



## Assessment of sulphates effect on pH and pozzolanic reactions of soil–lime–natural pozzolana mixtures

Hamid Gadouri , Khelifa Harichane & Mohamed Ghrici

To cite this article: Hamid Gadouri , Khelifa Harichane & Mohamed Ghrici (2017): Assessment of sulphates effect on pH and pozzolanic reactions of soil–lime–natural pozzolana mixtures, International Journal of Pavement Engineering, DOI: [10.1080/10298436.2017.1337119](https://doi.org/10.1080/10298436.2017.1337119)

To link to this article: <http://dx.doi.org/10.1080/10298436.2017.1337119>



Published online: 07 Jun 2017.



Submit your article to this journal [↗](#)



View related articles [↗](#)



View Crossmark data [↗](#)



## Assessment of sulphates effect on pH and pozzolanic reactions of soil–lime–natural pozzolana mixtures

Hamid Gadouri<sup>a,b</sup> , Khelifa Harichane<sup>b</sup> and Mohamed Ghrici<sup>b</sup>

<sup>a</sup>Department of Matter Engineering, University of Medea, Medea, Algeria; <sup>b</sup>Geomaterials Laboratory, Department of Civil Engineering, University of Chlef, Chlef, Algeria

### ABSTRACT

The geotechnical properties of subgrade soils may need to be enhanced for appropriateness in pavement construction using mineral additives such as cement, lime (L) and fly ash. An experimental investigation was undertaken to study the effects of sodium ( $\text{Na}_2\text{SO}_4$ ) and calcium ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) sulphates on pH and pozzolanic reactions of soil–lime–natural pozzolana (soil–L–NP) mixtures in order to choose an adequate mixture for pavement subgrade soil stabilisation. The pH was measured for different curing periods with and without sulphates. The results showed that increases and decreases in pH values depend on the type of additive and its amount, type of sulphate and its content, mineralogical composition of stabilised soil and curing period. In addition, the pH parameter can be used as an indicator to track the pozzolanic reactions process. On the other hand, clayey subgrade soils can be stabilised with Lime–Natural Pozzolana (L–NP) mixtures containing any amounts of  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  which is highly recommended. However,  $\text{Na}_2\text{SO}_4$  with a low content has a better effect on the behaviour of these soils but become deleterious when its content is greater than 2%. In general, the addition of sulphates accelerates both the pozzolanic reactions and NP dissolution.

### ARTICLE HISTORY

Received 8 October 2016  
Accepted 26 May 2017

### KEYWORDS

Clayey soil; lime; natural pozzolana; sulphate; pH value

### Introduction

High volumes of problematic soils have been not recommended to be used as materials for construction due to their low quality. Indeed, in the world, it is known that the most frequent problem for all civil engineering projects is the presence of unsuitable soils which require a special technique for their improvement such as chemical stabilisation, dynamic compaction and soil replacement. Chemical soil stabilisation has been practised for several years with the main aim to make the unsuitable soils capable of meeting the requirements of the specific engineering projects (Kolias *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 1999). The production of one-metric-ton of cement leads to the emission of about one-metric-ton of  $\text{CO}_2$  and requires large amounts of energy (Ghrici *et al.* 2007, Segui *et al.* 2013). In order to reduce both energy consumption and  $\text{CO}_2$  emission, several researchers recommended the use of volcanic materials such as volcanic ash and NP (Hossain *et al.* 2007, Mfinanga and Kamuhabwa 2008, Harichane *et al.* 2010, 2011a, 2011b, 2011c, 2012, Zoubir *et al.* 2013, Segui *et al.* 2013, Al-Swaidani *et al.* 2016, Gadouri *et al.* 2016a, 2016b, 2016c). These mineral additives have been used in combination with L for soil stabilisation because of their economical 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 and unconfined compressive strength values of cohesive soils stabilised with the combination of NP and L are very larger than that of the untreated soils.

According to Khemissa and Mahamedi (2014), expansive and salted soils with low resistance (strength) and high plasticity are among 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 Northern territory 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. According to Baryla *et al.* (2000), various forms of degradation observed in road pavements are frequently related to the formation of new expansive phases such as ettringite and/or thaumasite due to the presence of sulphate ions ( $\text{SO}_4^{2-}$ ).

Furthermore, NP is found with high amounts in areas of Beni-Saf located in the West of Algeria (Ghrici *et al.* 2007). The effects of  $\text{Na}_2\text{SO}_4$  (Gadouri *et al.* 2016a) and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  (Gadouri *et al.* 2016b) on geotechnical properties of clayey soils stabilised

**Table 1.** Physico-mechanical and chemico-mineralogical properties of materials used.

Properties name	Chemical formula	Materials used	
<i>Chemico-mineralogical properties of soils</i>		GS	RS (%)
Calcium oxide (%)	CaO	14.43	2.23
Alumina (%)	Al <sub>2</sub> O <sub>3</sub>	14.15	19.01
Silica (%)	SiO <sub>2</sub>	43.67	57.02
pH	–	9.18	9.05
Calcite (%)	CaCO <sub>3</sub>	26.0	4.0
Quartz (%)	SiO <sub>2</sub>	20	30
Illite (%)	2K <sub>2</sub> O·Al <sub>2</sub> O <sub>3</sub> ·24SiO <sub>2</sub> ·2H <sub>2</sub> O	16.0	24.0
Kaolinite (%)	Al <sub>2</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	12.0	16.0
Montmorillonite (%)	Al <sub>2</sub> (Si <sub>4</sub> Al)O <sub>10</sub> (OH) <sub>2</sub> ·H <sub>2</sub> O	20.0	–
<i>Physico-mechanical properties of soils</i>			
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
<i>Chemical properties of additives</i>		L	NP
CaO (%)		83.3	9.90
MgO (%)		<0.5	2.42
Fe <sub>2</sub> O <sub>3</sub> (%)		<2.0	9.69
Al <sub>2</sub> O <sub>3</sub> (%)		<1.5	17.5
SiO <sub>2</sub> (%)		<2.5	46.4
CaCO <sub>3</sub> (%)		<10	–
<i>Physico-chemical properties of sulphates</i>		CaSO <sub>4</sub>	Na <sub>2</sub> SO <sub>4</sub>
Molar weight (g/mol)		172.2	142
Auauy (dried)		99	99.5
pH (50 g/L, 25 °C)		–	5–8

with L, NP and their combination have been investigated. They have reported in their study that sulphate ions react with calcium (Ca<sup>2+</sup>), hydroxyl (OH<sup>-</sup>) and alumina [Al(OH)<sub>4</sub>] and silica [SiO(OH)<sub>3</sub>]<sup>-</sup> compounds to form ettringite mineral.

Furthermore, the magnitude of damage caused by this mineral (ettringite) depends on the additive type and its content, the mineralogical composition of stabilised soil and the type of sulphate ions (e.g. K<sup>+</sup>, Na<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>,...etc.) and its concentration. Similar observations have been reported by several researchers (Kinuthia *et al.* 1999, Sivapullaiah *et al.* 2000, 2006, Le Borgne 2010, Segui *et al.* 2013, Aldaood *et al.* 2014a, 2014b, Hu *et al.* 2016). It has been reported that the presence of CaSO<sub>4</sub>·2H<sub>2</sub>O produced a beneficial effect on strength and plasticity of stabilised clayey soils (Yilmaz *et al.* 2009, Gadouri *et al.* 2016b), but the presence of Na<sub>2</sub>SO<sub>4</sub> with a high concentration induced a deleterious effect and affected the stabilisation process (Kinuthia *et al.* 1999, Ktnuthia and Wild 2001, Gadouri *et al.* 2016a, Hu *et al.* 2016). On the other hand, NP can be used in combination with L in order to resist to sulphate attacks (Gadouri *et al.* 2016a) and in the improvement of general durability of clayey soils (Harichane *et al.* 2010).

In Algeria, intensive road networks currently built as well as large amounts of soils with insufficient or poor mechanical characteristics requires developing new hydraulic binders based on several mixtures. Di Sante *et al.* (2014) have studied the progression of physico-chemical reactions in compacted soil–lime mixtures and their effect on the mechanical and hydraulic performance with time as a method based only on pH measurement. They have reported that the method adopted in their study allowed to appropriately analyse the results obtained from both permeability and oedometer tests. On the other hand, Rao and Shivananda (2005) have assessed the effects of ambient

temperature on the progress of lime–soil reactions of an expansive black cotton soil. They have reported that higher ambient temperatures do accelerate the progress of lime–soil reactions. In addition, the pH parameter was used to monitor the progression of the lime–clay reactions Al-Mukhtar *et al.* (2010). So, the pozzolanic reactions can be controlled by the pH value measurement because the pH value is responsible for the dissolution of silica (SiO<sub>2</sub>) and alumina (Al<sub>2</sub>O<sub>3</sub>) which react with calcium (provided from lime) to form cementing agents (C–S–H and C–A–H) responsible for the development of mechanical performance (strength development), particularly, with the curing period. Conversely, the decrease in strength development can be reflected by the decrease in the pH value, and consequently the decrease in pozzolanic reactions. So, the pH can be used as a good indicator (or index parameter) to track the pozzolanic reactions process.

