

Effect of sodium sulphate on the shear strength of clayey soils stabilised with additives

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Abstract The effect of sulphates on the soil stabilisation using mineral additives such as lime, cement and fly ash has been reported by several researchers. The effect of sodium sulphate (Na_2SO_4) (0–6% by dry weight of soil) on the behaviour of the grey clayey soil (GS) and red clayey soil (RS) stabilised with lime (L) (0–8%), natural pozzolana (NP) (0–20%) and with a combination of lime-natural pozzolana (L–NP) was investigated. The soil specimens were subjected to testing of direct shear strength after 7, 30, 60 and 120 days of curing period. In the absence of Na_2SO_4 , the results show that both clayey soils can be successfully stabilised with L or with a combination of L–NP, which substantially increases their shear strength and produces high values of shear parameters. However, at short curing period and for any content of Na_2SO_4 , a further increase in shear strength and shear parameters is observed. Moreover, after 30 days of curing, the RS specimens stabilised with L or with NP alone are altered when the Na_2SO_4 is greater than 2%, whereas the GS specimens are not altered. However, the alteration of RS specimens is little when the L and NP are combined on curing with a high content of Na_2SO_4 . Generally, the effect of Na_2SO_4 on both stabilised clayey soils depends on the curing time, percentage of additives used and their type, mineralogical composition of stabilised soils and Na_2SO_4 content.

Keywords Clayey soil · Lime (L) · Natural pozzolana (NP) · Stabilisation · Sodium sulphate (Na_2SO_4) · Shear strength

Introduction

Chemical soil stabilisation using L, cement and other mineral additives is not new and remain so far the cheapest technique used in soil stabilisation (Ola 1977; Rahman 1986; Afès and Didier 2000; Kavak and Akyarli 2007). When no sulphates are present, the cation exchange capacity of the soil depends largely on its particles with negatively charged surfaces (Grim 1968). This negative charge develops repulsive forces between the clay particles. However, in the absence of sulphates, the lime hydrates and ionises after its contact with water to form calcium ions and hydroxyl (Ouhadi and Yong 2008). This change has the effect of reducing the size of the double layer of clay particles, lowering the repulsive forces between them and increasing the alkalinity of the solution system (George et al. 1992; Smith et al. 1994). The reduction in repulsive forces between these particles creates a bond between them and forms flocks (Locat et al. 1990). This change caused by lime reduces the plasticity of the stabilised soil (Osula 1996; Manasseh and Olufemi 2008), decreases their maximum dry density and increases their optimum moisture content (George et al. 1992; Harichane et al. 2011b).

However, the increase in hydroxyl (OH^-) concentration raises the pH of the soil, and causes the dissolution of alumina and silica which interact with calcium ions to form cementitious products such as calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H) (Glenn and Handy 1963; Mitchell 1986; Abdi and Wild 1993). The formation of these compounds was confirmed by several researchers (Mitchell 1986; Hunter 1988; Abdi and Wild 1993). These cementitious products are responsible for the increase of both

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compressive strength (Lin et al. 2007; Harichane et al. 2012) and shear strength of the stabilised soil (Gay and Schad 2000; Sezer et al. 2006).

However, a high volume of problematic soils can be excluded to be used as materials for construction due to their low quality. Indeed, it is known that the most frequent problem in the world for various civil engineering projects is the presence of inappropriate soils which require a special technique for their improvement such as chemical stabilisation, dynamic compaction and soil replacement. Chemical soil stabilisation has been practiced for several years with the main aim to render these soils capable of meeting the requirements of the specific engineering projects (Koliass et al. 2005). However, cement has been used as a main hydraulic binder for civil engineering projects such as road pavements, earth dams and building constructions (Mehta 1983). But, the production of 1 MT of cement leads to the emission of about 1 MT of CO₂ and requires large amounts of energy (Segui et al. 2013). In order to reduce both energy consumption and CO₂ emission, several researchers recommended the use of volcanic materials such as volcanic ash and natural pozzolana (NP) (Al-Rawas et al. 2005; Hossain et al. 2007; Mfinanga and Kamuhabwa 2008; Harichane et al. 2012; Segui et al. 2013; Zoubir et al. 2013; al-Swaidani et al. 2016; Gadouri et al. 2016a, 2016b, 2016c). These mineral additives have been used in combination with L for soil stabilisation because of their economic benefits and advantageous properties. Indeed, it has been reported that the combination of volcanic ash with L produced beneficial effects on the physico-mechanical behaviour of the stabilised soil (Hossain et al. 2007). In addition, Harichane et al. (2011a) reported that for a longer curing period, shear strength and unconfined compressive strength values of cohesive soils stabilised with the combination of L and NP are very large compared with that of the untreated soils. According to Khemissa and Mahamedi (2014), expansive and salted soils with low resistance (strength) and high plasticity are amongst the problematic soils most met in the Algerian arid and semi-arid regions. It was necessary to improve these soils in order to render them acceptable for construction. For example, most of the soils used in the East-West highway project located in the north of Algeria have been improved using cement and/or L in order to make them able to carry the traffic loads. But, these soils caused severe damage to infrastructures in form of cracks and swelling. In fact, various forms of degradation observed in road pavements are frequently dependent on the formation of new expansive phases such as ettringite and/or thaumasite due to the presence of sulphate ions (SO₄²⁻) (Baryla et al. 2000). Also, the magnitude of damage caused by the ettringite mineral depends on the soil nature (Wild et al. 1998; Sivapullaiah et al. 2006), additive type and its content (Le Borgne 2010) and sulphate concentration and/or the type of cations associated with SO₄²⁻ (Kinuthia et al. 1999; Sivapullaiah et al. 2000). On the other

hand, the effects of Na₂SO₄ on geotechnical properties of clayey soils stabilised with L, NP and their combination have been investigated, where they have reported that the combination of both L and NP resist to the sulphate attack (Gadouri et al. 2016a).

However, the combination of volcanic materials with lime produces a beneficial effect on the behaviour of stabilised soils (Hossain et al. 2006; Kumar et al. 2007). Due to the availability of NP with high amounts in areas of Beni-Saf located in the west of Algeria (Ghrici et al. 2007), the NP was used in combination with L in order to improve the geotechnical properties of two clayey soils such as Atterberg limits, unconfined compressive strength, shear strength and durability (Harichane and Ghrici 2009; Harichane et al. 2010, 2011a, 2011b, 2011c, 2012). The soil shear strength is the main factor for any analysis related with stability including slope stability analysis (Sadrjamali et al. 2015). However, there is no investigation regarding the effects of sulphates on the geotechnical properties of these clayey soils. This paper is devoted in order to study the effect of Na₂SO₄ on the shear strength of two clayey soils by the addition of L, NP and their combination. Direct shear strength test was selected due to its simplicity and used for obtaining shear strength parameters (cohesion and internal friction angle), and Mohr-Coulomb theory was used for calculating them.

Experimental investigation

Materials used

Soils

In the present study, two soils were used; the first is a grey clayey soil (GS) which was obtained from an embankment

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- μ m 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 ($\gamma_{d_{max}}$; 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 ₂ O ₃	5.56	7.22
Alumina	Al ₂ O ₃	14.15	19.01
Silica	SiO ₂	43.67	57.02
Sulphite	SO ₃	0.04	0.19
Sodium oxide	Na ₂ O	0.34	0.93
Potassium oxide	K ₂ O	1.96	3.17
Titan dioxide	TiO ₂	0.65	0.83
Phosphorus	P ₂ O ₅	0.18	0.14
pH	–	9.18	9.05
Calcite	CaCO ₃	26.0	4.0
Albite	NaAlSi ₃ O ₈	–	8.0
Illite	2K ₂ O.Al ₂ O ₃ .24SiO ₂ .2H ₂ O	16.0	24.0
Kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄	12.0	16.0
Montmorillonite	Al ₂ ((Si ₄ Al)O ₁₀)(OH) ₂ .H ₂ O	20.0	–
Chlorite	Mg ₂ Al ₄ O ₁₈ Si ₃	–	9.0
Ferruginous minerals	–	6.0	7.0
Organic matter	–	0.33	–

project site, and the second is a red clayey soil (RS) which was obtained from a highway project site and both near Chelif town in the west of Algeria. Both clayey soils were excavated, placed in plastic bags and transported to the laboratory for preparation and testing. Laboratory tests were carried out to classify each type of soil. The physico-mechanical and chemico-mineralogical properties of two clayey soils are depicted in Tables 1 and 2, respectively. The particle size distribution curves of both GS and RS samples (Fig. 1) were obtained by using a dry sieving method according to NF P 94–056. On the other hand, both values 85% (for GS) and 97.5% (for RS) given in Table 1 were obtained by passing 80- μ m sieve using a wet sieving method (water was used as a solution for clay

particle dispersion) in order to obtain a maximum dispersion of clay particles (maximum particle-particle separation), and consequently a maximum clay particle content passing 80- μ m sieve.

