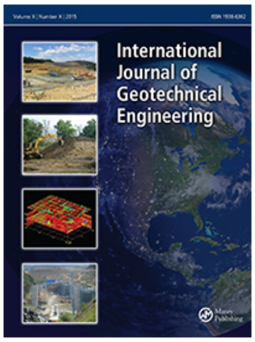

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Assessment of sulphates effect on the classification of soil–lime–natural pozzolana mixtures based on the Unified Soil Classification System (USCS)

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Assessment of sulphates effect on the classification of soil–lime–natural pozzolana mixtures based on the Unified Soil Classification System (USCS)

Hamid Gadouri[1,2]*, Khelifa Harichane[2] and Mohamed Ghrici[2]

According to the Unified Soil Classification System (USCS), fine-grained soils, such as clays and silts, can be classified by plotting the values of their plasticity index and liquid limit on a plasticity chart. However, soil classification can be affected by mineral additives and sulphates. The effect of both sodium (Na_2SO_4) and calcium ($CaSO_4{\cdot}2H_2O$) sulphates on the soil classification of soil–natural pozzolana, soil–lime and soil–lime–natural pozzolana mixtures has been studied. The results showed that in the absence of sulphates, the addition of lime and lime–natural pozzolana to both clayey soils improved considerably their soil classification. However, a negligible change in soil classification was recorded when natural pozzolana was used alone. The presence of sulphates influenced significantly the soil classification of these mixtures, especially with the curing period. The modification in the soil classification was more pronounced with the Na_2SO_4 than with the $CaSO_4{\cdot}2H_2O$. Furthermore, the sensitivity of the soil classification to the sulphate effect was also more pronounced with the Na_2SO_4 than with the $CaSO_4{\cdot}2H_2O$. The utilisation of $CaSO_4{\cdot}2H_2O$ as on additive is highly recommended for obtaining the best class soil. In general, the transformation in the class soil of both stabilised grey and red soils depends largely on the type of additive and its amount, the type of sulphate and its amount, the mineralogical composition of the stabilised soil and the curing period.

Keywords: Clayey soil, Lime, Natural pozzolana, Stabilisation, Sulphates, Soil classification

Introduction

Chemical soil stabilisation using cement, lime and fly ash has been practised for several years with the main aim to render the bad soil able of meeting the requirements of the specific engineering projects (Kolias *et al*. 2005). However, cement was used as a main hydraulic binder for various projects such as road pavements, earth dams and constructions (Mehta 1999). Several researchers (Hossain *et al*. 2007, Mfinanga and Kamuhabwa 2008, Harichane *et al*. 2010, 2011a, 2011b, 2011c, 2012, Zoubir *et al*. 2013, Segui *et al*. 2013, al-Swaidani *et al*. 2016, Gadouri *et al*. 2016a, 2016b) have studied the effect of volcanic materials on geotechnical properties of clayey soils. In fact, the combination of volcanic ash with lime caused beneficial effects on the physico-mechanical behaviour of stabilised soils (Hossain *et al*. 2007). Moreover, for a longer curing period, the shear strength values of cohesive soils stabilised with the combination of natural pozzolana and lime are very larger as compared to those of untreated soils (Harichane *et al*. 2011a).

In Algeria, bad soils with high expansion, high plasticity index and low-bearing capacity are usually encountered. For example, most of the soils used in the highway project have been stabilised using cement and/or lime in order to make them able to carry the traffic loads. However, these stabilised soils have caused severe damages to infrastructures in form of cracks and expansion. According to Mitchell (1986) and Baryla *et al*. (2000), the formation of ettringite and/or thaumasite was responsible for these damages due to the presence of sulphate ions.

The natural pozzolana is available with high amounts in areas of Beni-Saf located in the west of Algeria. This volcanic material can be used in civil and geotechnical engineering projects (Ghrici *et al*. 2007). The effects of Na_2SO_4 and $CaSO4{\cdot}2H_2O$ on the unconfined compressive strength of clayey soils stabilised with lime and natural pozzolana have been investigated by Gadouri

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et al. (2016a, 2016b). They have reported in their study that sulphate ions react with alumina $[Al(OH)_4]$ and silica $[SiO(OH)_3]^-$ compounds, calcium (Ca^{2+}) and hydroxyl (OH^-) ions to form the ettringite mineral responsible for the degradation of stabilised clayey soils. Furthermore, the magnitude of the damage caused by this mineral depends on the additive type and its content, the mineralogical composition of the soil, the type of sulphate and its content and the curing period (Kinuthia *et al*. 1999, Sivapullaiah *et al*. 2000, 2006, Le Borgne 2010, Segui *et al*. 2013, Aldaood *et al*. 2014a, 2014b, Hu *et al*. 2016, Gadouri *et al*. 2016a, 2016b). Furthermore, Yilmaz and Civelekoglu, 2009 and Gadouri *et al*. (2016b) reported that the utilisation of gypsum as an additive produced a beneficial effect on strength and plasticity of clayey soils, whereas the Na_2SO_4 induced a disagreeable effect (Kinuthia *et al*. 1999, Hu *et al*. 2016, Gadouri *et al*. 2016a). However, the natural pozzolana in combination with lime showed a high resistance to sulphate attacks (Gadouri *et al*. 2016a).

