves the compactness of the soil (Gadouri et al., 2016).

Moreover, in the presence of water ($2H_2O$), the reaction between sodium sulfates and soil-lime or soil-lime-NP mixtures leads to the formation of sodium hydroxide (NaOH), which develops a higher alkaline solution as compared with calcium hydroxide [Ca $(OH)_2$]. The high pH value developed by NaOH produced a large amount of silica (SiO_2) and alumina (Al_2O_3), which react with the remaining lime to from high amount of cementitious products responsible for the increase of strength and the decrease of the swell potential at an early stage.

However, as shown in Eqs. (2) and (3), the dissolution of sodium- and calcium- sulfate minerals increased the concentration of sulfate ions (SO_4^{2-}) and then led to the formation of ettringite mineral $[\mathrm{Ca_6Al_2(SO_4)_3(OH)_{12}, 26H_2O}]$, as shown in Eq. (7).

$$6\mathrm{Ca}^{2+} + 2\mathrm{Al(OH)}^{-4} + 6\mathrm{H_2O} + 4\mathrm{OH}^- + 3(\mathrm{SO_4})^{-2} \rightarrow \mathrm{Ca_6Al_2(SO_4)_3(OH)_{12}, 26H_2O} \quad (7)$$

(Formation of ettringite mineral)

At an early stage, the effect of primary ettringite mineral $[\mathrm{Ca_6Al_2(SO_4)_3(OH)_{12}, 26H_2O}]$ on the soil-lime-NP-$CaSO_4{\cdot}2H_2O$ mixture is to absorb a large amount of water molecules, which are responsible for the lower swell potential and the higher increase of dry density. However, after a longer curing period and for the soil-lime mixtures containing 4% and 6% sodium sulfates, the swell potential and the dry density were altered due to the formation of expansive ettringite mineral, which is known as a secondary ettringite mineral (Gadouri et al., 2019b). In addition, the secondary ettringite mineral showed a better effect on both swell potential and dry density when adding sodium sulfates with a low content (2% Na_2SO_4).

CONCLUSIONS

The effect of sodium and calcium sulfates on compaction characteristics and swell potential of two clayey soils was studied. Based on the results of the tests, the following conclusions can be drawn:

- Using NP alone as an additive was found to slightly decrease the OMC and marginally increase the MDD values of both clayey soils. However, a considerable increase was recorded when using lime alone or in combination with NP. This behavior can be explained by the increase in the pore volume of the soil-lime mixture due to the agglomeration of clay particles.
- The presence of calcium sulfates in both unstabilized clayey soils considerably increased their OMC and decreased their MDD, but a negligible effect was observed in the presence of sodium sulfates. However, the OMC of all mixtures (soil-lime, soil-NP and soil-lime-NP) considerably increased with increasing sodium- and calcium-sulfate contents, but the MDD significantly decreased as the amount of sodium and calcium sulfates, increased.
- Variations (increases or decreases) in compaction characteristics of all mixtures were found to be more pronounced with calcium sulfates than with sodium sulfates. Thus, the sensitivity of both the OMC and MDD to the sulfate effect was found to be more pronounced with calcium sulfates than with sodium sulfates.
- The addition of calcium sulfates with any content to the GS and RS samples stabilized with 8%L, 20%NP or 8%L+20%NP was found to be very effective in reducing the swell potential, especially after a longer curing period. However, the same effect was recorded in the case of sodium sulfates added with 2% as an optimum value.
- The presence of sodium sulfates with a high content in lime-stabilized GS and RS soil samples resulted in an abnormal increase in their swell potential. However, XRD pattern results showed that the abnormal increase in the swell potential is due to the formation of a new expansive mineral (known as secondary ettringite) from sodium sulfates added. This adverse effect was almost suppressed and swelling was prevented when using the

combination of 8%L and 20%NP.

- It should be noted that the presence of sodium sulfates with high contents (more than 2%) in natural soils or groundwater should be considered and classified as a deleterious element for soil stabilization because of its harmful effect, which can negatively affect the cation-exchange process. For this reason, soil-stabilization success depends strongly on the type of additive used and its amount, the type and content of sulfates, the soil nature and the curing period.

In general, the obtained results point out that the lime-stabilized clayey soils containing a high amount of sodium sulfates may not always be a perfect solution to volume-change problems. Soil stabilization using lime alone can cause the formation of ettringite minerals in soil containing high sodium-sulfate content and consequently increase swelling potential. Therefore, the use of lime as a soil stabilizer in sulfate-bearing soils should be approached with great care. The determination of the sulfate level in the soil will be very important before any field application.

NOTATIONS

GS	Grey Clayey Soil
RS	Red Clayey Soil
CH	Clay of High Plasticity
CL	Clay of Low Plasticity
L	Lime
NP	Natural Pozzolana
Na_2SO_4	Sodium Sulfates (Na)
$CaSO_4 \cdot 2H_2O$	Calcium Sulfates (Ca)
OMC	Optimum Moisture Content
MDD	Maximum Dry Density
UCS	Unconfined Compressive Strength
LL	Liquid Limit
PL	Plastic Limit
PI	Plasticity Index
WBCSD	World Business Council for Sustainable Development
ASTM	American Society for Testing and Materials
USCS	Unified Soil Classification System
GGBFS	Ground Granulated Blast Furnace Slag
C_3A	Cement Tricalcium Aluminate
XRD	X-Ray Diffraction
SM	Soil Mixture
C–S–H	Calcium-Silicate Hydrates
C–A–H	Calcium-Aluminate Hydrates

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Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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