Mineral additives

The NP used in this study was collected from Beni-Saf located in the west of Algeria. It was ground to the specific surface area of 420 m²/kg. However, the L used in this study is commercially available lime typically used for construction purposes. The physico-chemical properties of these additives are presented in Table 3.

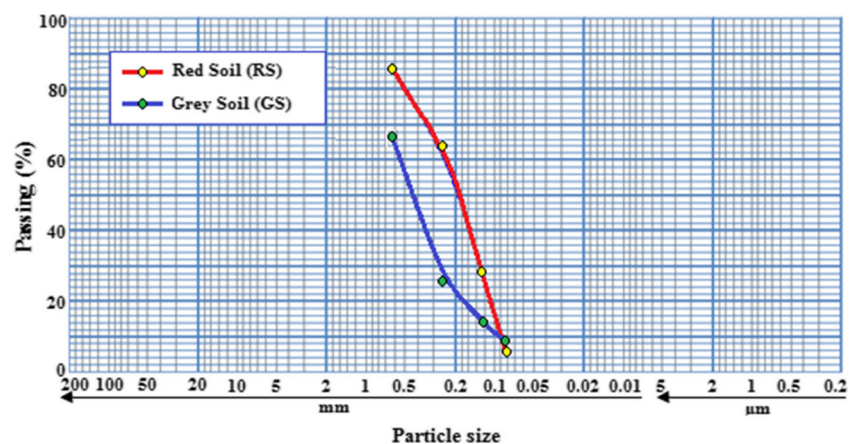
Fig. 1 Particle size distribution curves of both grey and red clayey soils

Table 3 Physico-chemical properties of both 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 ₂ O ₃	<2.0	9.69
Al ₂ O ₃	<1.5	17.5
SiO ₂	<2.5	46.4
SO ₃	<0.5	0.83
Na ₂ O	0.4–0.5	3.30
K ₂ O	–	1.51
CO ₂	<5.0	–
TiO ₂	–	2.10
P ₂ O ₃	–	0.80
CaCO ₃	<10.0	–

Chemical compound

The chemical element used in this study was Na₂SO₄. The physical and chemical properties of this element are depicted in Table 4.

Test procedure

Laboratory tests of shear strength were conducted on both selected clayey soils. Several combinations of NP and L were used for their stabilisation. These combinations were also mixed with Na₂SO₄. A total of 72 combinations based on GS and RS is shown in Table 5.

Table 4 Physico-chemical properties of sodium sulphate

Physico-chemical properties	Sodium sulphate
Physical form	White
Chemical formula	Na ₂ SO ₄
Molar weight (g/mol)	142.04
Auay (dried; %)	99.5
pH (50 g/L, 25 °C)	5 to 8
Insoluble matter (%)	0.005
Chloride (Cl; %)	0.001
Iron (Fe; %)	0.0005
Calcium (Ca; %)	0.01
Phosphorus (PO ₄ ; %)	0.001

Table 5 Combinations of both clayey soils

Designation	Sample mixture (%)			
	Soil	NP	L	Sodium sulphate
P0L0N0	100	0	0	0
P0L4N0	96	0	4	0
P0L8N0	92	0	8	0
P10L0N0	90	10	0	0
P20L0N0	80	20	0	0
P10L4N0	86	10	4	0
P20L4N0	76	20	4	0
P10L8N0	82	10	8	0
P20L8N0	72	20	8	0
P0L0N2	98	0	0	2
P0L4N2	94	0	4	2
P0L8N2	90	0	8	2
P10L0N2	88	10	0	2
P20L0N2	78	20	0	2
P10L4N2	84	10	4	2
P20L4N2	74	20	4	2
P10L8N2	80	10	8	2
P20L8N2	70	20	8	2
P0L0N4	96	0	0	4
P0L4N4	92	0	4	4
P0L8N4	88	0	8	4
P10L0N4	86	10	0	4
P20L0N4	76	20	0	4
P10L4N4	82	10	4	4
P20L4N4	72	20	4	4
P10L8N4	78	10	8	4
P20L8N4	68	20	8	4
P0L0N6	94	0	0	6
P0L4N6	90	0	4	6
P0L8N6	86	0	8	6
P10L0N6	84	10	0	6
P20L0N6	74	20	0	6
P10L4N6	80	10	4	6
P20L4N6	70	20	4	6
P10L8N6	76	10	8	6
P20L8N6	66	20	8	6

Shear strength tests

The type of the apparatus used in this work is a TG 14/1761 model. The direct shear tests are performed according to ASTM D6528 (2000) and were conducted on untreated and treated soil specimens on curing with and without Na₂SO₄. The specimens (6 cm of diameter and 4 cm of length) were prepared by compaction at the maximum dry unit weight and optimum moisture

content deduced of compaction tests. The specimens were stored in plastic boxes to prevent possible loss of moisture which they were kept in the laboratory at the temperature of 25 °C and the relative humidity of 50%. Furthermore, samples are prepared for different curing periods (7, 30, 60 and 120 days). Indeed, the specimens were not saturated and excessive pore water pressure would not be expected in them. The direct shear test was unconsolidated undrained (UU) and the load was applied at a rate of 1 mm/min. The fast shear test (UU) using a high displacement rate was selected for a short-term stability verification using total strengths for the calculation of the stability just after construction. 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.

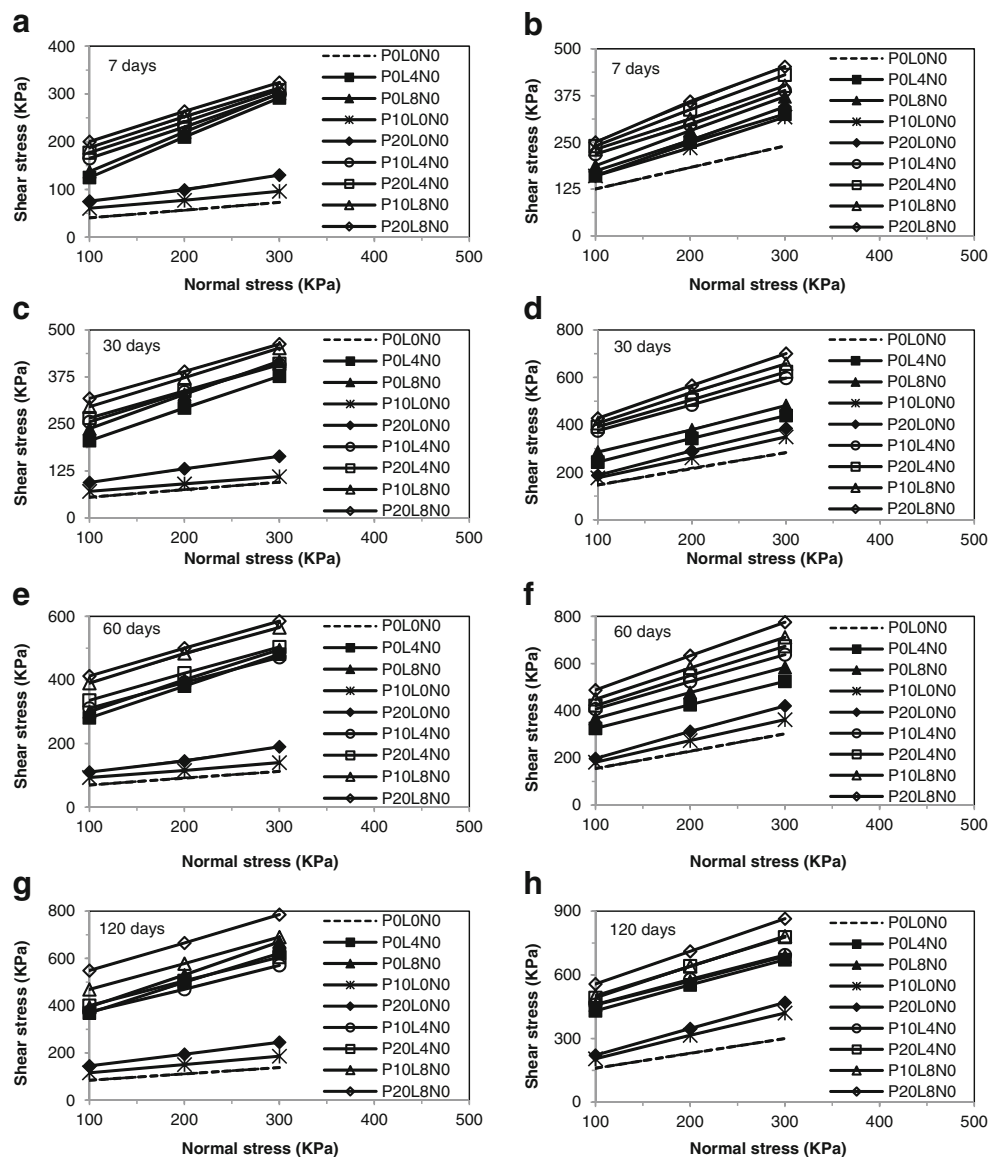
Results and discussions

Shear strength

Temporal variation of the shear stress without sodium sulphate

Figure 2 illustrates the results of the effect of L, NP and their combination on curing without Na₂SO₄ on maximum shear stresses of two stabilised clayey soils. Generally, there is a negligible effect on maximum shear stresses of two clayey soils when the NP is used alone. The maximum shear stresses of two clayey soils increase with increasing L content and curing period. The same behaviour was obtained by Gay and Schad (2000). The stabilisation of two clayey soils with L binds their particles and provokes a better effect on their shear stress, particularly beyond 30 days of curing. The