In Algeria, intensive road networks are currently in building require an improvement. However, the soil classification is very important in practices of geotechnical engineering. The effect of lime, natural pozzolana and their combination on the soil classification has been studied by Harichane and Ghrici (2009). In this study, the assessment of sulphates effect on the soil classification of soil–lime–natural pozzolana mixtures has been investigated based on the USCS according to ASTM D2487-06 (2006).

Materials extractions and characterisation

Extraction of soils and natural pozzolana

In this study, two clayey soils were obtained from Chelif town located in the west of Algeria. The grey soil (GS) and red soil (RS) were obtained from an embankment project site and a highway project site, respectively. However, the natural pozzolana was used as an additive for soil stabilisation. It was obtained from Beni–Saf deposit located in the west of Algeria. All these materials were extracted and transported to the laboratory for preparation and testing.

Soils

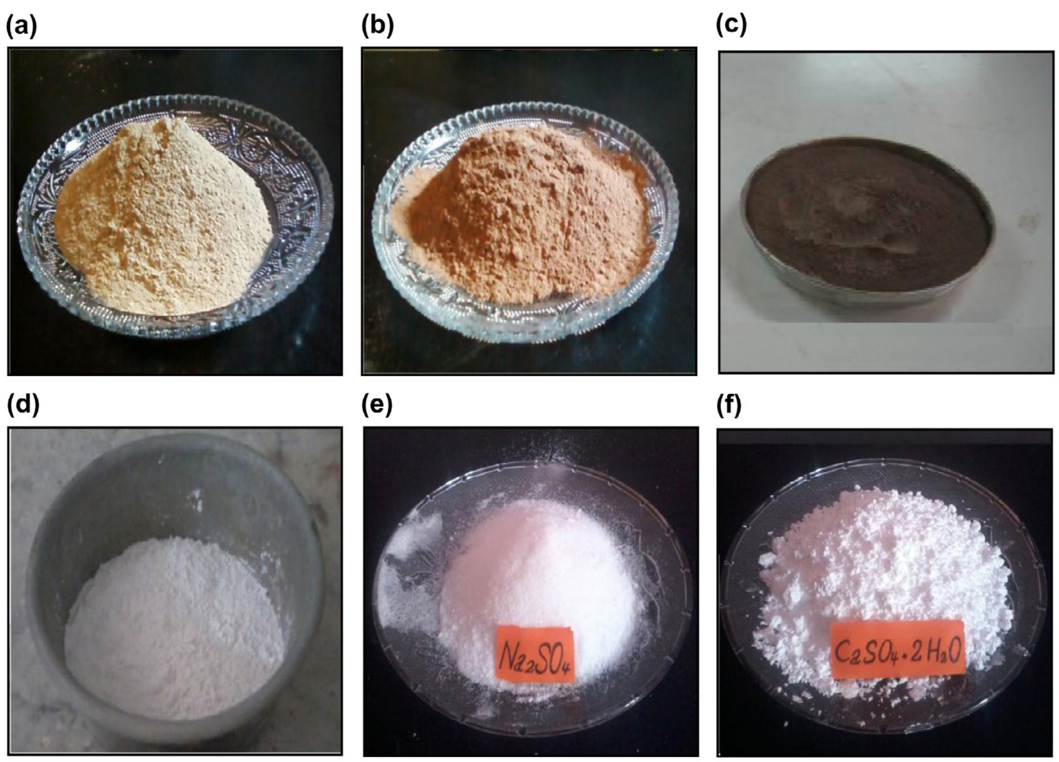
Laboratory tests were carried out for the characterisation and classification of both clayey soils (Fig. 1(a) and (b)). The physico-mechanical and chemico-mineralogical properties of these soils are depicted in Tables 1 and 2, respectively.

Mineral additives

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

Sulphates

In this study, two chemical compounds were used. The first is a sodium sulphate (Na_2SO_4) (Fig. 1(e)). The second is a calcium sulphate dihydrate ($CaSO_4{\cdot}2H_2O$) (Fig. 1(f)). Both sulphates were produced by Biochem Chemopharma, which is a leading international manufacturer and supplier of laboratory reagents. The physico-chemical properties of these elements are shown in Table 4.



