Experimental characterisation of clay-sand mixtures treated with lime

Mir Amid Hashemi, Thierry Jacques Massart & Bertrand François

Taylor & Francis
Taylor & Francis

Experimental characterisation of clay-sand mixtures treated with lime

Mir Amid Hashemi, Thierry Jacques Massart and Bertrand François*

Building Architecture and Town Planning Department (BATir), Université Libre de Bruxelles (ULB), Brussels, Belgium

Lime stabilisation is a process which chemically improves numerous characteristics of the soils, among which aspects, the mechanical properties increase are the most noticeable. This paper investigates the lime treatment of mixtures of sand and bentonite at different proportions. Three physical characteristics are measured at different curing times: the mechanical strength is deduced from unconfined compressive strength (UCS); the chemical reaction is evaluated based on the lime consumption (LC) and the electrical properties are obtained from electrical resistivity (ER). Results show that all three physical characteristics increase with curing time and that the optimal UCS appears at mixtures with low bentonite content (i.e. 10–15% bentonite). LC curves show that the kinetics of the lime reaction is also slower at these low bentonite contents. Finally, the ER curves show similar patterns for all mixtures and are closely related to the LC.

Keywords: unconfined compressive strength; electrical resistivity; lime treatment; clay–sand mixtures

1. Introduction

Lime treatment of soils is widely used in civil engineering, especially for embankment construction (Makki-Szymkiewicz et al., 2015), in order to increase the soil mechanical properties, leading to improved cohesion levels and load-bearing capacities. Lime, calcium oxide or hydroxide, is an industrial mineral obtained from the decarbonation process of calcium carbonate rocks by heating. Silty and clayey soils can be improved by the addition of small weight fractions of lime (Little, 1995). The advantage of this treatment lies in the low quantity of lime added and in the potential ecological advantages obtained by improving the properties of the soil already in place without requiring replacement.

Lime treatment influences the soil behaviour on two different timescales. First, lime quickly reacts with clay by modifying its structure, and allowing the clay minerals to merge to form larger aggregates. Lime addition improves the soil towards a higher bearing capacity, a lower plasticity and a shift towards a higher grain size distribution (Little, 1995). The second effect is soil stabilisation owing to the fact that long-term pozzolanic reactions also take place after the immediate soil improvement (Eades, Nichols, & Grim, 1962). The mineral formations obtained from the pozzolanic reactions indeed confer relevant soil mechanical properties such as a higher cohesion level (Thompson, 1965), frost resistance (Arabi, Wild, & Rowlands, 1989), reduction in swelling potential (Khattab, Al-Mukhtar, & Fleureau, 2007; Mrabent, Hachichi, Souli, Taibi, & Fleureau, 2016) and compressive/tensile strength. Bell (1996), De Bel, Gomes, and Verbrugge (2009), Diamond and Kinter (1965), Estéoule and Perret (1979) and many others observed an increase of the unconfined

---

*Corresponding author. Email: bertrand.francois@ulb.ac.be

compressive strength (UCS) in lime-treated soils as a function of curing time. In lime-treated clayey soils, such reactions take place between the calcium of the lime and the silicates and aluminates of the clay minerals; resulting in the formation of calcium silicate hydrate (CSH), calcium aluminate hydrate (CAH) and CASH (Diamond & Kinter, 1965). However, the reaction of kinetics is slow because it requires the dissolution of clay minerals into silicate and aluminate species and this dissolution is only possible for highly alkaline solutions (pH >10) (Keller, 1964).

Research on soil stabilisation has been active during the last decades, which allowed the identification of many important parameters that influence soil stabilisation, such as: (i) interfering materials like organic matter, gypsum and iron minerals (Locat, Bérubé, & Choquette, 1990; Netterberg & Paige-Green, 1984; Sherwood, 1993), (ii) the grain shapes and sizes of the skeleton (sand part), (iii) the reactivity of silt and the complexity of its microstructure, (iv) the lime quantity, the water content and the compaction density (Bell, 1996; Locat et al., 1990), (v) the temperature that increases the kinetics of the reaction (De Bel et al., 2009; Estéoule & Perret, 1979) and (vi) the clay mineral type which is an important parameter of soil stabilisation. Montmorillonite, for example, has a better efficiency for lime adsorption compared to kaolinite (Carroll, 1959), illustrating the importance to consider the cation exchange capacity (CEC) in the assessment of lime treatment.

The goal of the present study is to build a progressive understanding of the reaction by investigating its effect on different parameters. The minerals of fine soil particles react chemically with lime while the larger soil particles provide a skeleton around the lime-cemented matrix explaining the improvement in the mechanical properties. Unlike previous efforts focused on complex soils, in this study, lime treatment is investigated through the mixture of a well-defined set of sand and bentonite as a model of synthetic material. The quantities varied during the study are the proportion of the two soils and the quantity of lime.

In the present approach, studies of these controlled mixtures are carried on with three kinds of tests simultaneously: UCS, lime consumption (LC) and electrical resistivity (ER). Mixtures of sand and bentonite treated with lime have been studied in the past (Arabani & Veis Karami, 2007). Many previous studies of lime treatment as a function of curing times involved the study of UCS as mentioned above. LC was also studied by means of dilution in saccharose (De Bel et al., 2009) or atomic absorption spectrometer (Al-Mukhtar, Lasledj, & Alcover, 2010a; Al-Mukhtar, Lasledj, & Alcover, 2010b; Al-Mukhtar, Lasledj, & Alcover, 2014). ER (or conductivity) was also carried earlier for lime-treated soils (Al-Mukhtar et al., 2010a; Al-Mukhtar et al., 2010b; Zha, Liu, Du, & Cui, 2009) and for cemented materials (Tashiro, Ikeda, & Inoue, 1994). This paper investigates a combined approach by correlating the different physical evolutions of the lime treatment: chemical (LC) vs. mechanical (UCS) vs. electrical (ER).