Fig. 2 Shear stress produced under normal stress without sodium sulphate for different curing periods. **a, c, e, g** Grey clayey soil. **b, d, f, h** Red clayey soil



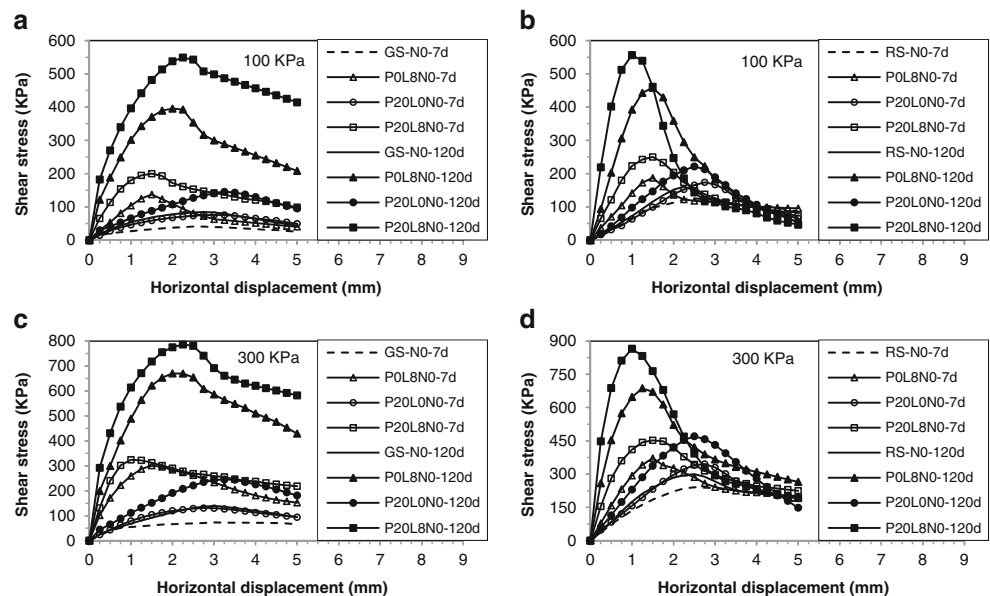
differences in maximum shear stresses between L and NP as additives are more pronounced with the GS than with the RS. This behaviour is probably due to the mineralogical composition and high plasticity index value of the GS as compared with those of the RS. The better results of maximum shear stresses are achieved when the combination of lime-natural pozzolana (L–NP) is used. The increase in maximum shear stresses is very important when the amount of L and NP increases. In addition, it is clear to observe that the combination L–NP presents better effects on maximum shear stresses of the RS than of the GS. The dissolution of alumina and silica from soil and/or NP depends strongly on the L content which produces more cementitious products responsible for the increase in maximum shear stresses of two clayey soils. In all cases, maximum shear strengths were observed for samples stabilised with a combination of L–NP compared to those stabilised with L or NP alone.

Figure 3 depicts the results of the typical shear stress-strain for both unstabilised and stabilised soil specimens using 8% L, 20% NP and their combination (8% L + 20% NP) without Na_2SO_4 for only 7 and 120 days of curing period. In this experimental program, results are obtained from 0- to 5-mm horizontal displacement which can be taken for design regarding the stabilised soils to fail. As shown in Fig. 3, for any curing period and for any normal stress, a negligible change in shear stresses was observed for NP treated both GS and RS specimens compared with untreated soil specimens. In contrast, the higher the normal stress applied on L treated or L–NP treated is, both GS and RS specimens will give higher shear stresses which correspond to small horizontal displacements. Indeed, the increment of horizontal displacement in these specimens (L treated or L–NP treated both GS and RS) varied between 0 and 3 mm, which correspond to maximum shear stresses; e.g. after 7-day curing period and for 100- and 300-

kPa normal stresses, the shear stress values of L-treated GS specimens are 137.29 and 300.81 kPa, which correspond to 1.5-mm horizontal displacement. But after 120-day curing period, the previous shear stresses (137.29 and 300.81 kPa) increase up to 395.4 and 669.97 kPa, respectively, with 100- and 300-kPa normal stresses where the horizontal displacement was also increased up to 2 mm. However, a further increase in both shear stress and horizontal displacement was recorded when L and NP are used as a combined treatment; e.g. after 7-day curing period and for 100- and 300-kPa normal stresses, the shear stress values of L–NP treated the same soil (GS specimens) are 200.13 and 324.1 kPa, which correspond to 1.5- and 1-mm horizontal displacements. But after 120-day curing period, the previous shear stresses (200.13 and 324.1 kPa) become 594 and 785.99 kPa, respectively, with 100- and 300-kPa normal stresses where the horizontal displacement was increased up to 2.25 mm (Fig. 3a, c). The same behaviour was observed for the RS specimens stabilised with L alone or in combination with NP, whereby the RS has the greatest results compared with the GS (Fig. 3b, d). In all cases and for any type of treatment (L, NP and L–NP), maximum shear stresses of both GS and RS specimens increase with curing period, meaning that the shear strength is higher for stabilised specimens compared to untreated soil specimens, especially when using the combination L–NP.

Furthermore, it is obvious to observe that for both L-treated and L–NP-treated GS specimens, maximum shear stresses are reached at 1 and 1.5 mm after 7-day curing period, whereas after 120-day curing period, maximum shear stresses are reached at 2 and 2.25 mm (Fig. 3a, c). A converse behaviour was observed for the RS specimens stabilised with the same additives (L and L–NP) (Fig. 3b, d). As a comparison, both L-treated and L–NP-treated GS specimens will fail more slowly

Fig. 3 A typical shear stress-strain for both unstabilised and stabilised soil specimens using 8% L, 20% NP and 8% L + 20% NP without sodium sulphate for 7 and 120 days of curing period. **a**, **c** Grey clayey soil with 100- and 300-kPa normal stress. **b**, **d** Red clayey soil with 100- and 300-kPa normal stress



for a shorter curing period (7 days) compared to the longer curing period (120 days), whereas a converse effect was observed for the RS. However, both stabilised GS and RS are more consolidated by cementing agents (C–S–H and/or C–A–H), and this gives strength to both stabilised soils. Also, the sensitivity of the horizontal displacement to the curing period effect was more pronounced with the GS than with the RS.

Temporal variation of the shear stress with sodium sulphate

A comparison of the effects of different contents of Na₂SO₄ on maximum shear stresses of two stabilised clayey soils is depicted in Figs. 4, 5 and 6. There is a negligible increase in maximum shear stresses of two

clayey soils when the NP is used with 2% of Na₂SO₄ but decreases with increasing Na₂SO₄ content. However, maximum shear stresses of L-treated two clayey soils with 2% Na₂SO₄ increase with increasing L content and curing period. But after 60 days of curing, maximum shear stresses of the GS stabilised with NP or L alone decrease gradually when the Na₂SO₄ is greater than 2% (Figs. 5e, g and 6e, g). The decrease in maximum shear stresses can be explained by the reduction in the capacity of cementing due to the adsorption of sulphates on the surfaces of C–S–H (Mehta 1983). Moreover, after 30 days of curing, maximum shear stresses of the RS specimens stabilised with NP or L alone are altered when the Na₂SO₄ content is greater than 2% (Figs. 5h and 6f, h). The alteration of NP-treated RS specimens is certainly not linked with the

Fig. 4 Effect of 2% sodium sulphate on the shear strength of both stabilised clayey soils for different curing periods. **a, c, e, g** Grey clayey soil. **b, d, f, h** Red clayey soil