1 Materials used *a* grey soil sample *b* red soil sample *c* natural pozzolana powder *d* hydrated lime *e* Na_2SO_4 and *f* $CaSO_4{\cdot}2H_2O$

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

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 Chemicomineralogical properties of both clayey soils (After Gadouri *et al*. 2016a)

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
Sulphite	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	$Al_2((Si_4Al)O_{10})(OH)_2.H_2O$	20.0	–
Chlorite	$Mg_2Al_4O_{18}Si_3$	–	9.0
Other minerals	–	6.0	7.0
Organic matter	–	0.33	–

Test procedures and samples preparation

Atterberg limits test

Atterberg limits of both untreated and treated soils containing Na_2SO_4 (Gadouri *et al*. 2016a) and $CaSO_4{\cdot}2H_2O$ (Gadouri *et al*. 2016b) were studied and performed according to ASTM D4318 (2000). However, several samples were studied in order to assess the effect of these chemical compounds on the soil classification of soil–lime, soil–natural pozzolana and soil–lime–natural pozzolana mixtures. Table 5 represents a total of 126 combinations based on both grey and red soils.

Samples preparation

Soil–lime, soil–natural pozzolana and soil–lime–natural pozzolana mixtures

Both clayey soils were stabilised by using natural pozzolana (0, 10 and 20%), lime (0, 4 and 8%) and the combination of both (lime–natural pozzolana). The distilled water was added to the soil mixture for the Atterberg limits test. The samples were preserved in the airtight container for about 1 and 30 days of curing prior to testing in order to let the water invades through the soil mixture. After curing, the obtained paste was remixed again with each additive thoroughly for at least 15 min before performing the first test. The plastic limit tests were performed on material prepared for the liquid limit test. The plastic limit values were calculated as the average of both water contents. Both liquid limit and plastic limit tests were conducted at room temperature. However, the plasticity index value is the difference between both liquid limit and plastic limit.

Soil–lime–sulphates, soil–natural pozzolana–sulphates and soil–lime–natural pozzolana–sulphates mixtures

The samples were mixed in the same way as presented earlier except that different contents of Na_2SO_4 and $CaSO_4{\cdot}2H_2O$ powders (0-6% by weight of dry soil) were also added to the soil–lime, soil–natural pozzolana and soil–lime–natural pozzolana mixtures in a dry state. Moreover, when the distilled water was added to the mixtures the Atterberg limits tests were performed in the same way as presented earlier and tested after the same curing periods.

Experimental results and discussion

Effect of additives on the soil classification of both clayey soils

According to ASTM D2487-06 (2006), the A-line on the plasticity chart separates silts (symbolised by M) from clays (symbolised by C). However, liquid limit = 50% separates high plasticity soils (symbolised by H) from low plasticity soils (symbolised by L). In addition, the dual classification (clay–silt class of low plasticity symbolised by CL–ML) must be used when the Atterberg limits plot in the hatched region on the plasticity chart near the origin.

Both untreated (grey and red soils) and treated (soil–lime, soil–natural pozzolana and soil–lime–natural pozzolana mixtures) clayey soil samples are classified by plotting the values of their plasticity index and liquid limit on a plasticity chart in order to determine the new soil classification according to the USCS after curing for 1 and 30 days (Fig. 2).

The grey soil classified as clay of high plasticity (symbolised by CH in the plasticity chart) because the point (liquid limit, plasticity index) representing the grey soil class was above the A-line and in the right of liquid limit = 50% line. However, when lime and lime–natural pozzolana have added the point representing the grey soil class was dropped below the A-line and transformed to high plasticity silt (symbolised by MH in the plasticity chart). On the other hand, no soil class transformation was observed when the natural pozzolana was added to the grey soil. In addition, there is a negligible modification in the classification of both untreated and treated-grey soil with the curing period.

However, a similar trend was observed for the red soil classified as clay of low plasticity (symbolised by CL in the plasticity chart) that was transformed to silt of high plasticity for stabilisation with lime alone or in combination with natural pozzolana. However, no transformation in the red soil class was observed with natural pozzolana addition. After 30 days of curing, the addition of lime or lime–natural pozzolana brings the red soil

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

Physical/chemical name	L (%)	NP (%)
Physical form	Dry white powder	Dry brown powder
Specific gravity	2.0	–
Over 90 μm (%)	<10.0	–
Over 630 μm (%)	0	–
Insoluble material (%)	<1.0	–
Bulk density (g /L)	600–900	–
Loss on ignition	–	5.34
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 Physicochemical properties of chemical compounds used (After Gadouri *et al.* 2016a)

Physicochemical properties	Calcium sulphate (%)	Sodium sulphate (%)
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
Auuay (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

(classified as clay of low plasticity) to a region near grey soil (transformed to silt of high plasticity). The changes in soil classes can be explained by the flocculation and agglomeration of clay particles due to the lime or lime–natural pozzolana addition.

