Journal of Engg. Research Vol. 7 No. (2) June 2019 pp. 66-88

Effect of the interaction between calcium sulphate and mineral additives on shear strength parameters of clayey soils

Hamid Gadouri*, Khelifa Harichane** and Mohamed Ghrici**

**Department of Earth Sciences, Faculty of Nature and Life sciences and Earth Sciences, University of Khemis Miliana, Algeria*
**Department of Matter Engineering, Faculty of Sciences and Technology, University of Medea, Algeria*
***Department of Civil Engineering, Faculty of Civil Engineering and Architecture, University of Chlef, BP 151 Hay Salem 02000, Chlef, Algeria*
**Corresponding Author:hamid_gadouri2000@yahoo.fr*

ABSTRACT

In Algeria, inappropriate soils with high plasticity and low bearing capacity are commonly encountered. These soils can be improved using chemical stabilization technique in order to render them acceptable for construction projects. However, various forms of deterioration have been observed in these construction projects due to the presence of sulphates responsible for the formation of new expansive minerals such as mineral ettringite. For this raison, an experimental investigation was undertaken to study the effect of the presence of calcium sulphate ($CaSO_4 \cdot 2H_2O$) on the behavior of the shear strength of two clayey soils stabilized with lime (L; P0L0, P0L4, and P0L8), natural pozzolana (NP; P10L0 and P20L0), and their combination (L-NP; P10L4, P20L4, P10L8, and P20L8). In this study, the mechanical property investigated is the shear strength on samples cured for 7 to 120 days. In addition, X-ray diffraction (XRD) test is also conducted in order to investigate the mineralogical changes of both clayey soils. The results show that both clayey soil samples without $CaSO_4 \cdot 2H_2O$ can be successfully stabilized with L or with a combination of lime-natural pozzolana (L-NP), which substantially increases their shear strength and produces high values of shear parameters. In addition, when combining a fraction of $CaSO_4 \cdot 2H_2O$ (especially with high content) to samples containing L alone or a combination of L-NP, a further increase in shear strength values is obtained and higher shear parameters values are recorded. The increase in strength values in the presence of $CaSO_4 \cdot 2H_2O$ is attributed to the formation of ettringite, which is observed in XRD diagrams. In general, it is shown that the chemical soil stabilization success depends on several factors: the $CaSO_4 \cdot 2H_2O$ content, the type of additive and its content, the curing period, and the mineralogical composition of soil.

Keywords: Calcium sulphate; Clayey soils; Lime (L); Natural pozzolana (NP); Shear strength.

INTRODUCTION

Natural soils containing high proportions of clay minerals (e.g., montmorillonite and illite) are characterised by their high water absorption and retention. These soils are responsible for different problems occurring in various projects. For these reasons, the majority of soils encountered on site are not always suitable to be used as a building material in geotechnical and civil engineering projects as road pavements, earth dams, etc. In addition, civil engineering structures located in areas with inappropriate soils are 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 (Kolias *et al*., 2005). Chemical soil stabilization is a technique that requires the use of hydraulic binders alone or in combination with other mineral additives as fly ash, silica fume, ground granulated blast furnace slag, etc. Extensive studies have been carried out to investigate the different effects produced by the use of cement and/or L (Afès and Didier, 2000; Le Borgne, 2010; Asgari *et al*., 2015), rice husk ash (Rahman, 1986; Basha *et al*., 2003; Choobbasti *et al*., 2010), and fly ash (Goswami and Singh, 2005; Hossain *et al*., 2007) on the physico-mechanical properties of soils.

The bad soils have long been ignored in favor of their quality with technical difficulties and construction. According to the geology of Algeria, unsuitable soils with high plasticity and low bearing capacity are frequently encountered. These soils can be improved using chemical stabilization technique in order to render them acceptable for construction. In Algeria, the chemical soil stabilization technique using cement alone or in combination with L is largely used in the road construction field. e.g., the majority of the soils used as a building material in the East-West highway project (the soils were obtained from Northern territory of Algeria) have been improved using cement and/or L in order to make them able to carry the traffic loads. However, undesirable deteriorations in forms of cracks and swelling have been observed in the East-West highway. According to the literature, the various forms of degradation observed in the road pavements are usually related to the formation of new expansive phrases such as ettringite and/or thaumasite due to the presence of sulphate ions (Baryla *et al*., 2000). Indeed, the sulphate ions react with calcium, hydroxyl, and aluminium compounds from cement and/or L to form these expansive phases. Furthermore, the magnitude of damage caused by the ettringite depends on the type of additive and its content and the soil nature (Le Borgne, 2010), and the type of cation associated to the sulphate ions and its concentration (Kinuthia *et al*., 1999). Moreover, the effects caused by the presence of different types of sulphates on the geotechnical properties of soils stabilized with various types of additives have been investigated by several researchers (Kinuthia *et al*., 1999; Hunter, 1988; Sivapullaiah *et al*., 2000, 2006; Segui *et al*., 2013; Puppala *et al*., 2014; Aldaood *et al*., 2014a, b). Indeed, Yilmaz *et al*. (2009) and Aldaood *et al*. (2014a) confirmed that the use of gypsum as an additive produces much better effects on the physico-mechanical properties of treated soil.

On the other hand, it is known that the cement production requires large amounts of energy and produces a number of disagreeable products, which adversely affect the environment. In order to decrease both CO_2 emission and energy consumption, several researchers recommended the use of other mineral additives such as volcanic ash (Hossain *et al*., 2007), NP (Harichane *et al*., 2010). These natural materials have been used in soil stabilization as additives because of their advantageous properties and economic benefits. Hossain *et al*. (2007) reported that the combination of volcanic materials with L produces a better effect on the physico-mechanical behavior of the treated soil. In addition, it has been reported that, for longer curing period, the shear strength and UCS values of two clayey soil samples stabilized with the combination of 20% NP and 8% L are very large than those of the untreated soils (Harichane *et al*., 2011a). Furthermore, the NP is found in abundance in areas of Beni-Saf located in the West of Algeria (Ghrici *et al*., 2007). However, no investigation has been done to assess the effect of the interaction between L-NP additions and sulphates on the geotechnical properties of clayey soils. Also, influence of using L and NP in the presence of sulphates on the physico-mechanical properties is not well documented in the literature.

Indeed, sulphates are present with a soluble form in the groundwater (SO_4^{-2} ions) and with a solid form in sedimentary grounds (gypsum, $CaSO_4 \cdot 2H_2O$; epsomite, $MgSO_4 \cdot 7H_2O$; arcanite, K_2SO_4 and thenardite, $Na_2SO_4 \cdot 10H_2O$) (Rajasekaran, 2005). In addition, after a series of chemical reactions, the pyrite (FeS_2) can give birth to a formation of gypsum in the presence of certain conditions (Floyd *et al*., 2003). However, the presence of certain types of sulphates in the soil affects greatly the stabilization process by changing the cation exchange process and pozzolanic reactions (Hunter, 1988). The effect of NP, L, and L-NP on the geotechnical properties (shear strength, Atterberg limits and UCS) of cohesive soils has been studied (Harichane *et al*., 2010; 2011a, 2011b, 2011c; 2012). However, the effect of the presence of sulphates on these geotechnical properties has not been investigated.

The soil shear strength is a main factor for any analysis related with stability including slope stability analysis (Sadrjamali *et al*., 2015). The aim of this paper is to study the effect of calcium sulphate (gypsum, $CaSO_4 \cdot 2H_2O$) on the shear strength parameters of both grey and red clayey soils using L, NP, and the combination of both. Direct shear test has been selected due to its simplicity and has been used for obtaining shear strength parameters as well as Mohr-Coulomb theory that has been used for calculating them.

MATERIALS EXTRACTION AND IDENTIFICATION

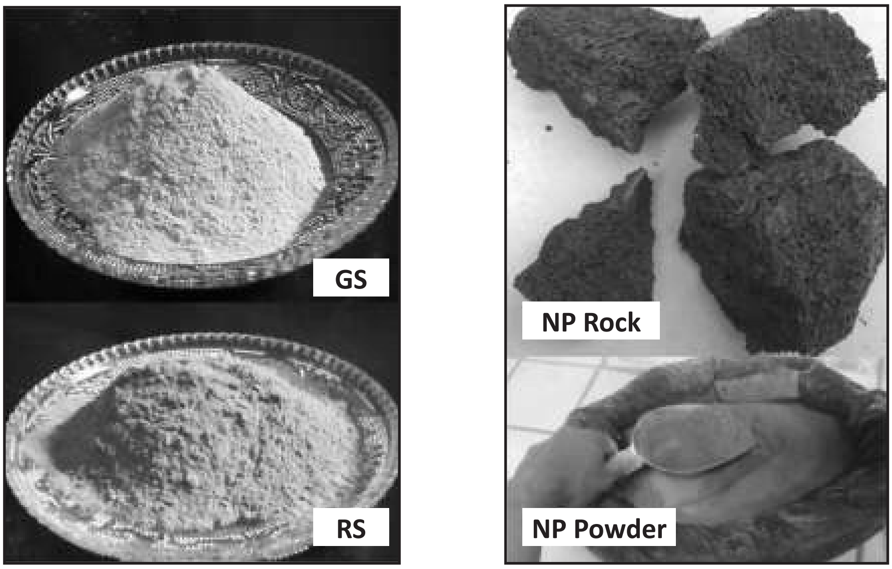
Extraction of soils and natural pozzolana

In the present study, two clayey soils were obtained from Chelif town located in the West of Algeria. The grey clayey soil (GS) and red clayey soil (RS) were obtained from an embankment project site and a highway project site, respectively. However, the natural pozzolana (NP) was used as an additive in order to improve the mechanical properties of these clayey soils. The NP was obtained from Beni-Saf deposit located in the Western of Algeria. Furthermore, the GS, RS, and NP were extracted and transported to the laboratory for preparation and testing.

Identification

Soils (GS and RS)

Laboratory tests were carried out for the characterization and classification of both clayey soils (Fig. 1(a)). However, the physico-mechanical and chemico-mineralogical properties of these clayey soils are depicted in Tables 1 and 2, respectively.



(a) Clayey soils sieved to 1mm sieve **(b)** Natural pozzolana

(c) Hydrated lime **(d)** Calcium sulphate dihydrate

Fig. 1. Materials used and their preparation.

Table 1. Physico-mechanical properties of both clayey soils (After Harichane *et al*. 2011a).

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 (γd_{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	$NaAlSi_3O_8$	-	8.00
Illite	$2K_2O.Al_2O_3.24SiO_2.2H_2O$	16.00	24.00
Kaolinite	$Al_2Si_2O_5(OH)_4$	12.00	16.00
Montmorillonite	$Al_2((Si_4Al)O_{10})(OH)_2.H_2O$	20.00	-
Chlorite	$Mg_2Al_4O_{18}Si_3$	-	9.00
Ferruginous minerals	-	6.00	7.00
Organic matter	-	0.33	-

Natural Pozzolana (NP)

The NP was ground using the Micro-Deval apparatus for 18 hours of time in order to obtain a specific surface area of 420 m^2/kg, which was verified according to ASTM C204-07 (2007) (Fig. 1(b)). The physico-chemical properties of this additive are depicted in Table 3.