Therefore, the main contribution of this study is twofold. First, by the study of a well-controlled material (i.e. mixtures of sand and bentonite), we are able to highlight the role of the clay minerals (essentially smectite) on the kinetics of reaction of lime with soil. Secondly, on the other hand, we also show that physical properties such as ER are strongly related to the amount of lime reaction which, in turn, affects the mechanical strength.

2. Methodology

2.1. *Constituents of the model mixtures*

The effects of the lime treatment of soils can be highly varying from one soil to another as a result of their complex mineral composition. Understanding the effects of lime treatment is therefore complex, and depends on numerous parameters. The study presented here aims

Qu. : Quartz - SiO$_2$
Ka. : Kaolinite 1A - Al$_2$Si$_2$O$_5$(OH)$_4$
Mo. : Montmorillonite - (Na,Ca)$_{0.3}$ (Al,Mg)$_2$Si$_4$O10(OH)$_2$.xH$_2$0
Ca. : Calcite - CaCO$_3$
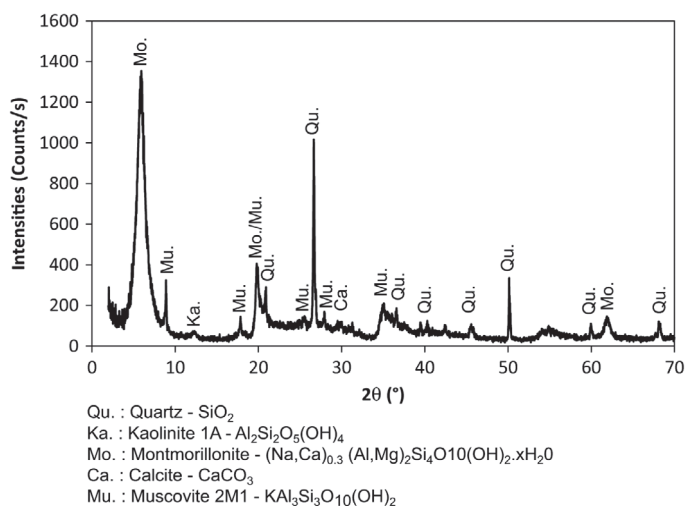Mu. : Muscovite 2M1 - KAl$_3$Si$_3$O$_{10}$(OH)$_2$

Figure 1. XRD of calcium bentonite showing the presence mainly of montmorillonite, muscovite and quartz with small amounts of kaolinite and calcite.

at understanding the effects associated with lime treatment avoiding however, in a first approach, the inter-related influence of too many parameters. To this end, the complex influence of the silt is not taken into account. The clay is selected with a single mineralogy and provides the clayey cohesive matrix that reacts with lime. The skeleton selected is chosen as a poorly graded sand. Based on these assumptions, the model materials studied in this work are mixtures of sand and bentonite at different proportions. Since lime treatment is only active for clayey and silty soils (and not with sandy soils), the characterisation of the lime treatment of sand–bentonite mixtures is a useful first approach towards lime treatment of sand using the addition of clay minerals.

The sand selected for the investigations is poorly graded ($D_{50} = 260 \, \mu$m and D_{60}/D_{10} = 1.5). The clay matrix is a bentonite, selected because of its high reactivity with lime (principally montmorillonite) and its wide availability in the market. The CEC of the bentonite is 60 ± 10 mval/100 g. Calcium bentonite is chosen over sodium bentonite to avoid any excessive swelling upon wetting (free swelling index of 7 mL/2g following ASTM D5890). Figure 1 shows the result of an X-ray diffraction test of calcium bentonite. It shows the presence of mainly montmorillonite, muscovite and quartz with small amounts of kaolinite and calcite. In view of this mineralogical composition, it appears that the clay constituents (montmorillonite, muscovite and kaolinite) will mainly provide the reaction compounds after dissolution of silicon and aluminium ions. After reaction with hydrated lime (Ca(OH)$_2$), CSHs and CAHs will be formed through the so-called pozzolanic reaction (see Bell, 1996, amongst others).

Calcium bentonite has a 65% weight fraction of fine particles ($D < 2 \, \mu$m), 28% silt ($2 \, \mu$m$> D > 67 \, \mu$m) and 7% sand ($D > 67 \, \mu$m). The lime used is named Proviacal®ST from Lhoist R&D S.A. which is a dry quicklime CL 90-Q in accordance with the norm EN 459-1. The lime has 91.2% in weight of pure CaO. All properties of the sand and bentonite are provided in Table 1. The grain sizes of the sand and bentonite are provided in Figure 2.

2.2. Mixtures

At the start of this study, our purpose was to cover a large range of bentonite content to identify the 'optimum' bentonite content (i.e. the bentonite content that provides the highest
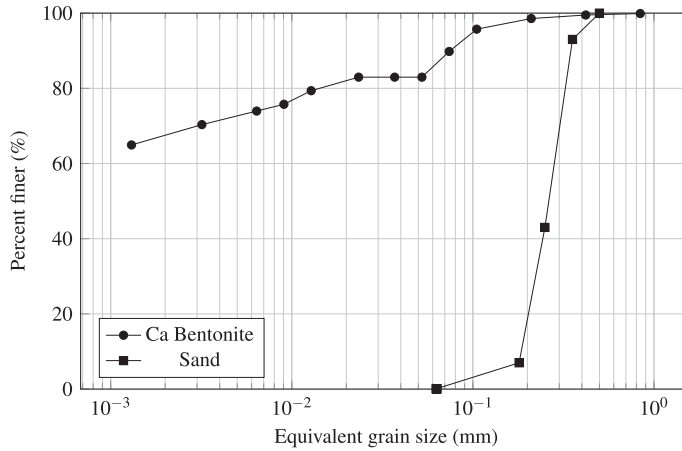
Figure 2. Grain size distributions of the calcium bentonite and the sand.

Table 1. Properties of the sand and bentonite.