Effect of additives on the soil classification of untreated soil samples containing sulphates

The changes in the soil classification of both untreated (grey and red soils) and treated soil samples (soil–lime, soil–natural pozzolana and soil–lime–natural pozzolana mixtures) caused by the presence of Na_2SO_4 and $CaSO_4{\cdot}2H_2O$ are presented in Figs. 3 and 4. For any curing period, both untreated soil samples showed a marginal transformation in soil classes upon the addition of various Na_2SO_4 contents. In contrast, the utilisation of 4% and 6% $CaSO_4{\cdot}2H_2O$ alone brings the grey soil (classified as clay of high plasticity) to a region between the silt class of low plasticity (symbolised by ML in the plasticity chart) and clay class of high plasticity after 1-day curing period (Fig. 3(a)). Whereas for the same soil (grey soil) the $CaSO_4{\cdot}2H_2O$ transformed the clay class of high plasticity to silt class of high plasticity after curing for 30 days (Fig. 3(b)).

In the case of the red soil, the incorporation of only 6% $CaSO_4{\cdot}2H_2O$ brings the clay class of low plasticity to a region between the silt and clay classes of low plasticity after curing for 30 days (Fig. 4(b)). It should be noted that the change in the soil classification of untreated soils was more affected by the presence of Ca^{2+} cations than by the presence of Na^+ cations. Furthermore, the sensitivity of the soil classification of untreated soils to the $CaSO_4{\cdot}2H_2O$ effect was more pronounced with the grey soil than with the red soil.

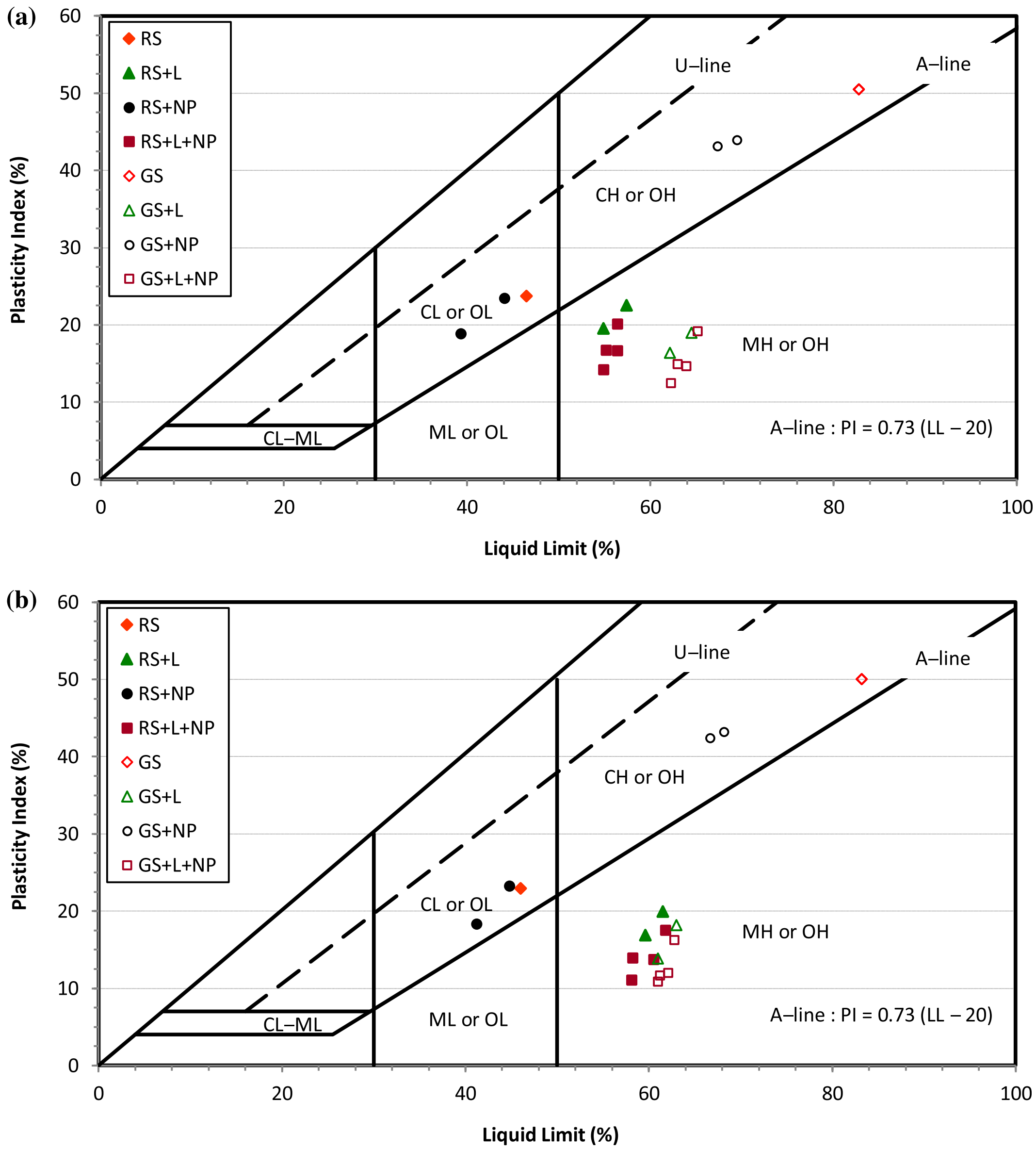
Effect of sulphates on the soil classification of soil–lime, soil–natural pozzolana and soil–lime–natural pozzolana mixtures