In this paper, according to ASTM D4972-01 (2001), the assessment of sulphates effect on pH value and pozzolanic reactions of soil–lime–natural pozzolana (soil–L–NP) mixtures has been investigated in order to develop hydraulic binders for pavement subgrade soil stabilisation.

## Materials extraction and identification

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

However, the NP was ground to the specific surface area of 420 m<sup>2</sup>/kg whereas the L used in this study was a hydrated lime (Ca(OH)<sub>2</sub>). It was commercially available lime typically used for construction purposes.

Moreover, two chemical compounds were used. The first is a calcium sulphate dihydrate (CaSO<sub>4</sub>·2H<sub>2</sub>O). The second is a sodium sulphate (Na<sub>2</sub>SO<sub>4</sub>). The main physico-mechanical, chemico-mineralogical and physico-chemical properties of soils, additives and sulphates are summarised in Table 1.

## Test procedures and samples preparation

### pH measurement test

In this study, a pH meter was used for testing in order to evaluate the degree of acidity (or alkalinity) in soil materials suspended in water. The pH parameter is useful in assessing the solubility of clayey soil minerals and the mobility of ions in the soil solution. An experimental test of pH measurement was conducted on both selected clayey soils and performed according to ASTM D4972-01 (2001). The pH of both stabilised clayey soils was measured in all samples with and without sulphates. Table 2 shows a summary of 56 combinations for both GS and RS samples. In this study, according to Harichane and Ghrici (2009) and Gadouri *et al.* (2016a), 8%L, 20%NP and the combination of both (8%L + 20%NP) were selected as optimum dosages for stabilisation.

**Table 2.** A summary of the mix combinations tested for both clayey soils stabilised with and without sulphates.

Sulphate type	Combinations	Mixture proportions (%)			
		Soil	NP	L	Sulphate
Without sulphate	POL0	100	0	0	0
	POL8	92	0	8	0
	P20L0	80	20	0	0
	P20L8	72	20	8	0
Calcium sulphate (CaSO <sub>4</sub> ·2H <sub>2</sub> O)	POL0C2	98	0	0	2
	POL8C2	90	0	8	2
	P20L0C2	78	20	0	2
	P20L8C2	70	20	8	2
	POL0C4	96	0	0	4
	POL8C4	88	0	8	4
	P20L0C4	76	20	0	4
	P20L8C4	68	20	8	4
	POL0C6	94	0	0	6
	POL8C6	86	0	8	6
	P20L0C6	74	20	0	6
	P20L8C6	66	20	8	6
Sodium sulphate (Na <sub>2</sub> SO <sub>4</sub> )	POLON2	98	0	0	2
	POL8N2	90	0	8	2
	P20LON2	78	20	0	2
	P20L8N2	70	20	8	2
	POLON4	96	0	0	4
	POL8N4	88	0	8	4
	P20LON4	76	20	0	4
	P20L8N4	68	20	8	4
	POLON6	94	0	0	6
	POL8N6	86	0	8	6
	P20LON6	74	20	0	6
	P20L8N6	66	20	8	6

### Samples preparation

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

For both clayey soils, several combinations of NP and L were used for their stabilisation. The air-dried soils were initially mixed with the predetermined quantity of NP and L in a dry state to obtain different mixtures. Before distilled water addition, all mixtures (soil–L, soil–NP and soil–L–NP) were sieved through a No. 10 sieve (2 mm sieve mesh openings) in order to eliminate the fractions with particles larger than 2 mm. For each mixture, 10 g (of air dried) was weighed and placed into a glass container. Thus, 10 g of distilled water was also added to each mixture and letting stand for 1 h prior to testing. All mixtures were placed into a glass container at a temperature and relative humidity of  $20 \pm 2$  °C and  $95 \pm 5\%$ , respectively. For all mixtures, the pH measurement was carried out in a slurry form but not on the pore water of a compacted sample. Furthermore, the samples were tested after curing for 7, 30, 60 and 120 days. The tests of all samples were repeated on three identical samples and the accepted pH value was an average of three tests carried out on each sample type.

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

In this case, the samples were mixed in the same way as presented above except that different contents of Na<sub>2</sub>SO<sub>4</sub> and CaSO<sub>4</sub>·2H<sub>2</sub>O powders (0–6% by weight of dry soil) were also added into the soil–L, soil–NP and soil–L–NP mixtures in a dry state. In addition, the pH tests were performed after the same curing periods in the same way as presented above once the distilled water was added to the mixtures.

### X-ray diffraction test and samples preparation

The X-ray diffraction (XRD) test was invited in order to investigate the mineralogical aspect of two clayey soils stabilised with L, NP and their combination. A PHILIPS PW3020 diffractometer was used for XRD analysis. The fractured samples obtained from unconfined compressive strength tests (Gadouri *et al.* 2016a, 2016b) were dried for 1 day at 40 °C. Before testing, the collected soil samples were crushed into a fine powder and passed through a 400 µm sieve to use as samples for the XRD test. The diffraction patterns were conducted using Cu–Kα radiation with a Bragg angle (2θ) range of 4–60° running at a speed of  $0.83 \times 10^{-2}/2$  s. The same XRD test was adopted by Aldaood *et al.* (2014a, 2014b). In this study, the examination of the eventual formation of cementing compounds and ettringite were conducted on untreated and treated clayey soil samples after 60 days of curing. In addition, the investigation of the formation of cementing compounds and ettringite were also conducted on soil samples containing 4% of both Na<sub>2</sub>SO<sub>4</sub> and CaSO<sub>4</sub>·2H<sub>2</sub>O.

### Experimental results and discussion

#### pH variation of both untreated and treated soil samples

Figure 1 shows the changes in the pH of soil–L, soil–NP and soil–L–NP mixtures measured at different curing periods. 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 increases the pH of both GS and RS from 9.18 and 9.08 to 12.3 and 12.35, respectively. A similar behaviour was observed by Al-Mukhtar *et al.* (2010). According to Samantasinghar (2014), the long-term pozzolanic reactions begin as an increase in hydroxyl ions (OH<sup>-</sup>) from the lime causes 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 decreases with curing period due to the consumption of L added by pozzolanic reactions to form cementing agents (Figures 5(g) and (h) and 6(g) and (h)). The highest effect on the pH of both clayey soil samples is achieved when the combination of 20%NP + 8%L was used. In all cases, the decrease in pH value with the curing period is 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 present 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 that RS presents a higher amount of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>, therefore, pozzolanic reactions can develop to a greater extent with RS, leading to a higher decrease in pH value.

#### pH variation of untreated soil samples containing various sulphate contents

Table 3 presents the results of pH variation of both untreated clayey soil samples measured under different sulphate contents at different curing periods. Both untreated soil samples showed negligible changes in the pH value upon the addition of various Na<sub>2</sub>SO<sub>4</sub> contents at different curing periods. For any curing