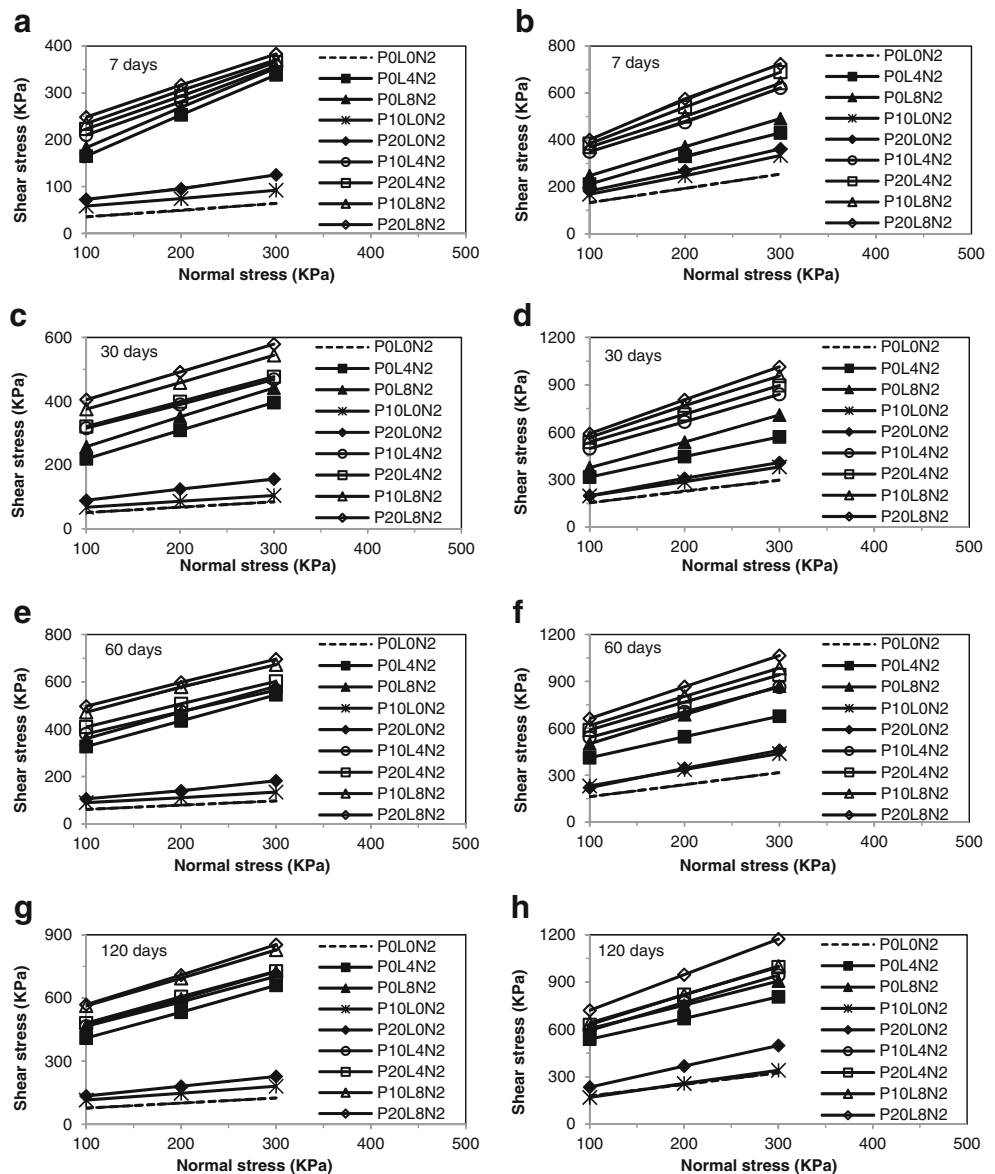
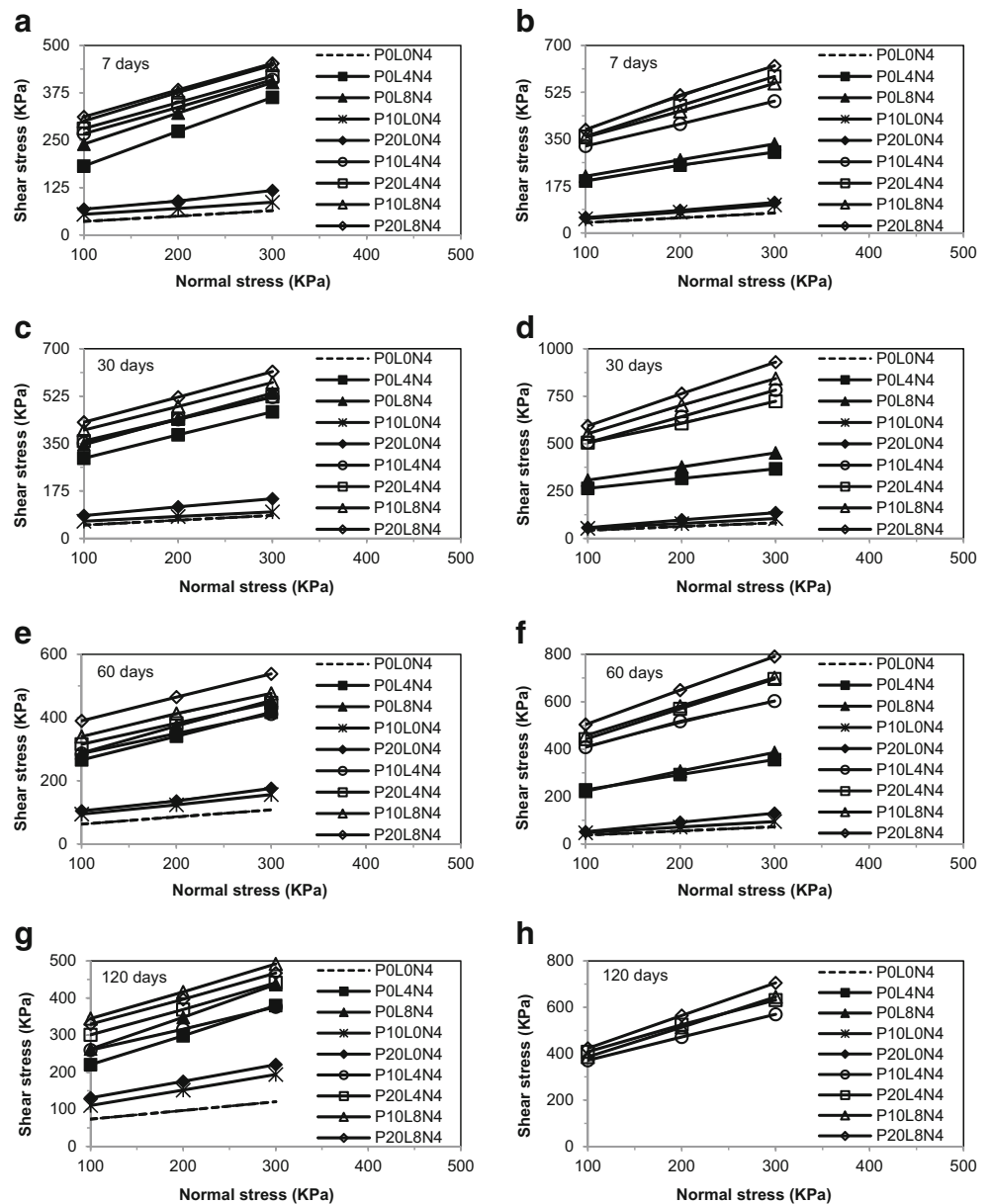


Fig. 5 Effect of 4% sodium sulphate on the shear strength of both stabilised clayey soils for different curing periods. **a, c, e, g** Grey clayey soil. **b, d, f, h** Red clayey soil