Sand	–
Sibelco©Mol M32	
D_{50} (µm)	260
$C_u = D_{60}/D_{10}$	1.5
ρ_s (g/cm^3)	2.65
Bentonite	–
Ibeco©Deponit CA	
Fine particles ($< 2\,\mu m$)	65%
Silt ($2\,\mu m > D > 67\,\mu m$)	28%
Sand ($>67\,\mu m$)	7%
ρ_s (g/cm^3)	2.72
Methylene-blue value (mg/g)	300 ± 30
CEC (mval/100g)	60 ± 10
Water absorption capacity	$\geq 160\%$
Free swelling index (mL/2g)	≥ 7
Liquid limit	115%
Plastic limit	33%
Plasticity index (calculated)	82%

mechanical resistance to the mixture after lime treatment). In a second step of the study, we focused on mixture with low bentonite content that exhibited the best resistance after lime treatment. Consequently, the considered mixtures are split into two categories: low bentonite contents (LBC) and high bentonite contents (HBC). The LBC group is composed of mixtures of 10, 15 and 20% in weight of bentonite and, respectively, 90, 85 and 80% in weight of sand. The HBC group is composed of mixtures of 30, 45 and 60% bentonite and, respectively, 70, 55 and 40% sand. Table 2 shows the composition of these mixtures in which sand and bentonite sum up to 100% of the dry weight. Afterwards, lime and water are added as an additional weight to the mixtures (hence the '+' sign before the weight percentage values of lime and water in Table 2).

Table 2. Ingredients for the nine different mixtures: the water content and density follows the MOP curve.

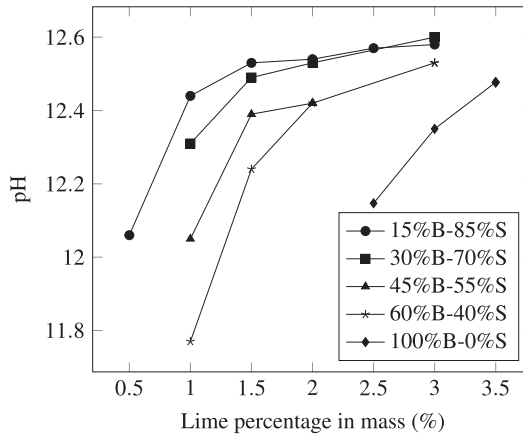|	LBC1			LBC2			HBC		
	10b1	15b1	20b1	10b2	15b2	20b2	30b	45b	60b
Bentonite (%)	10	15	20	10	15	20	30	45	60
Sand (%)	90	85	80	90	85	80	70	55	40
Lime (%)	+1	+1	+1	+2	+2	+2	+2	+2	+2
Water (%)	+14	+17	+20	+15	+18	+21	+26	+36	+41
ρ_d (g/cm^3)	1.74	1.70	1.64	1.76	1.72	1.66	1.47	1.26	1.15

Figure 3. Eades & Grim procedure for the determination of lime fixation point for the mixtures.

2.2.1. *Eades & Grim procedure*

The quantity of lime required for each mixture is determined based on the Eades & Grim procedure (Eades & Grim, 1966) (ASTM D-6276) and is called the lime fixation point. Figure 3 depicts the pH of each mixture as a function of the percentage of lime added. The lime quantity needed according to (ASTM D-6276) is of 1% lime for LBC mixtures, 2% for HBC mixtures and 3% for the pure bentonite. Therefore, LBC and HBC mixtures were treated with 1 and 2% lime, respectively. Another group of LBC mixtures were treated with 2% lime to allow comparison with the lime treatment on HBC mixtures. The mixtures of LBC treated with 1 and 2% lime are therefore called LBC1 and LBC2, respectively. The nomenclature of the mixtures are called 10, 15, 20b1 for the LBC1 group, 10, 15, 20b2 for the LBC2 group and 30, 45, 60b2 for the HBC group, as reported in Table 2.

2.2.2. *Modified Proctor Compaction Test*

The density of each sample was determined with the Modified Proctor Compaction Test (MPCT) curve of each mixture treated with 1% lime for LBC and 2% lime for HBC. The compaction was performed according to the Modified Proctor procedure ASTM D1557. In this procedure, the mixture of sand and bentonite is mixed dry by hand with the given lime quantity determined with the Eades & Grim procedure. Distilled water is then poured at
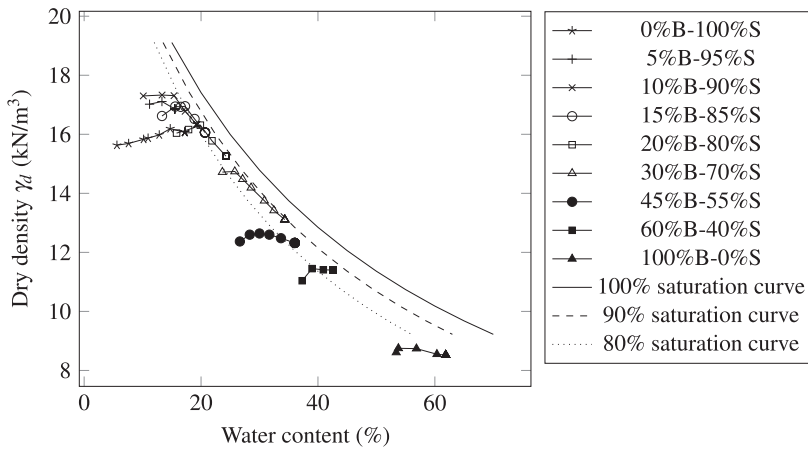
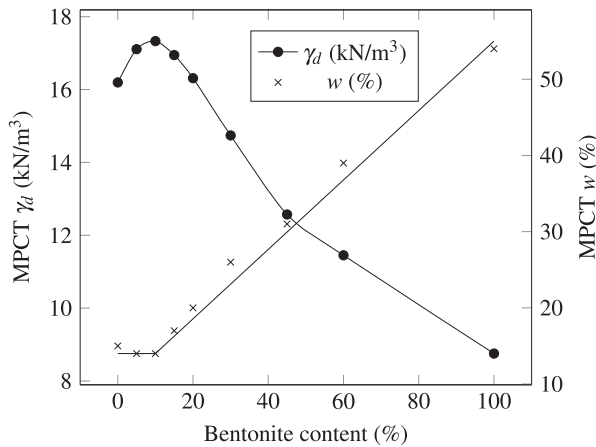Figure 4.   MPCT curves for different mixtures of sand and bentonite.