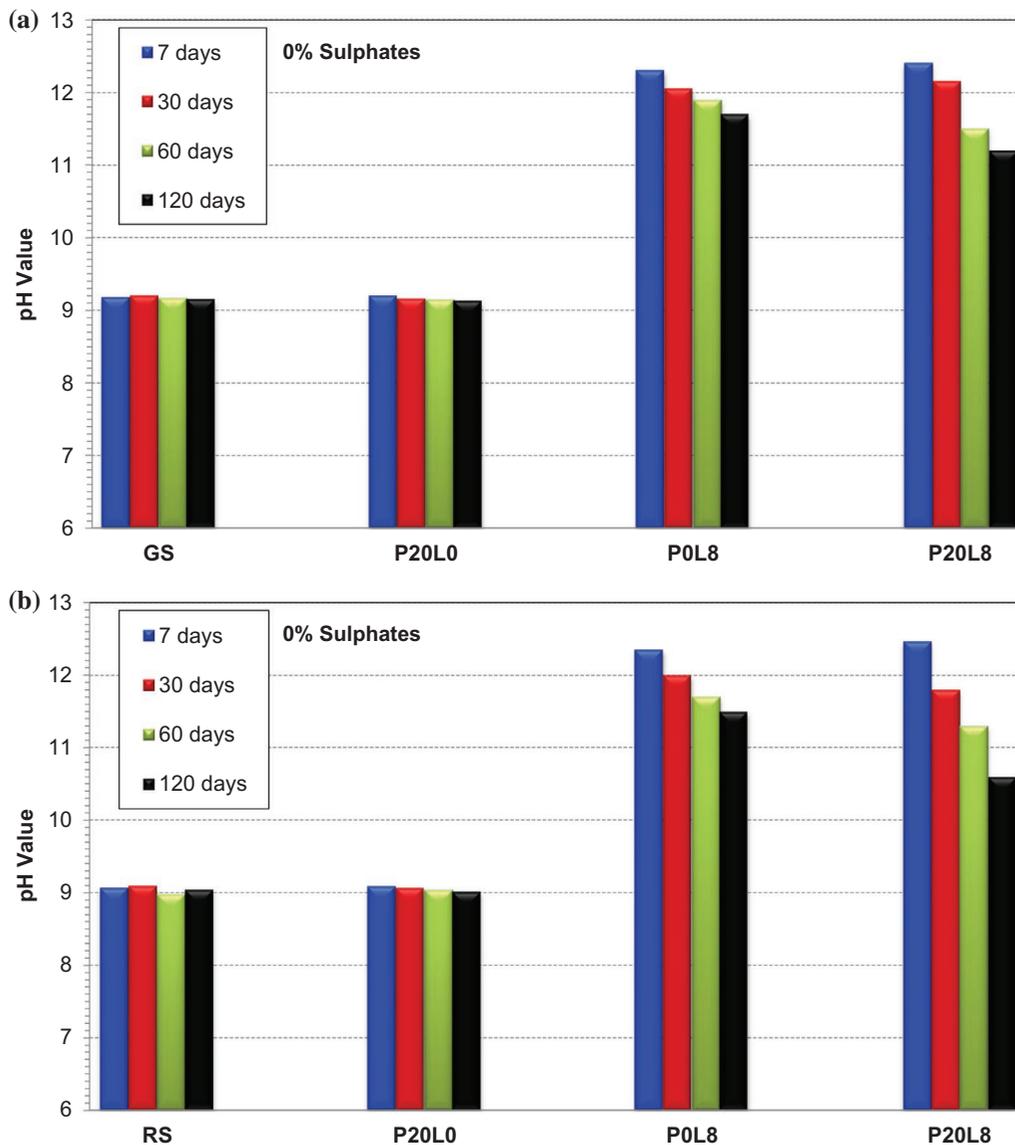


Figure 1. Effect of 20%NP, 8%L and their combination on the pH of both clayey soils (a) GS, (b) RS.

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

Sulphate type	Soil type	Combina-tions	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 ( $\text{Na}_2\text{SO}_4$ )	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 ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ )	GS	POLC2	9.54	9.25	9.15	9.14
		POLC4	10.07	9.80	9.42	9.20
		POLC6	10.15	9.91	9.61	9.32
	RS	POLC2	9.42	9.22	9.16	9.10
		POLC4	9.86	9.50	9.34	9.15
		POLC6	10.10	9.65	9.55	9.21

periods, it is obvious to see that no rate of  $\text{Na}_2\text{SO}_4$  has had any influence on pH of both untreated soils. In contrast, for both clayey soil samples, pH increases considerably with increasing  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  content but decreases with curing period. For comparison, the increase in pH value with  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  is 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 that of the RS because the CaO can considerably contribute to increasing the pH value.

#### pH variation of Soil-NP-Sulphate mixture

Figure 2 illustrates the results of  $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  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 decreases with curing period but increases with increasing sulphate contents. However, there is a slight decrease in pH values of both clayey soils with increasing  $\text{Na}_2\text{SO}_4$  content. For both clayey soils, the sensitivity

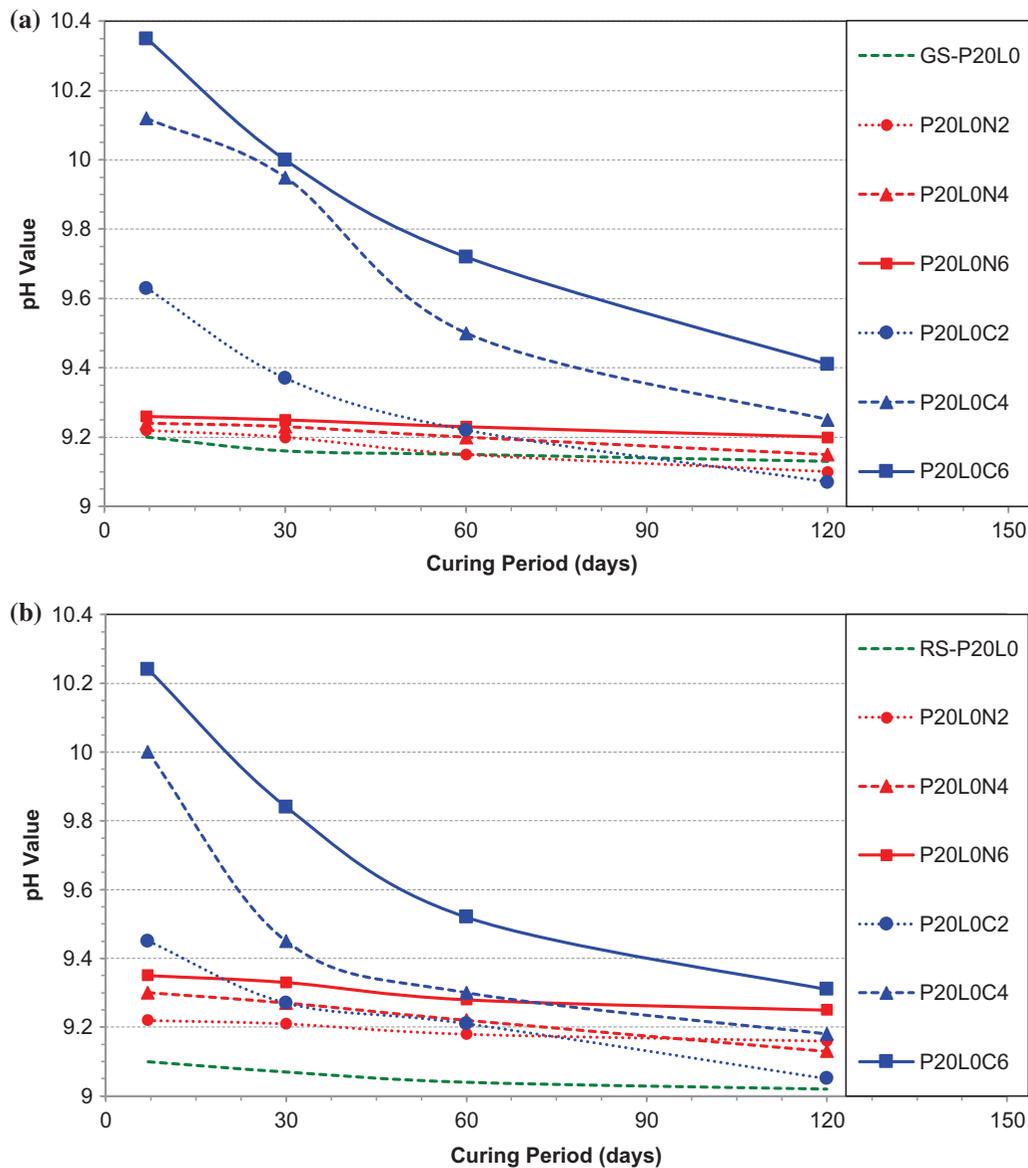


Figure 2. Effect of different contents of  $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  on the pH of both clayey soil samples stabilised with 20%NP (a) GS, (b) RS.

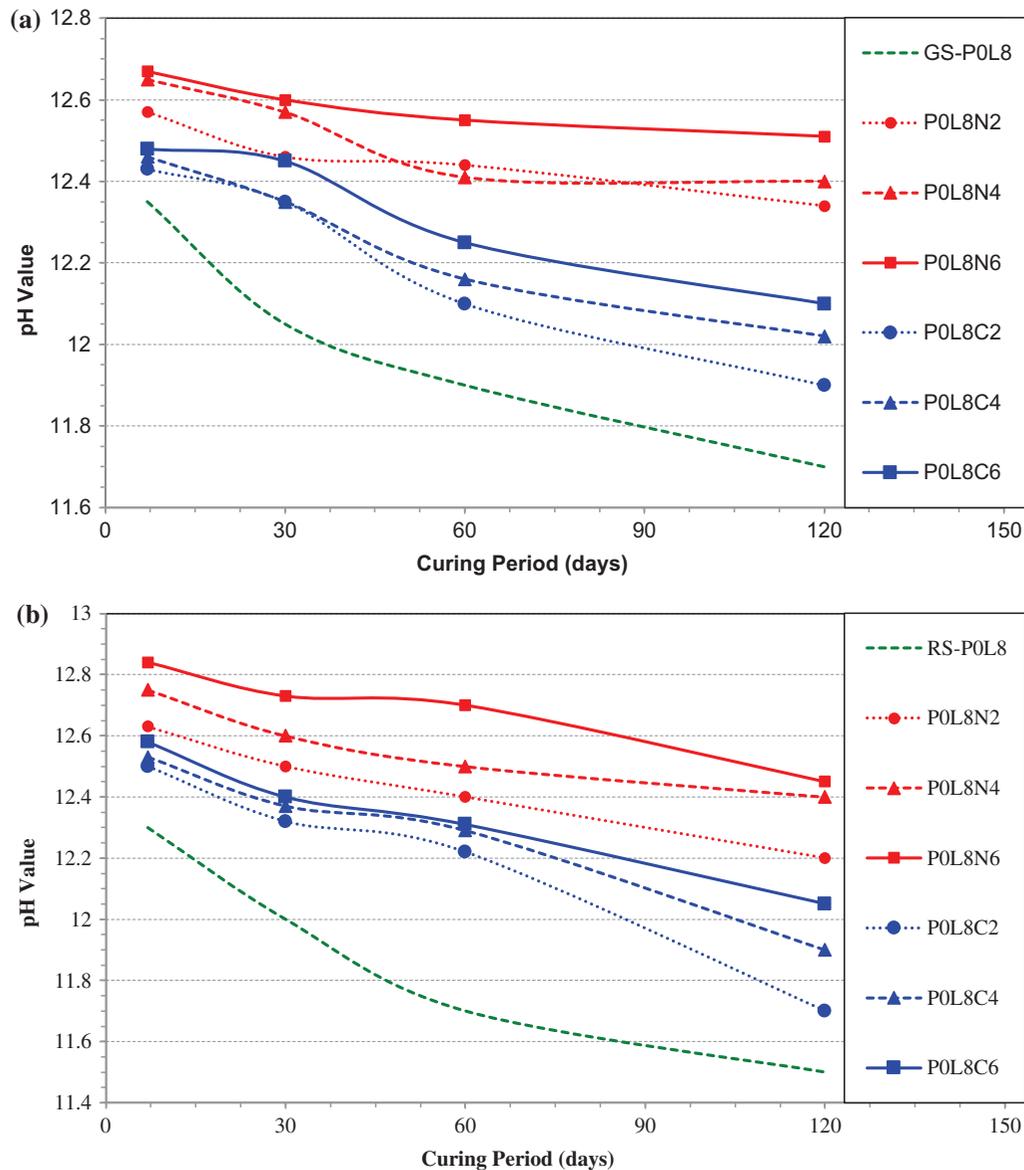
of the pH to the curing period effect is more pronounced with the  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  than with the  $\text{Na}_2\text{SO}_4$ . In the same way, it is also more pronounced with the  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  content than with the  $\text{Na}_2\text{SO}_4$  content. This behaviour confirms that the sensitivity of the amorphous silica ( $\text{SiO}_2$  from soil and/or NP) to the sulphate effect is more pronounced with divalent cations ( $\text{Ca}^{2+}$ ) than with monovalent cations ( $\text{Na}^+$ ). On the other hand, for a longer curing period (120 days), the  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  effect on the pH of both clayey soils is comparable to that of the  $\text{Na}_2\text{SO}_4$ .