Hydrated Lime (L)

The lime (L) used in this study is commercially available hydrated lime typically used for construction purposes (Fig. 1(c)). The physico-chemical properties of this additive are depicted in Table 3.

Table 3. Physico-chemical properties of lime and natural pozzolana (After Harichane *et al*. 2011a).

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	-

Calcium Sulphate Dihydrate ($CaSO_4·2H_2O$)

The chemical compound used in this study is a calcium sulphate dihydrate ($CaSO_4·2H_2O$). The $CaSO_4·2H_2O$ is made by Biochem Chemopharma located in France (Cosne-sur-Loire, 58200 France), which is a leading international Manufacturer and Supplier of Laboratory Reagents (Fig. 1(d)). The physico-chemical properties of this element are shown in Table 4.

Experimental programme

Laboratory tests of shear strength were conducted on both selected clayey soils. Several combinations of NP and L were used for their stabilization. These combinations were mixed with different content of $CaSO_4·2H_2O$ (0-6% by dry weight of soil). A total of 72 combinations based on GS and RS are shown in Table 5.

Table 4. Physico-chemical properties of calcium sulphate.

Physico-chemical properties	**Calcium sulphate**
Color	White
Chemical formula	$CaSO_4 \cdot 2H_2O$
Molar weight (g/mol)	172.17
Auuay (dried), (%)	99.0
Insoluble matter (%)	0.025
Chloride (Cl, %)	0.002
Nitrate (NO3, %)	0.002
Ammonium (NH4, %)	0.005
Carbonate (CO3, %)	0.05
Heavy metals (Pb, %)	0.001

.

Table 5. Combinations of both clayey soils studied.

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

Samples preparation

Soil–L, soil–NP and soil–L–NP mixtures

The air dried soils were initially mixed with the predetermined quantity of NP (0, 10, and 20%), L (0, 4, and 8%), and L-NP in a dry state. The calculated water was added to the soil mixture (Fig. 2(a)). The samples are preserved in the airtight container for about one hour of curing prior to the preparation of specimens by static compaction using a static press (Fig. 2(b)). Indeed, the obtained specimens were prepared by compaction at the maximum dry unit weight and optimum moisture content deduced of compaction tests (Fig. 2(c)). The specimens were stored in plastic boxes to prevent possible loss of moisture and preserved in the laboratory at the temperature of 25°c and the relative humidity of 50% (Fig. 2(d)). Furthermore, the samples are prepared for 7, 30, 60, and 120 days of curing period.

(a) Humidification **(b)** Confection with static press

(c) Specimens after compaction **(d)** Preservation in plastic boxes

Fig. 2. Specimens for shear strength test obtained by static compaction.

Soil–L–sulphate, soil–NP–sulphate and soil–L–NP–sulphate mixtures

The samples were mixed in the same way as presented above, but different contents of $CaSO_4 \cdot 2H_2O$ (in powder form) (0-6% by weight of dry soil) were added into the soil–L, soil–NP, and soil–L–NP mixtures in a dry state. In addition, once the calculated water is added to the mixtures, the specimens can be prepared in the same way as presented above and cured for 7 to 120 days.

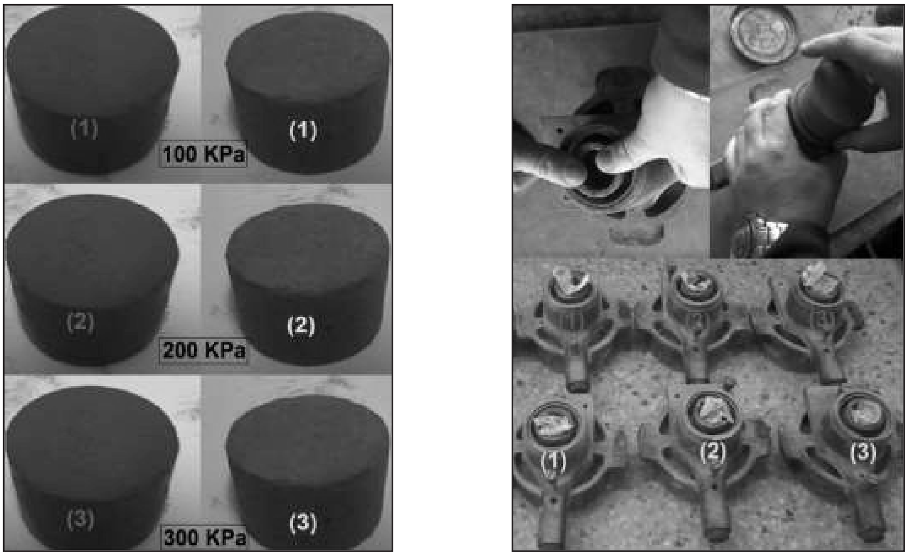
Laboratory tests

Shear strength test

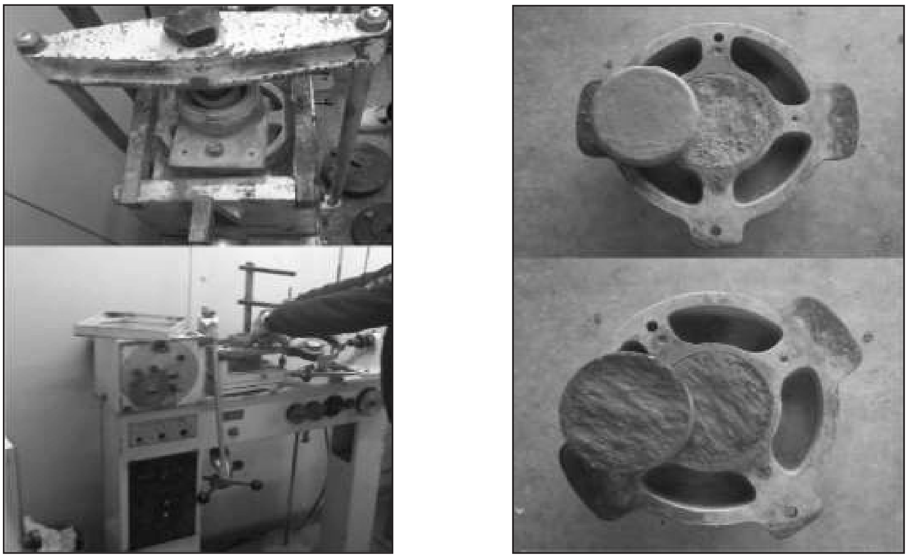
The direct shear tests were performed according to ASTM D6528-00 (2000) and conducted on the untreated and treated soil specimens on curing with or without $CaSO_4 \cdot 2H_2O$ (Fig. 3). The variations in maximum shear stresses and shear parameters of untreated clayey soils before and after admixtures added were studied. Indeed, the specimens were not saturated and excessive pore water pressure would not be expected in them. The direct shear test was undrained unconsolidated (UU) and the load was applied at a rate of 1 mm/min. The normal stress was chosen to be 100, 200, and 300 KPa for all specimens. Six identical specimens from each mixture were prepared for each curing period.

X-ray diffraction test

The XRD test was performed in order to investigate the mineralogical aspect of two clayey soil samples stabilized with L, NP, and L-NP. The modification in mineralogical composition of these soils can be reflected in the formation of cementing agents and/or ettringite mineral on XRD diagrams.



(a) Specimens for shear strength test **(b)** Installation of the specimens in the shear box



(c) Installation of the shear box in the shear apparatus **(d)** Specimens after shear strength test

Fig. 3. Shear strength test procedure.

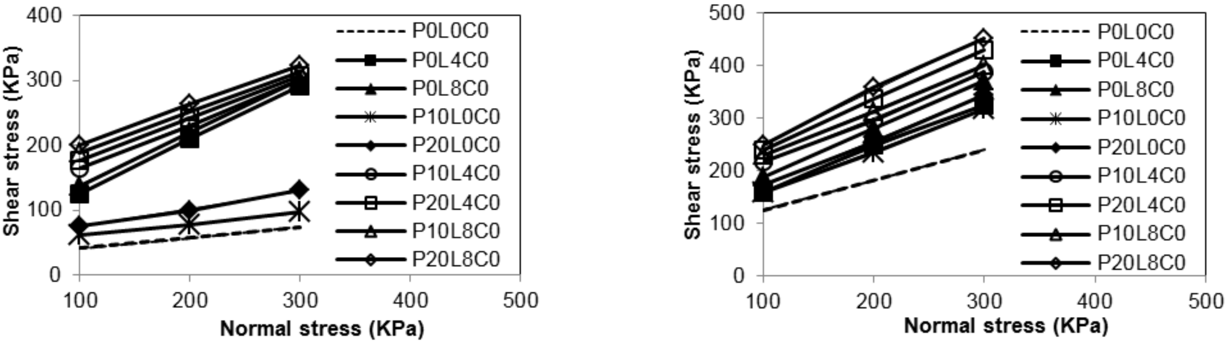
A PHILIPS PW3020 diffractometer was used for XRD analysis. After the unconfined compression test, the fractured samples produced were dried for 1 day at 40°C. Prior to the testing, the collected soil samples were ground as a fine powder and sieved throughout the 400 µm sieve. This fine powder will be used as a sample for the XRD test. The diffraction patterns were conducted using Cu–Kα radiation with a Bragg angle (2θ) range of 4°–60° running at a speed of $0.83.10^{-2}/2$ sec. After 60 days of curing, the examination of the eventual formation of ettringite and/or cementing compounds was conducted on the untreated and treated clayey soil samples. In addition, the investigation of the formation of ettringite and/or cementing compounds was also conducted on soil samples containing only 4% $CaSO_4 \cdot 2H_2O$.