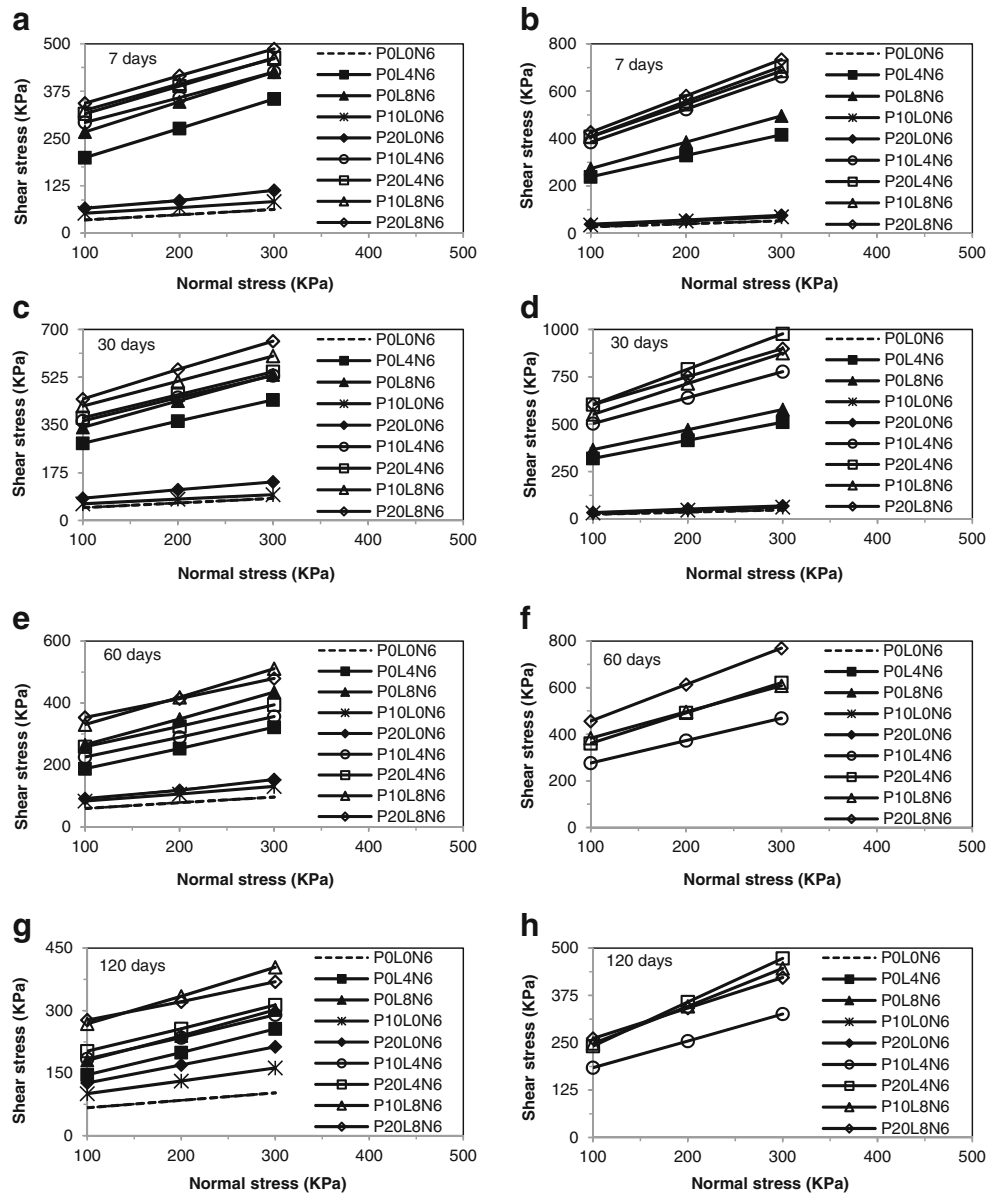


eventual formation of ettringite which is not observed in X-ray diffraction (XRD) patterns (Fig. 12c). But according to Fig. 12b, the alteration of L-treated RS specimens is probably linked with the formation of ettringite. Indeed, the pressure value developed by the ettringite mineral can be higher than that of the tensile strength value of the soil which leads to its degradation (Le Borgne 2010). Moreover, the alteration is not observed in GS specimens; this leads us to suppose that this alteration is due to the behaviour of the RS with the Na_2SO_4 interaction. From these results, it is possible to classify the Na_2SO_4 as a deleterious element for soil stabilisation when its content is greater than 2% by dry weight of soil. Generally, for any content of Na_2SO_4 , the differences in maximum shear stresses

between L and NP as additives are more pronounced with the GS than with the RS.

Furthermore, for a shorter curing period, the increase in maximum shear stresses of two clayey soils is strongly important when the combination L–NP is used as an additive, especially with increasing Na_2SO_4 content (Fig. 4). However, after 30 days of curing, maximum shear stresses of two clayey soils decrease gradually when the Na_2SO_4 content is greater than 2%. The decrease in maximum shear stresses is more pronounced in the RS than in the GS. The same behaviour was observed by Sivapullaiah et al. (2006). Generally, for any content of Na_2SO_4 , the RS specimens are not altered when the combination L–NP is used as an additive.

Fig. 6 Effect of 6% sodium sulphate on the shear strength of both stabilised clayey soils for different curing periods. **a, c, e, g** Grey clayey soil. **b, d, f, h** Red clayey soil



It is known that without Na₂SO₄, when the L is mixed with water (2H₂O), the hydroxide lime [Ca(OH)₂] hydrolyses first and increases the pH value of the solution very quickly as follows:



When Na₂SO₄ is added, the reaction between Ca(OH)₂ and Na₂SO₄ in the presence of 2H₂O has been given by Roy (1986) as follows:

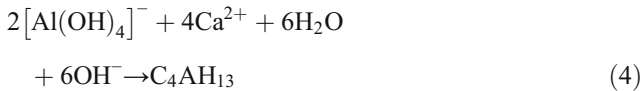
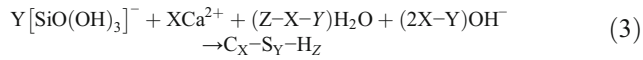


According to Sridhran et al. (1995), the reaction between L, NP and Na₂SO₄ in the presence of 2H₂O results in a higher alkaline solution than that of the

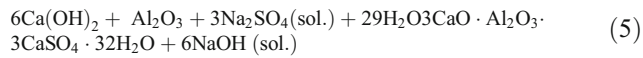
Ca(OH)₂ saturated solution; this leads to the dissolution of a large amount of alumina and silica which react with the remaining L to form a high amount of cementitious products responsible for the significant increase in maximum shear stresses of two clayey soils.

According to Shi and Day (2000), the dissolution of amorphous silica (SiO₂) increases very steeply if the pH of the soil solution is greater than 12.5. Generally, the pH will have a similar effect on the dissolution of NP as that on the amorphous SiO₂ because the main composition of NP is silica. However, the acceleration in the NP dissolution leads to the acceleration in the rate of pozzolanic reactions. Consequently, depolymerised monosilicate and aluminate species enter in the solution and form two main compounds [SiO(OH)₃]⁻ and [Al(OH)₄]. However, both C-S-H and C₄-A-H₁₃ compounds

can be formed when calcium ions (Ca^{2+}) contact these dissolved species (monosilicates and aluminates) as follows:



At the same time, the introduction of Na_2SO_4 in the stabilised soil increases the concentration of SO_4^{2-} and leads to the formation of ettringite which densifies the structure and increases the strength of the stabilised system as follows:



The high early increase in maximum shear stresses of two clayey soils stabilised with L or with the combination L–NP is attributed to the acceleration of early pozzolanic reactions and the formation of more ettringite due to the presence of Na_2SO_4 .

The results of the effects of Na_2SO_4 on the typical shear stress-strain of stabilised soil specimens using 8% L, 20% NP and 8% L + 20% NP for only 7 and 120 days of curing period are shown in Figs. 7 and 8. In all cases, it should be noted that

the value of 5 mm is also adopted as a maximum horizontal displacement for both GS and RS specimens stabilised with L, NP and their combination. It can be seen that for any curing period and for any normal stress, a marginal change in shear stresses was recorded for NP-treated both GS and RS specimens containing different Na_2SO_4 contents compared with stabilised specimens without Na_2SO_4 (Figs. 7 and 8). Conversely, the higher the shear stresses and the lower the horizontal displacements of L treated or L–NP treated are, both GS and RS specimens are observed when the higher normal stresses with a low Na_2SO_4 content (2%) are applied. In addition, it is quite clear to observe that the shear stresses for 8% L or 8% L + 20% NP gives a very consistent curve that collapse into one for the same normal stresses applied but highly influenced by the curing period. However, both treatment using 8% L alone or the combination 8% L + 20% NP develop higher stress-strain curves when the normal stresses were increased from 100 up to 300 kPa.

