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A comparison study between $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and Na_2SO_4 effects on geotechnical properties of clayey soils stabilised with mineral additives to recommend adequate mixtures as materials for road pavements

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ABSTRACT

This paper presents a comparison study between calcium ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and sodium (Na_2SO_4) sulphates effects on physico-mechanical properties (pH, plasticity index (PI), unconfined compressive strength (UCS) and shear strength parameters) of both grey and red clayey soils (GS and RS) stabilised with lime (L), natural pozzolana (NP) and their combination (L-NP) in order to recommend adequate mixtures which can be used as building materials for road pavements. In this study, Atterberg limits, pH, UCS and shear strength tests were carried out after different curing periods (1–120 days). Tests results showed that the addition of L as an additive produced a high decrease in the PI of both clayey soils but a considerable increase in UCS, cohesion (C), internal friction angle (φ) and pH was recorded, whereas the NP caused a slight effect. However, when combining both additives, a high decrease in the PI and a further increase in other properties were recorded. Moreover, it was found that the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ lowered the PI of both clayey soils whereas the Na_2SO_4 increased it. Thus, the increase in pH values of all mixtures with sulphate content was more pronounced with the Na_2SO_4 than with the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. On the other hand, both $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and Na_2SO_4 accelerated the pozzolanic reactions responsible for strength gain. However, at a later stage, the degradation of RS specimens can be explained by the formation of ettringite observed in X-ray diffraction (XRD) patterns. In general, the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ developed better effects for soil improvement whereas the presence of Na_2SO_4 (with a high content) can be classified as a deleterious element for soil stabilisation. From these results, two tables were given for choosing an adequate mixture for pavement subgrade soil stabilisation.

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Introduction

The requirement of a good quality of materials constitutes an inevitable economic stress to meet the technical needs of construction in order to fill the normative requirements for their achievement. Currently, the recourse to the use of local materials with low characteristics becomes a possible solution. However, problematic soils (or soils with insufficient geotechnical characteristics) can be improved using mineral additives such as cement, lime, silica fume, fly ash, natural pozzolana, slag (GGBS) ... etc. These additives are generally added to soils in order to improve their physico-mechanical properties (Ola 1977; Broms and Boman 1979; El-Rawi and Awad 1981; Rahman 1986; Locat, Bérubé, and Choquette 1990; George, Ponniah, and Little 1992; Bell 1996; Mathew and Narasimha 1997; Kinuthia, Wild, and Jones 1999; Afès and Didier 2000; Tonoç, Ulusay, and Gokceoglu 2004; Koliás, Kasselouri-Rigopoulou, and Karahalios 2005; Stavridakis 2005; Al-Rawas, Hago, and Al-Sarmi 2005; Hossain, Lachemi, and Easa 2007; Manasseh and Olufemi 2008; Harichane and Ghrici 2009; Harichane et al. 2010; Harichane, Ghrici, and Kenai 2011; Harichane et al. 2011; Harichane, Ghrici, and Missoum 2011; Harichane, Ghrici, and Kenai 2012; McCarthy

et al. 2012; Khemissa and Mahamedi 2014; Asgari, Dezfuli, and Bayat 2015; Yi, Gu, and Liu 2015; al-Swaidani, Hammoud, and Meziab 2016).

Nevertheless, the presence of some disruptive elements such as sulphates can lead to a failure treatment, or even exclude, some types of soils to the stabilisation process. The presence of sulphates in the mixture has complex effects on the stabilisation process (cation exchange and pozzolanic reactions). Several researchers have highlighted the great risk that may arise during or after the stabilisation of soils in the presence of certain chemical compounds such as sulphates (Mitchell 1986; Sivapullaiah, Sridharan, and Ramesh 2000, 2006; Cuisinier et al. 2011). Moreover, the effects of different types of sulphates (sulphates present in the soil or added) on the behaviour of different types of soils stabilised with different mineral additives have been studied by several researchers (Kujala 1986; Hunter 1988; Stipho 1989; Raja 1990; Mitchell and Dermatas 1992; Rajasekaran 1994; Sridharan, Sivapullaiah, and Ramesh 1995; Wild et al. 1999; Kinuthia, Wild, and Jones 1999; Sivapullaiah, Sridharan, and Ramesh 2000; Baryla et al. 2000; Puppala et al. 2004; Sivapullaiah, Sridharan, and Ramesh 2006; Yilmaz and

Table 1. Physico-mechanical and chemico-mineralogical properties of materials used (Gadouri, Harichane, and Ghrici 2016a).

Properties name	Chemical formula	Materials used	
Chemico-mineralogical properties of soils		GS	RS
Calcium oxide (%)	CaO	14.43	2.23
Alumina (%)	Al ₂ O ₃	14.15	19.01
Silica (%)	SiO ₂	43.67	57.02
pH	–	9.18	9.05
Calcite (%)	CaCO ₃	26.0	4.0
Quartz (%)	SiO ₂	20	30
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) ₁₀ (OH) ₂ ·H ₂ O	20.0	–
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
Classification System (USCS), (-)		CH	CL
Unconfined Compressive Strength (UCS, kPa)		100	510
Chemical properties of mineral additives		L	NP
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
CaCO ₃ (%)		<10	–
Physico-chemical properties of sulphates		CaSO ₄	Na ₂ SO ₄
Molar weight (g/mol)		172.2	142
Auay (dried)		99	99.5
pH (50 g/L, 25 °C)		–	5 to 8

Civelekoglu 2009; Segui et al. 2013; Celik and Nalbantoglu 2013; Aldaood, Bouasker, and Al-Mukhtar 2014a, 2014b).

It has been reported that sulphates promote the formation of new expansive phases such as ettringite responsible for the damage observed in built structures (Mitchell 1986; Wild, Abdi, and Leng-Ward 1993; Hunter 1988; Rajasekaran 1994; Baryla et al. 2000; Le Borgne 2010). These damages depend on the additive content and test conditions (Le Borgne 2010; Cuisinier et al. 2011), the mineralogical composition of stabilised soils (Sivapullaiah, Sridharan, and Ramesh 2000, 2006; Gadouri, Harichane, and Ghrici 2016a, 2016b) and the type of cations

associated with sulphate ions (Kinuthia, Wild, and Jones 1999; Gadouri, Harichane, and Ghrici 2016a, 2016b).

The NP is found in abundance in areas of Beni-Saf located in the west of Algeria (Ghrici, Kenai, and Said-Mansour 2007). The aim of this work is to make a comparison study between CaSO₄·2H₂O and Na₂SO₄ effects on pH parameter, PI, UCS, C and φ of both GS and RS stabilised with L, NP and L–NP in order to recommend adequate mixtures for using as building materials for road pavements.

Materials collection, preparation and identification

In the present study, two clayey soils were obtained from Chelif town located in the west of Algeria (GS and RS were obtained from an embankment project site and a highway project site, respectively). However, the NP was obtained from Beni-Saf deposit located in the west of Algeria. It was ground to the specific surface area of 420 m²/kg. However, the L used was a hydrated lime (Ca(OH)₂) which was commercially available lime typically used for construction purposes. Moreover, two chemical compounds were used (CaSO₄·2H₂O and Na₂SO₄). The main physico-mechanical, chemico-mineralogical and physico-chemical properties of soils, mineral additives and sulphates are summarised in Table 1.

Experimental programme

Laboratory tests of pH, Atterberg's limits, UCS and shear strength were conducted on both selected clayey soils. Several mix combinations of L, NP and L–NP with and without sulphates (Na₂SO₄ and CaSO₄·2H₂O) were used. A total of 72 combinations based on GS and RS were studied for each property. A summary of the mix combinations is shown in Table 2.

Test procedures and samples preparation

Atterberg's limits, pH measurement, UCS and Shear strength tests were prepared and then performed according to ASTM D4318 (2000), ASTM D4972-01 (2001), ASTM D2166 (2000) and ASTM D6528-00 (2000), respectively. Variations in PI, pH,

Table 2. A summary of the mix combinations tested for two clayey soil samples with and without sulphates.

D	SM (%)				D	SM (%)				D	SM (%)				D	SM (%)			
	S	NP	L	Ca		S	NP	L	Ca		S	NP	L	Na		S	NP	L	Na
POL0	100	0	0	0	POL0C4	96	0	0	4	POL0N2	98	0	0	2	POL0N6	94	0	0	6
POL4	96	0	4	0	POL4C4	92	0	4	4	POL4N2	94	0	4	2	POL4N6	90	0	4	6
POL8	92	0	8	0	POL8C4	88	0	8	4	POL8N2	90	0	8	2	POL8N6	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
POL0C2	98	0	0	2	POL0C6	94	0	0	6	POL0N4	96	0	0	4	D – Designation SM – Soil Mixture S – Soil Ca – CaSO ₄ ·2H ₂ O Na – Na ₂ SO ₄				
POL4C2	94	0	4	2	POL4C6	90	0	4	6	POL4N4	92	0	4	4					
POL8C2	90	0	8	2	POL8C6	86	0	8	6	POL8N4	88	0	8	4					
P10L0C2	88	10	0	2	P10L0C6	84	10	0	6	P10L0N4	86	10	0	4					
P20L0C2	78	20	0	2	P20L0C6	74	20	0	6	P20L0N4	76	20	0	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					

UCS and shear strength parameters (C and ϕ) of two selected clayey soils before and after admixtures added were obtained after different curing periods (1–120 days). The air-dried soils were initially mixed with the predetermined quantity of NP, L or L–NP in a dry state. The water (the distilled water was used for both Atterberg's limits and pH tests) was added to the soil mixture. To let the water invade through the soil mixture, samples and/or specimens (mixtures with and without sulphates Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) were stored in the airtight container prior to testing and then tested after different curing periods.

Experimental results and discussion

Atterberg limits

Effects of mineral additives on the PI of both stabilised clayey soils in the absence of sulphates

The results of the changes in the PI of two clayey soils stabilised with L, NP and L–NP without sulphates are depicted in Figures 1(a, b) and 2(a, b). It can be seen that the workability of both clayey soils was improved with L addition due to the considerable decrease in their PI. For both GS and RS, the increase in L content caused a better decrease in the PI especially after 30 days of curing period when this reduction was more pronounced with the GS than with the RS. Similar observations were obtained by several researchers (Ola 1977; Attoh-Okine 1995; Afès and Didier 2000; Okagbue and Yakubu 2000; Bagherpour and Choobbasti 2003; Ansary, Noor, and Islam 2006).

On the other hand, the use of NP alone in the improvement of both clayey soils caused a slight decrease in the PI as compared with the L addition. Similar behaviours were observed by several researchers (Rahman 1986; Parsons and Kneebone 2005; Yadu and Tripathi 2013; Eberemu 2013; Sivrikaya, Yavascan, and Cecen 2014). However, an inverse effect has been observed by Degirmenci, Okucu, and Turabi (2007) where they have reported that the PI increased with increasing fly ash amount which presents smaller size particles with a high surface area as compared with the size particles of NP.

In general, the combination of both L and NP leads to obtain the better results of PI. It is clear to observe that the combination L–NP produced a considerable effect on the PI of the GS as compared with the RS. Also, there is an important decrease of the PI with increasing L–NP amount and curing period (Figure 1(a, b)). Ansary, Noor, and Islam (2006) reported that for a similar class soil, the PI decreased from 19 to 2.3% for a combined treatment of 6% fly ash and 3%L. In all cases, the high decrease in the PI value was observed for samples improved with L and NP. It should be noted that the combination of both L and NP play a complementary role where the beneficial effects of one can compensate for the disadvantages that could present another.