RESULTS AND DISCUSSION

Shear Strength

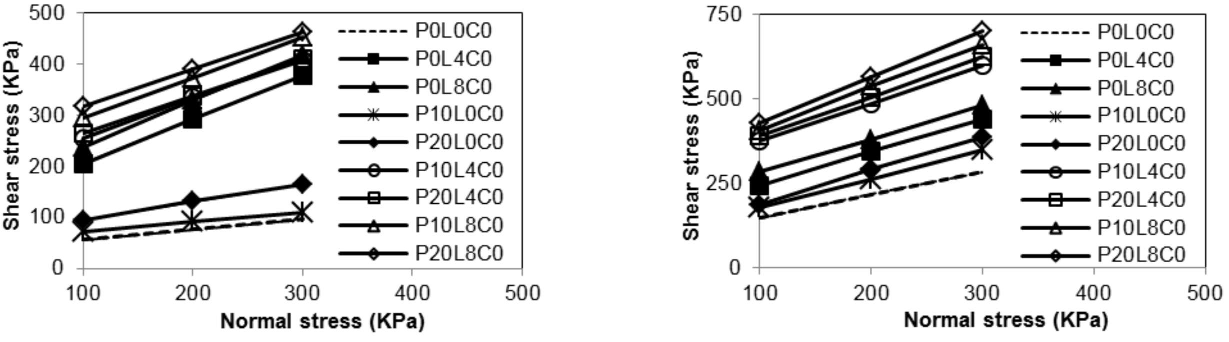
Temporal variation of the shear stress in the absence of $CaSO_4 \cdot 2H_2O$

The results of the effect of L, NP, and L-NP without $CaSO_4 \cdot 2H_2O$ on the temporal variation of maximum shear stresses of two stabilized clayey soils are depicted in Figure 4. The effect of NP without $CaSO_4 \cdot 2H_2O$ on maximum shear stresses of both clayey soils is negligible due to its low reactivity with the clay particles, whereas the addition of L alone to two clayey soils binds their particles and produces a significant effect on their maximum shear stresses. Indeed, the maximum shear stresses of both soils increase with increasing L content and curing period. The same behavior was observed by Gay and Shad (2000). The differences in maximum shear stresses between L and NP used as additives are more pronounced with the GS than with the RS. This behavior is probably due to the mineralogical composition and high plasticity index value of the GS to compare with the RS. However, the better results of maximum shear stresses are achieved when the treatment with L-NP is used. The increase in maximum shear stresses is considerably important when the amount of the combined treatment L-NP increases. In addition, it is obvious to observe that the combined treatment L-NP has a much better effect on maximum shear stresses of the RS than the GS.



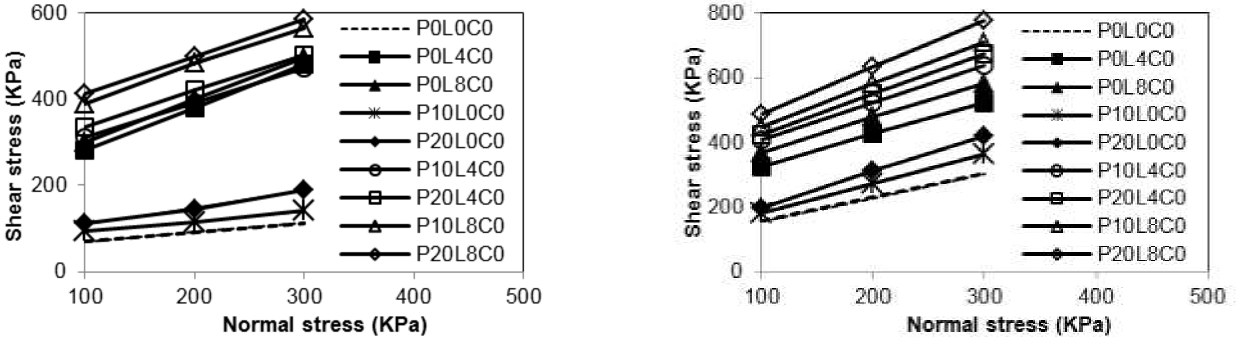
(a) Treated GS after 7 days of curing

(b) Treated RS after 7 days of curing

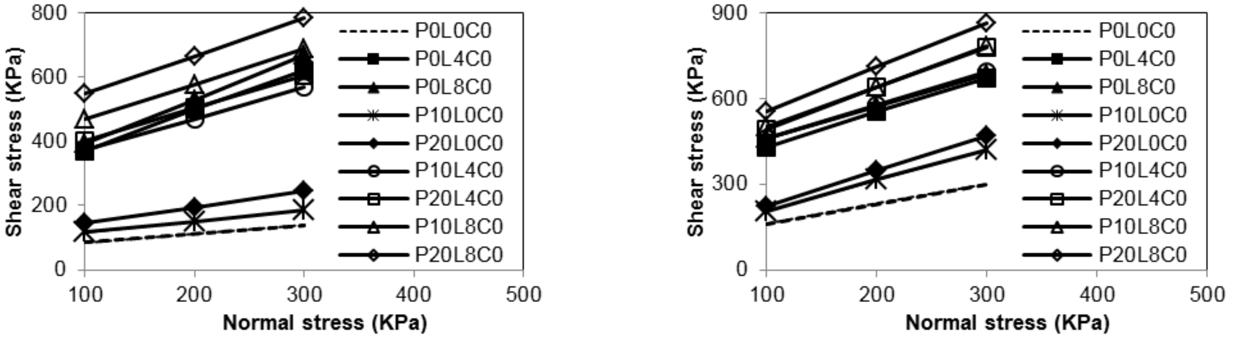


(c) Treated GS after 30 days of curing

(d) Treated RS after 30 days of curing



(e) Treated GS after 60 days of curing **(f)** Treated RS after 60 days of curing



(g) Treated grey GS 120 days of curing **(h)** Treated RS after 120 days of curing

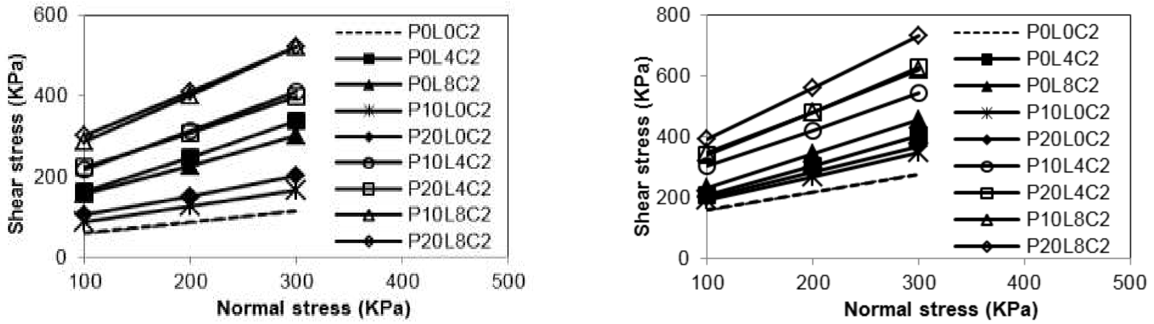
Fig. 4. Shear stress of both RS and GS samples produced under normal stress in the absence of $CaSO_4 \cdot 2H_2O$ for different curing period.

The dissolution of alumina and silica from soil and/or NP depends considerably on the L content which produces more cementitious products responsible to the increase in maximum shear stresses of these soils. In all cases, maximum shear strengths are observed for samples treated with L-NP as compared to samples containing L or NP alone.

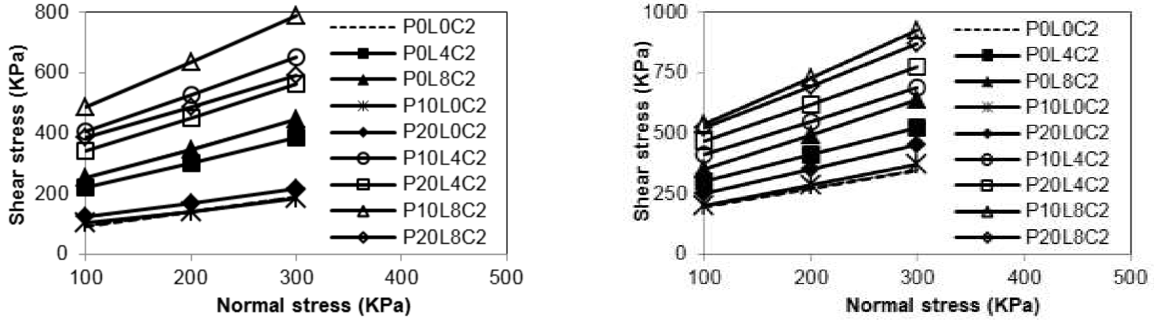
Temporal variation of the shear stress in the presence of $CaSO_4 \cdot 2H_2O$

The results of the effect of $CaSO_4 \cdot 2H_2O$ on the temporal variation of maximum shear stresses of two clayey soils stabilized with L, NP and L-NP are depicted in Figures 5-7. The addition of NP to two clayey soils on curing with $CaSO_4 \cdot 2H_2O$ improves considerably their maximum shear stresses. Indeed, maximum shear stresses of both soils increase with increasing $CaSO_4 \cdot 2H_2O$ content and curing period. Moreover, the increase in maximum shear stresses is more pronounced in the RS than the GS. This is depends on the mineralogical composition and the clay particles content of these soils.

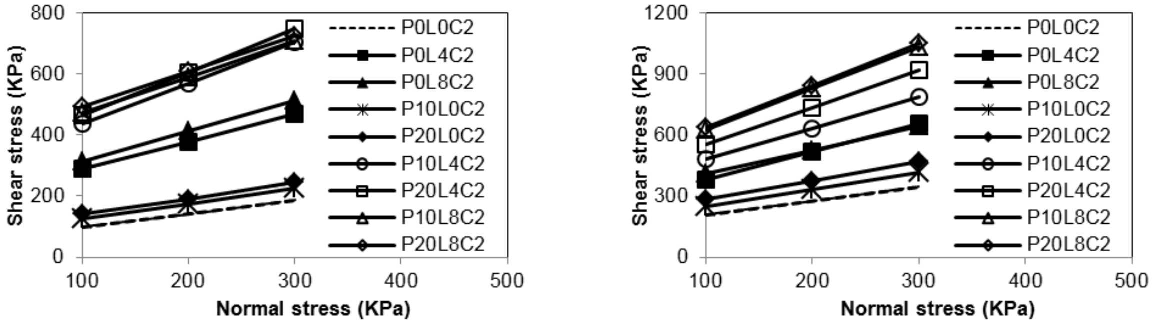
However, the maximum shear stresses of L-treated two clayey soil samples on curing with $CaSO_4 \cdot 2H_2O$ increase with increasing L content and curing period. But the increase in maximum shear stresses with $CaSO_4 \cdot 2H_2O$ content is little. This is due to the fact that the $CaSO_4 \cdot 2H_2O$ has the capacity to reduce the solubility of hydrated lime (Shi and Day, 2000). In addition, after 120 days of curing period, a further increase in maximum shear stresses is recorded when the L and NP are combined in the presence of different content of $CaSO_4 \cdot 2H_2O$. However, Aldaood *et al*. (2014a) indicated that the early increase in strength of soil samples containing L is due to the presence of $CaSO_4 \cdot 2H_2O$ which accelerates the chemical reaction between soil and L. Furthermore, for any content of $CaSO_4 \cdot 2H_2O$ the differences in maximum shear stresses between L and L-NP used as additives are more pronounced with the GS than with the RS.