On the one hand, for a shorter curing period (7 days) and for any normal stresses, it can be observed that the shear stresses of L-treated GS specimens' increase with increasing Na_2SO_4 content but decrease with its increasing at a later stage (120 days); e.g. after 7-day curing period and for a normal stress of 100 kPa, the L-treated GS specimens increase the shear stresses from 137.29 up to 183, 239.4 and 267.5 kPa

Fig. 7 A typical shear stress-strain for unstabilised and stabilised grey clayey soil specimens using 8% L, 20% NP and 8% L + 20% NP in the presence of 2, 4 and 6% sodium sulphate for 7 and 120 days of curing period. **a, c, e** Shear test with 100-kPa normal stress. **b, d, f** Shear test with 300-kPa normal stress

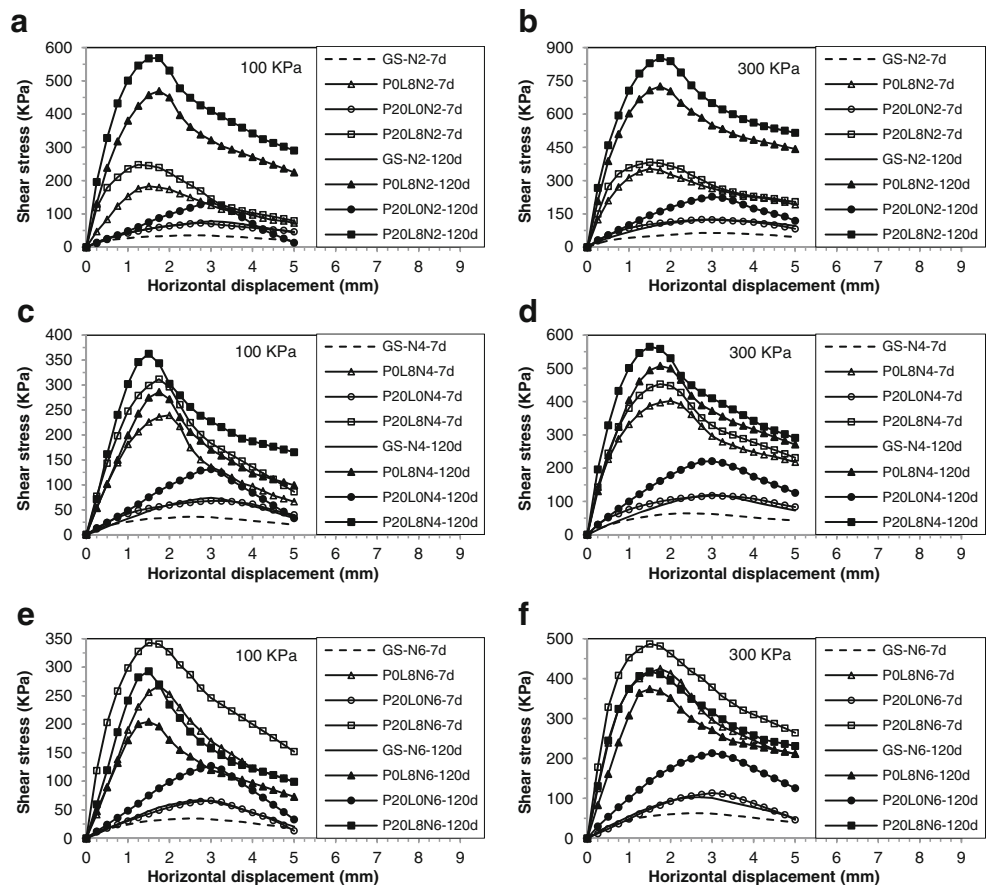
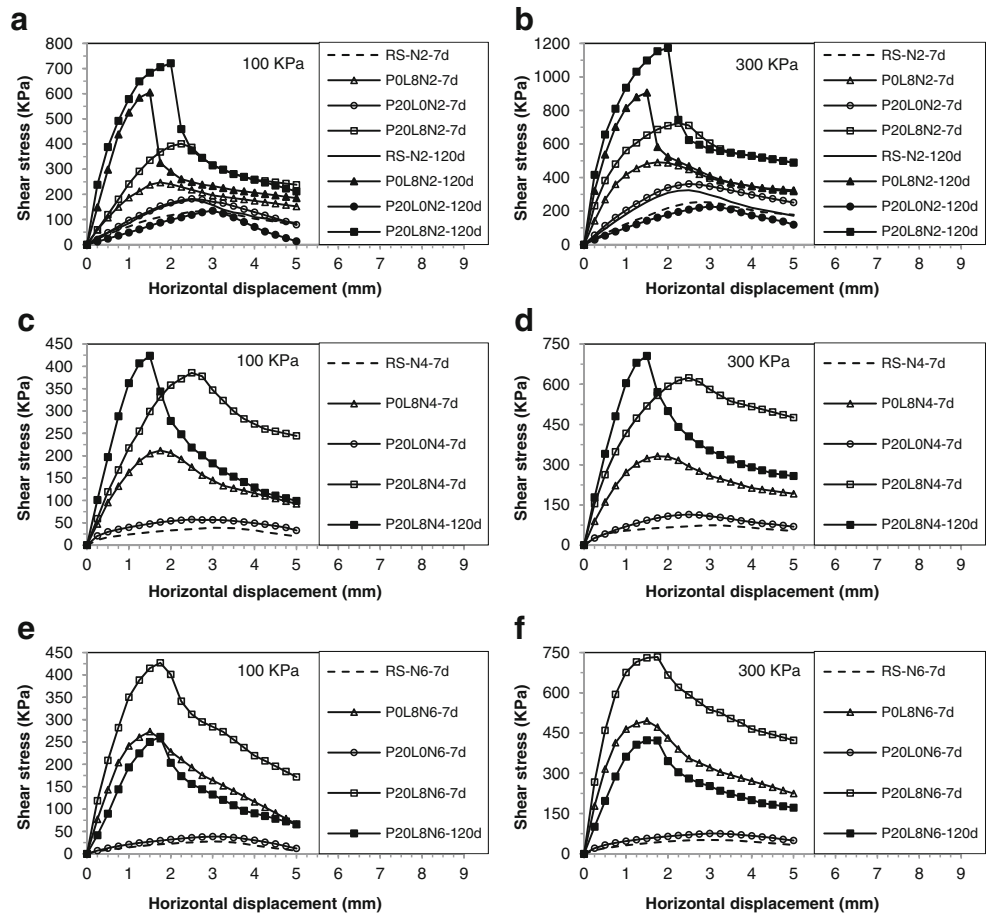


Fig. 8 A typical shear stress-strain for unstabilised and stabilised red clayey soil specimens using 8% L, 20% NP and 8% L + 20% NP in the presence of 2, 4 and 6% sodium sulphate for 7 and 120 days of curing period. **a, c, e** Shear test with 100-kPa normal stress. **b, d, f** Shear test with 300-kPa normal stress



in the presence of 2, 4 and 6% Na₂SO₄, respectively. However, for a longer curing period (120 days), the shear stresses of the same soil (L-treated GS specimens) increase up to 469.3, 285.9 and 204.4 kPa, respectively, with the presence of 2, 4 and 6% Na₂SO₄. The same behaviour was observed when a maximum normal stress (300 kPa) is applied (Fig. 7). An additional increase in shear stresses was observed when using the combined treatment of L and NP.

On the other hand, for a shorter curing period (7 days) and for any normal stresses, it can be seen that the shear stresses of L-treated RS specimens' increase with increasing Na₂SO₄ content, but for a longer curing period, all RS specimens were altered (specimens were broken during curing before testing) in the presence of 4 and 6% Na₂SO₄ (Fig. 8) due to the formation of a new expansive mineral (ettringite) (Figs. 11 and 12). However, it should be noted that the combination of L and NP can resist to the sulphate attack (when Na₂SO₄ content is more than 2%) especially at a later stage (Fig. 8c–f) (Gadouri et al. 2016a). For comparison, there is a small change in horizontal displacements of L-treated and L–NP-treated both GS and RS specimens containing Na₂SO₄ compared to specimens without Na₂SO₄. In addition, the sensitivity of shear stresses to the Na₂SO₄ effect is more pronounced with the RS than with the GS, particularly at a later stage (120 days).