Figure 5.   MPCT optima for various compositions of the mixture.
Note: The graph shows the optimum dry densities and water contents as a function of bentonite contents.

different water contents corresponding to the MPCT curve of each mixture and the resulting mixture is then mixed by hand. Finally, the wet soil is put in a plastic bag to mellow for 24h at 20 °C. After 24h, the compaction is carried out and the results are shown in Figure 4. Finally, the optimum density and moisture content are deduced and summarised in Figure 5 for all mixtures ranging from pure sand to pure bentonite, as a function of bentonite content.

2.2.3. *Sample preparation*

For the sample preparation of the group LBC1 and HBC, mixtures were compacted at 98.5% of their MPCT optimum density to reflect the conditions met in the field (Setra, 2007) and their water content is equal to the MPCT water content. The compaction conditions of the group LBC2 were the same as those of LBC1 except that their dry density was increased of 1% to take into account the addition of 1% lime. Their water content was also increased

of 1% to account for the hydration of the additional lime. Table 2 summarises the materials used, the water contents and the densities for preparation of the three mixtures.

2.3. Unconfined compressive strength

Unconfined compression tests allow measuring the compression resistance of the mixtures. Five cylindrical samples of each composition and for each curing time have been prepared. Their dimensions are of 70 mm length and 36 mm diameter. In order to avoid any exchange with the environment, the samples are protected by a plastic film, an aluminium film and a layer of paraffin. The samples are then stored at 20 °C and stay for curing. Afterwards, unconfined compression tests are performed to determine the force vs. displacement curve and obtain the UCS. The compression is made using the universal testing device Wykeham Farrance Tritech 50 at the rate of 4 mm/h. This displacement rate allows to keep quasi-undrained conditions while we remain far away from dynamic effects. The value of UCS is calculated as the mean value from three samples. If amongst the three tested samples, the highest UCS differs up to 10% from the lowest, a new test is performed until three results are in a range of less than 10% from each other. Consequently, the accuracy of the UCS results shown in this paper is of 10% between the minimum and maximum values in the three samples.

2.4. Lime consumption

LC is determined according to the norm NF EN 459-2/2001. Its measurement can be obtained here based on a fragment (15 g) of each sample after unconfined compression. LC is an effective tool to characterise the kinetics of the lime stabilisation process. Unreacted lime is released by stirring the soil in a solution of 40 g of saccharose in 200 mL distilled water for one hour. After stirring, the quantity of unreacted lime is deduced by titration of the solution with hydrochloric acid (HCl at 0.1 mol/l) until a pH of 7 is reached. The titration is made with a 50 mL burette with a precision of 0.1 mL. Since a fragment of 15 g is taken from a sample of approximately 140 g, the results highly depend on the heterogeneity of lime distribution with the sample. This heterogeneity is probably the main cause of results variation (more than the precision of reading during titration). However, through comparison of results from different fragments taken from the samples, we observed that the variation in the results is never higher than 10% of the initial lime content.

2.5. Electrical resistivity

ER tests were performed on mixtures LBC1 and LBC2 following ASTM standard (ASTM G57-06). In this test, the mixtures are prepared and compacted in a parallelepipedic box in three layers under the same conditions than for UCS samples. The box contains four equally spaced electrodes. The upper right corner of Figure 10 shows a diagram explaining the experiment. Current passes from I_{in} to I_{out} (the two extreme electrodes) and voltage is measured between V_+ and V_- (the two middle electrodes). The electrical resistance is equal to $R = (V_+ - V_-)/I$ following Ohm's law. The apparatus used to measure the electrical resistance is an ABEM Terrameter SAS 300. The value of electrical resistance given by a digital display showing four digits resolution. To calculate the resistivity of the soil, the electrical resistance is multiplied by a characteristic length depending on the shape of the box and the location of the electrodes. This characteristic length is measured by calibrating the box with a saline solution of a known resistivity. The measurement of the ER depends
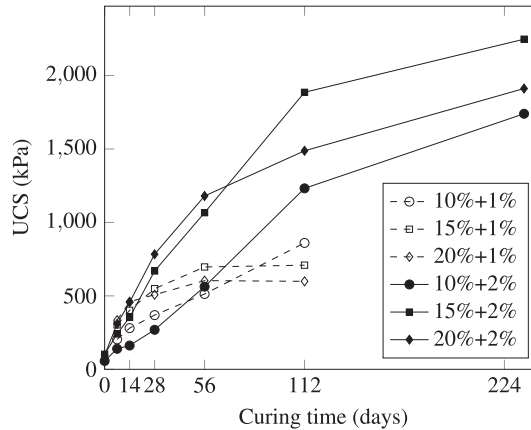
Figure 6. Unconfined compressive strength for LBC mixtures treated with 1% (dashed) and 2% lime (solid) as a function of curing time.

on room temperature and is corrected at $18\,°C$ using the following formula taken from Dakhnov (1959):

$$\rho(18\,°C) = \rho(T)(1 + 0.025(T - 18\,°C))$$

where T is in Celsius degrees.

The repeatability of the results on the same sample with time is ensured by the fact that the test is non-destructive. Consequently, the sample remains in the same set-up all along the measuring period. Three distinct boxes were used to perform three tests in parallel. However, the calibration with the same saline solution in the three boxes guarantees the same basis for comparison between each test.