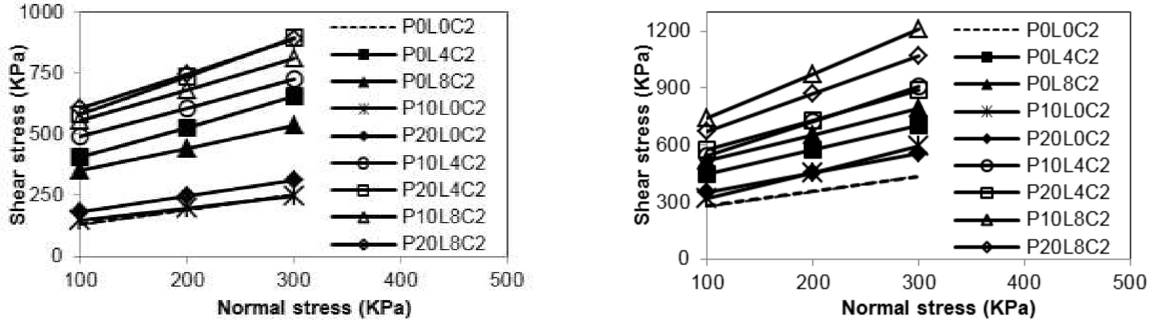
(a) Treated GS after 7 days of curing **(b)** Treated RS after 7 days of curing



(c) Treated GS after 30 days of curing **(d)** Treated RS after 30 days of curing

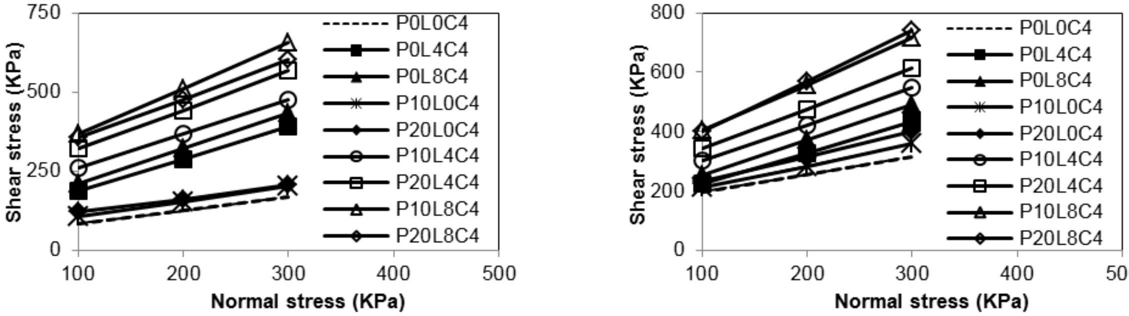


(e) Treated GS after 60 days of curing **(f)** Treated RS after 60 days of curing



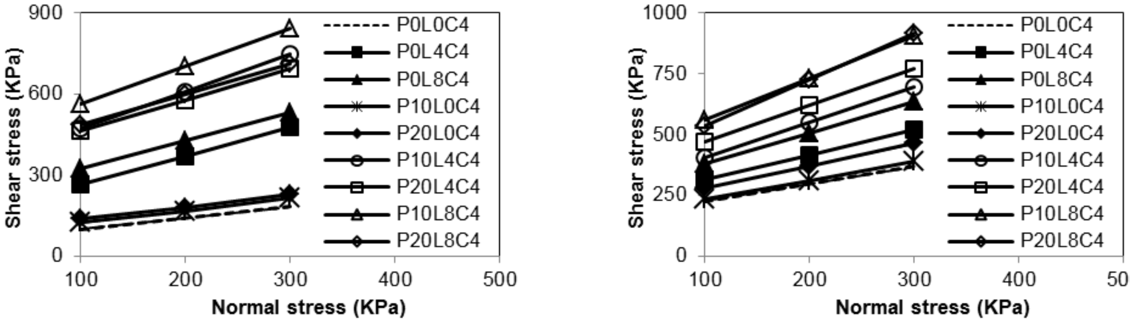
(g) Treated GS after 120 days of curing **(h)** Treated RS after 120 days of curing

Fig. 5. Shear stress of both RS and GS samples produced under normal stress in the presence of 2% $CaSO_4 \cdot 2H_2O$ for different curing period.



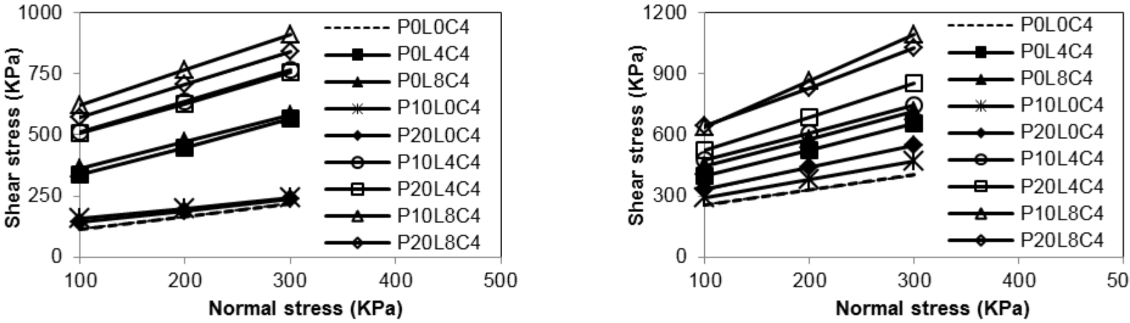
(a) Treated GS after 7 days of curing

(b) Treated RS after 7 days of curing



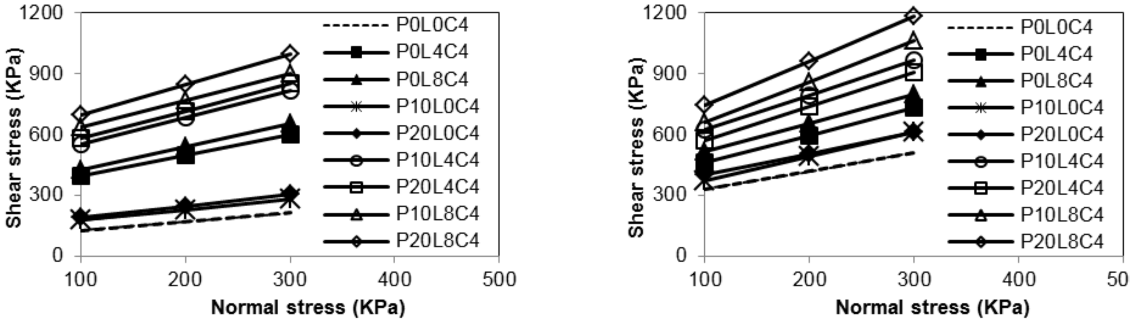
(c) Treated GS after 30 days of curing

(d) Treated RS after 30 days of curing



(e) Treated GS after 60 days of curing

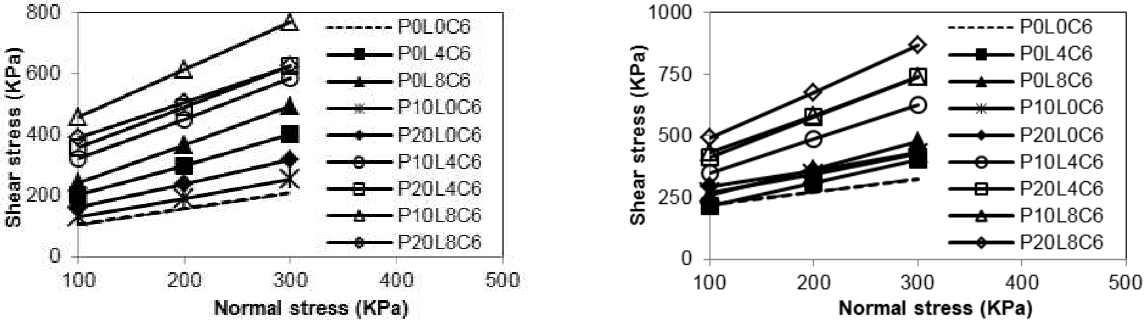
(f) Treated RS after 60 days of curing



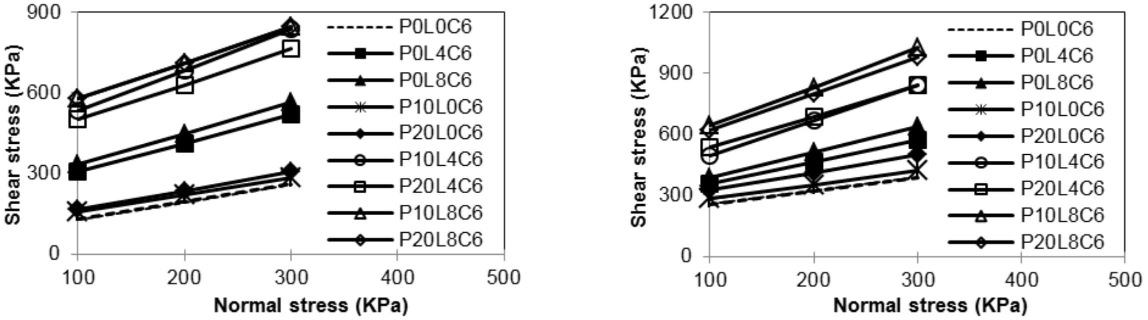
(g) Treated GS after 120 days of curing

(h) Treated RS after 120 days of curing

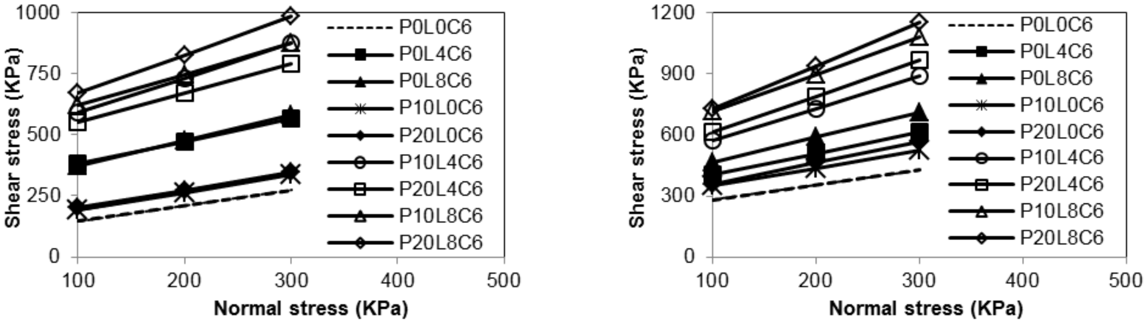
Fig. 6. Shear stress of both RS and GS samples produced under normal stress in the presence of 4% $CaSO_4 \cdot 2H_2O$ for different curing period.