The pH is a better indicator for the tracking of pozzolanic reactions evolution which leads to the formation of cementing agents responsible for strength improvement. It has been demonstrated that the presence of  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  improves considerably the strength of soil-NP mixture as compared with mixture without  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  (Gadouri *et al.* 2016b).

#### pH variation of soil-L-sulphate and soil-L-NP-sulphate mixtures

The results of  $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  effects on the pH of soil-L and soil-L-NP mixtures measured at different curing periods are shown in Figures 3 and 4, respectively. In all cases, the pH of both soil-L and soil-L-NP mixtures increases with increasing  $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  content but decreases with curing period. A similar trend was observed by Shi and Day (2000) and Aldaood *et al.* (2014b) when they used  $\text{Na}_2\text{SO}_4$  and gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), respectively. However, when  $\text{Na}_2\text{SO}_4$  is 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 is more pronounced with the  $\text{Na}_2\text{SO}_4$  than with the  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ . This is



**Figure 3.** Effect of different contents of  $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  on the pH of both clayey soil samples stabilised with 8%L (a) GS, (b) RS.

attributed to the sodium hydroxide (NaOH) which increases considerably the pH of soil and causes the dissolution of a large amount of alumina and silica that come into reaction with the remaining L to form cementitious products (Sridhran *et al.* 1995). It has been reported that chemical reactions between L, NP and  $\text{Na}_2\text{SO}_4$  increase the pH of the mixture and produces an early increase in unconfined compressive strength of both GS and RS samples containing  $\text{Na}_2\text{SO}_4$  (Gadouri *et al.* 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 is more pronounced with the presence of  $\text{Na}_2\text{SO}_4$  than with the  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  addition. Moreover, for both clayey soils, the sensitivity of the pH to the curing period effect is more pronounced with the  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  than with the  $\text{Na}_2\text{SO}_4$  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 is greater with  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  (Mfinanga and Kamuhabwa 2008, Gadouri *et al.* 2016b) than with  $\text{Na}_2\text{SO}_4$  (Gadouri *et al.* 2016a). This is because with  $\text{Na}_2\text{SO}_4$  the cation exchange requirements must be met from L addition, whereas the calcium ions ( $\text{Ca}^{2+}$ ) required for cation exchanges of soil are provided by  $\text{Ca}^{2+}$  from  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  dissolution. Thus, there is a high decrease in the L content available for pozzolanic reactions in soil with  $\text{Na}_2\text{SO}_4$  compared with that available in soil with  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  (Mitchell 1986).

However, for a longer curing period the  $\text{Na}_2\text{SO}_4$  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 *et al.* 2016a). This is because the pH of these mixtures decreases with curing period which facilitates the formation of an expansive mineral (ettringite) responsible for the strength alteration.

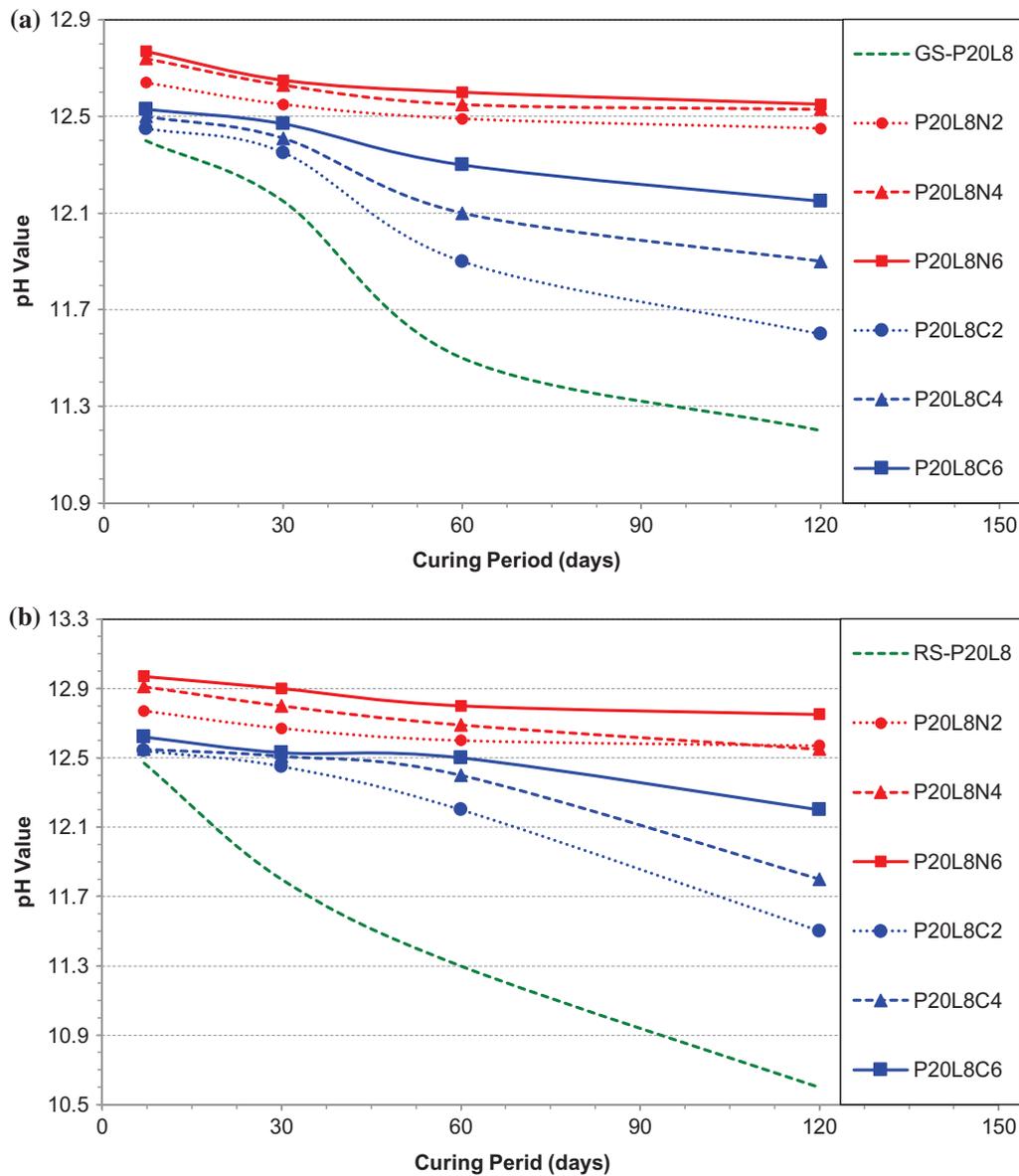


Figure 4. Effect of different contents of  $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  on the pH of both clayey soil samples stabilised with the combination of 20%NP and 8%L (a) GS, (b) RS.

### Effect of sulphates on the mineralogical composition of soil-NP, soil-L and soil-L-NP mixtures

Figures 5 and 6 show the XRD patterns of both GS and RS samples stabilised with 8%L, 20%NP and 20%NP + 8%L in the presence of only 4% of both  $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  after 60 days of curing period.