3. Results

3.1. Unconfined compression strength

Low Bentonite Content samples were treated with 1 and 2% lime and tested under unconfined compression for different curing times. Figure 6 shows the evolution of UCS as a function of time. It is shown that for all the mixtures, the UCS always increases in time. This is exclusively due to lime reaction, the other parameters remaining constant because the samples are sealed as explained in 2.2.3.

For the mixtures treated with 1%, the composition with the highest UCS depends on the curing time. At the start of curing (i.e. 7–14 days), the mixture 20b1 presents the highest UCS while at 28 and 56 days, the mixture 15b1 overpasses 20b1. Finally, after 112 days, the UCS of the mixture 10b1 overtakes all the previous mixtures and has the maximum UCS. As time goes by, the mixture with the highest UCS evolves towards lower bentonite content mixtures. Note also that the improvement in mechanical properties presents a saturation (i.e. an horizontal plateau between 56 and 112 days) for the two largest bentonite contents of LBC1, while this 'saturation' is not reached yet at 112 days for the 10b1 mixture.

For the mixtures treated with 2% lime, curing times range from 1 to 235 days. The results depicted in Figure 6 are similar to the ones obtained for LBC1 mixtures but with an expanded timescale. The curing time at which the UCS of the mixture 15b2 overpasses 20b2 is more than doubled with respect to the previous case (LBC1). The mixture 10b2 never reaches the maximum UCS either because the curing time is not long enough (even until 224
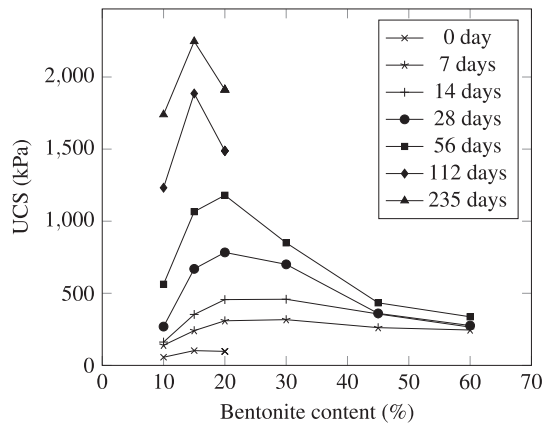
Figure 7. Unconfined compressive strength for LBC & HBC mixtures treated with 2% lime at different curing times as a function of bentonite content.

days) or because the optimum mixture remains the 15b2 one. Moreover, comparing both lime treatment contents, it can be seen that increasing the lime content increases the UCS of the mixtures for all curing times. The UCS of the 15b2 mixture reaches high resistance values up to 1.9 MPa at 112 days and 2.25 MPa at 235 days.

The UCS of HBC mixtures all treated with 2% of lime was evaluated at curing times of 7, 14, 28 and 56 days. By combining the results obtained for the samples of LBC treated with 2% lime and HBC treated with 2% lime, the UCS of the mixtures treated with 2% lime is plotted as a function of their bentonite content for different curing times. Figure 7 shows that the mixture with the highest UCS is located between 20 and 30% bentonite content at 7 days and finally reaches the 15% bentonite content at 235 days.

3.2. *Lime consumption*

Figure 8 shows the proportion of reacted lime in the LBC mixtures as a function of curing time for the treatment with 1% (dashed lines) and 2% of lime (solid lines). The LC before 7 days is as important as the rest of the curing time. The figure shows that lime reacts faster with higher bentonite content regardless of the added lime content. The mixture 20b1 shows that the reaction is not active anymore from 56 to 112 days, which is consistent with the non-evolving UCS between 56 and 112 days. Figure 9 shows the LC of LBC and HBC mixtures treated with 2% lime. The curves are closer to each other when the bentonite content increases. This demonstrates a higher reaction rate for higher bentonite content mixtures that confirms the observation made in Figure 8.

3.3. *Electrical resistivity*

ER is measured on the samples of LBC treated with 1 and 2% lime. Figure 10 depicts the evolution of the resistivity of lime-treated LBC mixtures with curing time ranging up to more than 2 years for the 1% lime treatment and 8 months for the 2% lime treatment. The resistivity of the mixture 20b1 stops increasing after approximately 8 weeks (which confirms the stop of the lime reaction already seen with LC charts), whereas the resistivity of both other mixtures (10b1 and 15b1) continues increasing even after 2 years. For the 2% lime-treated mixtures, the aspect of the curves is similar to the treatment at 1% lime
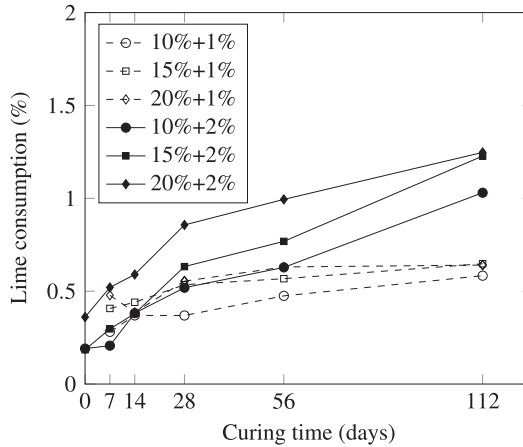
Figure 8. Lime consumption for LBC mixtures treated with 1% (dashed) and 2% (solid) lime as a function of curing time.
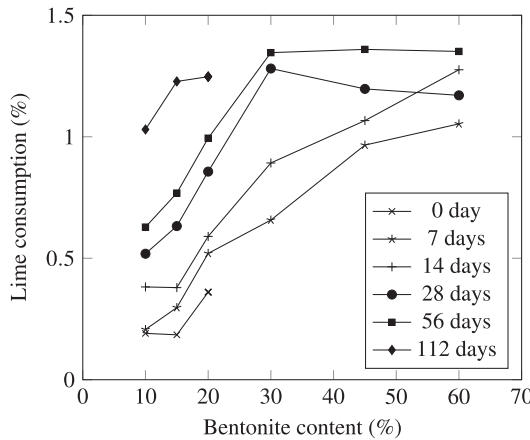

Figure 9. Lime consumption for LBC & HBC mixtures treated with 2% lime at different curing times as a function of bentonite content.

but the timescale also seems expanded, similarly to the observation made for UCS. From the similar trends seen on both lime treatments, the behaviour of ER for all curves can be divided in three phases depending on their rate of increase: a first phase with a low rate of increase, a second phase of acceleration and a third phase of deceleration. The estimation of the curing times at the phase changes was done for all six curves and shown in Table 3. The first phase of the 20b1 mixture cannot be observed and the third phase of 10b2 is seen to begin later than the curing times measured. Estimations show that time limits increase for decreasing bentonite contents and increasing lime contents.