For any curing period, the addition of 2% of Na_2SO_4 to the grey soil–natural pozzolana mixture has no effect on its classification (because the grey soil–natural pozzolana–Na_2SO_4 mixture presented the same class soil to compare to the soil–natural pozzolana mixture without Na_2SO_4). However, after 1 and 30 days curing period, the presence of 4% and 6% Na_2SO_4 transformed the grey soil–natural pozzolana mixture (classified as clay of high plasticity) to silt class of high plasticity (Fig. 3). On the other hand, after 1 day of curing period, there is no change in the soil class of both clayey soils when the natural pozzolana was used as an additive in the presence of any content of $CaSO_4{\cdot}2H_2O$ (Figs. 3(a) and 4(a)). But after 30 days of curing period, the presence of any contents of $CaSO_4{\cdot}2H_2O$ transformed the grey soil–natural pozzolana mixture (classified as clay of high plasticity) to silt class of high plasticity (Fig. 3(b)). However, for any curing period, no soil class transformation was observed when the natural pozzolana was added to the red soil samples containing different amounts of $CaSO_4{\cdot}2H_2O$. However, after curing for 30 days, the red soil stabilised with natural pozzolana (classified as clay of low plasticity) was transformed to silt class of low plasticity when the samples containing 4% and 6% $CaSO_4{\cdot}2H_2O$ (Fig. 4(b)). It should be noted that the sensitivity of the soil classification of the soil–natural pozzolana mixture to the $CaSO_4{\cdot}2H_2O$ effect was more pronounced with the grey soil than with the red soil.

For any curing period, the Na_2SO_4 transformed the grey soil–lime and grey soil–lime–natural pozzolana mixtures (classified as silt of high plasticity) to extremely high plasticity silt class, whereas the $CaSO_4{\cdot}2H_2O$ presents a negligible effect (Fig. 3). The same behaviour was observed by Celik and Nalbantoglu (2013) and Kinuthia *et al.* (1999). However, a similar trend was observed for the red soil–lime and red soil–lime–natural pozzolana mixtures when the Na_2SO_4 transformed these mixtures (classified as silt of high plasticity) to very high plasticity and extremely high plasticity silt classes after 1 and 30 days of curing period, respectively (Fig. 4). However, after 30 days of curing, the red soil–lime–natural pozzolana mixture (classified as silt of high plasticity) containing 6% $CaSO_4{\cdot}2H_2O$ was transformed to silt class of low plasticity (Fig. 4(b)). In general, the $CaSO_4{\cdot}2H_2O$ has a much better effect on the soil classification of studied mixtures to compare with the Na_2SO_4. It is obvious to observe that the sensitivity of the soil classification of both treated clayey soils to the Na_2SO_4 effect was more pronounced with the addition of lime than with the lime–natural pozzolana addition.

Table 5 A summary of the mix combinations tested for two clayey soil samples with and without sulphates