The XRD analysis indicated that the GS was composed of quartz, Montmorillonite, illite, kaolinite and calcite clay minerals, while this soil was predominantly composed of calcite (Figure 5(j)). However, the RS was contained of illite, kaolinite and quartz clay minerals, while the clay mineral was predominantly composed of quartz (Figure 6(j)). In the absence of sulphates, the identification using the XRD analysis revealed that the changes observed in the mineralogical composition of soil-L and soil-L-NP mixtures can be reflected in the formation of C-S-H and

C-A-H compounds (Figures 5(g) and (h) and 6(g) and (h)). However, the formation of these compounds was not observed in XRD patterns when using the NP alone as a stabiliser of both clayey soils (Figures 5(i) and 6(i)). This can be explained by the low pH value measured in the soil-NP mixture due to the fact that NP can't react with clay minerals in the absence of L or other activators of pozzolanic reactions such as the temperature known as physical activation method. On the other hand, the formation of ettringite in both soil-L and soil-L-NP mixtures was clearly observed in XRD patterns when both  $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  are present (Figures 5(a), (b), (d), (e) and 6(a), (b), (d), (e)). According to Gadouri *et al.* (2016a), the ettringite is a calcium aluminium sulphate hydrate (C-A-S-H) type of mineral which is responsible for both the early strength increase and structural distress at later stage, as will be chemically discussed in the next section.

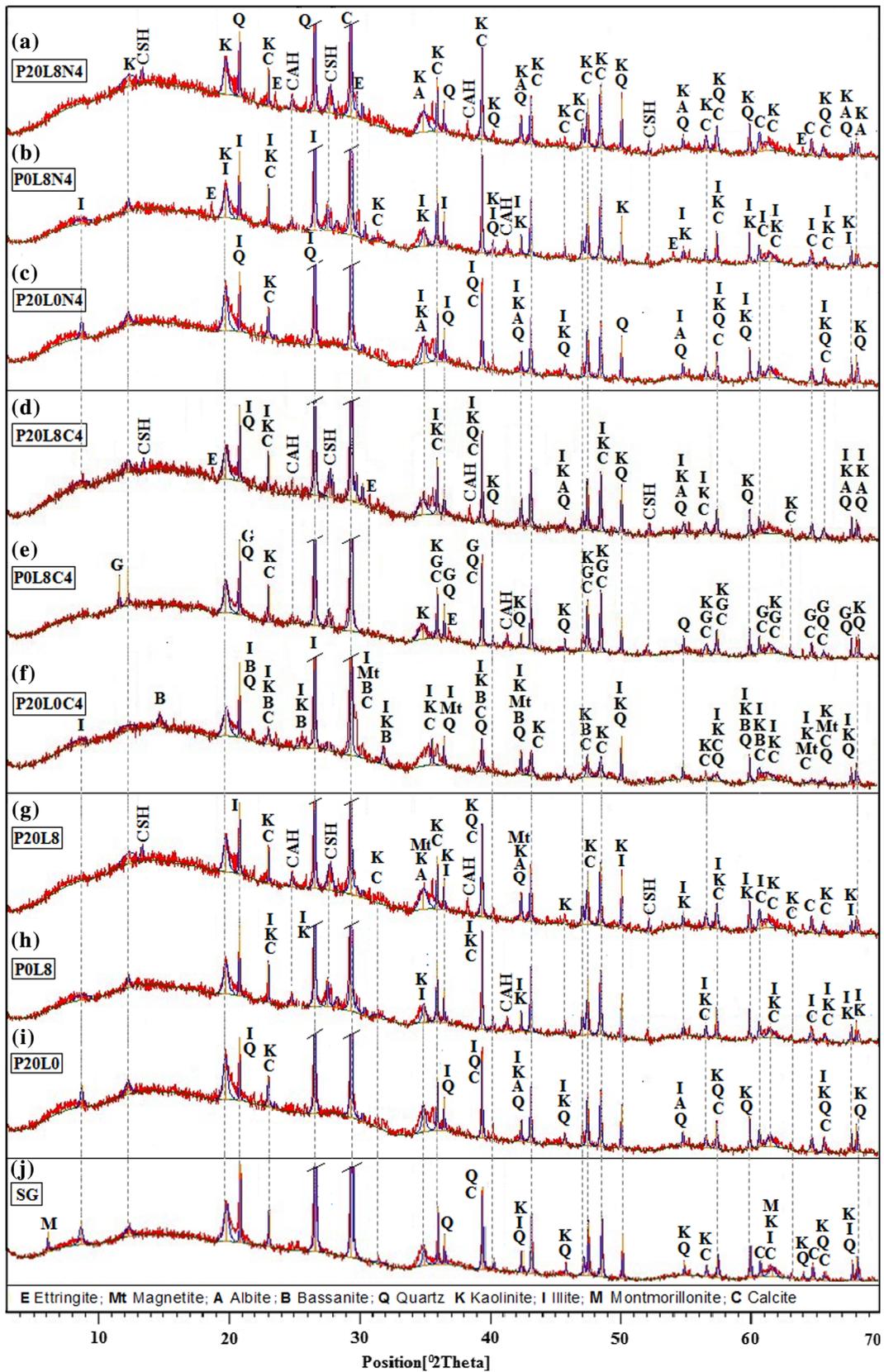
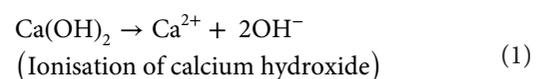


Figure 5. XRD patterns of GS samples stabilised with 8%L, 20%NP and 20%NP + 8%L in the presence of 4% of both  $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  after 60 days of curing period.

### Effect of sulphates on pozzolanic reactions and pH variation

The addition of water ( $2\text{H}_2\text{O}$ ) to the  $[\text{Ca}(\text{OH})_2]$  increases the pH value of the soil solution as follows (Equation (1)):



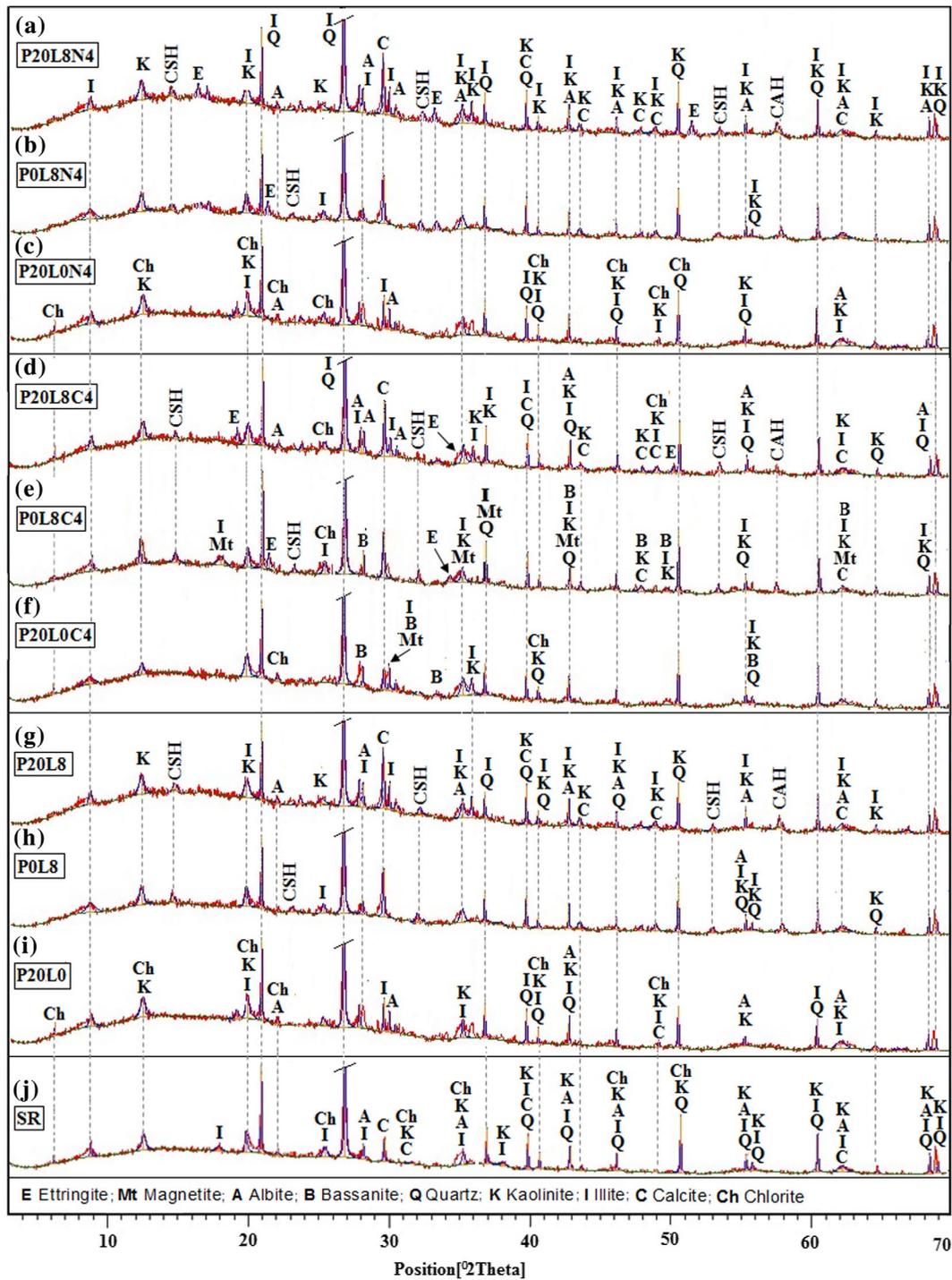
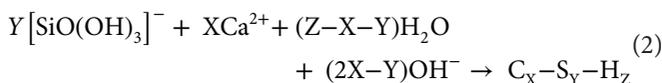


Figure 6. XRD patterns of RS samples stabilised with 8%L, 20%NP and 20%NP + 8%L in the presence of 4% of both  $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  after 60 days of curing period.