The lime content in soils decreases their ER (i.e. increases the conductivity) due to the presence of Ca^{2+} cations and the increase of pH in the soil. This effect can be seen by comparing the values of ER at short curing times between the different initial lime contents (i.e. 15–20 Ωm, for 1% of lime and 10–15 Ωm, for 2% of lime). At longer curing times, this effect continues and the ER of the mixtures treated with 2% lime remains lower than the ones of the mixtures treated with 1% lime.
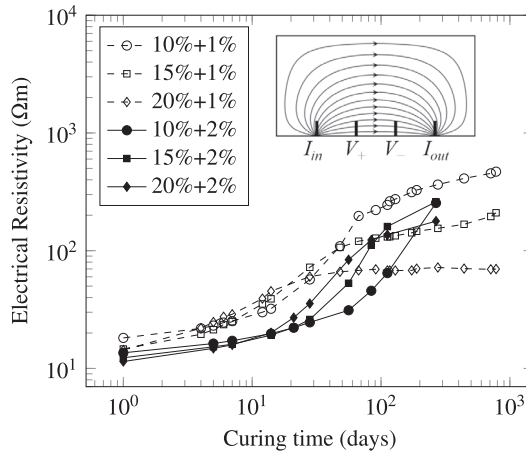
Figure 10. Electrical resistivity for LBC mixtures treated with 1% (dashed) and 2% (solid) lime as a function of curing time.

Table 3. Estimated time limits (in days) between changes in rate of increase in ER for the three LBC mixtures treated with 1% and 2% lime.
Note: Time limits increase for decreasing bentonite contents and increasing lime contents.

Mixture (%)	1→2	2→3
10 + 1	13	60
15 + 1	8	50
20 + 1	–	30
10 + 2	60	–
15 + 2	30	150
20 + 2	15	80

For a given lime percentage, the mixtures have relatively the same ER at short curing times. Then, an acceleration of ER occurs sooner for higher bentonite contents (i.e. first phase change) which lead to a higher ER. At the end, this effect is reversed and the ER decreases for increasing bentonite content. This is due to a higher proportion of unreacted bentonite at HBC which keeps the resistivity of the whole mixture to lower values.

4. Results analysis

4.1. Correlation between LC and UCS

Figure 11 exhibits the relative increase in UCS as a function of LC for LBC2 and HBC mixtures, both of them being treated with 2% of lime. The slope of curves in Figure 11 is the rate by which UCS increases as a function of LC. This gain of strength per amount of LC can be called lime efficiency in the frame of the improvement process.

For the mixtures treated at 2% lime, Figure 11 demonstrates that the efficiency is maximum for the mixture 15b2.

By assuming a linear correlation between UCS and LC within the range of the studied curing time, it is possible to quantitatively deduce the efficiency of the lime treatment in function of bentonite content by calculating the slope of the linear regression. Figure 12
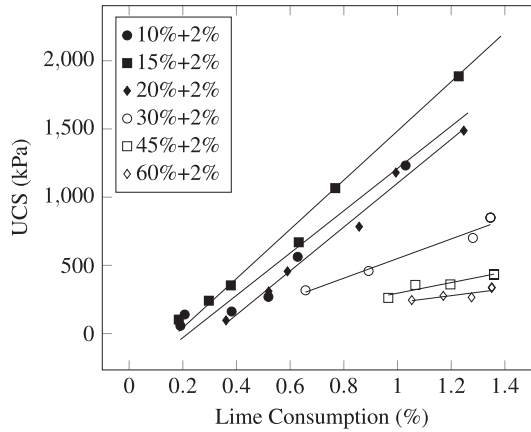
Figure 11. Unconfined compressive strength shown versus lime consumption for LBC mixtures treated with 2% lime.
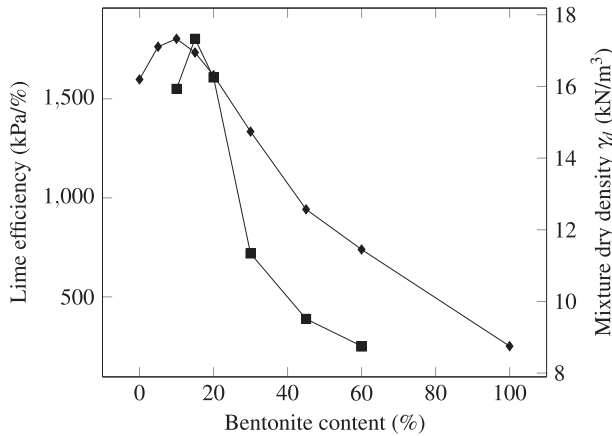

Figure 12. Lime efficiency for each bentonite content treated with 2% lime (circles).
Notes: The initial dry density of the mixtures (diamonds) is suspected to highly influence UCS and therefore lime efficiency.

shows the efficiency of the lime treatment for the six mixtures treated with 2% lime, in parallel with the dry density. The two curves resembles each other. The maximum lime efficiency is located at 15% bentonite and is equal to 1.8 MPa per %CaO.