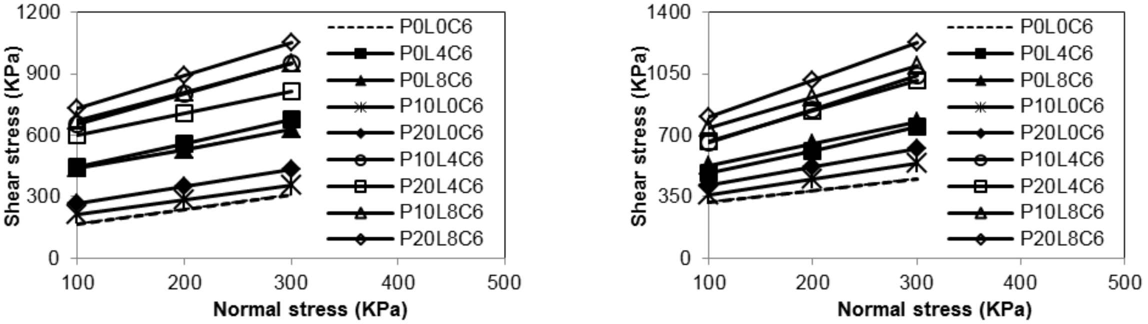
(a) Treated GS after 7 days of curing **(b)** Treated RS after 7 days of curing



(c) Treated GS after 30 days of curing **(d)** Treated RS after 30 days of curing



(e) Treated GS after 60 days of curing **(f)** Treated RS after 60 days of curing



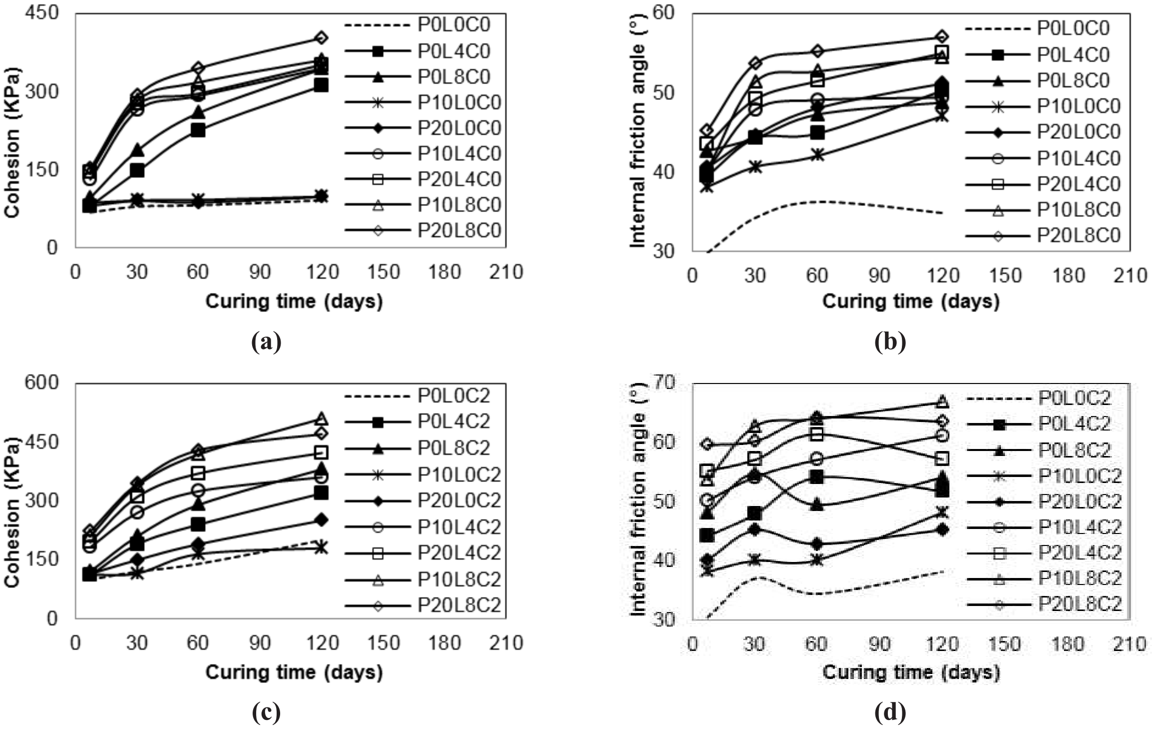
(g) Treated GS after 120 days of curing **(h)** Treated RS after 120 days of curing

Fig. 7. Shear stress of both RS and GS samples produced under normal stress in the presence of 6% $CaSO_4 \cdot 2H_2O$ for different curing period.

Shear Parameters

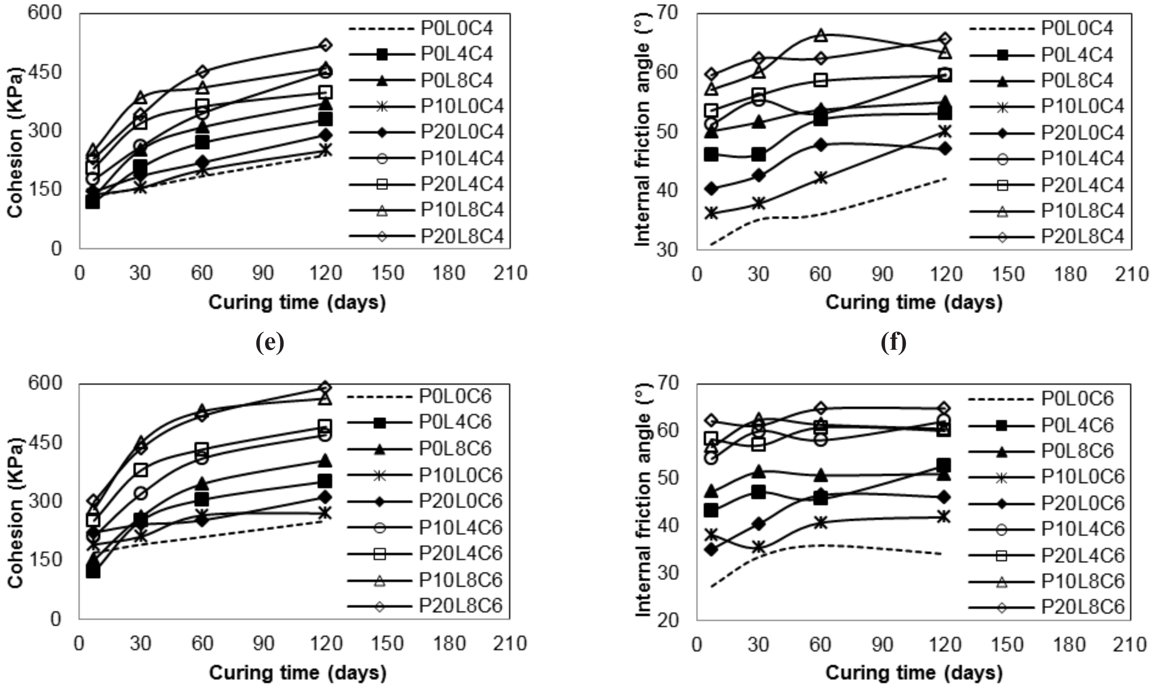
Temporal variation of the cohesion in the absence of $CaSO_4 \cdot 2H_2O$

Figures 8(a) and 9(a) depict the results of the effect of using L, NP, and L-NP without $CaSO_4 \cdot 2H_2O$ on the temporal variation of cohesion of two clayey soils. Only the shear parameters using the maximum shear stresses were calculated. In all cases there is a much better increase in cohesion values to compare with the untreated soils. This increase is particularly noticeable in both clayey soils with the combination L-NP. However, the addition of NP to two clayey soils increases slightly their cohesion, which is probably due to its low reactivity with the clay particles. In addition, the XRD diagrams confirm that the formation of cementitious compounds (CSH and CAH) in both clayey soil samples stabilized with NP is not observed (Figs. 10(f) and 11(f)). However, it can be seen that, in the case of L-treated two clayey soils without $CaSO_4 \cdot 2H_2O$, the cohesion increases with increasing L content and curing period particularly at later stages. The increase in cohesion is very pronounced in the RS than the GS. e.g., for 8%L the cohesion values of the RS and GS are, respectively, 95.8 and 56.1 KPa after 7 days of curing but increase, respectively, up to 343.4 and 256.9 KPa after curing for 120 days. A similar behavior was obtained by Gay and Schad (2000). The increase in cohesion with increasing L content can be attributed to the cementation of particles, which develops larger aggregates (coarse-grained) and strongly bonds the stabilized material (Ola, 1978; Harichane *et al*., 2011a). On the other hand, this behavior is probably due to the self-hardening effect related to the L (Harichane *et al*., 2011b). Likewise, this behavior can be attributed to the cementation and the pozzolanic reactions, which occur over time (Bell, 1989). Indeed, the formation of cementitious compounds in the L-treated two clayey soils is confirmed by XRD diagrams (Figs. 10(e) and 11(e)).



(a) (b)

(c) (d)