	SM (%)					SM (%)					SM (%)					SM (%)			
D	S	NP	L	Ca	D	S	NP	L	Ca	D	S	NP	L	Na	D	S	NP	L	Na
P0L0	100	0	0	0	P0L0C4	96	0	0	4	P0L0N2	98	0	0	2	P0L0N6	94	0	0	6
P0L4	96	0	4	0	P0L4C4	92	0	4	4	P0L4N2	94	0	4	2	P0L4N6	90	0	4	6
P0L8	92	0	8	0	P0L8C4	88	0	8	4	P0L8N2	90	0	8	2	P0L8N6	86	0	8	6
P10L0	90	10	0	0	P10L0C4	86	10	0	4	P10L0N2	88	10	0	2	P10L0N6	84	10	0	6
P20L0	80	20	0	0	P20L0C4	76	20	0	4	P20L0N2	78	20	0	2	P20L0N6	74	20	0	6
P10L4	86	10	4	0	P10L4C4	82	10	4	4	P10L4N2	84	10	4	2	P10L4N6	80	10	4	6
P20L4	76	20	4	0	P20L4C4	72	20	4	4	P20L4N2	74	20	4	2	P20L4N6	70	20	4	6
P10L8	82	10	8	0	P10L8C4	78	10	8	4	P10L8N2	80	10	8	2	P10L8N6	76	10	8	6
P20L8	72	20	8	0	P20L8C4	68	20	8	4	P20L8N2	70	20	8	2	P20L8N6	66	20	8	6
P0L0C2	98	0	0	2	P0L0C6	94	0	0	6	P0L0N4	96	0	0	4	D–Designation				
P0L4C2	94	0	4	2	P0L4C6	90	0	4	6	P0L4N4	92	0	4	4	SM–Soil Mixture				
P0L8C2	90	0	8	2	P0L8C6	86	0	8	6	P0L8N4	88	0	8	4	S–Soil				
P10L0C2	88	10	0	2	P10L0C6	84	10	0	6	P10L0N4	86	10	0	4	Ca–$CaSO_4.2H_2O$				
P20L0C2	78	20	0	2	P20L0C6	74	20	0	6	P20L0N4	76	20	0	4	Na–Na_2SO_4				
P10L4C2	84	10	4	2	P10L4C6	80	10	4	6	P10L4N4	82	10	4	4					
P20L4C2	74	20	4	2	P20L4C6	70	20	4	6	P20L4N4	72	20	4	4					
P10L8C2	80	10	8	2	P10L8C6	76	10	8	6	P10L8N4	78	10	8	4					
P20L8C2	70	20	8	2	P20L8C6	66	20	8	6	P20L8N4	68	20	8	4					



2 Effect of 20% natural pozzolana, 8% lime and their combination on the classification of both clayey soil samples for different curing period *a* 1 day and *b* 30 days

Effects of additives on the soil classification of both clayey soils

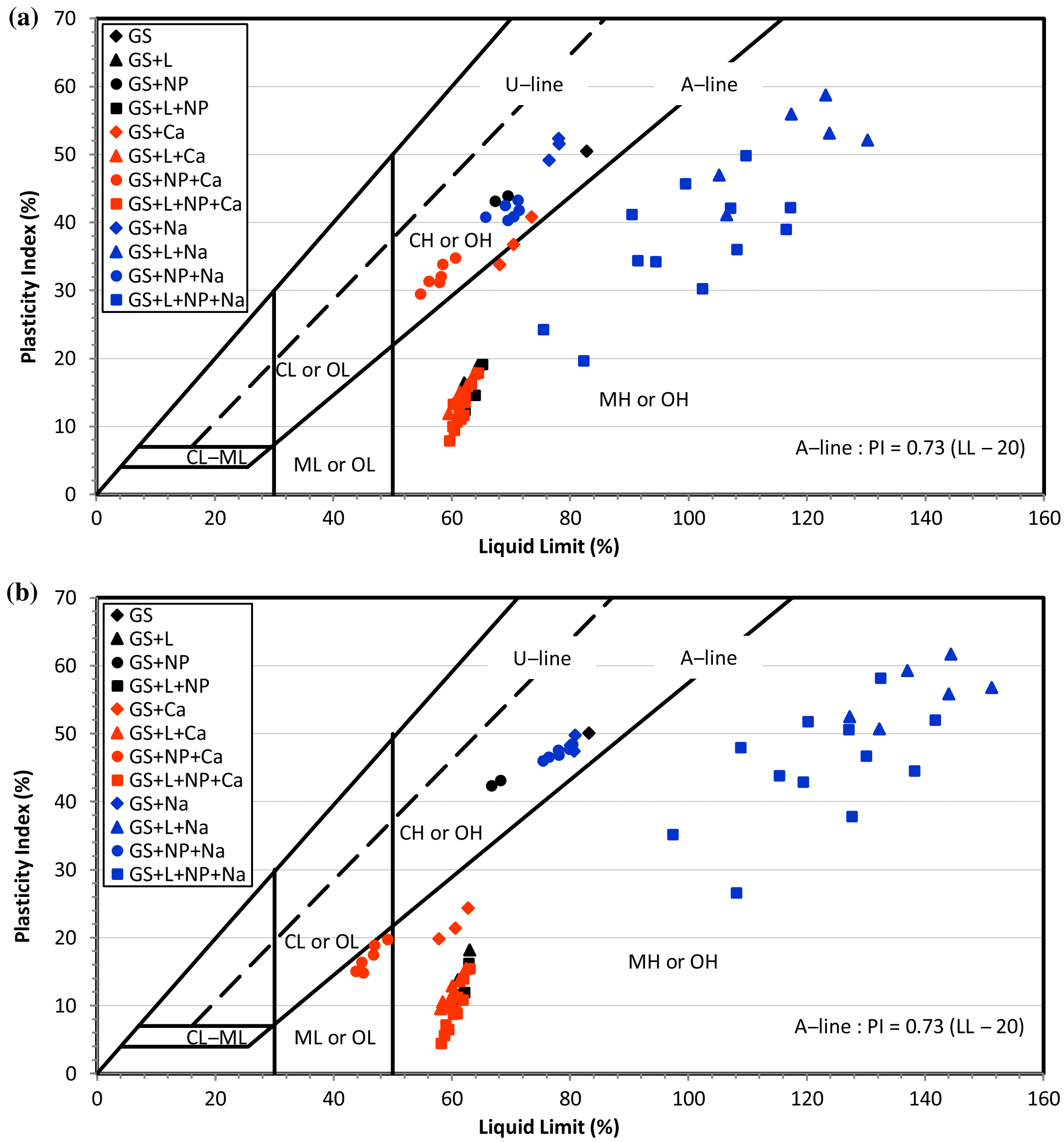
When sulphates are absent, the addition of lime alone or lime–natural pozzolana to the fine-grained soils produces an immediate effect on their physical properties due to the cation-exchange capacity. Electrically, clay particles surface is negatively charged, which develops high repulsive forces between them. However, the ionisation of calcium hydroxide ($Ca(OH)_2$) in the presence of water produces Ca^{2+} and hydroxyl (OH^-) ions when they are attracted to the surface of clay particles, shown as Equation (1). This reduces the repulsive forces and consequently increases the adhesion between clay particles to form flocks by flocculation and agglomeration (Locat *et al.* 1990). Particles flocculation is the result of the electric reaction between clay particles and Ca^{2+} which leads to the immediate change in consistency limits (Gadouri *et al.* 2016a), and consequently, the modification in the soil classification (Rahman 1986, George *et al.* 1992, Harichane and Ghrici 2009).