The density of any soil is well known to influence its mechanical properties. A higher density leads to a higher resistance, independently from the lime reaction. This feature can also be extended when bentonite has reacted with lime. At the equal level of LC, the effect of the treatment will be more significant when the density of the mixture is higher, which explain the similarity between MPCT optimum density and lime efficiency. The correlation between lime efficiency and MPCT optimum density is not linear, but it can be stated that the initial density of the treated soil highly influences its UCS and therefore its efficiency with lime treatment.

Figure 13 shows the partial densities of sand and bentonite in the mixture. The values are simply deduced by multiplying the overall dry density to the percentage of each component. At bentonite contents between 0 and 15%, the partial density of sand stays relatively constant
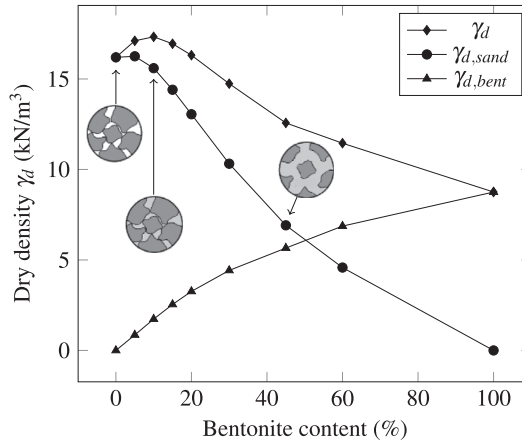
Figure 13. Conceptual model of partial densities: The optimum density is obtained when bentonite fills the void between sand particles without pushing them apart.

Table 4. Ratios of water content and lime content (w_b and l_b respectively) per bentonite content (b) and dry density of bentonite ($\rho_{d,b}$) for each mixture.

Mixture (%)	b (%)	w (%)	w_b (%)	l_b (%)	$\rho_{d,b}$ (g/cm^3)
10 + 1	10	14	140	10	0.566
15 + 1	15	17	113	6.7	0.666
20 + 1	20	20	100	5	0.731
10 + 2	10	15	150	20	0.535
15 + 2	15	18	120	13.3	0.638
20 + 2	20	21	105	10	0.705
30 + 2	30	26	86.7	6.7	0.810
45 + 2	45	36	80	4.4	0.856
60 + 2	60	41	68.3	3.3	0.951

Notes: A decrease in w_b increases the dry density of bentonite for increasing bentonite contents and may influence the speed of the reaction.

and the partial density of bentonite increases. Consequently, the lime efficiency increases in this interval (0–15%) due to the increasing presence of bentonite. In this interval, the sand particles stay relatively close together, while bentonite fills in the interparticle voids. However, as bentonite content increases above 15%, bentonite pushes the sand particles apart from each other, reducing the partial density of sand. This effect leads to a lower interparticle bonding and hence a lower lime efficiency.

4.2. Kinetics of the reaction vs. density of bentonite

It is observed in Figures 8 and 9 that the speed of lime reaction depends on the bentonite content. This could be related to the density of bentonite aggregates. Parallel investigations into these sand–bentonite mixtures have been carried out in Hashemi, Massart, Salager, Herrier, and François (2015) at the micro scale. It was demonstrated by X-ray tomography, that all the water is stored in bentonite aggregates to reach quasi-saturated conditions while

the macro-pores (between bentonite aggregates and sand) are free of water. Under this assumption, the water content in the bentonite (w_b) influences the density of the bentonite aggregates ($\rho_{d,b}$) as computed in Table 4 for all the mixtures studied. The ratio lime content/bentonite content is also shown in this table as l_b. The table shows that for increasing bentonite contents, the water content (w) determined by MPCT does not increase as fast and the ratio of the two (w_b) decreases. Consequently, the dry density of bentonite also decreases leading to a higher lime concentration in bentonite aggregates and thus a faster reaction.

5. Conclusion

This paper investigated the behaviour of sand–bentonite mixtures with lime treatment. The mixtures studied were composed of 10, 15, 20% (low bentonite content, LBC) and 30, 45, 60% (high bentonite content, HBC) of bentonite and 90, 85, 80, 70, 55, 40%, respectively, of sand. The mixtures with LBC were treated with 1 and 2% of lime and the mixtures with HBC were treated with 2% lime. Three complementary tests, UCS, LC and ER, were carried out to investigate the evolution of the behaviour due to lime treatment as a function of curing time from 0 day up to 4 to 8 months.

Results clearly show evolving properties with time due to the lime reaction with bentonite. Investigation into the combination of UCS and LC give the following important points:

- The UCS measurements can be summarised in twotime scales:
  - At short curing times, the stronger mixture is between 20 and 30% of bentonite content.
  - At long curing times, stronger mixtures are given by lower bentonite content mixtures (10% bentonite for 1% lime and 15% bentonite for 2% lime).

- The LC measurements show a faster reaction for higher bentonite contents.
- Combining UCS with LC demonstrates that the relatively low strength of mixture with 10 and 15% of bentonite at short curing times is due to the slower LC for lower bentonite contents.
- If we consider a given LC, the mixtures with 10% bentonite + 1% lime and 15% bentonite + 2% lime are always stronger than the other mixtures treated at their respective lime content. Thus, low bentonite content always confer a higher UCS/LC ratio (called lime efficiency) than mixtures with high bentonite content for any curing time.
- This lime efficiency is shown to be highly influenced by the total dry density of the mixture.
- The rate of lime reaction is shown to depend on the density of bentonite aggregates which is controlled by the water content (a lower ratio of water/bentonite brings clay particles closer and increases lime concentration).

The evolution of ER can be divided into three stages characterised by the rate of increase. The change between the stages occurs sooner for higher bentonite contents and lower lime contents. There is also a qualitative relationship between both LC and ER measurements; e.g. the stop of both LC and ER for the mixture with 20% bentonite after 2 months.

Lime-treated sand–bentonite mixtures are also interesting for the stabilisation of a sandy soil. This paper shows that the quantity of clay and lime needed to stabilise sand with lime is not high.