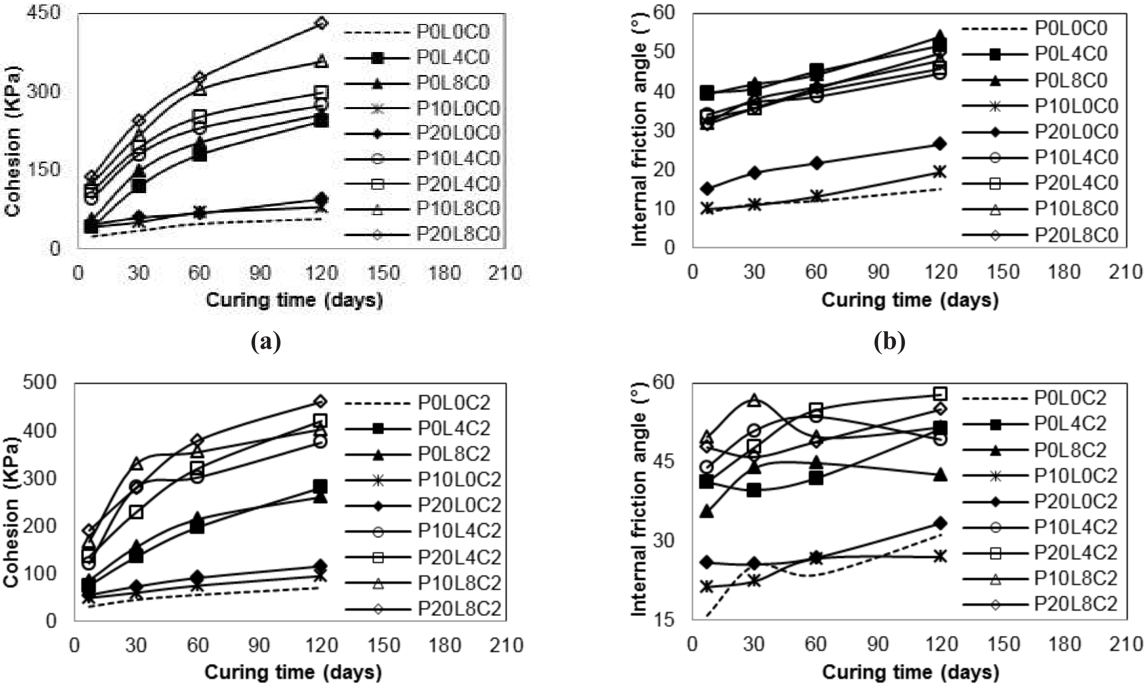


(e) **(f)**

(g) **(h)**

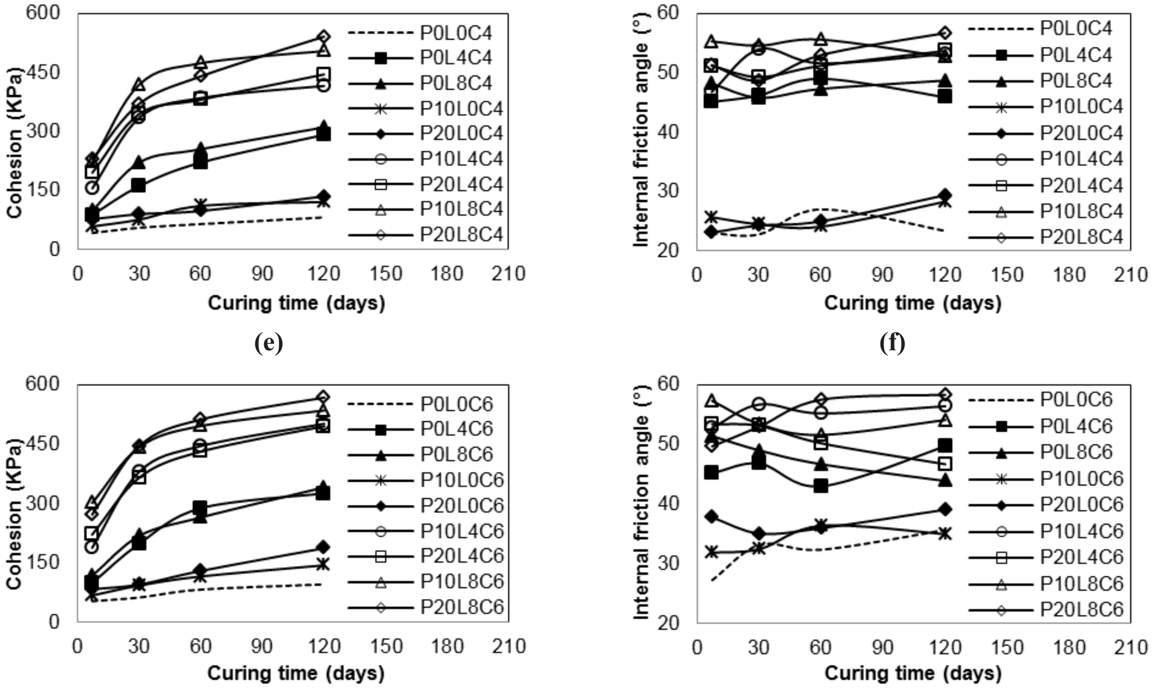
Fig. 8. Temporal variation of shear strength parameters of the RS in the presence of different contents of $CaSO_4{\cdot}2H_2O$ (a, c, e & g) cohesion and (b, d, f & h) internal friction angle.

.



(a) **(b)**

(c) (d)



(e) (f)

(g) (h)

Fig. 9. Temporal variation of shear strength parameters of the GS in the presence of different contents of $CaSO_4 \cdot 2H_2O$ (a, c, e & g) cohesion and (b, d, f & h) internal friction angle.

It is clear to observe that, for both GS and RS, the highest cohesion values are obtained when the L and NP are combined whereby the RS has the best values. e.g., the cohesion values of the GS stabilized with the addition of 4%L and 10%NP are 96.8 and 274 KPa after 7 and 120 days of curing, respectively. However, for the same content of L and NP, the RS develops cohesion values of 131.4 and 344.1 KPa after 7 and 120 days of curing, respectively. In addition, a further increase in cohesion value is observed for both clayey soils with increasing L-NP content. e.g., after 120 days of curing the GS develops a cohesion value of only 274 KPa for the addition of 10%NP and 4%L. However, for the same soil and the same curing period, the cohesion becomes 429.7 KPa with the addition of 20%NP and 8%L as a combined treatment. For the same combination and the same curing period, the cohesion developed by the RS is 402.9 KPa, which represents an increase of 1.2 times compared with 10%NP+4%L, and 4.4 times compared with untreated RS. From these examples the difference in cohesion values developed by these two clayey soils is probably due to the plasticity index of the RS with little value to compare with the GS. The cohesion of two clayey soils becomes very higher when the combination 20%NP+8%L is used as an additive. The considerable increase in cohesion of two clayey soil samples with curing period is attributed to the formation of cementitious compounds, which bind the soil particles together.

Temporal variation of the cohesion in the presence of $CaSO_4 \cdot 2H_2O$

The results of the effect of L, NP, and L-NP in the presence of $CaSO_4 \cdot 2H_2O$ on the temporal variation of the cohesion of two stabilized clayey soil samples are depicted in Figures 8(c, e & g) and 9(c, e & g). There is a significant increase in cohesion of NP-treated two clayey soil samples with increasing $CaSO_4 \cdot 2H_2O$ content and curing period. The same behavior is observed for two untreated clayey soil samples containing any content of $CaSO_4 \cdot 2H_2O$.

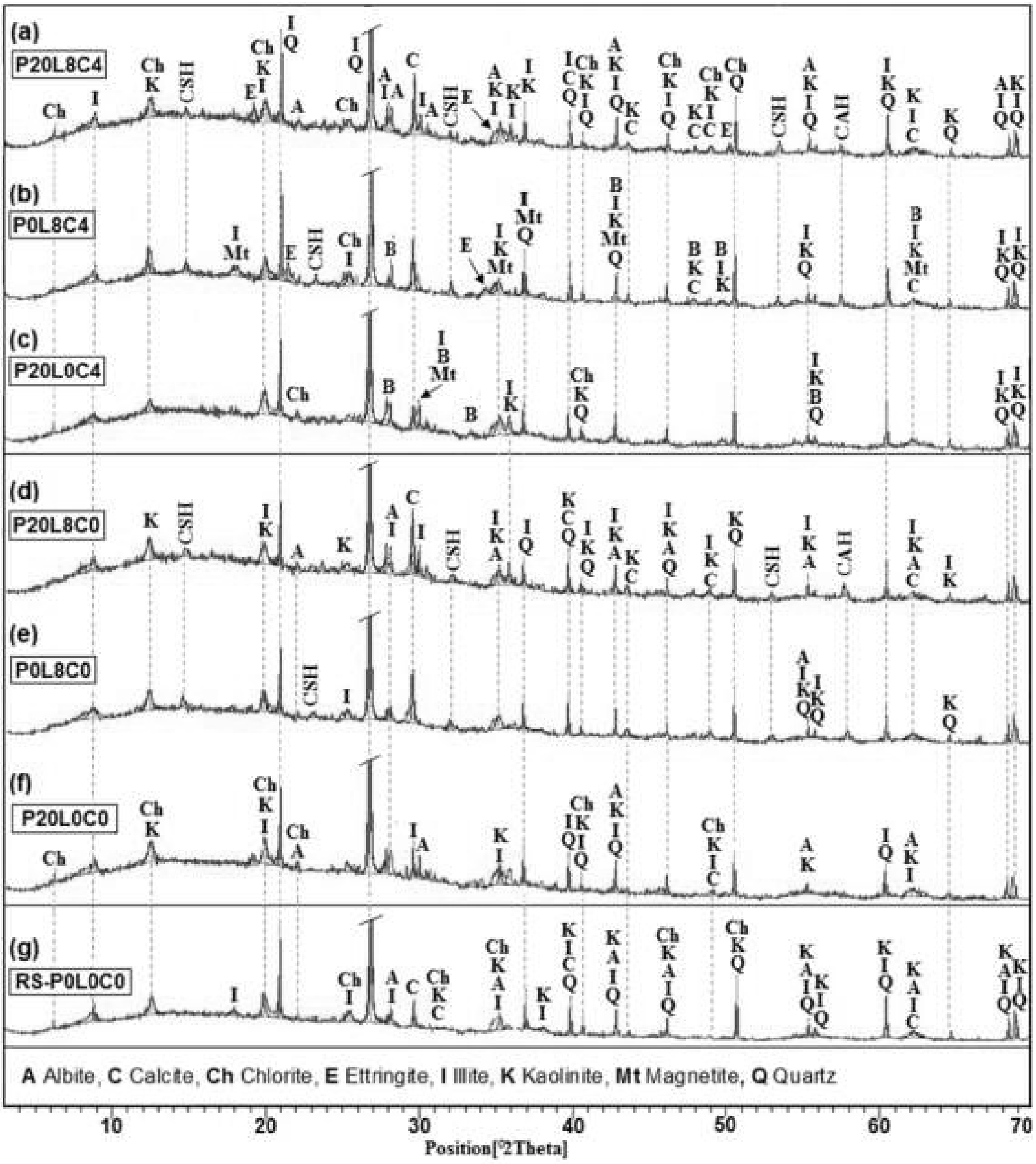



Fig. 10. XRD diagrams of the RS samples obtained after 60 days of curing period (a, b & c) treated RS samples containing 4% of $CaSO_4 \cdot 2H_2O$, (d, e & f) treated RS samples without $CaSO_4 \cdot 2H_2O$ and (g) untreated RS sample without $CaSO_4 \cdot 2H_2O$.

The increase in cohesion of these clayey soil samples containing $CaSO_4 \cdot 2H_2O$ is clearly reflected in the improvement of their shear strengths. Figures 10(c) and 11(c) indicate that the increase in cohesion of NP-treated two clayey soils is certainly not linked with the eventual formation of cementitious compounds and/or ettringite. However, the increase in cohesion values is probably due to the finer grained of $CaSO_4 \cdot 2H_2O$, which increases the compactness of soil samples (Aldaood *et al.*, 2014a). In addition, the increase in cohesion with both curing period and $CaSO_4 \cdot 2H_2O$ content is more pronounced in the RS than the GS. This is leading us to suppose that the increase in cohesion could be due to the behavior of the RS with the $CaSO_4 \cdot 2H_2O$ interaction.