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

(*Ionisation of calcium hydroxide in the presence of water*)

Effects of sulphates on the soil classification of soil–lime, soil–natural pozzolana and soil–lime–natural pozzolana mixtures

The dissolution of both Na_2SO_4 and $CaSO_4{\cdot}2H_2O$ in the presence of water produces Ca^{2+} and Na^+ cations shown as (Equations (2) and (3)).



3 Effect of different amounts of Na_2SO_4 and $CaSO_4{\cdot}2H_2O$ on the classification of the grey soil stabilised with lime, natural pozzolana and their combination after different curing period *a* 1 day and *b* 30 days

$$Na_2SO_4 \rightarrow 2Na^+ + SO_4^{2-} \quad \text{(Dissolution of sodium sulphate)} \tag{2}$$

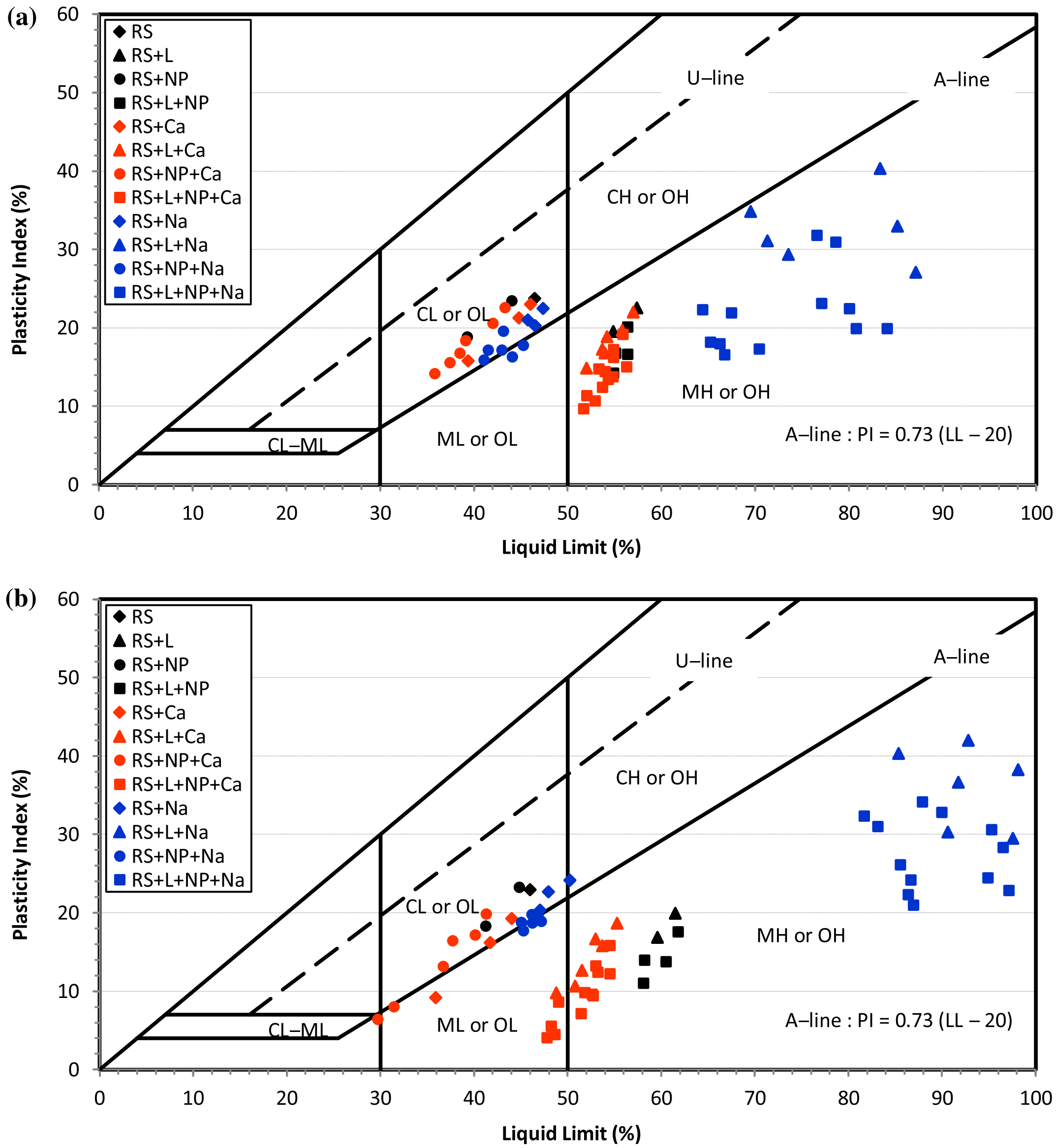
$$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \quad \text{(Dissolution of calcium sulphate)} \tag{3}$$