In this study, the mixtures are composed of a poorly graded sand (which keeps a high porosity once compacted) and a pure bentonite clay. Therefore, we can expect that for a better graded sand with natural lower porosity, the amount of clay needed to fill the pores could be lower.

Moreover, a rapid increase of mechanical properties in soil stabilisation (i.e. 4–8 weeks of curing time) can be achieved using high contents of bentonite (i.e. ratio of 20% bentonite & 80% sand for 2% lime treatment). On the other hand, if longer curing times can be accomplished (more than 8 weeks), one can consider using lower bentonite contents (i.e. ratios around 15–85% for 2% lime treatment) and expect, in the end, higher mechanical properties. At the end of this study, we may conclude that the key parameter that controls the lime efficiency (i.e. the gain of soil resistance per per cent of LC) is the density of bentonite, which in turn is a function of the initial water content. As a perspective, we plan to investigate the lime reaction rate on pure bentonite at different water contents and initial lime content to highlight the effect of initial water content on the efficiency of lime reaction.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Al-Mukhtar, M., Lasledj, A., & Alcover, J.-F. (2010a). Behaviour and mineralogy changes in lime-treated expansive soil at 20 °C. *Applied Clay Science, 50*, 191–198.

Al-Mukhtar, M., Lasledj, A., & Alcover, J.-F. (2010b). Behaviour and mineralogy changes in lime-treated expansive soil at 50 °C. *Applied Clay Science, 50*, 199–203.

Al-Mukhtar, M., Lasledj, A., & Alcover, J.-F. (2014). Lime consumption of different clayey soils. *Applied Clay Science, 95*, 133–145.

Arabani, M., & Veis Karami, M. (2007). Geomechanical properties of lime stabilized clayey sands. *The Arabian Journal for Science and Engineering, 32*, 11–25.

Arabi, M., Wild, S., & Rowlands, G. (1989). Frost resistance of lime-stabilized clay soil. *Transportation Research Record, 1219*, 93–102.

Bell, F. (1996). Lime stabilization of clay minerals and soils. *Engineering Geology, 42*, 223–237.

Carroll, D. (1959). Ion exchange in clays and other minerals. *Geological Society of America Bulletin, 70*, 749–779.

Dakhnov, V. N. (1959). *The application of geophysical methods; electrical well logging: Moscow Petroleum Institute; translated by GV Keller (1962)*. Colorado School of Mines Quart, 57.

De Bel, R., Gomes, A. C., & Verbrugge, J. C. (2009). Contribution of loamy soil treatment to improve embankments performance. *Geotechnical Special Publication ASCE, 189*, 61–72.

Diamond S., & Kinter, E. (1965). Mechanisms of soil-lime stabilization. *Highway Research Record, 92*, 83–102.

Eades, J., & Grim, R. (1966). A quick test to determine lime requirements for lime stabilization. *Highway Research Record, 139*, 61–72.

Eades, J., Nichols, F. P., & Grim, R. E. (1962). Formation of new minerals with lime stabilization as proven by field experiments in virginia. *Highway Research Board Bulletin, 335*, 31–39.

Estéoule, J., & Perret, P. (1979). Etude expérimentale des phénomènes de stabilization des sols fins par la chaux [Experimental study of stabilisation processes of fine-grained soils with lime]. *Bulletin des Laboratoires des Ponts et Chaussées, 99*, 99–109.

Hashemi, M. A., Massart, T. J., Salager, S., Herrier, G., & François, B. (2015). Pore scale characterization of lime treated sand–bentonite mixtures. *Applied Clay Science, 111*, 50–60.

Keller, W.D. (1964). Processes of origin and alteration of clay minerals. Soil clay mineralogy, 3–76.

Khattab, S., Al-Mukhtar, M., & Fleureau, J.-M. (2007). Long-term stability characteristics of a lime-treated plastic soil. *Journal of Materials in Civil Engineering, 19*, 358–366.

Little, D. N. (1995). *Handbook for stabilization of pavement subgrades and base courses with lime*. Kendall/Hunt, Iowa.

Locat, J., Bérubé, M., & Choquette, M. (1990). Laboratory investigations on the lime stabilization of sensitive clays: Shear strength development. *Canadian Geotechnical Journal, 27*, 294–304.

Makki-Szymkiewicz, L., Hibouche, A., Taibi, S., Herrier, G., Lesueur, D., & Fleureau, J.-M. (2015). Evolution of the properties of lime-treated silty soil in a small experimental embankment. *Engineering Geology, 191*, 8–22.

Mrabent, S. A. B., Hachichi, A., Souli, H., Taibi, S., & Fleureau, J.-M. (2016). Effect of lime on some physical parameters of a natural expansive clay from algeria. *European Journal of Environmental and Civil Engineering*. doi:10.1080/19648189.2015.1093963(0)

Netterberg, F., & Paige-Green, P. (1984). *Carbonation of lime and cement stabilized layers in road construction*. (Tech. Rep.). Pretoria, South-Africa: National Institute for Transport and Road Research, CSIR.

Setra. (2007). *Traitement des sols à la chaux et/ou aux liants hydrauliques - Application à la réalisation des assises de chausses*. Guide Technique, Service d'Etudes Techniques des Routes et Autoroutes, Bagneux Cedex, France. In French.

Sherwood, P. (1993). *Soil stabilization with cement and lime*. *State of the art review* (Tech. Rep.). London: Transport Research Laboratory, HSMO.

Tashiro, C., Ikeda, K., & Inoue, Y. (1994). Evaluation of pozzolanic activity by the electric resistance measurement method. *Cement and Concrete Research, 24*, 1133–1139.

Thompson, M. (1965). *Shear strength and elastic properties of lime–soil mixtures*. Urbana: University of Illinois.

Zha, F.-S., Liu, S.-Y., Du, Y.-J., & Cui, K.-R. (2009). Evaluation of physicochemical process in stabilized expansive soils using electrical resistivity method. *Rock and Soil Mechanics, 30*, 1711–1718.