Effects of Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the PI of both stabilised clayey soils

Figures 1(c–h) and 2(c–h) present the modifications in the PI of two clayey soils stabilised with NP, L and their combination in the presence of different contents of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. The PI of L-treated GS increases with increasing Na_2SO_4 content and DTN. Celik and Nalbantoglu (2013) indicated that the PI of clayey soil stabilised with 5%L increased up to 34 and 38%, respectively,

with the presence of 5000 and 10000 ppm of Na_2SO_4 but decreased from 32 to 15% for 2000 ppm of Na_2SO_4 addition. However, the PI of L-treated RS decreased with increasing Na_2SO_4 content but increased with DTN. In contrast, the addition of L alone on curing with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ decreased the PI of both clayey soils especially with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content, L content and DTC. Kinuthia, Wild, and Jones (1999) indicated that the interaction between two clay particles can be affected by the cation exchange process.

The high PI values of both L-treated clayey soils in the presence of Na_2SO_4 is probably due to the large surface area of clay particles which has a large storage capacity of water governed probably by the exchange of monovalent cations such as sodium ions (from Na_2SO_4). In general, the divalent cations (Ca^{2+} , from $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) decreased the PI of two clayey soils while the monovalent ones (Na^+ , from Na_2SO_4) increased it. According to Kinuthia, Wild, and Jones (1999), the variation in PI values is the result of cation exchange process which affected the viscosity of the clay–water mix.

On the other hand, the PI of two stabilised clayey soils decreased with increasing NP content, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and DTC whereby RS has the best results. It can be seen that the addition of NP to two clayey soils in the presence of any content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ showed a better reduction in the PI to compare with both untreated and treated soil without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. This behaviour is due to the replacement of monovalent ions (K^+ , Na^+ ... etc.) by calcium ions which reduced the diffuse double layer thickness and consequently a decrease in the PI (Yilmaz and Civelekoglu 2009).

For comparison, after 30 days of curing period, both untreated RS and NP-treated RS samples containing 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ produced a high PI value if compared with the same soil stabilised with 8%L in the presence of 6% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. However, the addition of NP to both stabilised clay soils in the presence of any content of Na_2SO_4 produced a slight decrease in the PI. It should be noted that the sensitivity of NP to the sulphate effect was more pronounced with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ than with Na_2SO_4 . Also, the difference in the PI value between Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ was more pronounced with the GS than with the RS.

Furthermore, for a combined treatment of L and NP, a further decrease in the PI was recorded for both clayey soils, particularly, with increasing of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content, L–NP amount and DTC (Figures 1(c–h) and 2(c–h)). In all cases, the PI values of L–NP-treated both clayey soils in the presence of any content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ were very higher as compared with samples without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. However, the PI of both clayey soils was deeply affected when using L–NP as a combined treatment on curing with any content of Na_2SO_4 . For comparison, the presence of Na_2SO_4 produced a marginal effect on the PI of the RS but caused an adverse effect on the PI of the GS.

pH parameter

pH variation of both untreated and treated soil samples in the absence of sulphates

The results of the changes in the pH parameter of soil–L, soil–NP and soil–L–NP mixtures measured at different curing periods are shown in Figure 3. For both clayey soils, there are marginal changes in pH values of soil–NP mixture to compare with untreated soils. In contrast, for a shorter curing period (7 days), the addition of 8%L increased the pH of both GS and RS from 9.18

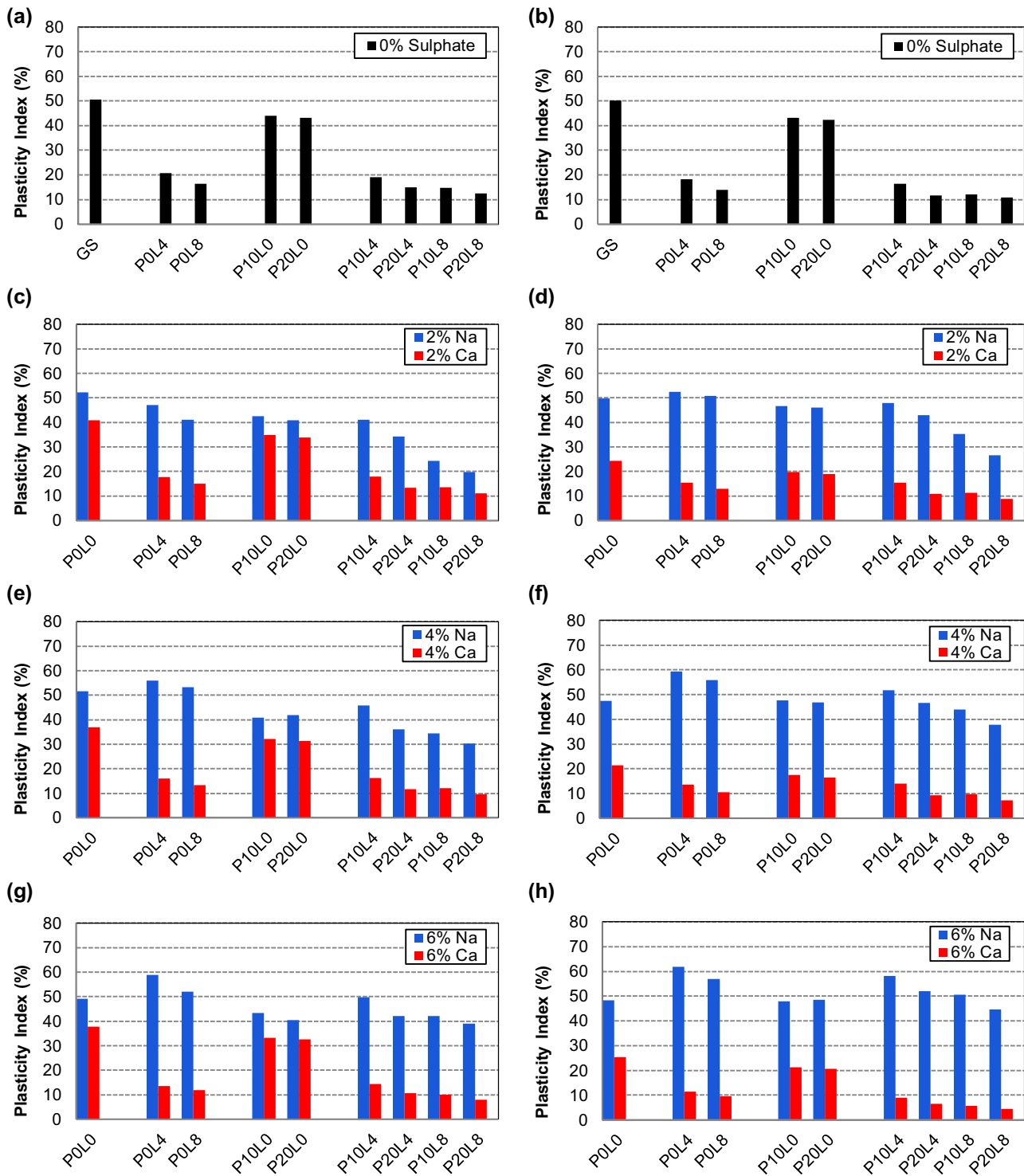


Figure 1. Effect of different content of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the PI of the GS stabilised with L, NP and their combination (a, c, e and g) after curing for 1 day, (b, d, f and h) after curing for 30 days.

and 9.08 to 12.3 and 12.35, respectively. A similar behaviour was observed by Al-Mukhtar, Lasledj, and Alcover (2010). According to Samantasinghar (2014), the long-term pozzolanic reactions begin as an increase in hydroxyl ions (OH^-) from the lime caused an increase in the pH of the soil water (or soil solution).

Furthermore, the pH of both clayey soils stabilised with L alone or in combination with NP decreased with curing period due to the consumption of L during the pozzolanic reactions

to form cementing agents. The highest effect on the pH of both clayey soil samples was achieved when the combination of 20%NP+8%L was used. In all cases, the decrease in pH value with the curing period was more pronounced with the RS than with the GS. This can be explained by the difference in chemical composition between both soils when the GS presents a high amount of natural CaO (14.43%) as compared with the RS (2.23%). On the other hand, it is probably also due to the fact

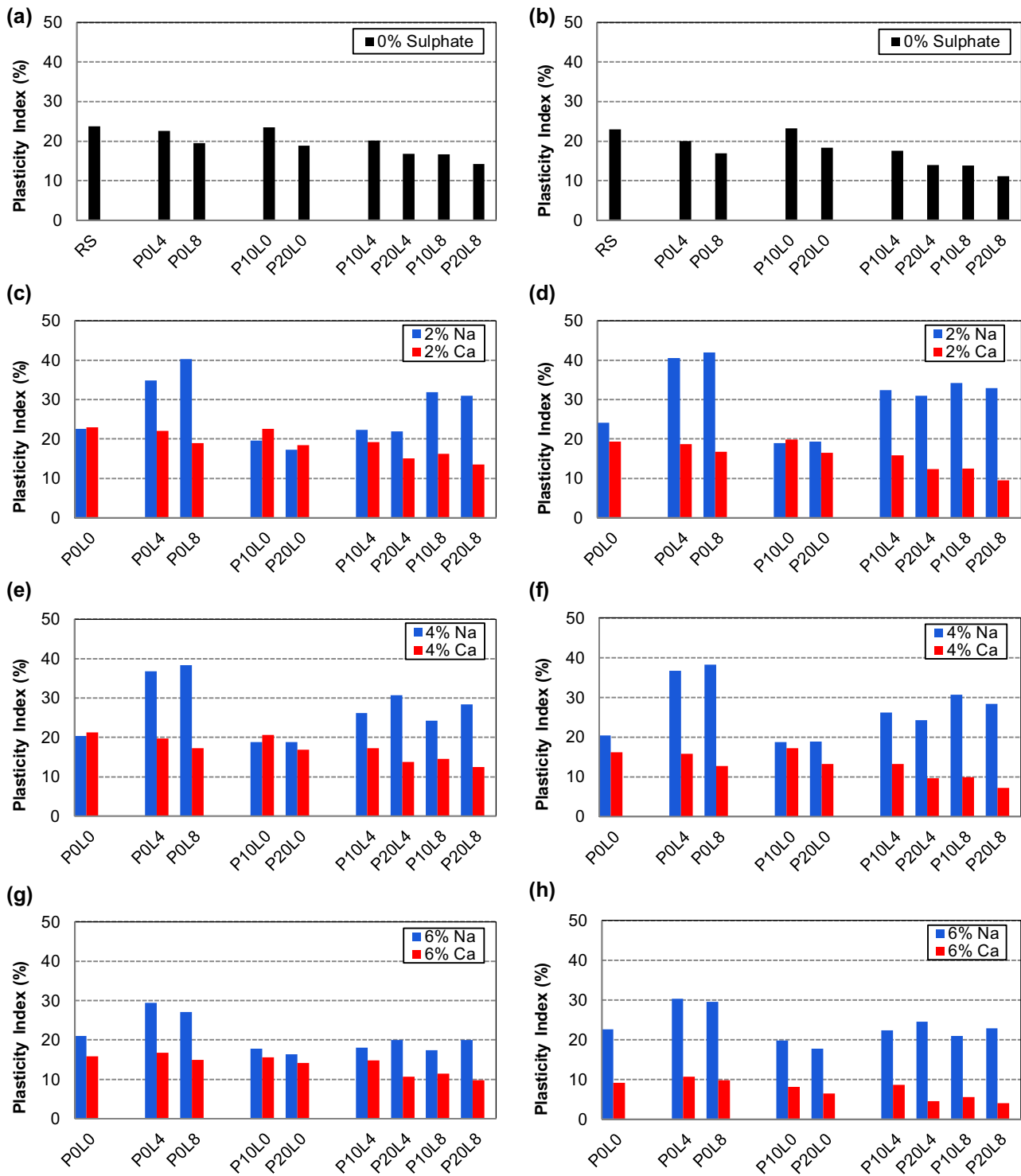


Figure 2. Effect of different content of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the PI of the RS stabilised with L, NP and their combination (a, c, e and g) after curing for 1 day, (b, d, f and h) after curing for 30 days.