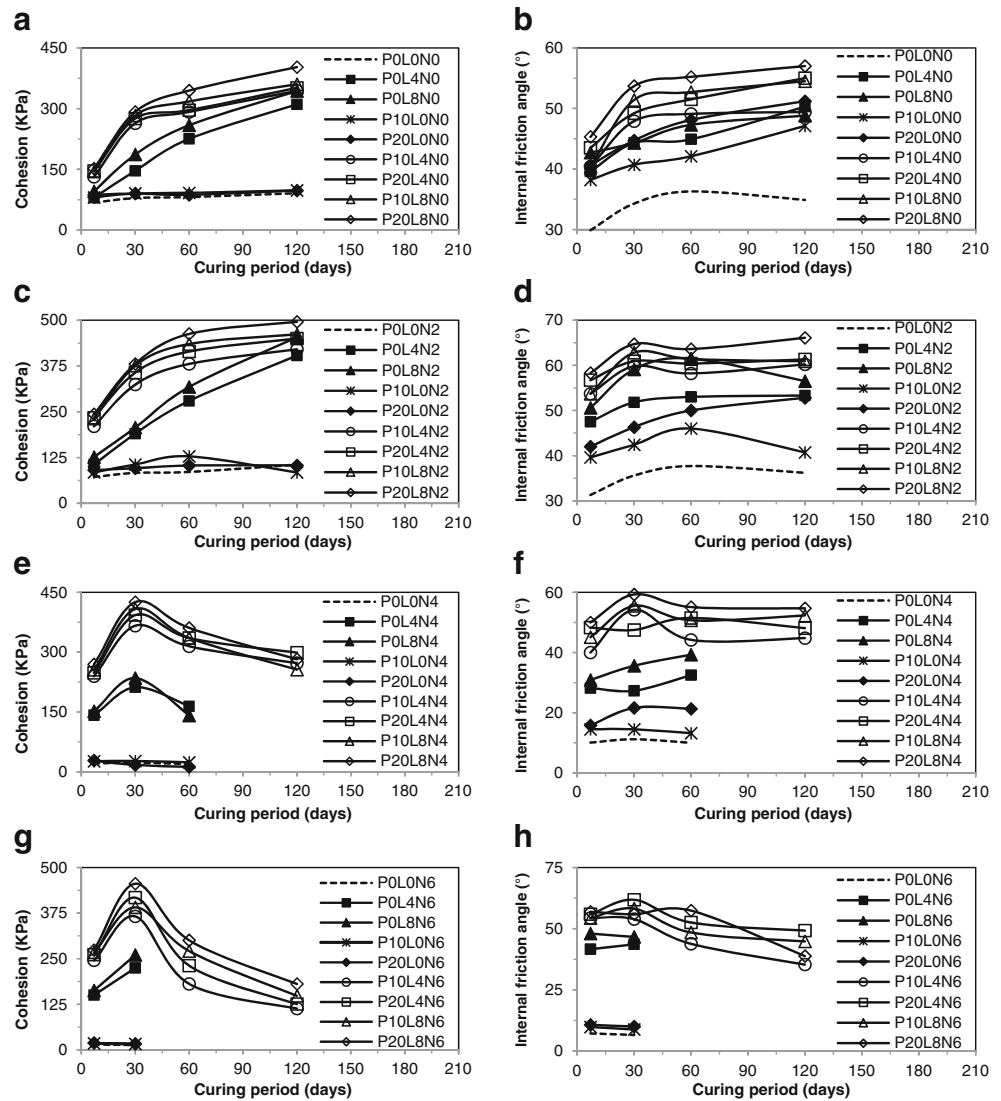
Shear parameters

Temporal variation of the cohesion without sodium sulphate

Figures 9 and 10 depict the results of the effects of L, NP and their combination with and without Na₂SO₄ on the temporal variation of shear parameters of two clayey soils. In this study, only the shear parameters using the maximum shear stresses were calculated, because, in slope stability analysis, the maximum shear strength is generally of primary importance.

The results of the temporal variation of cohesion of two stabilised clayey soils without Na₂SO₄ are presented in Figs. 9a and 10a. In all cases, there is a much better increase in the cohesion as compared with that of the untreated soil. This is particularly noticeable in both clayey soils with the combination L–NP. But the addition of NP to two clayey soils increases slightly their cohesion due probably to its little reactivity with the clay particles. In addition, the XRD analyses confirm that the formation of cementitious compounds (C–S–H and C–A–H) in NP-treated two clayey soils is not observed (Figs. 11f and 12f). However, it can be seen that in the case of L-treated two clayey soils without Na₂SO₄, the cohesion increases with increasing L content and curing period, particularly at later stages. The increase in cohesion is very

Fig. 9 Temporal variation of shear strength characteristics of red clayey soil with curing period in the presence of different contents of sodium sulphate. **a, c, e, g** Cohesion. **b, d, f, h** Internal friction angle

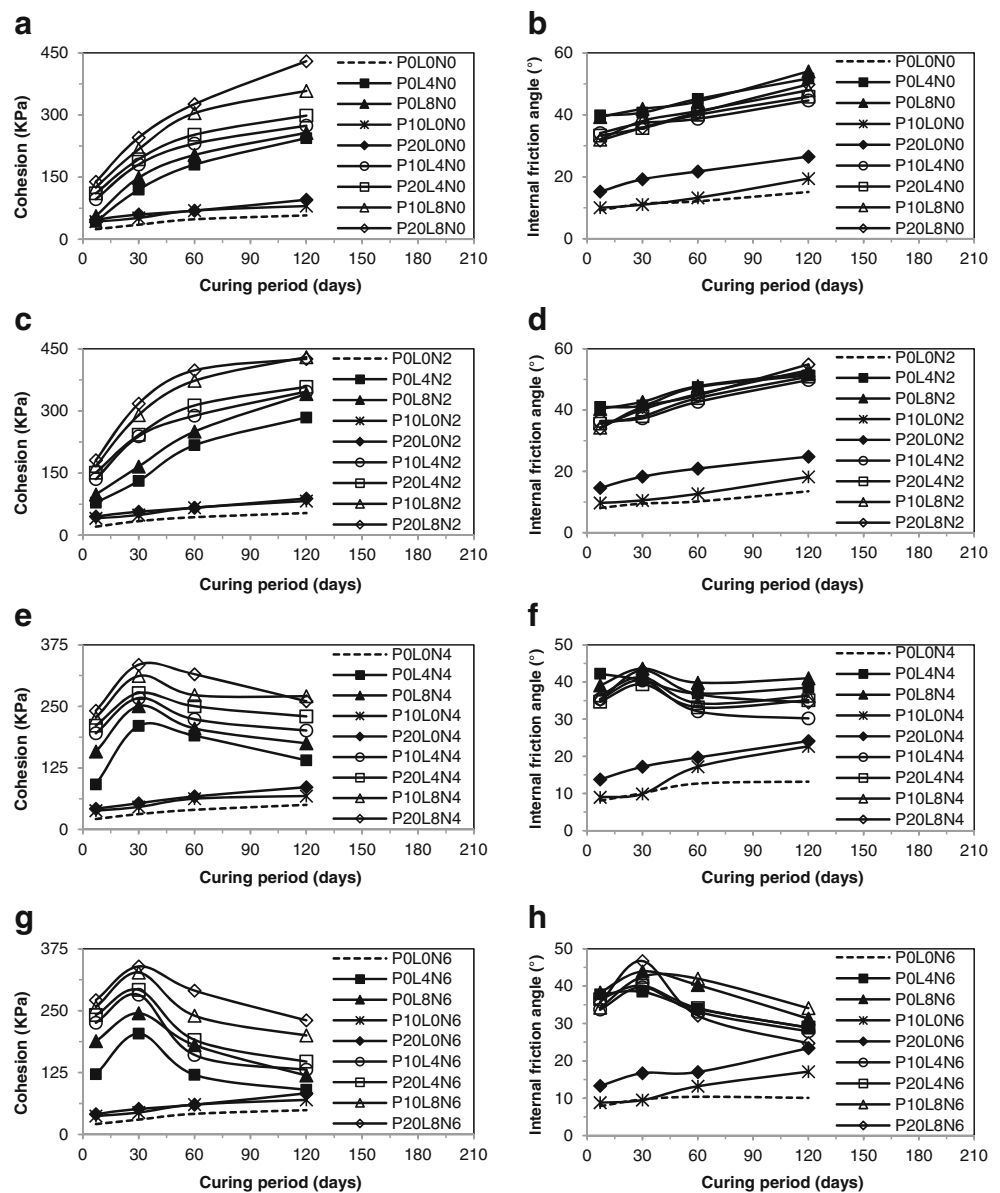


pronounced in the RS than in the GS; e.g. for 8% L, the cohesion of the GS and RS is, respectively, 56.1 and 95.8 kPa after 7 days of curing but increases, respectively, up to 256.9 and 343.4 kPa after curing for 120 days. A similar behaviour was observed by Gay and Schad (2000). The increase in cohesion with the L content was due to the bonding of particles to form larger aggregates so that the soil behaves as a coarse-grained, strongly bonded particulate material (Ola 1978). On the other hand, this behaviour is probably due to both the cementation and pozzolanic reactions which occur over time (Lees et al. 1982; Bell 1989), and also to the self-hardening effect related to the L (Harichane et al. 2011c). Indeed, the formation of cementitious compounds in L-treated two clayey soils is confirmed by XRD analyses (Figs. 11e and 12e).