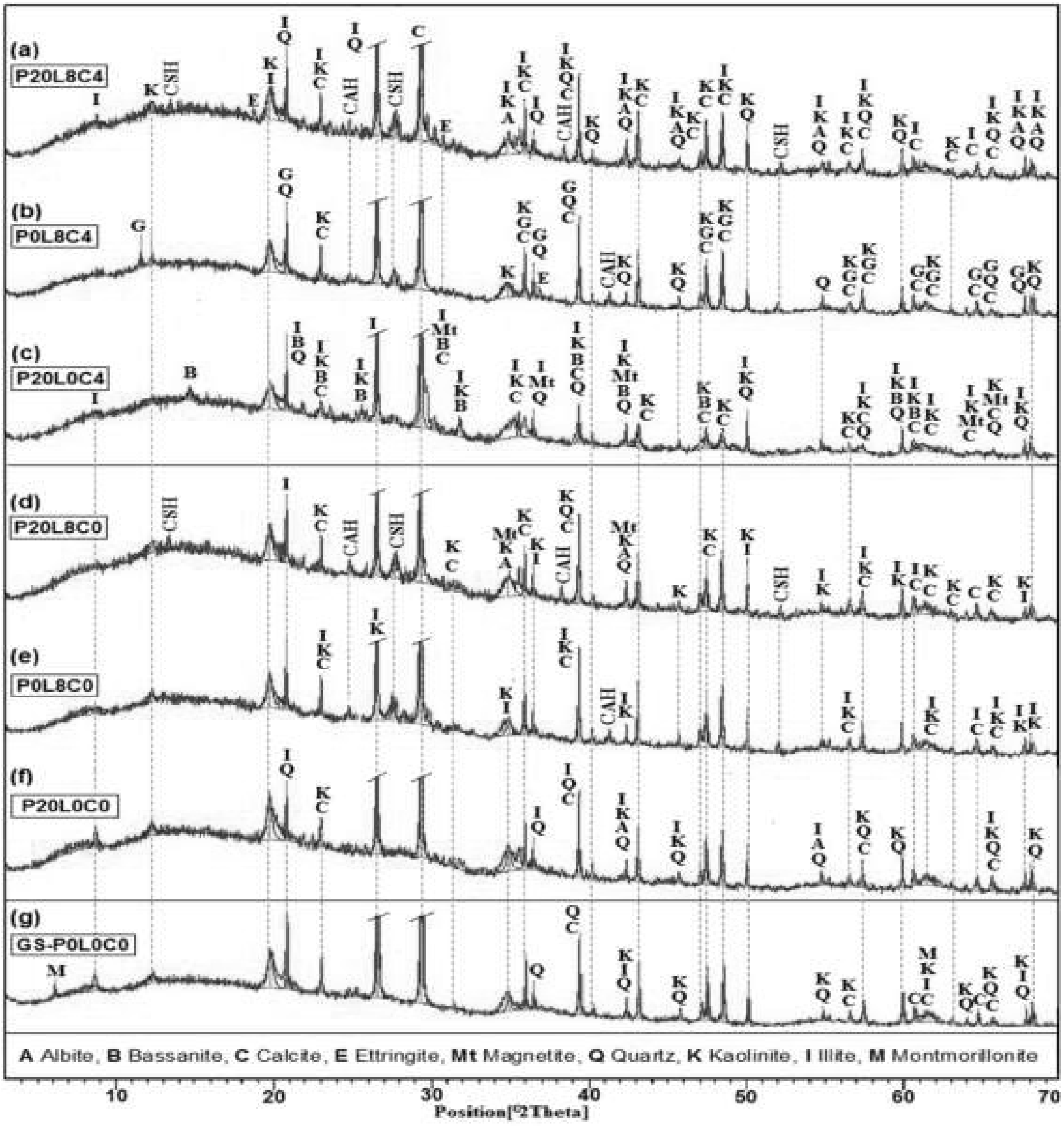


Fig. 11. XRD diagrams of the GS samples obtained after 60 days of curing period (a, b & c) treated GS samples containing 4% of $CaSO_4 \cdot 2H_2O$, (d, e & f) treated GS samples without $CaSO_4 \cdot 2H_2O$ and (g) untreated GS sample without $CaSO_4 \cdot 2H_2O$.

For any curing periods there is a little increase in cohesion of L-treated two clayey soil samples with increasing $CaSO_4 \cdot 2H_2O$ and L content to compare with samples without $CaSO_4 \cdot 2H_2O$. Furthermore, the cohesion of L-NP-treated two clayey soil samples increases sharply with increasing $CaSO_4 \cdot 2H_2O$ content, L-NP content, and curing period. e.g., with the combination 10%NP+4%L the GS and RS samples containing 2% $CaSO_4 \cdot 2H_2O$ develop, respectively, cohesion values of 375.5 and 360.9 kPa after curing for 120 days. However, with the same content of $CaSO_4 \cdot 2H_2O$ and the same curing period, the cohesion of both GS and RS samples stabilized with 20%NP+8%L becomes 461 and 470.6 kPa, respectively. On the other hand, in the presence of 6% $CaSO_4 \cdot 2H_2O$, both GS and RS samples stabilized with the combination 10%NP+4%L develop, respectively, cohesion values of 501.3 and 469.9 kPa after curing for 120 days, whereas, for the same content of $CaSO_4 \cdot 2H_2O$ and the same curing period, the cohesion of both GS and RS samples stabilized with 20%NP+8%L becomes 567.5 and 590.4 kPa, respectively. The early increase in cohesion and strength of both clayey soil samples can be explained by the presence of $CaSO_4 \cdot 2H_2O$, which accelerates the chemical reaction between soil and lime (Aldaood *et al*., 2014a). Moreover, at the later stage there is a much better increase in cohesion values, which may be due to the formation of ettringite (Figs. 10(a & b) and 11(a & b)).

Temporal variation of the internal friction angle in the absence of $CaSO_4 \cdot 2H_2O$

The results of the temporal variation of internal friction angle of two stabilized clayey soils without $CaSO_4 \cdot 2H_2O$ are depicted in Figures 8(b) and 9(b). Generally, the stabilization with L alone or in combination with NP changes the structural form of both clayey soils from dispersed to flocculated form. This is appearing in the significant increase in their internal friction angle. The internal friction angle of both stabilized clayey soil samples increases with increasing NP content and curing period. This is probably due to the fact that the NP has a high internal friction angle than that of the untreated soil. Indeed, Sezer *et al*. (2006) reported that the combination of fly ash+L with high content produces an increase in the internal friction angle of the treated soil. This is due to the fact that the fly ash has a high internal friction angle than that of the soil. Moreover, the flocculation of particles increases the internal friction angle value, whereas cementation of particles increases the cohesion value. However, it can be seen that, in the case of L-treated both clayey soils, the internal friction angle increases with increasing L content and curing period (Figs. 8(b) and 9(b)). The increase in the internal friction angle is more pronounced in the RS than the GS.

The differences in the internal friction angle between L and NP used as additives are more pronounced with the GS than with the RS. However, the internal friction angle of the RS stabilized with the combination of L-NP increases very quickly up to 30 days of curing, but after this curing period the rate of increase is still little. In contrast, the internal friction angle of the GS stabilized with the same additive (L-NP) increases linearly with curing period. The same behavior is observed when the GS is stabilized with the L alone. According to Harichane *et al*. (2011b), the improvement in the shear parameters values may be due to the pozzolanic activity and self-cementitious characteristics of the mixed L-NP.

Temporal variation of the internal friction angle in the presence of $CaSO_4 \cdot 2H_2O$

The results of the effect of L, NP, and L-NP in the presence of $CaSO_4 \cdot 2H_2O$ on the temporal variation of the internal friction angle of two stabilized clayey soils are presented in Figures 8(b, f & h) and 9(b, f & h). It is clear that the internal friction angle of two clayey soil samples developed by the addition of 20%NP is higher than that of the untreated soil. This behavior is probably due to the specific surface area of NP, which has a higher internal friction angle than that of the untreated soil. With NP as an additive, the increase in the internal friction angle with increasing $CaSO_4 \cdot 2H_2O$ content and curing period is more pronounced in the RS than the GS. However, the internal friction angle of two clayey soil samples stabilized with L alone or with a combination of L-NP increases considerably with increasing $CaSO_4 \cdot 2H_2O$ and curing period. e.g., with 2% of $CaSO_4 \cdot 2H_2O$ the internal friction angle of GS stabilized with 8%L presents a value of35.6 ° after 7 days of curing and then increases up to 42.6° after curing for 120 days whereas, for the same content of L, the internal friction angle of RS develops a value of 48.2° after 7 days of curing and becomes 54.1° after curing for 120 days. However, when the content of $CaSO_4 \cdot 2H_2O$ is greater than 2%, the internal friction angle of two clayey soils increases sharply with curing period. e.g., with 6% of $CaSO_4 \cdot 2H_2O$ the two GS and RS stabilized with a combination of 20%NP+8%L develop an internal friction angle values of 58.3 and 64.8° after curing for 120 days, respectively. It is clear to see that the internal friction angle values of two clayey soil samples stabilized with L alone or with L-NP on curing with or without $CaSO_4 \cdot 2H_2O$ increase with increasing cohesion values (Figs. 8 and 9). In general, the larger values of internal friction angle are coupled with high cohesion values. It is proposed that this behavior is probably due to the high normal loads used during the direct shear test, which increases the compressibility of the soil structure and activates the frictional properties between cementitious compounds and soil particles leading to the high increase in the internal friction angle.

CONCLUSIONS

The effect produced by the presence of $CaSO_4 \cdot 2H_2O$ on maximum shear stresses and shear parameters of two clayey soils stabilized with L, NP, and L-NP was studied. Based on the test results, the following conclusions can be drawn:

- The stabilization with lime without $CaSO_4 \cdot 2H_2O$ increases significantly the shear strength and shear parameters of two clayey soils, whereas the NP has the negligible effect. The rate of increase depends on the L content and curing period. Furthermore, the highest shear strength and shear parameters are achieved with a combination of L-NP, which is appearing to develop higher shear parameters to compare with L.
- With NP as an additive there is a significant increase in maximum shear stresses and shear parameters of two clayey soil samples containing $CaSO_4 \cdot 2H_2O$ to compare with samples without $CaSO_4 \cdot 2H_2O$, whereby RS has the best results. This is probably due to the finer grain of $CaSO_4 \cdot 2H_2O$, which increases the compactness of NP-treated two clayey soil samples. A slight increase in maximum shear stresses and shear parameters is observed for L-treated two clayey soils samples containing $CaSO_4 \cdot 2H_2O$ to compare with samples without $CaSO_4 \cdot 2H_2O$. This is due to the fact that the $CaSO_4 \cdot 2H_2O$ reduces the solubility of hydrated L added. However, for two clayey soils samples containing $CaSO_4 \cdot 2H_2O$, there is a much better increase in maximum shear stresses and shear parameters when the combination L-NP is used.
- The high early values of cohesion and shear strength developed by two stabilized clayey soils can be attributed to the presence of $CaSO_4 \cdot 2H_2O$, which accelerates the chemical reaction between soil, L, and NP.
- The increase in cohesion and shear strength of two stabilized clayey soils with curing period can be explained by the formation of ettringite due to the presence of $CaSO_4 \cdot 2H_2O$, especially with high content.
- The increase in cohesion and shear strength of both clayey soils depends mainly on the mineralogical composition of stabilized soils, the type of additive used and its content, the $CaSO_4 \cdot 2H_2O$ content, and curing period.
- The mineralogical composition of soil has a capital importance and plays an important role in the stabilization process success, especially with the presence of $CaSO_4 \cdot 2H_2O$.
- The $CaSO_4 \cdot 2H_2O$ can be used in civil engineering projects as an accelerator of chemical reactions between soil, L, and NP.