The acceleration in the rate of pozzolanic reactions leads to the acceleration of NP dissolution which forms monosilicates  $[\text{SiO}(\text{OH})_3]^-$  and aluminates  $[\text{Al}(\text{OH})_4]^-$  compounds. When calcium ions ( $\text{Ca}^{2+}$ ) contact these compounds the C-S-H and C-A-H can be formed as follows (Equations (2) and (3)) (Shi and Day 2000):



(Formation of calcium silicates hydrates)



(Formation of calcium aluminates hydrates)

The role of these compounds in the soil-L-NP mixture is to produce a layer of stable protective film that envelops the soil particles, to bind the soil particles together, to seal the voids that decrease the void index and consequently the water permeability and to improve the compactness and consequently the unconfined compressive strength of soil (Gadouri *et al.* 2016a).

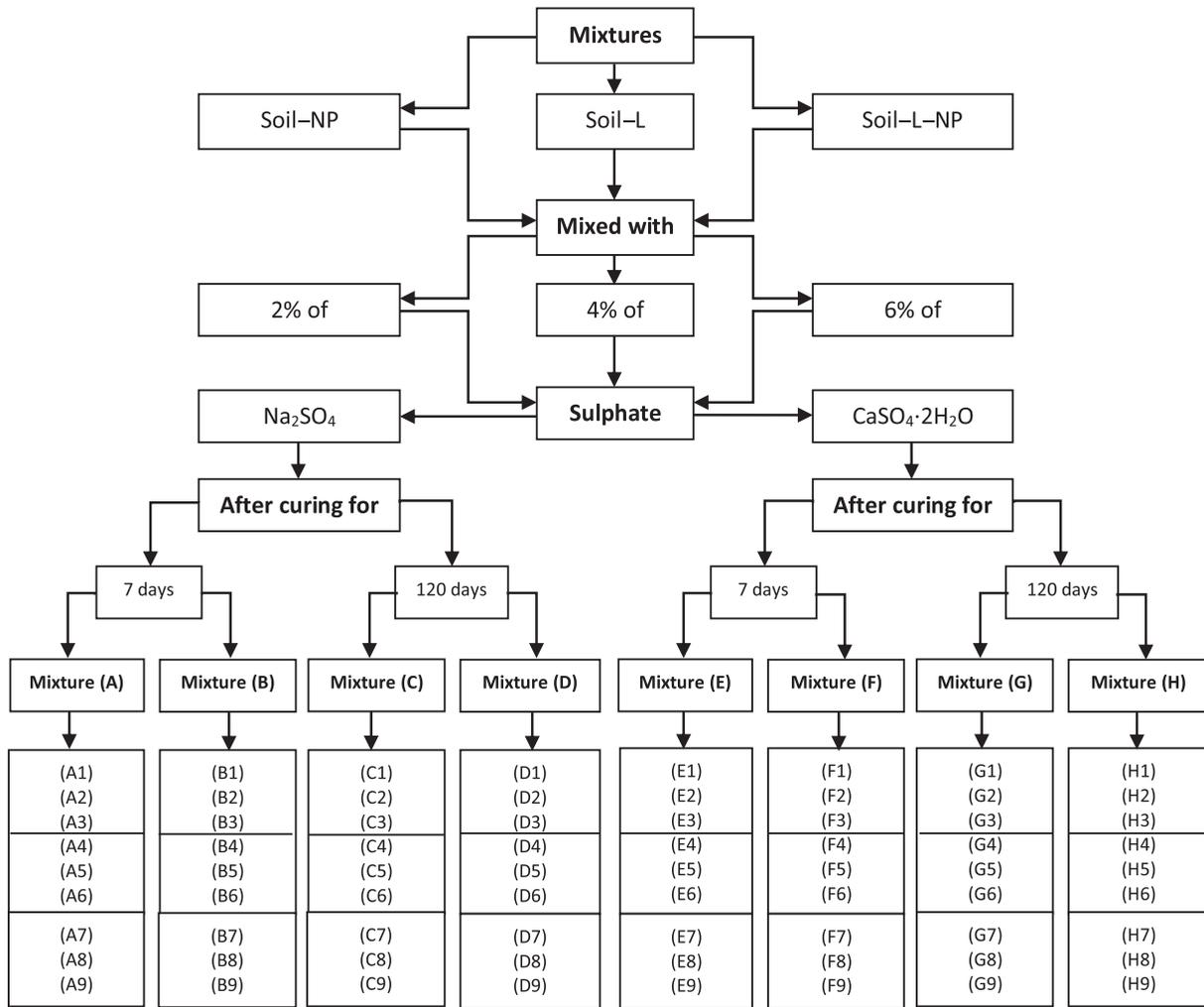
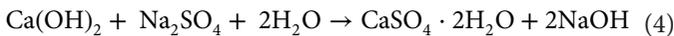


Figure 7. Flow chart shows the results obtained from different mixtures for using in pavement subgrade soil stabilisation.

Roy (1986) reported that the reaction between  $\text{Na}_2\text{SO}_4$  and  $\text{Ca}(\text{OH})_2$  in the contact of  $2\text{H}_2\text{O}$  can be presented as follows (Equation (4)):



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

Moreover, in the presence of  $\text{H}_2\text{O}$ , the reaction between  $\text{Na}_2\text{SO}_4$  and soil-L or soil-L-NP mixtures leads to the formation of NaOH which develops a higher alkaline solution to compare with that of the  $\text{Ca}(\text{OH})_2$ . The high pH developed by NaOH produces, by dissolution, a large amount of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  which react with the remaining L to form a high amount of cementitious products responsible for the increase in soil strength.

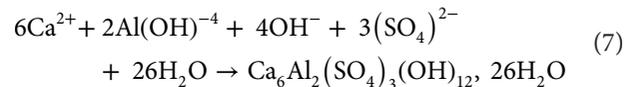
However, the dissolution of sulphates minerals ( $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) increases the concentration of  $\text{SO}_4^{2-}$  ions and then leads to the formation of ettringite ( $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$ ), shown as (Equations (5)–(7)):



(Dissolution of sodium sulphate)



(Dissolution of calcium sulphate)



(Formation of ettringite mineral)

The effect of ettringite mineral ( $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$ ) on the soil-L-NP mixture is to absorb a high content of water molecules which produce a high swelling, to decrease the void volume, to improve the compressive strength in the initial period and to alter the specimens in the later stage (Gadouri *et al.* 2016a).

In this study, according to Figures 5 and 6, the formation of cementitious compounds (C-S-H and C-A-H) and ettringite is due to the presence of both  $\text{Na}_2\text{SO}_4$  and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ .

**Table 4.** Recommendations for a better selection of an adequate mixture for pavement subgrade soil stabilisation (case of clayey soils of high plasticity).