It is clear to observe that in all cases, the highest cohesion is obtained when the L and NP are combined, whereby the RS has the greatest values; e.g. the cohesion of both GS and RS

stabilised with the combination 10% NP + 4% L is, respectively, 96.8 and 131.4 kPa after 7 days of curing but increases, respectively, up to 274 and 344.1 kPa after curing for 120 days. In addition, the cohesion of two clayey soils is further most when the amount of the combination L–NP is considerably important; e.g. the stabilisation of the GS with the combination 20% NP + 8% L develops a cohesion of 429.7 kPa after curing for 120 days, which represents an increase of 1.6 times compared with the combination 10% NP + 4% L and 7.4 times compared with the untreated GS. 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 the combination 10% NP + 4% L alone and 4.4 times compared with the 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 a little value as compared to that of the GS. The significant increase in the cohesion of two clayey soils, especially

Fig. 10 Temporal variation of shear strength characteristics of grey clayey soil with curing period in the presence of different contents of sodium sulphate. **a, c, e, g** Cohesion. **b, d, f, h** Internal friction angle



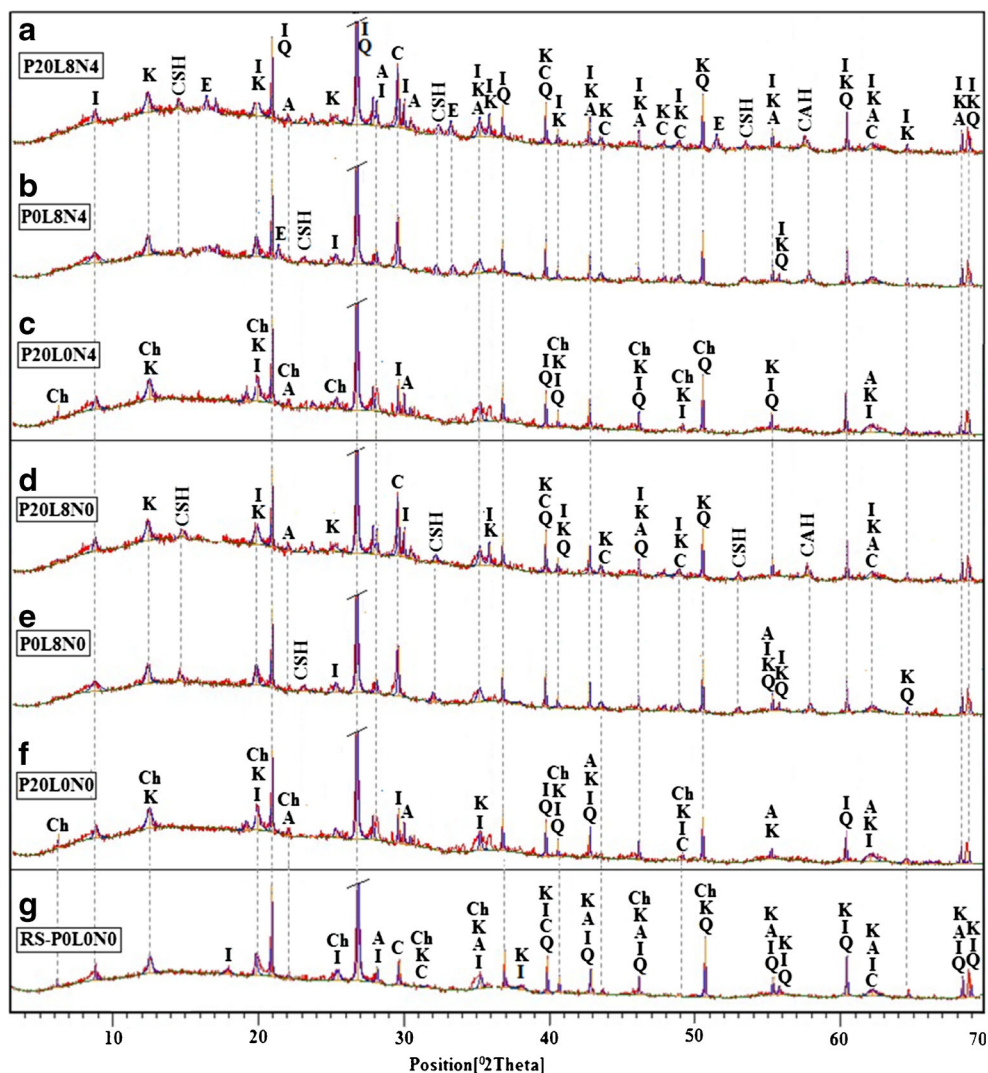
with curing period, is attributed to the formation of cementitious compounds which bind the soil particles together.

Temporal variation of the cohesion with sodium sulphate

The results of the temporal variation of cohesion of two stabilised clayey soils on curing with different contents of Na₂SO₄ are shown in Figs. 9c, e, g and 10c, e, g. In all cases and for a shorter curing period, there is a better increase in cohesion values of two clayey soils with increasing Na₂SO₄ content as compared with that of the treated soil. This behaviour is due to enhanced lime reactions by increased availability of silica due to the increase in pH of soil solution (Davidson et al. 1960). With 2% of Na₂SO₄ and with any curing periods, the cohesion of two clayey soils is greater with the

combination of L–NP than with the L alone, but the differences in cohesion between these two types of treatment (L–NP and L alone) are more pronounced with the RS than with the GS (Figs. 9c and 10c); e.g. with 2% of Na₂SO₄, the cohesion of both GS and RS stabilised with 8% L is, respectively, 98.4 and 126.4 kPa after 7 days of curing but increases, respectively, up to 340.9 and 453.3 kPa after curing for 120 days. Whereas for the same content of Na₂SO₄, the cohesion of both GS and RS stabilised with the combination 20% NP + 8% L is, respectively, 181.3 and 243.2 kPa after 7 days of curing but increases, respectively, up to 425.7 and 495.4 kPa after curing for 120 days. However, for a longer curing period, the decrease in cohesion and/or the degradation of soil specimens stabilised with L or NP alone occurs with an increase in Na₂SO₄ content. This confirms that the effect of Na₂SO₄ with

Fig. 12 a–g X-ray diffraction analyses of untreated and treated red clayey soil samples without or with 4% of sodium sulphate after curing for 60 days, *E* ettringite, *A* albite, *Ch* chlorite, *Q* quartz, *K* kaolinite, *I* illite, *C* calcite



period. The same behaviour is observed when the GS is stabilised with L alone. The enhancement in the shear parameter values may be due to the pozzolanic activity and self-cementitious characteristics of the mixed (Harichane et al. 2011c).

Temporal variation of the internal friction angle with sodium sulphate

The results of the temporal variation of the internal friction angle of two stabilised clayey soils on curing with different contents of Na₂SO₄ are shown in Figs. 9b, f, h and 10b, f, h. Generally, the internal friction angle of two clayey soils stabilised with NP increases slightly with curing period but decreases with Na₂SO₄ content. With NP as an additive, the decrease in the internal friction angle is more pronounced in the RS than in the GS. However, the internal friction angle of two clayey soils stabilised with L alone or with a combination

of L–NP on curing with 2% Na₂SO₄ increases with curing period but decreases gradually with increasing Na₂SO₄ content. An exception of the case of the stabilised GS on curing with 4% Na₂SO₄ the internal friction angle decreases from 30 up to 60 days of curing but after this curing period the rate of decrease to be still constant (Fig. 10f). Additionally, with 6% of Na₂SO₄, the internal friction angle of both clayey soils stabilised with L or with a combination of L–NP decreases very quickly with curing period (Figs. 9h and 10h). It is clear to see that the internal friction angle of two clayey soils stabilised with L alone or with a combination of L–NP on curing without or with 2% of Na₂SO₄ increases with increasing of cohesion (Figs. 9a–d and 10a–d). Moreover, when the Na₂SO₄ content is greater than 2%, the internal friction angle initially increases with increasing of cohesion up to 30 days of curing but both internal friction angle and cohesion decrease, or even alter, after this curing period (Figs. 9e–h and 10e–h).

Conclusions

The effect of Na_2SO_4 on both shear stress and shear parameters of two clayey soils stabilised with L, NP and their combination has been studied. Based on the test results, the following conclusions can be drawn:

The addition of L to two clayey soils stabilised without Na_2SO_4 improves significantly their shear strengths and shear parameters which increase with increasing L content and curing period. However, the stabilisation of the same soils by using the NP without Na_2SO_4 produces a negligible effect on their shear strengths and shear parameters. In addition, when the combination L–NP is used without Na_2SO_4 , the shear strength and shear parameters become the very greatest, which increase with increasing additives content and curing period.

However, at any curing periods, the shear strength and shear parameters of both stabilised clayey soils on curing with 2% sodium sulphate are still higher than that of the L and/or L–NP treated the same soils without sodium sulphate. The high early values of cohesion and shear strength of two stabilised clayey soils can be attributed to the acceleration of early pozzolanic reactions caused by sodium hydroxide from Na_2SO_4 addition.

The degradation of two stabilised clayey soil specimens after 30 days of curing and the gradual reduction of their cohesions and shear strengths can be explained by the formation of ettringite due to the presence of a high content of Na_2SO_4 . The alteration of both stabilised clayey soil specimens depends on their mineralogical composition, the type and the content of additives, the Na_2SO_4 content and finally the curing period.

The presence of a low content of Na_2SO_4 (2%) in L–NP-treated both clayey soils increases their shear strengths, and there is a better resistance to the alteration when the Na_2SO_4 is present with a high content (greater than 2%).

The mineralogical composition of the soil has a capital importance and plays a very important role in the success or the failure of the stabilisation process.

For a shorter curing period, the Na_2SO_4 (with a low content, less than 2%) can be used as an accelerator of both pozzolanic reactions and NP dissolution without altering the stabilisation process.

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