that RS presents a higher amount of SiO_2 and Al_2O_3 , therefore, pozzolanic reactions can develop to a greater extent with RS soil, leading to a higher decrease in pH value.

pH variation of untreated soil samples in the presence of sulphates

The results of the pH variation of both untreated clayey soils measured under different sulphate contents at different curing periods are given in Table 3. Both untreated soil samples showed

negligible changes in the pH value upon the addition of various Na_2SO_4 contents at different curing periods. For any curing periods, it is obvious to see that no rate of Na_2SO_4 has had any influence on pH of both untreated soils. In contrast, for both clayey soil samples, pH increased considerably with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content but decreased with curing period. For comparison, the increase in pH value with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ was more pronounced with the GS than with the RS. This is probably due to the high content of CaO (14.43%) of the GS to compare with

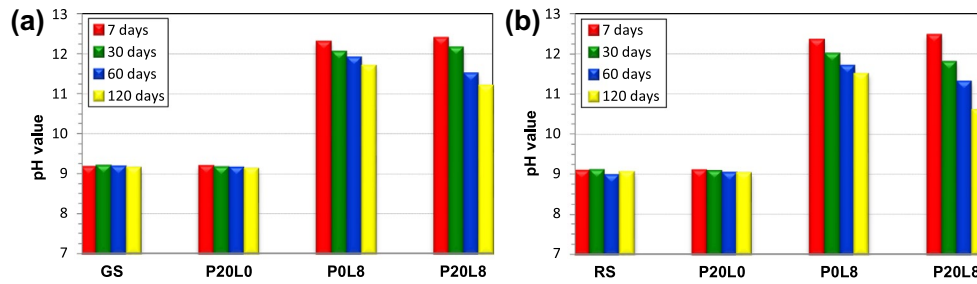


Figure 3. Effect of 20%NP, 8%L and their combination (20%NP+8%L) on the pH parameter of both clayey soils at different curing period (a) GS, (b) RS.

Table 3. Changes in pH values of both untreated soil samples containing different contents of sulphates.

Suphate type	Soil type	Combinations	pH value measured for different curing periods (days)			
			7	30	60	120
Without sulphate	GS	POL0	9.18	9.20	9.17	9.15
	RS	POL0	9.08	9.10	8.98	9.05
Sodium sulphate (Na ₂ SO ₄)	GS	POLON2	9.17	9.19	9.21	9.13
		POLON4	9.14	9.21	9.09	9.12
		POLON6	9.16	9.16	9.21	9.09
	RS	POLON2	9.07	9.10	9.12	9.08
		POLON4	9.10	9.10	9.11	9.09
		POLON6	9.07	9.01	9.07	9.08
Calcium sulphate (CaSO ₄ ·2H ₂ O)	GS	POLOC2	9.54	9.25	9.15	9.14
		POLOC4	10.07	9.80	9.42	9.20
		POLOC6	10.15	9.91	9.61	9.32
	RS	POLOC2	9.42	9.22	9.16	9.10
		POLOC4	9.86	9.50	9.34	9.15
		POLOC6	10.10	9.65	9.55	9.21

that of the RS because the CaO can considerably contribute to increasing the pH value.

pH variation of both clayey soils stabilised with NP in the presence of sulphates

Figure 4(a, b) illustrates the results of Na₂SO₄ and CaSO₄·2H₂O effects on the pH of soil–NP mixture measured at different curing periods. It is obvious to observe that for both sulphates, the pH of two clayey soil samples decreased with curing period but increased with increasing sulphate contents. However, there is a slight decrease in pH values of both clayey soils with increasing Na₂SO₄ content. For both clayey soils, the sensitivity of the pH to the curing period effect was more pronounced with the CaSO₄·2H₂O than with the Na₂SO₄. In the same way, it was also more pronounced with the CaSO₄·2H₂O content than with the Na₂SO₄ content. This behaviour leading us to confirm that the sensitivity of the amorphous silica (SiO₂ from soil and/or NP) to the sulphate effect was more pronounced with divalent cations (Ca²⁺) than with monovalent cations (Na⁺). On the other hand, for a longer curing period (120 days), the CaSO₄·2H₂O effect on the pH of both clayey soils was comparable to that of the Na₂SO₄.

pH variation of both clayey soils stabilised with L and L–NP in the presence of sulphates

The results of Na₂SO₄ and CaSO₄·2H₂O effects on the pH of soil–L and soil–L–NP mixtures measured at different curing periods are shown in Figure 4(c–f). In all cases, the pH of both

soil–L and soil–L–NP mixtures increased with increasing Na₂SO₄ and CaSO₄·2H₂O content but decreased with curing period. A similar trend was observed by Shi and Day (2000b) and Aldaood, Bouasker, and Al-Mukhtar (2014b) when they used Na₂SO₄ and gypsum, respectively. However, when Na₂SO₄ was present, the pH of both soil–L and soil–L–NP mixtures can reach a value of approximately 13. The same value was obtained by Wang and Gillott (1991).

The increase in pH value with sulphate content was more pronounced with the Na₂SO₄ than with the CaSO₄·2H₂O. This is attributed to the sodium hydroxide (NaOH) which increased considerably the pH of soil and caused the dissolution of a large amount of alumina and silica that come into reaction with the remaining L to form cementitious products (Sridharan, Sivapullaiah, and Ramesh 1995). It has been reported that chemical reactions between L, NP and Na₂SO₄ increased the pH of the mixture and produced an early increase in unconfined compressive strength of both GS and RS samples containing Na₂SO₄ (Gadouri, Harichane, and Ghrici 2016a).

Contrarily to the pH variation of soil–NP mixture, for both clayey soils, the sensitivity of the pH to the L and L–NP effect was more pronounced with the presence of Na₂SO₄ than with the CaSO₄·2H₂O addition. Moreover, for both clayey soils, the sensitivity of the pH to the curing period effect was more pronounced with the CaSO₄·2H₂O than with the Na₂SO₄ whereby the RS has the best results.

It has been reported that for a shorter curing period, the unconfined compressive strength of both soil–L and soil–L–NP mixtures was greater with CaSO₄·2H₂O (Mfinanga and Kamuhabwa 2008; Gadouri, Harichane, and Ghrici 2016b) than with Na₂SO₄ (Gadouri, Harichane, and Ghrici 2016a). This is because with Na₂SO₄, the cation exchange requirements must be met from L addition, whereas the calcium ions (Ca²⁺) required for cation exchanges of soil are provided by Ca²⁺ from CaSO₄·2H₂O dissolution. Thus, there is a high decrease in the L content available for pozzolanic reactions in soil with Na₂SO₄ compared with that available in soil with CaSO₄·2H₂O (Mitchell 1986).

However, for a longer curing period, the Na₂SO₄ with high concentrations alters only the strength of soil–NP and soil–L mixtures, whereas the soil–L–NP mixture resists to the alteration (Gadouri, Harichane, and Ghrici 2016a). This is because the pH of these mixtures decreased with curing period and motivated the formation of an expansive mineral (ettringite) responsible for the strength degradation.

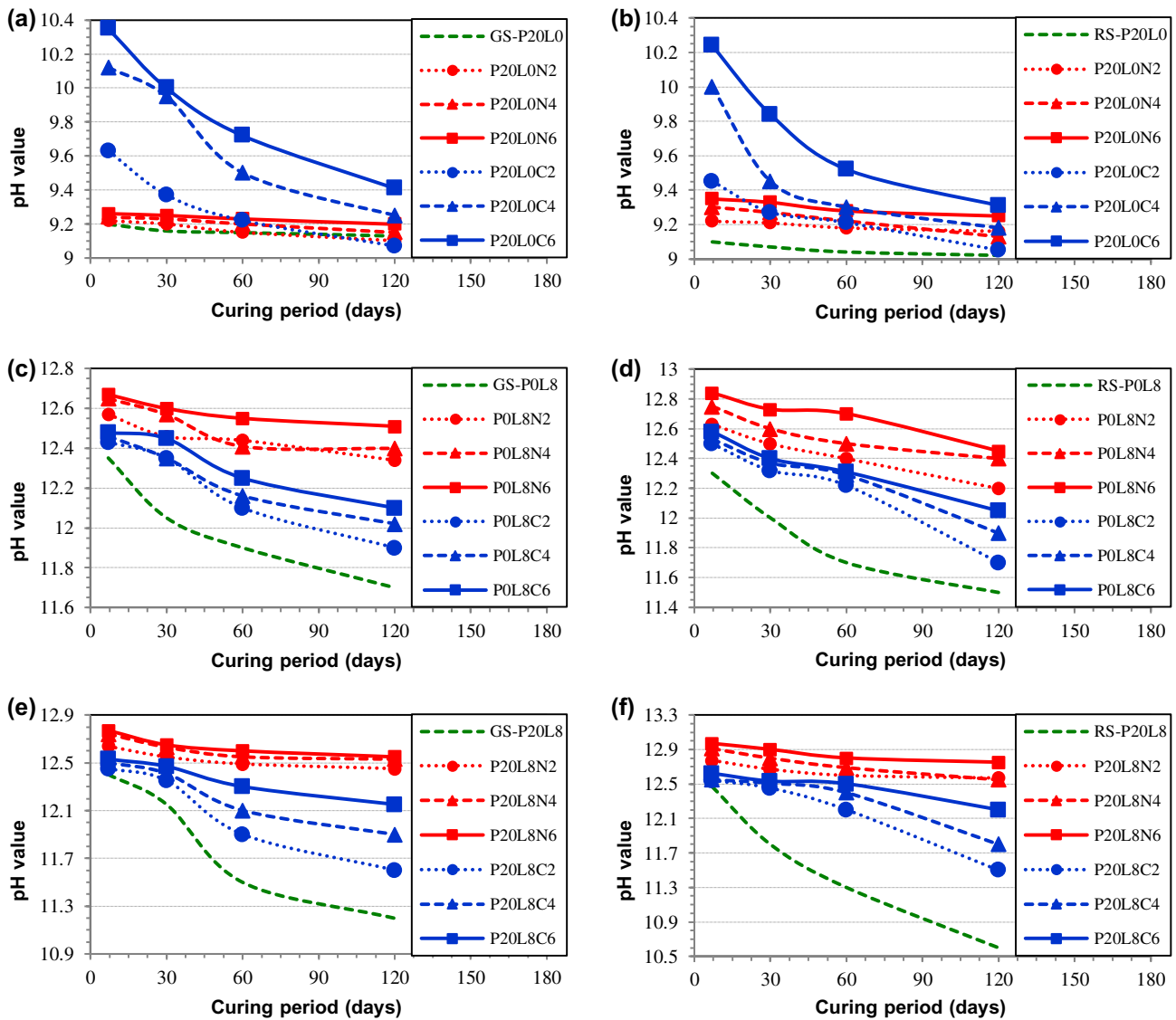


Figure 4. Effect of different contents of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the pH parameter of both clayey soils at different curing period (a, b) both clayey soils stabilised with 20%NP alone, (c, d) both clayey soils stabilised with 8%L alone, (e, f) both clayey soils stabilised with the combination of 20%NP+8%L.

Unconfined compressive strength

Effects of L, NP and L-NP on the UCS of both stabilised clayey soils

The results of the effect of L, NP and L-NP without sulphates on the UCS of two clayey soils are depicted in Figures 5(a, b) and 6(a, b). It is obvious to observe that the addition of L to both clayey soils produced an important increase in the UCS which increased with increasing of both L content and curing period. Similar observations were reported by McCarthy et al. (2014) and Asgari, Dezfuli, and Bayat (2015). According to Harichane, Ghrici, and Kenai (2012), the increase in strength is attributed to the formation of cementing agents by pozzolanic reactions which are the result of the reaction between L and clay particles (after the dissolution of SiO_2 and Al_2O_3 at high pH value).