Moreover, as shown in Equation (4), the reaction between Na_2SO_4 and lime in the presence of water leads to the formation of NaOH that develops a higher alkaline solution to compare with that of the $Ca(OH)_2$ (Roy 1986).

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

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

The introduction of any contents of $CaSO_4{\cdot}2H_2O$ to both stabilised clayey soil samples presents the tendency to lower the particle–particle separation due to the exchange of Ca^{2+} cations between the clay particles and $CaSO_4{\cdot}2H_2O$. This decreases the plasticity index of soil–lime, soil–natural pozzolana and soil–lime–natural pozzolana mixtures (Gadouri *et al*. 2016b) and then develops a suitable soil classification. In contrast, the presence of Na_2SO_4 with any contents has the tendency to increase the particle–particle separation due to the exchange of Na^+ cations between the clay particles and Na_2SO_4. This increases the plasticity index of soil–lime, soil–natural pozzolana and soil–lime–natural pozzolana mixtures (Gadouri *et al*. 2016a) and then develops an unsuitable soil classification.



4. Effect of different amounts of Na_2SO_4 and $CaSO_4{\cdot}2H_2O$ on the classification of the red soil stabilised with lime, natural pozzolana and their combination after different curing period *a* 1 day and *b* 30 days

Conclusions

The effect of Na_2SO_4 and $CaSO_4{\cdot}2H_2O$ on the soil classification of soil–lime, soil–natural pozzolana and soil–lime–natural pozzolana mixtures has been studied. Based on the test results, the following conclusions can be drawn:

- In the absence of sulphates, the soil classification of both clayey soils tended to be transformed according to the USCS. The utilisation of lime alone or in combination with natural pozzolana transformed the grey soil (classified as clay of high plasticity) and red soil (classified as clay of low plasticity) to silt class of high plasticity. In addition, no soil class transformation was observed for both clayey soils when using natural pozzolana alone.
- Both clayey soils can be used for most engineering projects such as road pavements or even under brutal environmental conditions due to the modification of their plasticity properties caused by the addition of lime and lime–natural pozzolana.
- When sulphates are present, the Ca^{2+} cations (from $CaSO_4{\cdot}2H_2O$ and lime addition) affect considerably the soil classification of both clayey soils compared to the Na^+ cations (from Na_2SO_4). Furthermore, the sensitivity of the soil classification of both untreated and soil–natural pozzolana mixture to the $CaSO_4{\cdot}2H_2O$ effect was more pronounced with the grey soil than with the red soil.
- For a longer curing period (30 days), the presence of any contents of $CaSO_4{\cdot}2H_2O$ alone or in a combination of natural pozzolana transformed the grey soil (classified as clay of high plasticity) and red soil (classified as clay of low plasticity) to silt class of low plasticity.

- It is very important to categorise the Na_2SO_4 as a deleterious element for soil classification when it is present with high concentration due to the alteration of soil stabilisation process by modifying of the cation-exchange capacity.
- The effects of Na_2SO_4 and $CaSO_4 \cdot 2H_2O$ on the classification of studied mixtures depend on several factors such as the amount of additive used and its type, the sulphate concentration and its type, the mineralogical composition of the stabilised soil and the curing period.

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Conflict of interest

No potential conflict of interest was reported by the authors.

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