ACKNOWLEDGMENT

The authors would like to thank the Dr. Othman Boukendakdji for their language help and precious comments to improve the scientific quality of this paper. We thank the director of the Habitat Laboratory and Construction Center (HLCC, Oued-Smar, Algeria) for providing excellent working conditions and financial support. We also thank the technicians of the HLCC for their help during the experimental work; without them this study would not have been possible. Furthermore, our thanks are also addressed to the Head of the Hydraulic Department of Chlef University for providing excellent working conditions during materials preparation.

REFERENCES

Afès, M. & Didier, G. 2000. Stabilisation des sols gonflants: cas d'une argile en provenance de Mila (Algérie). Bulletin of Engineering Geology and the Environment, **59**(1): 75-83.

Aldaood, A., Bouasker, M. & Al-Mukhtar, M. 2014a. Geotechnical properties of lime-treated gypseous soils. Applied Clay Science, **88-89**: 39-48.

Aldaood, A., Bouasker, M. & Al-Mukhtar, M. 2014b. Impact of wetting–drying cycles on the microstructure and mechanical properties of lime-stabilized gypseous soils. Engineering Geology, **174**: 11-21.

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

ASTM C204-07. 2007. Fineness of Hydraulic Cement by Air-Permeability Apparatus. Annual book of ASTM Standards, American Society for Testing and Materials (ASTM), West Conshohocken, PA.

ASTM D6528-00. 2000. Standard test method for consolidated undrained direct simple shear testing of cohesive soils. Annual book of ASTM Standards, American Society for Testing and Materials (ASTM), Philadelphia **04**: 08.

Baryla, J. M., Chenais, V., Gavois, L. & Havard, H. 2000. Effet de sulfates et sulfures sur des marnes traitées à la chaux et au liant routier sur un chantier autoroutier. Bulletin de liaison des Laboratoires des Ponts et Chaussées, **224**: 39-48.

Basha, E. A., Hashim, R. & Muntohar, AS. 2003. Effect of the cement-rice husk ash on the plasticity and compaction of soil. Electronic Journal of Geotechnical Engineering, **8**(1): 1-8.

Bell, F. G. 1989. Lime stabilisation of clay soils. Bulletin of the International Association of Engineering Geology, **39**(1): 67-74.

Choobbasti, A. J., Ghodrat, H., Vahdatirad, M. J., Firouzian, S., Barari, A., Torabi, M. & Bagherian, A. 2010. Influence of using rice husk ash in soil stabilization method with lime. Frontiers of Earth Science, **4**(4): 471-480.

Floyd, M., Czerewko, M. A., Cripps, J. C. & Spears, D. A. 2003. Pyrite oxidation in Lower Lias Clay at concrete highway structures affected by thaumasite, Gloucestershire, UK. Cement and Concrete Composites, **25**(8): 1015-1024.

Gay, G. & Schad, H. 2000. Influence of cement and lime additives on the compaction properties and shear parameters of fine grained soils. Otto-Graf Journal, **11**: 19-31.

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

Goswami, R. K. & Singh, B. 2005. Influence of Fly Ash and Lime on Plasticity characteristics of Residual Lateritic Soil. Proceedings of the Institution of Civil Engineers–Ground Improvement, **9**(4): 175-182.

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

Harichane, K., Ghrici, M. & Missoum, H. 2011b. Influence of natural pozzolana and lime additives on the temporal variation of soil compaction and shear strength. Frontiers of Earth Science, **5**(2): 162-169.

Harichane, K., Ghrici, M. & Kenai, S. 2012. Effect of the combination of lime and natural pozzolana on the compaction and strength of soft clayey soils: a preliminary study. Environmental Earth Sciences, **66**(8): 2197-2205.

Harichane, K., Ghrici, M., Kenai, S. & Grine, K. 2011c. Use of natural pozzolana and lime for stabilization of cohesive soil. Geotechnical and Geological Engineering, **29**(5): 759-769.

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

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

Hunter, D. 1988. Lime-induced heave in sulphate-bearing clay soils. ASCE, Journal of Geotechnical Engineering, 114(2): 150-167.

Kinuthia, J. M., Wild, S. & Jones, G. I. 1999. Effects of monovalent and divalent metal sulphates on consistency and compaction of lime-stabilized kaolinite. Applied Clay Science, **14**(1): 27-45.

Kolias, S., Kasselouri-Rigopoulou, V. & Karahalios, A. 2005. Stabilization of clayey soils with high calcium fly ash and cement. Cement and Concrete Composites, **27**: 301-313.

Le Borgne, T. 2010. Effects of potential deleterious chemical compounds on soil stabilization. Ph.D. thesis Nancy-University, French.

Ola, S. A. 1978. Geotechnical properties and behaviour of some stabilized Nigerian laterite soils. Engineering Geology, **11**(2):145-160.

Puppala, A. J., Talluri, N. & Chittoori, B. C. 2014. Calcium-based stabiliser treatment of sulfate-bearing soils. Proceedings of the Institution of Civil Engineers – Ground Improvement, **167**(3): 162-172.

Rajasekaran, G. 2005. Sulphate attack and ettringite formation in the lime and cement stabilized marine clays. Ocean Engineering, **32**(8): 1133-1159.

Rahman, M. D. A. 1986. The potentials of some stabilizers for the use of lateritic soil in construction. Building and Environment, **21**(1): 57-61.

Sadrjamali, M., Athar, S. M. & Negahdar, A. 2015. Modifying Soil Shear Strength Parameters Using Additives in Laboratory

Condition. Current World Environment, 10(1): 120-130.

Segui, P., Aubert, J. E., Husson, B. & Measson, M. 2013. Utilization of a natural pozzolan as the main component of hydraulic road binder. Construction and Building Materials, **40**: 217-223.

Sezer, A., Inan, G., Yilmaz, H. R. & Ramyar, K. 2006. Utilization of a very high lime-fly ash for improvement of Izmir clay. Building and Environment, **41**(2): 150-155.

Shi, C. & Day, R. L. 2000. Pozzolanic reaction in the presence of chemical activators Part I. Reaction kinetics. Cement and Concrete Research, **30**(1): 51-58.

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

Sivapullaiah, P. V., Sridharan, A. & Ramesh, H. N. 2006. Effect of sulphate on the shear strength of lime treated kaolinitic soil. Proceedings of the Institution of Civil Engineers–Ground Improvement, **10**(1): 23-30.

Yilmaz, I. & Civelekoglu, B. 2009. Gypsum: an additive for stabilization of swelling clay soils. Applied Clay Science, **44**: 166-172.

Submitted: 10/05/2016
Revised: 21/02/2019
Accepted: 18/12/2017

تأثير التفاعل الناتج بين كبريتات الكالسيوم والإضافات المعدنية على خصائص مقاومة القص للأتربة الطينية

***حميد قدوري، **خليفة حريشان و**محمد غريسي**

*قسم علوم الأرض، كلية علوم الطبيعة والحياة وعلوم الأرض، جامعة خميس مليانة، الجزائر

*قسم هندسة المواد، كلية العلوم والتكنولوجيا، جامعة المدية، الجزائر

**قسم الهندسة المدنية، كلية الهندسة المدنية والمعمارية، جامعة الشلف، الجزائر

الخلاصة

في الجزائر، غالباً ما نصادف الأتربة غير المستقرة التي تتميز بلدونة عالية ومقاومة تحمل صغيرة. إلا أنه يمكن تحسين هذه الأتربة من خلال استعمال طريقة التثبيت الكيميائي بغرض جعلها مقبولة للإستعمال في مشاريع البناء. ومع ذلك، فقد تم ملاحظة وجود عدة أشكال تعكس عدم استقرار هذه المشاريع المُنجزة، وهذا راجع إلى وجود الكبريتات المسؤولة على تشكل معادن جديدة قابلة للتمدد والإنتفاخ كمعدن الإترنجيت. ولهذا السبب تم إجراء بحث تجريبي يهدف إلى دراسة تأثير وجود كبريتات الكالسيوم (CaSO4·2H2O) على سلوك مقاومة القص لكل من التربتين الطينيتين المثبتتين كيميائياً باستعمال الجير المعالج (L; P0L0, P0L4, P0L8) والبوزولان الطبيعي (NP; P10L0, P20L0) وكذا دمجهما سوياً كخليط واحد وبنفس النسب المئوية السابقة (L-NP; P10L4, P20L4, P10L8, P20L8). الخاصية الميكانيكية التي تم التنقيب عنها في هذه الدراسة هي مقاومة القص وهذا بعد خمر العينات بعيداً عن العوامل الخارجية خلال مدة زمنية تتراوح بين 7 و 120 يوم. بالإضافة إلى متابعة تطور وتغير التركيبة المعدنية لنفس العينات المدروسة لكلا التربتين بواسطة تجربة الانحراف الإشعاعي باستعمال أشعة إكس (XRD). وتبين النتائج المخبرية التي تم الحصول عليها في غياب CaSO4·2H2O أنه يمكن تثبيت كل عينات التربتين بنجاح وذلك باستعمال الجير المعالج لوحده أو بدمجه مع البوزولان الطبيعي L–PN حيث أن هذه الإضافات تقوم برفع كل من مقاومة القص للتربتين وكذا خاصيتي القص. علاوة على ذلك، فإن إضافة CaSO4·2H2O (خصوصاً بكميات كبيرة) للعينات التي تحتوي على الجير المعالج لوحده أو العلاج المدمج L–PN يسمح بزيادات معتبرة في قيمة كل من مقاومة القص والخواص المرفقة بها. إن الزيادة في قدرة التحمل للقص للعينات التي تحتوي على CaSO4·2H2O يرجع أساساً إلى تشكل معدن الإترنجيت الذي تم ملاحظته على مستوى المنحنيات البيانية الإشعاعية XRD لكلا التربتين. وبشكل عام فإنه من خلال النتائج المتحصل عليها يظهر جلياً أن نجاح التثبيت الكيميائي للتربة يتعلق بعدة عوامل وهي: كمية CaSO4·2H2O، نوع وكمية العنصر المضاف، مدة التخمر وأخيراً التركيبة المعدنية للتربة.