However, a marginal increase in UCS values was observed for both GS and RS when using the NP alone. This behaviour was probably due to the low reactivity of NP with clay particles (Gadouri, Harichane, and Ghrici 2016b). For comparison, the

differences in UCS values between L and NP were more pronounced with the RS than with the GS. This difference can be explained by the high PI value of the GS to compare with that of the RS.

However, the better results of the UCS were achieved when the combination of both L and NP was used, especially at a later stage. Similar observations were recorded by Kumar, Walia, and Bajaj (2007) and McCarthy et al. (2014). According to Gadouri, Harichane, and Ghrici (2016a), the dissolution of silica (SiO_2) and alumina (Al_2O_3) can be controlled by the L content which produced a high content of cementing agents responsible for the increase of compressive strength. In fact, the XRD patterns show that the high increase in UCS values of both L- and L-NP-treated two clayey soils was due to the formation of cementing agents such as C-S-H and C-A-H (Figures 7(g, i) and 8(g, i)). In addition, Harichane et al. (2011) reported that the increase in strength is due to the pozzolanic reactions which form new cementing agents and bind the soil particles together.

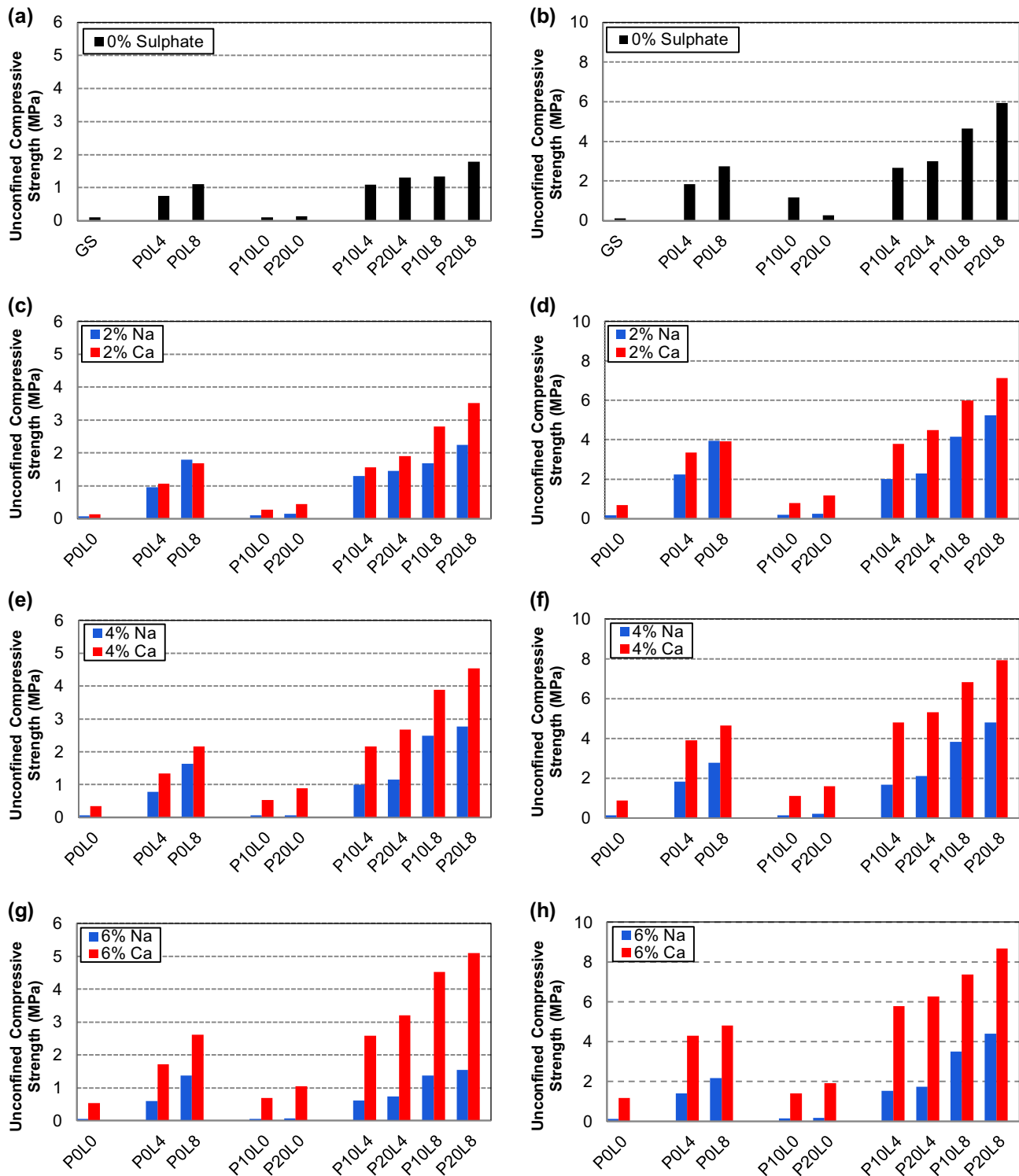


Figure 5. Effect of different content of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of the GS stabilised with L, NP and their combination (a, c, e and g) after curing for 7 days, (b, d, f and h) after curing for 120 days.

Effects of Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of both stabilised clayey soils

Figures 5(c–h) and 6(c–h) illustrate the results of the effect of Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of two clayey soils stabilised with L, NP and L–NP. For comparison, the UCS values of both clayey soils stabilised with L, NP and L–NP on curing with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ are very larger as compared to samples stabilised without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. On the other hand, for both untreated and

NP-treated clayey soils, a significant increase in the UCS was recorded when the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content increased, especially at a later stage. A similar behaviour was observed by Yilmaz and Civelekoglu (2009). As shown in Figures 7(c) and 8(c), the increase in the UCS of NP-treated both clayey soils containing 4% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ was certainly not linked with the eventual formation of cementing agents. On the other hand, Gadouri, Harichane, and Ghrici (2016b) reported that the increase in strength value

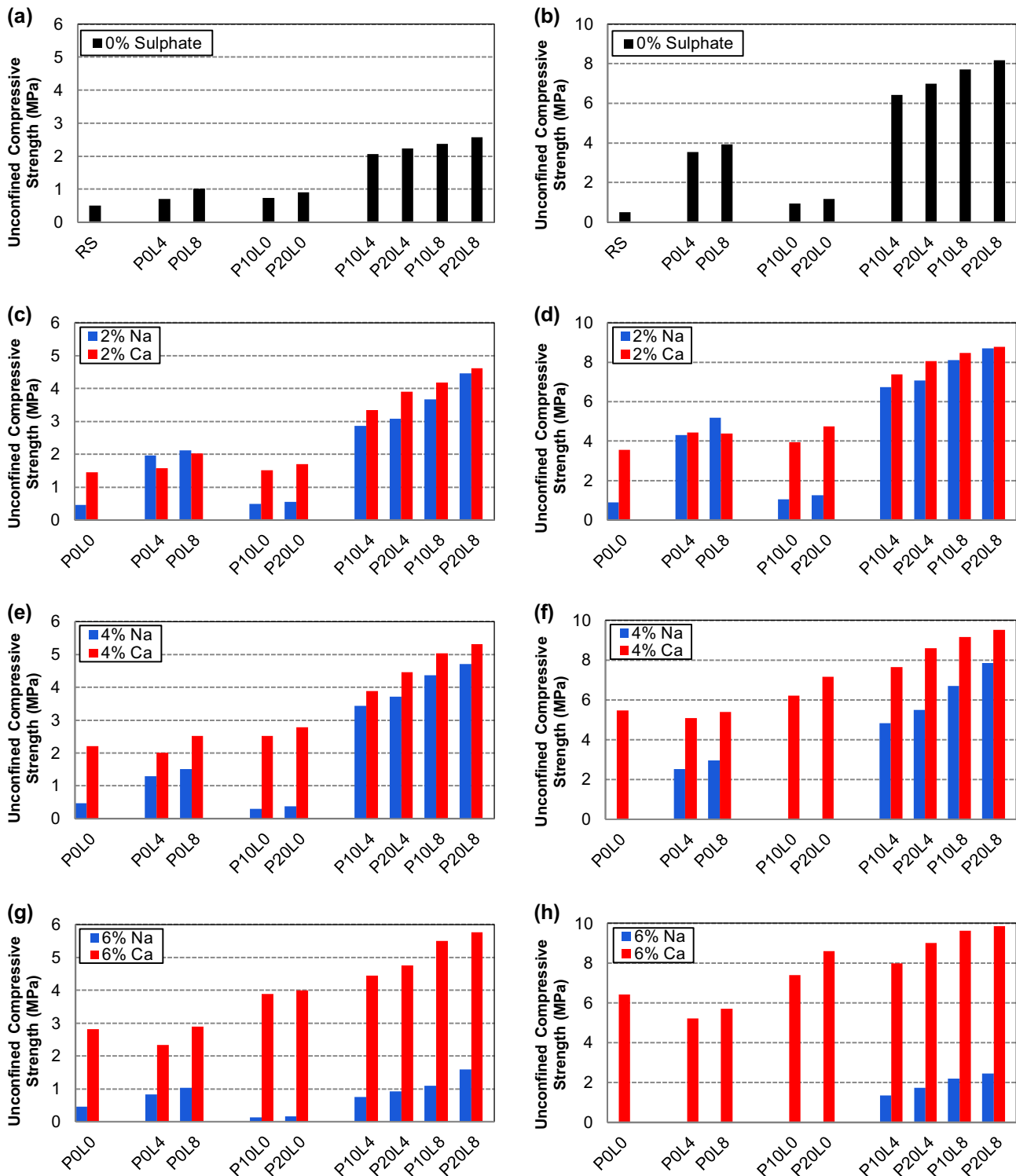


Figure 6. Effect of different content of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the UCS of the RS stabilised with L, NP and their combination (a, c, e and g) after curing for 7 days, (b, d, f and h) after curing for 120 days.

was attributed to the formation of micro-hydrate gels observed in scanning electronic microscope (SEM) images of both clayey soils stabilised with NP in the presence of 4% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ after 60 days of curing period. In addition, the presence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ improved the compactness of stabilised clayey soils due to the finer grained of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. The same trend was observed by Aldaood, Bouasker, and Al-Mukhtar (2014a).