Sulphate type	Age (days)	Mixture and designation	Assessment and recommendations
Na <sub>2</sub> SO <sub>4</sub>	7	(A)	<p>(A1), P20L0N2 (A4), P20L0N4 (A7), P20L0N6 (A2), P0L8N2 (A5), P0L8N4 (A8), P0L8N6 (A3), P20L8N2 (A6), P20L8N4 (A9), P20L8N6</p> <p>Present very low pH values (in this study, 9.22 &lt; pH &lt; 9.26), very low UCS values (0.07 &lt; UCS (MPa) &lt; 0.15) and no pozzolanic reactions (Gadouri <i>et al.</i> 2016a)</p> <p>Present high pH values (in this study, 12.57 &lt; pH &lt; 12.67), high UCS values (1.37 &lt; UCS (MPa) &lt; 1.79), acceleration of early pozzolanic reactions (Gadouri <i>et al.</i> 2016a)</p> <p>Present high pH values (in this study, 12.64 &lt; pH &lt; 12.77), high UCS values (1.55 &lt; UCS (MPa) &lt; 2.76), acceleration of early pozzolanic reactions (Shi and Day 2000, Hu <i>et al.</i> 2016, Gadouri <i>et al.</i> 2016a)</p>
		(C)	<p>(C1), P20L0N2 (C4), P20L0N4 (C7), P20L0N6 (C2), P0L8N2 (C5), P0L8N4 (C8), P0L8N6 (C3), P20L8N2 (C6), P20L8N4 (C9), P20L8N6</p> <p>Present very low pH values (in this study, 9.10 &lt; pH &lt; 9.20), very low UCS values (0.17 &lt; UCS (MPa) &lt; 0.26) and no pozzolanic reactions (Gadouri <i>et al.</i> 2016a), not recommended for pavement engineering</p> <p>Present high pH values (in this study, 12.34 &lt; pH &lt; 12.51), high UCS values (2.17 &lt; UCS (MPa) &lt; 3.94), decrease in pozzolanic reactions, formation of ettringite mineral (Gadouri <i>et al.</i> 2016a), recommended as materials for pavement engineering</p> <p>Present high pH values (in this study, 12.45 &lt; pH &lt; 12.55), very high UCS values (4.39 &lt; UCS (MPa) &lt; 5.23), decrease in pozzolanic reactions and formation of ettringite mineral (Shi and Day 2000, Gadouri <i>et al.</i> 2016a), highly recommended as materials for pavement engineering</p>
		(E)	<p>(E1), P20L0C2 (E4), P20L0C4 (E7), P20L0C6 (E2), P0L8C2 (E5), P0L8C4 (E8), P0L8C6 (E3), P20L8C2 (E6), P20L8C4 (E9), P20L8C6</p> <p>Present intermediate pH values (in this study, 9.63 &lt; pH &lt; 10.35), low UCS values (0.45 &lt; UCS (MPa) &lt; 1.05), acceleration of early pozzolanic reactions (Aldaood <i>et al.</i> 2014a, 2014b, Gadouri <i>et al.</i> 2016b), cheapest and economic</p> <p>Present high pH values (in this study, 12.43 &lt; pH &lt; 12.53), low to very high UCS values (1.68 &lt; UCS (MPa) &lt; 5.10), acceleration of early pozzolanic reactions (Aldaood <i>et al.</i> 2014a, 2014b, Gadouri <i>et al.</i> 2016b), cheapest and economic</p>
		(G)	<p>(G1), P20L0C2 (G2), P0L8C2 (G3), P20L8C2 (G4), P20L0C4 (G5), P0L8C4 (G6), P20L8C4 (G7), P20L0C6 (G8), P0L8C6 (G9), P20L8C6</p> <p>Present low to high pH values (in this study, 9.07 &lt; pH &lt; 12.15), extremely very high UCS values (3.93 &lt; UCS (MPa) &lt; 8.67), decrease in pozzolanic reactions, formation of ettringite mineral, no destruction has been observed in studied specimens (Aldaood <i>et al.</i> 2014a, 2014b, Gadouri <i>et al.</i> 2016b), cheapest and economic, highly recommended as materials for pavement engineering</p>

**Table 5.** Recommendations for a better selection of an adequate mixture for pavement subgrade soil stabilisation (case of clayey soils of low plasticity).

Sulphate type	Age (days)	Mixture and designation	Assessment and recommendations
Na <sub>2</sub> SO <sub>4</sub>	7	(B) (B1), P20L0N2 (B4), P20L0N4 (B7), P20L0N6 (B2), P0L8N2 (B5), P0L8N4 (B8), P0L8N6	Present very low pH values (in this study, 9.22 < pH < 9.35), very low UCS values (0.16 < UCS (MPa) < 0.55) and no pozzolanic reactions (Gadouri <i>et al.</i> 2016a)
		(B3), P20L8N2 (B6), P20L8N4 (B9), P20L8N6	Present high pH values (in this study, 9.22 < pH < 9.26), high UCS values (1.03 < UCS (MPa) < 2.12), acceleration of early pozzolanic reactions (Gadouri <i>et al.</i> 2016a)
		(D1), P20L0N2	Present high pH values (in this study, 9.22 < pH < 9.26), high UCS values (1.59 < UCS (MPa) < 4.71), acceleration of early pozzolanic reactions (Shi and Day 2000, Hu <i>et al.</i> 2016, Gadouri <i>et al.</i> 2016a)
		(D4), P20L0N4 (D7), P20L0N6	Present very low pH values (in this study, pH = 9.16), very low UCS values (UCS = 1.26 MPa), (Gadouri <i>et al.</i> 2016a), not recommended
		(D2), P0L8N2 (D5), P0L8N4 (D3), P20L8N2 (D6), P20L8N4 (D8), P0L8N6	Present very low pH values (in this study, 9.13 < pH < 9.25), all specimens have been broken (deteriorated) before UCS test due to the ettringite formation (Gadouri <i>et al.</i> 2016a), strictly not recommended for pavement engineering
	120	(D9), P20L8N6	Present very low pH values (in this study, pH < 12.84), all specimens have been broken (deteriorated) before UCS test due to the ettringite formation (Gadouri <i>et al.</i> 2016a), strictly not recommended for pavement engineering
		(D9), P20L8N6	Present very low pH values (in this study, pH 12.97), low UCS values (UCS = 2.46 MPa), decrease in pozzolanic reactions and formation of ettringite mineral (Shi and Day 2000, Gadouri <i>et al.</i> 2016a), not recommended for pavement engineering
		(F1), P20L0C2 (F4), P20L0C4 (F7), P20L0C6 (F2), P0L8C2 (F5), P0L8C4 (F8), P0L8C6 (F3), P20L8C2 (F6), P20L8C4 (F9), P20L8C6	Present intermediate pH values (in this study, 9.45 < pH < 10.24), high UCS values (1.52 < UCS (MPa) < 3.89), formation of cementing agents by pozzolanic reactions (Aldaood <i>et al.</i> 2014a, 2014b, Gadouri <i>et al.</i> 2016b), cheapest and economic
		(H1), P20L0C2 (H2), P0L8C2 (H3), P20L8C2 (H4), P20L0C4 (H5), P0L8C4 (H6), P20L8C4 (H7), P20L0C6 (H8), P0L8C6 (H9), P20L8C6	Present high pH values (in this study, 12.50 < pH < 12.62), high UCS values (2.02 < UCS (MPa) < 5.76), acceleration of early pozzolanic reactions (Aldaood <i>et al.</i> 2014a, 2014b, Gadouri <i>et al.</i> 2016b)
		(H1), P20L0C2 (H2), P0L8C2 (H3), P20L8C2 (H4), P20L0C4 (H5), P0L8C4 (H6), P20L8C4 (H7), P20L0C6 (H8), P0L8C6 (H9), P20L8C6	Present low to very high pH values (in this study, 9.31 < pH < 12.20), very high UCS values (4.93 < UCS (MPa) < 9.87), decrease in pozzolanic reactions, formation of ettringite mineral (Le Borgne 2010, Aldaood <i>et al.</i> 2014a, 2014b, Gadouri <i>et al.</i> 2016b), highly recommended as materials for pavement engineering

### Adequate mixture for pavement subgrade soil stabilisation

The flowchart (Figure 7) and Tables 4 and 5 were proposed to be used only for cohesive soils of high or low plasticity. This flowchart can be used as the way to identify possible mix-designs and to associate them to a label (A<sub>1-9</sub> up to H<sub>1-9</sub>) with which look up the contents presented in Tables 4 and 5. In fact, the adequate mixture for pavement subgrade soil stabilisation can be selected according to the Figure 7 based also on both Tables 4 and 5, which were obtained using the pH values and previous results of strength (e.g. Aldaood *et al.* 2014a, 2014b, Hu *et al.* 2016, Gadouri *et al.* 2016a, 2016b). On the other hand, Tables 4 and 5 present the different mixtures of the clayey soil of high plasticity and clayey soil of low plasticity, respectively. Both Tables 4 and 5 explain the components of Figure 7 and present detailed recommendations to choose an adequate mixture with suitable technical and economic conditions for only a longer curing period. It will be recommended only for all clayey soils stabilised with L alone or in combination with natural pozzolana in the presence of monovalent (Na<sub>2</sub>SO<sub>4</sub>) and divalent (CaSO<sub>4</sub>·2H<sub>2</sub>O) sulphates.

### Conclusions

The effect of sulphates on pH and pozzolanic reactions of soil–lime–natural pozzolana mixtures has been studied in order to select an adequate mixture for pavement subgrade soil stabilisation. Based on the test results, the following conclusions can be drawn:

- In the absence of sulphates, the addition of L alone to both clayey soils produces a considerable increase in the pH value. However, a further increase was recorded when using the L in combination with NP. In all cases, the pH of both clayey soils stabilised with L alone or in combination with NP decreases with curing period. On the other hand, a negligible change in the pH value was observed when using NP alone.
- The increase in the pH value of both soil–NP and soil–L–NP mixtures with increasing sulphate content was more pronounced with the Na<sub>2</sub>SO<sub>4</sub> than with the CaSO<sub>4</sub>·2H<sub>2</sub>O, this is due to the fact that the NaOH (from Na<sub>2</sub>SO<sub>4</sub>) developed a high pH value in the soil solution to compare to that developed by the Ca(OH)<sub>2</sub> (from L and/or CaSO<sub>4</sub>·2H<sub>2</sub>O). On the other hand, for the same mixtures (soil–NP and

soil–L–NP), 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  $\text{Na}_2\text{SO}_4$ . In addition, it was also more pronounced with the  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  content than with the  $\text{Na}_2\text{SO}_4$  content. Furthermore, 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  $\text{Na}_2\text{SO}_4$  than with the  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  addition.