However, the low strength value has been explained by the presence of macropores observed in both L-treated clayey soils due probably to the high specific surface area of NP (Gadouri, Harichane, and Ghrici 2016b). For comparison, there is a negligible increase in UCS values of both GS and RS samples stabilised with NP alone in the presence of 2% Na_2SO_4 as compared with samples containing 2% of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

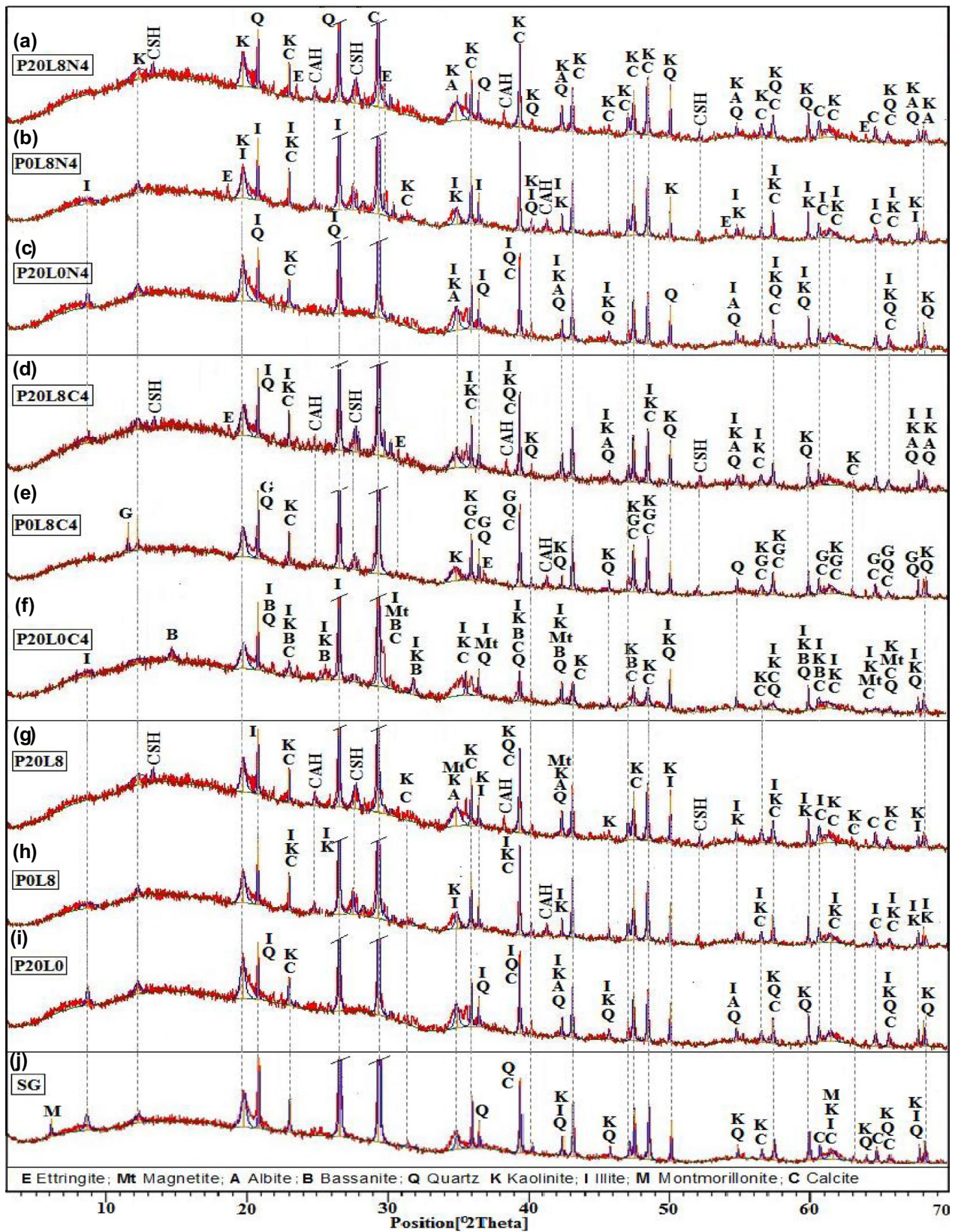


Figure 7. XRD patterns of GS samples stabilised with 8%L, 20%NP and 20%NP+8%L in the presence of 4% of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ after 60 days of curing period.

However, the use of L as an additive in the presence of any content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ increased the UCS of both clayey soils, particularly with curing period. For any curing period, the UCS of both L-treated clayey soils increased

with increase in both $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and L content. The same behaviour was observed by Segui et al. (2013). For any content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, the GS stabilised with NP developed high UCS values as compared to L addition. According to Shi

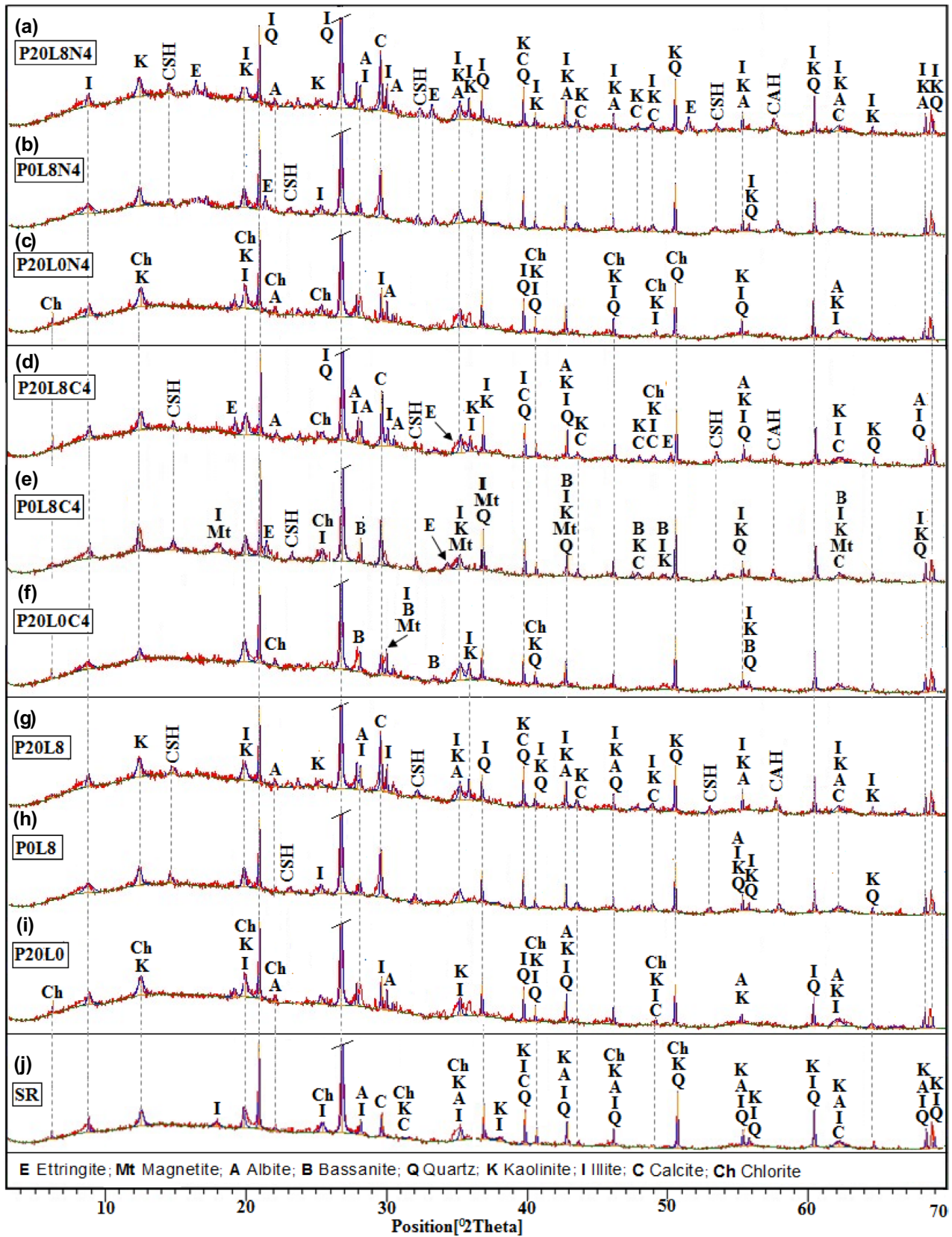


Figure 8. XRD patterns of RS samples stabilised with 8%L, 20%NP and 20%NP+8%L in the presence of 4% of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ after 60 days of curing period.

and Day (2000a), the slight change in strength value of soil stabilised with L alone was due to the fact that the gypsum presents the capacity to decrease the solubility of hydrated L.

For comparison, the increase in UCS values with increasing of both $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period was more pronounced in the RS than in the GS.

For any content of Na_2SO_4 and after seven days of curing period, both clayey soils samples stabilised with L alone developed high UCS values as compared with samples without Na_2SO_4 (Figures 5(c, e, g) and 6(c, e, g)). The early increase in strength can be attributed to the presence of sodium hydroxide which accelerates the pozzolanic reaction rate mainly during the short time (Shi and Day 2000a). Moreover, the presence of sodium hydroxide (NaOH from Na_2SO_4) increased the pH and caused the dissolution of a large amount of SiO_2 and Al_2O_3 that come into reaction with the remaining L to form cementing agents (Sridharan, Sivapullaiah, and Ramesh 1995). This explains the early increase in UCS values of both clayey soils. On the other hand, after 120 days of curing period, the UCS of both clayey soils stabilised with L decreased when the Na_2SO_4 content was greater than 2% whereas the RS samples were completely deteriorated before testing (Figures 5(c, d) and 6(c, d)).

According to Hunter (1988), the OH^- provided by L hydration reacts with montmorillonite to form aluminium compounds and then reacts with sulphates to form the ettringite mineral responsible for the deterioration of stabilised soil. Indeed, Le Borgne (2010) reported that the pressure value produced by the expansion of ettringite mineral can be very larger than that of the tensile strength value of the soil which was the main reason of the soil degradation. In addition, Mehta (1983) reported that the reduction in the strength value can be explained by the decrease in the capacity of cementing due to the adsorption of sulphates on the surfaces of C-S-H. It should be noted that the alteration of RS samples stabilised with NP was certainly not linked with the eventual formation of ettringite which was not observed in XRD patterns (Figure 7(f)). However, the alteration of RS samples stabilised with L was certainly related with the ettringite formation (Figure 7(e)).

For a combined treatment with L and NP, the UCS of both clayey soils increased sharply with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content, L-NP content and curing period when this increase was very marked with the RS (Figures 5(c-h) and 6(c-h)). According to Aldaood, Bouasker, and Al-Mukhtar (2014a), the presence of gypsum accelerates the chemical reaction between soil and L to form ettringite mineral responsible for the early increase of the strength value. As shown in Figures 7(a, b) and 8(a, b), the high increase in UCS values of both clayey soils stabilised with L or L-NP in the presence of 4% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ was related to the formation of cementing agents and ettringite mineral.

In the presence of Na_2SO_4 and after seven days of curing period, a high increase in UCS was recorded for both GS and RS samples stabilised with the combination of L and NP. This increase becomes very important with increasing Na_2SO_4 content. In contrast, for a longer curing period (120 days), the UCS of both clayey soils stabilised with the combination of L and NP decreased progressively with increasing of Na_2SO_4 content. A similar behaviour was observed by Sivapullaiah, Sridharan, and Ramesh (2006). It should be noted that the RS samples resist the Na_2SO_4 attack when the L and NP were used as a combined treatment. In addition, after seven days of curing period, a high increase in UCS values was observed for both GS and RS samples stabilised with the combination L-NP in the presence of any content of Na_2SO_4 .

For comparison, for any curing period, the sensitivity of the UCS of both clayey soils stabilised with L alone or L-NP to the

sulphate effect was more pronounced with the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ than with the Na_2SO_4 . This is due to the decrease in the L content available for pozzolanic reactions in soil with Na_2SO_4 as compared with that available in soil with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. Thus, the calcium ions required for the cation exchange of soil are provided by calcium ions of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, whereas with Na_2SO_4 , the cation exchange requirements must be met from L addition (Mitchell 1986).

Shear strength parameters (C and ϕ)

Effects of L, NP and L-NP on the cohesion of both stabilised clayey soils in the absence of sulphates

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 effect of L, NP and L-NP on the temporal variation of cohesion of two clayey soils are depicted in Figures 9(a, b) and 10(a, b). A better increase in cohesion values was recorded when using the L alone or in combination with NP, especially with time. The high increase in cohesion values with curing period can be explained by the formation of a high amount of cementing agents which bind the soil particles together. However, the NP caused a slight effect on the cohesion of both clayey soils due probably to the low reactivity of NP when L was absent. Also, the formation of cementitious compounds on the two NP-treated clayey soils was not observed in XRD patterns (Figures 7(i) and 8(i)). On the other hand, it can be seen that the cohesion of L-treated two clayey soils increased with increasing L content and curing period, particularly at later stages. The increase in cohesion was very pronounced with the RS than with the GS. A similar behaviour was observed by Gay and Schad (2000). The increase of the cohesion value with 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). Also, this behaviour is probably due to the self-hardening effect related to L (Harichane et al. 2011). Moreover, this behaviour can be attributed to the cementation of particles and the pozzolanic reactions which occur over time (Bell 1989). Indeed, the formation of cementing agents in the two L-treated clayey soils was confirmed by XRD patterns (Figures 7(h) and 8(h)).

Effects of Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the cohesion of both stabilised clayey soils

The results of the changes produced by the presence of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the temporal variation of the cohesion of both stabilised clayey soils are depicted in Figures 9(c-h) and 10(c-h). There is a better increase in cohesion values of both untreated and two NP-treated clayey soils with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period. However, it should be noted that the increase in cohesion values of two NP-treated clayey soils was certainly not related to the eventual formation of cementing agents and/or ettringite (Figures 7(f) and 8(f)).

On the other hand, the increase in cohesion values was probably due to the finer grained of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ which increases the compactness of stabilised soils (Aldaood, Bouasker, and Al-Mukhtar 2014a). Moreover, Gadouri, Harichane, and Ghrici (2016b) reported that all the changes in both microstructures

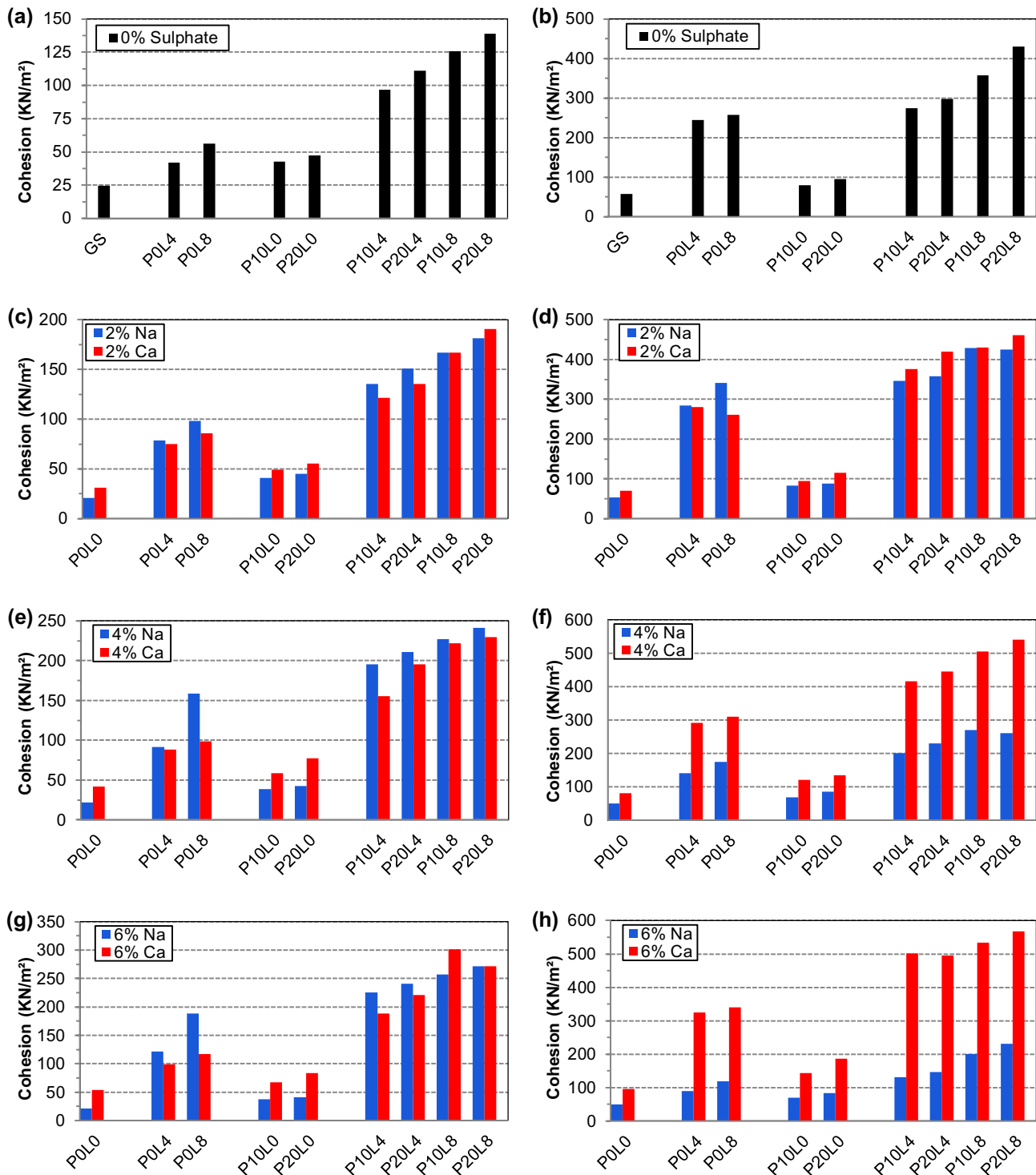


Figure 9. Effect of different content of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the Cohesion of the GS stabilised with L, NP and their combination (a, c, e and g) after curing for 7 days, (b, d, f and h) after curing for 120 days.

and strengths of NP-treated both GS and RS samples were due to the formation of macro-hydrates gel (cementing agents: C-S-H and C-A-H). For comparison, the increase in the cohesion with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period was more pronounced with the RS than with the GS. This behaviour leads to suppose that the increase in the cohesion could be due to the behaviour of the RS with the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ interaction.

For any curing periods, there is a slight increase in the cohesion of L-treated both GS and RS samples with increasing

$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and L content to compare with samples treated without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. Furthermore, the cohesion of L-NP-treated GS and RS samples increased sharply with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content, L-NP content and curing period. For example, for a combined treatment of 10%NP+4%L and for 2% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, both GS and RS developed a cohesion value of 375.5 and 360.9 kPa after curing for 120 days, respectively.

However, for the same content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and the same curing period but with a combined treatment of 20%NP+8%L,

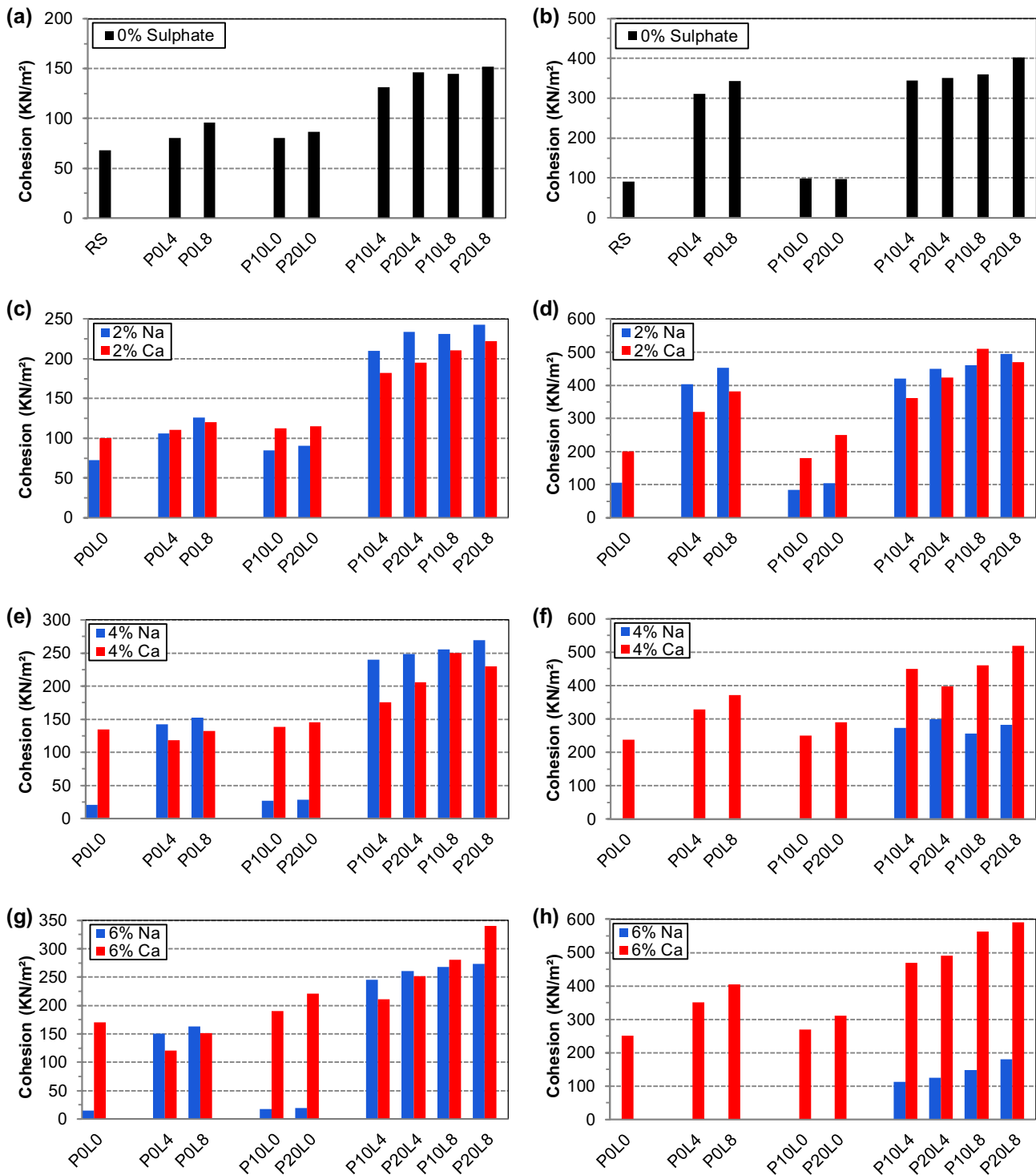


Figure 10. Effect of different content of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the Cohesion of the RS stabilised with L, NP and their combination (a, c, e and g) after curing for 7 days, (b, d, f and h) after curing for 120 days.

the cohesion of both GS and RS samples becomes 461 and 470.6 kPa, respectively. However, both GS and RS samples stabilised with the combination 10%NP+4%L on curing with 6% of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ developed a cohesion value of 501.3 and 469.9 kPa after curing for 120 days, respectively. Whereas, for the same content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and the same curing period but with a combined treatment of 20%NP+8%L, the cohesion of two GS and RS becomes 567.5 and 590.4 kPa, respectively.

Furthermore, the early increase in cohesion and strength of two clayey soils stabilised with L alone or in combination with NP can be explained by the presence of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ which accelerates the chemical reaction between soil and lime. The same behaviour was observed by Aldaood, Bouasker, and Al-Mukhtar (2014a). However, for a longer curing period, there is a better increase in the cohesion which may be due to the formation of ettringite (Figures 7(d, e) and 8(d, e)).