- For a shorter curing period, the  $\text{Na}_2\text{SO}_4$  can be used as an accelerator of NP dissolution when its content is less than 2%. However, it is necessary to classify the  $\text{Na}_2\text{SO}_4$  as a deleterious element for pavement engineering when its content is greater than 2%. Conversely, the  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  can be used as an additive with any content for soil stabilisation. However, for any curing periods, the pH of both GS and RS samples stabilised with L alone or in combination with NP was very higher than that of samples stabilised without  $\text{Na}_2\text{SO}_4$ .
- Increases and decreases in the pH value depend largely on the type of additive used and its content, type of sulphate and its content, mineralogical composition of the stabilised soil and curing period.
- It should be noted that the use of a suitable type of treatment for pavement subgrade soil stabilisation requires respect the recommendations presented in both Tables 4 and 5.

## Acknowledgements

The authors would like to acknowledge the director of the Habitat Laboratory and Construction Center (HLCC, Oued-Smar, Algeria) for providing excellent working conditions and financial support.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## ORCID

Hamid Gadouri  <http://orcid.org/0000-0002-0753-3569>

## References

- Aldaoood, A., Bouasker, M., and Al-Mukhtar, M., 2014a. Geotechnical properties of lime-treated gypseous soils. *Applied Clay Science*, 88–89, 39–48.
- Aldaoood, A., Bouasker, M., and Al-Mukhtar, M., 2014b. Impact of wetting–drying cycles on the microstructure and mechanical properties of lime-stabilized gypseous soils. *Engineering Geology*, 174, 11–21.
- Al-Mukhtar, M., Lasledj, A., and Alcover, J.F., 2010. Behaviour and mineralogy changes in lime treated expansive soil at 20 °C. *Applied Clay Science*, 50 (2), 191–198.
- Al-Swaidani, A., Hammoud, I., and Meziab, A., 2016. Effect of adding natural pozzolana on geotechnical properties of lime-stabilized clayey soil. *Journal of Rock Mechanics and Geotechnical Engineering*, 8 (5), 714–725.
- ASTM D4972–01, 2001. Standard test method for pH of soils. *Annual book of ASTM Standards*. Philadelphia: American Society for Testing and Materials, 04, 08, 1–3. doi:10.1520/D4972-01.
- Baryla, J.M., et al., 2000. Effet de sulfates et sulfures sur des marnes traitées à la chaux et au liant routier sur un chantier autoroutier. *Bulletin de liaison des Laboratoires des Ponts et Chaussées*, 224, 39–48.
- Di Sante, M., et al., 2014. Time of reactions in a lime treated clayey soil and influence of curing conditions on its microstructure and behaviour. *Applied Clay Science*, 99, 100–109.
- Gadouri, H., Harichane, K., and Ghrici, M., 2016a. Effect of the interaction between calcium sulphate and mineral additives on shear strength parameters of clayey soils. *International Journal of Geotechnical Engineering*, 1–13. doi:10.1080/19386362.2016.1238562.
- Gadouri, H., Harichane, K., and Ghrici, M., 2016b. Effect of calcium sulphate on the geotechnical properties of stabilized clayey soils. *Periodica Polytechnica Civil Engineering*, 61 (2), 256–271. doi:10.3311/PPci.9359.
- Gadouri, H., Harichane, K., and Ghrici, M., 2016c. Assessment of sulphates effect on the classification of soil–lime–natural pozzolana mixtures based on the Unified Soil Classification System (USCS). *International Journal of Geotechnical Engineering*, 1–9. doi:10.1080/19386362.2016.1275429.
- Ghrici, M., Kenai, S., and Said-Mansour, M., 2007. Mechanical properties and durability of mortar and concrete containing natural pozzolana and limestone blended cements. *Cement and Concrete Composites*, 29 (7), 542–549.
- Harichane, K. and Ghrici, M., 2009. Effect of combination of lime and natural pozzolana on the plasticity of soft clayey soils, *2nd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering*, 30 May 2009 Nicosia. North Cyprus: Near East University.
- Harichane, K., et al., 2010. Effect of the combination of lime and natural pozzolana on the durability of clayey soils. *Electronic Journal of Geotechnical Engineering*, 15, 1194–1210.
- Harichane, K., Ghrici, M., and Kenai, S., 2011a. Effect of curing period on shear strength of cohesive soils stabilized with combination of lime and natural pozzolana. *International Journal of Civil Engineering*, 9 (2), 90–96.
- Harichane, K., et al., 2011b. Use of natural pozzolana and lime for stabilization of cohesive Soils. *Geotechnical and Geological Engineering*, 29 (5), 759–769.
- Harichane, K., Ghrici, M., and Missoum, H., 2011c. Influence of natural pozzolana and lime additives on the temporal variation of soil compaction and shear strength. *Frontiers of Earth Science*, 5 (2), 162–169.
- Harichane, K., Ghrici, M., and Kenai, S., 2012. Effect of the combination of lime and natural pozzolana on the compaction and strength of soft clayey soils: a preliminary study. *Environmental Earth Sciences*, 66 (8), 2197–2205.
- Hossain, K.M.A., Lachemi, M., and Easa, S., 2007. Stabilized soils for construction applications incorporating natural resources of Papua new Guinea. *Resources, Conservation and Recycling*, 51 (4), 711–731.
- Hu, Z., et al., 2016. The effects of sulfate on the strength of lime-fly ash stabilized soil. *Electronic Journal of Geotechnical Engineering*, 21 (10), 3669–3676.
- Khemissa, M. and Mahamedi, A., 2014. Cement and lime mixture stabilization of an expansive overconsolidated clay. *Applied Clay Science*, 95, 104–110.
- Kinuthia, J.M., Wild, S., and Jones, G.I., 1999. Effects of monovalent and divalent metal sulphates on consistency and compaction of lime-stabilised kaolinite. *Applied Clay Science*, 14 (1–3), 27–45.
- Kolias, S., Kasselouri-Rigopoulou, V., and Karahalios, A., 2005. Stabilization of clayey soils with high calcium fly ash and cement. *Cement and Concrete Composites*, 27 (2), 301–313.
- Ktnuthia, J.M. and Wild, S., 2001. Effects of some metal sulfates on the strength and swelling properties of lime-stabilised kaolinite. *International Journal of Pavement Engineering*, 2 (2), 103–120.
- Le Borgne, T., 2010. *Effects of potential deleterious chemical compounds on soil stabilisation*. Thesis (PhD). Nancy-Université.
- Mehta, P.K., 1999. Concrete technology for sustainable development. *Concrete International*, 21 (11), 47–53.
- Mfinanga, D.A. and Kamuhabwa, M.L., 2008. Use of natural pozzolan in stabilising lightweight volcanic aggregates for roadbase construction. *International Journal of Pavement Engineering*, 9 (3), 189–201.
- Mitchell, J.K., 1986. Practical problems from surprising soil behaviour. *Journal of Geotechnical Engineering*, 112 (3), 274–279.
- Rao, S.M. and Shivananda, P., 2005. Role of curing temperature in progress of lime-soil reactions. *Geotechnical and Geological Engineering*, 23 (1), 79–85.

- Roy, D.M., 1986. Mechanism of cement paste degradation due to chemical and physical process. *Proceedings of 8th International Congress on the Chemistry of Cement*, Brazil, (I), 359–380.
- Samantasinghar, S., 2014. *Geo-engineering properties of lime treated plastic soils*. MS thesis. Orissa, India: National Institute of Technology, 61.
- Segui, P., et al., 2013. Utilization of a natural pozzolan as the main component of hydraulic road binder. *Construction and Building Materials*, 40, 217–223.
- Shi, C. and Day, R.L., 2000. Pozzolanic reaction in the presence of chemical activators: part II – reaction products and mechanism. *Cement and Concrete Research*, 30 (4), 607–613.
- Sivapullaiah, P.V., Sridharan, A., and Ramesh, H.N., 2000. Strength behaviour of lime-treated soils in the presence of sulphate. *Canadian Geotechnical Journal*, 37 (6), 1358–1367.
- Sivapullaiah, P.V., Sridharan, A., and Ramesh, H.N., 2006. Effect of sulphate on the shear strength of lime treated kaolinitic soil. *Proceedings of the Institution of Civil Engineers – Ground Improvement*, 10 (1), 23–30.
- Sridharan, A., Sivapullaiah, P.V., and Ramesh, H.N., 1995. Consolidation behaviour of lime treated sulphate soils. *Proceedings of International Symposium on Compression Consolidation Clayey Soils*. Hiroshima, Japan, vol. 1, 183–188.
- Wang, H. and Gillott, J.E., 1991. Effect of  $\text{Ca}(\text{OH})_2$  on alkali–silica reaction. *Magazine of Concrete Research*, 43 (156), 215–218.
- Yilmaz, I. and Civelekoglu, B., 2009. Gypsum: an additive for stabilization of swelling clay soils. *Applied Clay Science*, 44 (1–2), 166–172.
- Zoubir, W., Harichane, K., and Ghrici, M., 2013. Effect of lime and natural pozzolana on dredged sludge engineering properties. *Electronic Journal of Geotechnical Engineering*, 18 (c), 589–600.