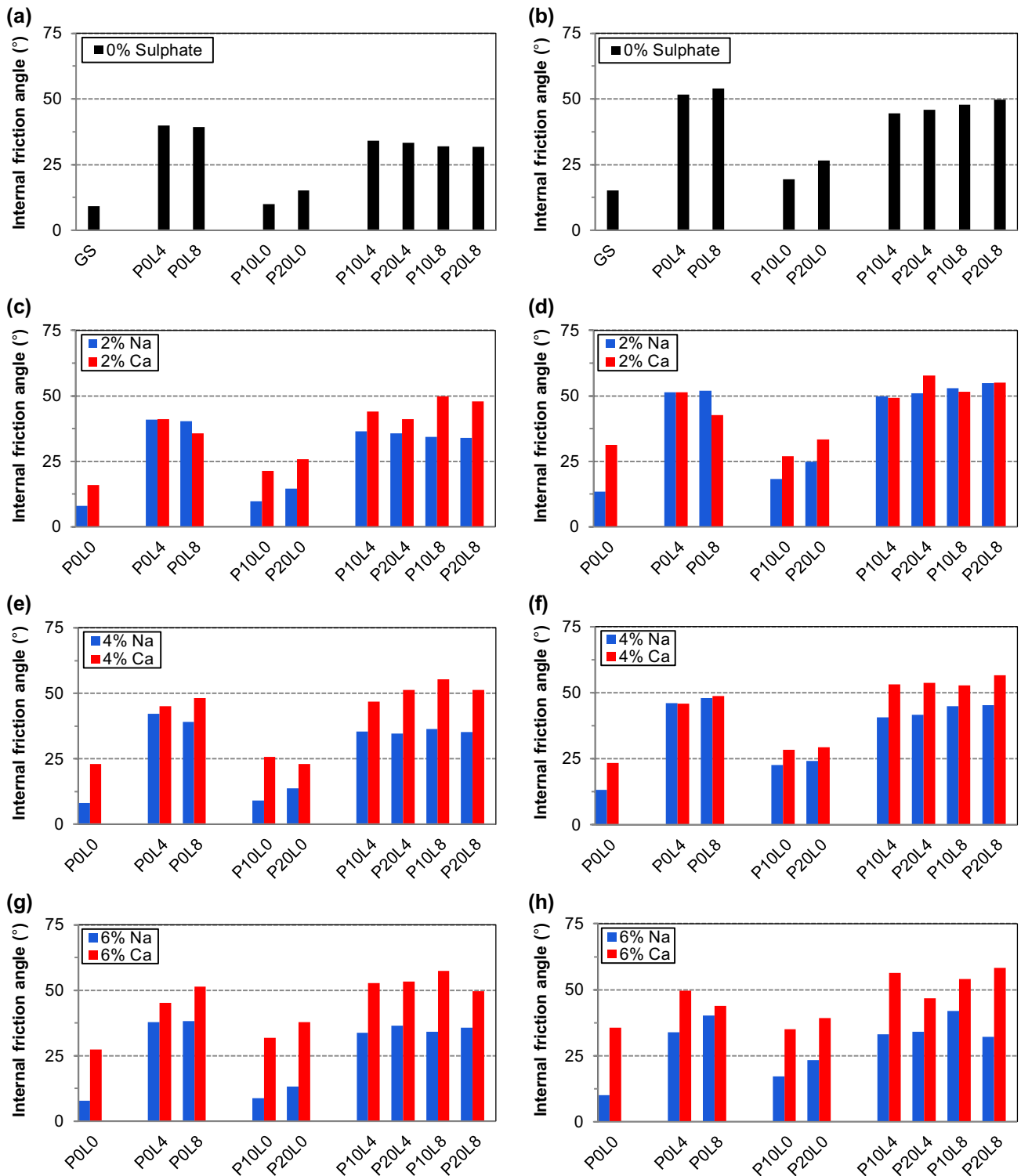


Figure 11. Effect of different content of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the internal friction angle of the GS stabilised with L, NP and their combination (a, c, e and g) after curing for 7 days, (b, d, f and h) after curing for 120 days.

When Na_2SO_4 was present, in all cases and for a shorter curing period, a high increase in cohesion values of both GS and RS samples was recorded, especially, with increasing Na_2SO_4 . This behaviour can be explained by the enhancement of lime reactions by increasing of silica availability due to the increase in pH value of soil solution (Davidson, Mateos, and Barnes 1960). With 2% of Na_2SO_4 and for any curing periods, the cohesion of both clayey soils seems very higher with the combination of

L-NP than with the L alone. However, the difference in cohesion values between these both types of treatment (L-NP and L alone) was more pronounced with the RS than with the GS (Figures 9(c, d) and 10(c, d)). However, after 120 days of curing, the decrease in cohesion and/or the degradation of soil specimens stabilised with L or NP occurred with an increase in Na_2SO_4 content. This behaviour confirms that the effects of Na_2SO_4 (more than 2% Na_2SO_4) on the strength of soil-L and

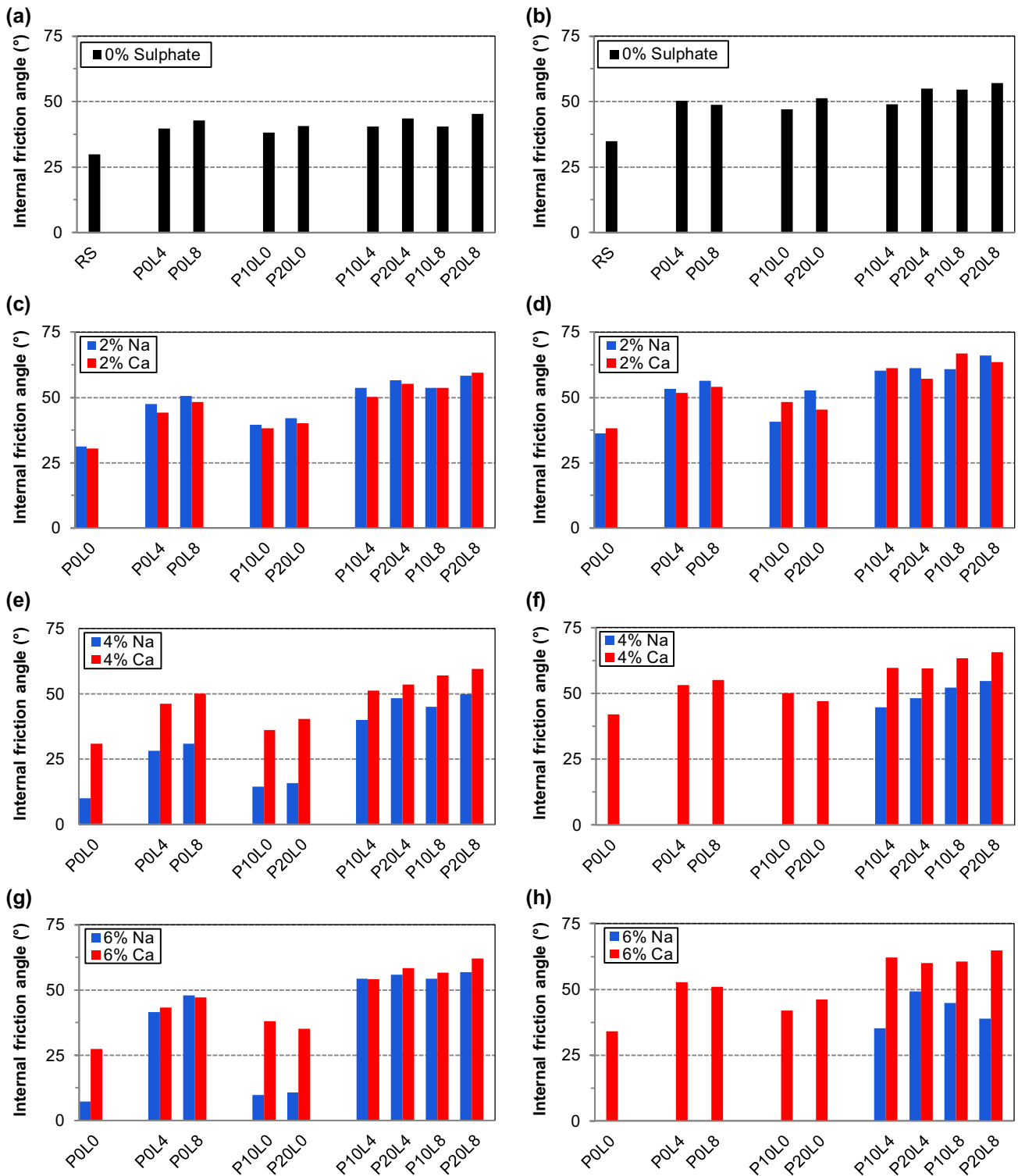


Figure 12. Effect of different content of both Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the internal friction angle of the RS stabilised with L, NP and their combination (a, c, e and g) after curing for 7 days, (b, d, f and h) after curing for 120 days.

soil-NP mixtures were to destroy both the stabilisation process (physical properties) and cemented particles (mechanical properties).

For comparison, for any curing period, there is a high increase in cohesion values of RS samples stabilised with NP alone in the presence of 2% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ as compared with samples containing 2% Na_2SO_4 . Also, it should be noted that the sensitivity of the

cohesion of both GS and RS samples to the sulphate effect was more pronounced with the Na_2SO_4 than with the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

Effects of L, NP and L-NP on the internal friction angle of both stabilised clayey soils in the absence of sulphates

The results of the temporal variation of internal friction angle of two stabilised clayey soils are shown in Figures 11(a, b) and

Table 4. A summary presents the difference between the effects caused by the presence of different contents of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and Na_2SO_4 on physico-mechanical properties of GS-8%L, GS-20%NP and GS-8%L-20%NP mixtures after 7 and 120 days of curing period.

Curing period (day)	Sulphate type	Additive used	Degree of sulphate effects on each property					Assessment and detailed recommendations produced according to both pH and compressive strength values as main indicators of pozzolanic reactions
			pH	PI (%)	UCS (MPa)	C (KN/m ²)	ϕ (°)	
7 (1-Day for PI)	Na_2SO_4	L	*****	*****	**	**	***	P0L8N2, P0L8N4 and P0L8N6: Present very high pH values (12.57 < pH < 12.67), low UCS values (1.37 < UCS (MPa) < 1.79), acceleration of early pozzolanic reactions (Gadouri, Harichane, and Ghrici 2016a)
		NP	*	*****	*	*	*	P20L0N2, P20L0N4 and P20L0N6: Present very low pH values (9.22 < pH < 9.26), very low UCS values (0.07 < UCS (MPa) < 0.15) and no pozzolanic reactions (Gadouri, Harichane, and Ghrici 2016a)
	CaSO_4	L-NP	*****	*****	**	***	***	P20L8N2, P20L8N4 and P20L8N6: Present very high pH values (12.64 < pH < 12.77), intermediate UCS values (1.55 < UCS (MPa) < 2.76), acceleration of early pozzolanic reactions (Shi and Day 2000a; Hu et al. 2016; Gadouri, Harichane, and Ghrici 2016a)
		NP	**	*****	*	*	***	P20L0C2, P20L0C4 and P20L0C6: Present very low to intermediate pH values (9.63 < pH < 10.35), very low to low UCS values (0.45 < UCS (MPa) < 1.05), acceleration of early pozzolanic reactions (Aldaood, Bouasker, and Al-Mukhtar 2014a, 2014b; Gadouri, Harichane, and Ghrici 2016b), cheapest and economic
120 (30-Days for PI)	Na_2SO_4	L	*****	***	***	**	****	P0L8C2, P0L8C4, P0L8C6, P20L8C2, P20L8C4 and P20L8C6: Present very high pH values (12.43 < pH < 12.53), low to high UCS values (1.68 < UCS (MPa) < 5.10), acceleration of early pozzolanic reactions (Aldaood, Bouasker, and Al-Mukhtar 2014a, 2014b; Gadouri, Harichane, and Ghrici 2016b), cheapest and economic
		L-NP	*****	**	****	***	****	P20L0N2, P20L0N4 and P20L0N6: Present very high pH values (12.34 < pH < 12.51), intermediate UCS values (2.17 < UCS (MPa) < 3.94), decrease in pozzolanic reactions, formation of ettringite mineral (Gadouri, Harichane, and Ghrici 2016a), recommended as mixtures for pavement engineering
	CaSO_4	NP	*	*****	*	*	**	P20L0N2, P20L0N4 and P20L0N6: Present very low pH values (9.10 < pH < 9.20), very low UCS values (0.17 < UCS (MPa) < 0.26) and no pozzolanic reactions (Gadouri, Harichane, and Ghrici 2016a), not recommended for pavement engineering
		L-NP	*****	*****	****	***	**	P20L8N2, P20L8N4 and P20L8N6: Present very high pH values (12.45 < pH < 12.55), very high UCS values (4.39 < UCS (MPa) < 5.23), decrease in pozzolanic reactions and formation of ettringite mineral (Shi and Day 2000a; Gadouri, Harichane, and Ghrici 2016a), highly recommended as mixtures for pavement engineering
CaSO_4	L	*****	**	****	***	***	All mixtures: Present very low to very high pH values (9.07 < pH < 12.15), intermediate to very high UCS values (3.93 < UCS (MPa) < 8.67), decrease in pozzolanic reactions, formation of ettringite mineral, no destruction has been observed in studied specimens (Aldaood, Bouasker, and Al-Mukhtar 2014a, 2014b; Gadouri, Harichane, and Ghrici 2016b), cheapest and economic, highly recommended as mixtures for pavement engineering	
	L-NP	*****	*	****	****	****	****	

* Very low, ** Low, *** Intermediate, **** High, ***** Very high.

Table 5. A summary presents the difference between the effects caused by the presence of different contents of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and Na_2SO_4 on physico-mechanical properties of RS-8%L, RS-20%NP and RS-8%L-20%NP mixtures after 7 and 120 days of curing period.

Curing period (day)	Sulphate type	Additive used	Degree of sulphate effects on each property							Assessment and detailed recommendations produced according to both pH and compressive strength values as main indicators of pozzolanic reactions
			pH	PI (%)	UCS (MPa)	C (KN/m ²)	ϕ (°)			
7 (1-Day for PI)	Na_2SO_4	L	*****	****	*	**	****			P01.8N2, P01.8N4 and P01.8N6: Present very high pH values (12.63 < pH < 12.84), low to intermediate UCS values (1.03 < UCS (MPa) < 2.12), acceleration of early pozzolanic reactions (Gadouri, Harichane, and Ghrici 2016a)
		NP	*	**	*	*	*			P201.0N2, P201.0N4 and P201.0N6: Present very low pH values (9.22 < pH < 9.35), very low UCS values (0.16 < UCS (MPa) < 0.55) and no pozzolanic reactions (Gadouri, Harichane, and Ghrici 2016a)
		L-NP	*****	***	**	***	*****			P201.8N2, P201.8N4 and P201.8N6: Present very high pH values (12.77 < pH < 12.97), intermediate to high UCS values (1.59 < UCS (MPa) < 4.71), acceleration of early pozzolanic reactions (Shi and Day 2000a; Hu et al. 2016; Gadouri, Harichane, and Ghrici 2016a)
	CaSO_4	NP	**	***	****	***	***			P201.0C2, P201.0C4 and P201.0C6: Present very low to low pH values (9.63 < pH < 10.35), very low to low UCS values (0.45 < UCS (MPa) < 1.05), acceleration of early pozzolanic reactions (Aldaood, Bouasker, and Al-Mukhtar 2014a, 2014b; Gadouri, Harichane, and Ghrici 2016b), cheapest and economic
		L	*****	***	****	**	****			P01.8C2, P01.8C4, P01.8C6, P201.8C4 and P201.8C6: Present very high pH values (12.43 < pH < 12.53), low to high UCS values (1.68 < UCS (MPa) < 5.10), acceleration of early pozzolanic reactions (Aldaood, Bouasker, and Al-Mukhtar 2014a, 2014b; Gadouri, Harichane, and Ghrici 2016b), cheapest and economic
		L-NP	*****	**	****	***	*****			P201.0N2: Presents very low pH values (pH = 9.16), low UCS values (UCS = 1.26 MPa), (Gadouri, Harichane, and Ghrici 2016a), not recommended for pavement engineering
120(30-Days for PI)	Na_2SO_4	L	*****	****	≠	≠	≠			P201.0N4 and P201.0N6: Present very low pH values (9.13 < pH < 9.25), all specimens have been broken (deteriorated) before UCS test due to the ettringite formation (Gadouri, Harichane, and Ghrici 2016a), strictly not recommended for pavement engineering
		NP	*	**	≠	≠	≠			P01.8N2, P01.8N4, P201.8N2 and P201.8N4: Present very high pH values (12.63 < pH < 12.91), intermediate to very high UCS values (2.97 < UCS (MPa) < 8.70) (Gadouri, Harichane, and Ghrici 2016a), highly recommended as mixtures for pavement engineering
		L-NP	*****	***	***	**	***			P01.8N6: Presents very high pH values (pH < 12.84), all specimens have been broken (deteriorated) before UCS test due to the ettringite formation (Gadouri, Harichane, and Ghrici 2016a), strictly not recommended for pavement engineering
CaSO_4	L	*****	**	****	****	****			All mixtures: Present low to high pH values (9.07 < pH < 12.15), intermediate to very high UCS values (3.93 < UCS (MPa) < 8.67), decrease in pozzolanic reactions, formation of ettringite mineral, no destruction has been observed in studied specimens (Aldaood, Bouasker, and Al-Mukhtar 2014a, 2014b; Gadouri, Harichane, and Ghrici 2016b), cheapest and economic, highly recommended as mixtures for pavement engineering	
	NP	*	**	*****	***	*****				
	L-NP	*****	*	*****	****	*****				

*Very low, ** Low, *** Intermediate, **** High, ***** Very high, ≠ deteriorated specimen.

12(a, b). In general, the stabilisation using L alone or in combination with NP can modify the structure of both clayey soils from dispersed to flocculated form which reflected the significant increase in their internal friction angle.

The internal friction angle of both GS and RS samples increased 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. In fact, Sezer et al. (2006) reported that the combination of fly ash and L with a high content increased 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 increased the internal friction angle value whereas the cementation of particles increased the cohesion value. However, in the case of both L-treated clayey soils, it can be seen that the internal friction angle increased with increasing L content and curing period, particularly, at later stages. The increase in the internal friction angle was more pronounced with the RS than with the GS. Also, the difference in the internal friction angle value between L and NP was more pronounced with the GS than with the RS. This behaviour is probably due to the mineralogical composition and the high value of plasticity index of GS as compared with that of the RS. However, the internal friction angle of both GS and RS samples stabilised with L or in combination with NP becomes very higher after curing for 120 days. The improvement in shear strength parameters may be due to the pozzolanic activity and self-cementitious characteristics of the soil-L and soil-L-NP mixtures (Harichane et al. 2011).

Effects of Na_2SO_4 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ on the internal friction angle of both stabilised clayey soils in the absence of sulphates

The results of the effect of both $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and Na_2SO_4 on the temporal variation of the internal friction angle of two stabilised clayey soils are presented in Figures 11(c-h) and 12(c-h). It is quite clear to see that the internal friction angle of both GS and RS samples stabilised with the addition of 20%NP was very higher as compared with the untreated soil. This behaviour is probably due to the fact that the untreated soil has a low internal friction angle to compare with that of the NP. With NP as an additive, the increase in the internal friction angle with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content and curing period was more pronounced with the RS than with the GS. However, the internal friction angle of two clayey soils stabilised with L alone or in combination with NP increased strongly with increasing $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and curing period. However, when the content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ was greater than 2%, the internal friction angle of two clayey soils increased sharply with curing period. It is obvious to observe that the internal friction angle of both clayey soils stabilised with L alone or in combination with NP on curing with or without $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ increased with increasing cohesion values (Figures 11(a-h) and 12(a-h)). It should be noted that the large values of internal friction angle were coupled with high cohesion values. It is suggested that this behaviour is probably due to the high normal loads used during the direct shear test which increased the compressibility of the soil structure and consequently activated the frictional properties between cementing agents and soil particles leading to the high increase in the internal friction angle.

When Na_2SO_4 was present, the internal friction angle of both clayey soils stabilised with NP decreased with Na_2SO_4 content but increased slightly with curing period. With NP as an additive, the decrease in the internal friction angle was more pronounced with the RS than with the GS. However, the internal friction angle of both clayey soils stabilised with L or L-NP on curing with 2% Na_2SO_4 increased with curing period but decreased gradually with increasing Na_2SO_4 content. Additionally, with 6% of Na_2SO_4 the internal friction angle of both clayey soils stabilised with L or L-NP decreased very quickly after curing for 120 days (Figures 11(h) and 12(h)). For any curing period, the internal friction angle of both clayey soils stabilised with L or L-NP on curing without or with 2% Na_2SO_4 increased with increasing of cohesion (Figures 11(a-d) and 12(a-d)). On the other hand, it is clear to observe that for any curing period, the internal friction angle of both clayey soils stabilised with L or L-NP on curing without or with any content of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ increased with increasing of cohesion. For comparison, it is quite clear to observe that the sensitivity of the internal friction angle of both GS and RS samples to the sulphate effect was more pronounced with the Na_2SO_4 than with the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

Guide for choosing an adequate mixture as building materials for road pavements

Tables 4 and 5 depict the difference between the effects produced by both $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and Na_2SO_4 on pH parameter, plasticity index, UCS and shear strength parameters (C and ϕ) of two clayey soils stabilised with L, NP and their combination. Also, both Tables 4 and 5 can be used for choosing an adequate mixture for pavement subgrade soil stabilisation based on some physico-mechanical properties and previous results published in literature by several researchers (e.g. Aldaood, Bouasker, and Al-Mukhtar 2014a, 2014b; Hu et al. 2016; Gadouri, Harichane, and Ghrici 2016a, 2016b, 2016c).

Detailed recommendations were given in both Tables 4 and 5 in order to choose an adequate mixture (a better selection) with suitable technical and economic conditions. Both tables are recommended only for clayey soils stabilised with L, NP and their combination in the presence of monovalent (Na_2SO_4) and divalent ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) sulphates.

Conclusions

A comparison study between $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and Na_2SO_4 effects on geotechnical properties of clayey soils stabilised with L, NP and their combination has been made in order to recommend adequate mixtures which can be used as materials for road pavements. Based on the test results, the following conclusions can be drawn:

- The addition of L to both clayey soils stabilised without sulphates produced a significant increase in UCS, shear strength parameters and pH parameter but a high decrease in PI, whereas the NP induced slight changes. However, a further increase in UCS, shear strength parameters and pH parameter, and a better decrease in PI were recorded when using the L and NP as a combined treatment.

- The addition of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ to both clayey soils stabilised with any additive reduced considerably the PI, whereas the presence of Na_2SO_4 increased the PI of these soils. Moreover, both increases and decreases depend largely on additive type and its content, sulphate type and its content and curing period (DTC and DTN). In addition, the mineralogical composition of soil plays an important role in chemical reactions when sulphates are present.
- The increase in pH value of soil–NP and soil–L–NP mixtures with sulphate content was more pronounced with the Na_2SO_4 than with the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ due to the fact that the NaOH has the chemical property to increase the pH of the soil solution more than the $\text{Ca}(\text{OH})_2$. In addition, for the soil–NP mixture, the sensitivity of the pH to the curing period effect was more pronounced with the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ than with the Na_2SO_4 . Moreover, for both soil–L and soil–L–NP mixtures, the sensitivity of the pH to the L and L–NP effect was more pronounced with the presence of Na_2SO_4 than with the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ addition.
- Both $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and Na_2SO_4 accelerated the pozzolanic reactions responsible for the early increase of both UCS and cohesion of two clayey soils. However, the degradation of RS specimens after 120 days of curing can be explained by the formation of ettringite (observed in XRD diagrams) due to the presence of high Na_2SO_4 content.
- The $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ had no undesirable influence on soil improvement whereas the presence of Na_2SO_4 with a high content (more than 2%) can be classified as a deleterious chemical compound for soil stabilisation process. Furthermore, the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ is available and cheaper, and it can be used alone or in combination with NP as an accelerator of pozzolanic reactions. Also, the Na_2SO_4 with low content (less than 2%) can be used as an accelerator of pozzolanic reactions and NP dissolution without altering the stabilisation process.
- It should be noted that the selection of an adequate mixture for any pavement subgrade soil stabilisation requires, at this stage, to respect the above recommendations given in Tables 4 and 5.

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