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Stabilization of an expansive overconsolidated clay using hydraulic binders

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KEYWORDS

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California bearing ratio;
Bearing capacity

Abstract Urban areas of the wilaya of M'sila in Algeria nowadays experience a considerable development because of an unceasingly increasing demography, from where its extension toward virgin zones is often less favorable than those already urbanized. This wilaya is located in a zone classified as semi-arid, whose geology comprises clayey formations characterized by a high variation of volume when the conditions of their equilibrium are modified (natural climatic phenomena due to a prolonged dryness, human activity by modification of the ground water level because of excessive pumping, configuration of constructions in their environment). This paper presents and analyzes the results of a series of laboratory tests (identification, compaction, penetration and direct shear tests) performed on an expansive overconsolidated clay obtained from an urban site situated in Sidi-Hadjrès city (wilaya of M'sila, Algeria), where significant damages frequently appear in the road infrastructures and in the light structures. Test results obtained show that the geotechnical parameteric values deduced from these tests are concordant and confirm the bearing capacity improvement of this natural clay treated with hydraulic binders (composed Portland cement and extinct lime) and compacted under the optimum Proctor conditions, which is translated by a significant increase in soil strength and its durability.

Introduction

Expansive soils are a worldwide problem and occur in many parts of the world but particularly in arid and semi-arid regions [1]. The arid and semi-arid regions cover *inter alia* a good part of Algeria. These regions, delimited by the Tellian Atlas in North and the Saharian Atlas in South, extend from East to West until the bordering Maghreb's countries. Their meteorology is characterized by weak precipitations and important temperature variations between winter and summer (cold and wet winters von hot and dry summers). Their geology comprises clayey formations characterized by a high

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variation of volume when the conditions of their equilibrium are modified (natural climatic phenomena due to a prolonged dryness, intense human activity by modification of the ground water level because of excessive pumping, configuration of constructions in their environment). These clayey formations were the subject of some characterization studies, which confirmed their expansive character [2–8]. Damages appeared in the road infrastructures and in the small buildings because of the soil swelling [7,9–15] which compromises the use of expansive soils in their natural state in construction of fills and pavement base layers. At dry state, the expansive soils are very difficult to compact since their consistency varies from hard to very hard. At wet state, they are very sticky. However, their employment can be possibly decided based on specific treatment with hydraulic binders [16].

The short-term treatment of fine-grained soils and their long-term stabilization is a current technique in road construction. This process is mainly used to make compactable the soft soils by reduction of their plasticity and, consequently, to improve their bearing capacity. The limes mainly calcic (quicklime, extinct lime, lime slurry), road cements and special binders are the most used treatment products. The action of these products on the hydrous state of the fine-grained soils and on their clayey fraction is highlighted in practice [17–25]. The treatment studies carried out on some expansive soils confirm, they also, the action of cement and lime on their plasticity and swelling characteristics [19–21,23,26–32]. Other treatment products (dune sand, salt, fly ash, bitumen, rice husk ash, stone dust, or their combinations) were used to stabilize the swelling soils and other problematic soils [5,33–44]. The obtained test results show a certain improvement of geotechnical properties of the studied soils, but the effectiveness of the tested treatment products is not yet clearly established on the scale of the practice.

This paper presents the results of a study carried out on an expansive overconsolidated clay obtained from an urban site situated in Sidi-Hadjrès city (wilaya of M'sila, Algeria), where significant damages frequently appear in the road infrastructures and in the light structures. The carried out study aims at determining the physical and mechanical parameters of this natural clay treated with a locally manufactured stabilizers (composed Portland cement and extinct lime). The influence of treatment on its mechanical properties is then analyzed.

Brief description of the studied clay

Urban areas of the wilaya of M'sila in Algeria nowadays experience a considerable development because of an unceasingly increasing demography, from where its extension toward virgin zones is often less favorable than those already urbanized. This wilaya is located in a zone classified as semi-arid characterized by weak precipitations and significant variations in temperature between winter and summer. The soil samples used were collected between 1.30 and 1.70 m of depth in a layer of yellowish brown gypseous marly clay, reaching 1.50–4.50 m of depth according to the places. Tables 1 and 2 give the identification test results carried out on these soil samples and their chemical composition respectively. Fig. 1 shows their grain size

Table 1 Geotechnical properties of Sidi-Hadjrès clay (wilaya of M'sila, Algeria).

Parameters	Symbols	Range of variation	Mean values
Depth	z (m)	1.30–1.70	1.50
Natural water content	w_{nat} (%)	13.21–13.46	13.34
Wet unit weight	γ_h (kN/m^3)	20.4–24.2	22.3
Dry unit weight	γ_d (kN/m^3)	18.0–21.4	19.7
Liquid limit	w_L (%)	81.5–86.7	83.7
Plastic limit	w_P (%)	30.6–36.6	32.8
Plasticity index	I_P (%)	50.1–51.9	51.0
Consistency index	I_c (%)	1.33–1.47	1.38
Methylene blue value	MBV	7.40–9.77	8.31
Over to 2 mm	% < 2 mm	95.0–96.0	95.5
Over to 0.08 mm	% < 0.08 mm	64.6–81.9	73.2
Clay content	$C_{2\mu m}$ (%)	20.5–30.9	25.7
Activity of clay	A_c	1.95–2.02	1.98
Optimum water content	w_{opt} (%)	19.2–19.6	19.43
Maximum dry density	$\gamma_{d\text{-}max}$	1.59–1.61	1.60
Fragmentability coefficient	FR	2.93–3.51	3.26
Damage coefficient	DG	2.68–3.50	2.97
In-situ void ratio	e_o	0.60–0.78	0.67
Preconsolidation pressure	σ'_p (kPa)	650–1000	700
Overconsolidation ratio	OCR	8.7–13.5	9.1
Compression index	C_c	0.16–0.19	0.18
Recompression index	C_s	0.04–0.06	0.05
Coefficient of permeability	k_{vo} (m/s)	2.1×10^{-11}–3.2×10^{-11}	3×10^{-11}
Creep index	$C_{\alpha e}$	0.002–0.011	0.006
Swelling pressure	σ_s (kPa)	430–850	600
Free swelling	ε_{fs} (%)	4.1–68.4	32.7
Secondary rate of swelling	$C_{\alpha s}$	0.012–0.132	0.214
Conventional shrinkage limit	w_R	11.6–11.8	11.7
Effective shrinkage limit	w_{RE}	17.3–21.8	19.9
Effective shrinkage ratio	I_R	58.9–71	62.4

Table 2 Chemical composition of Sidi-Hadjrès clay (wilaya of M'sila, Algeria).

Constituents	SiO_2	CaO	MgO	Fe_2O_3	Al_2O_3	SO_3	K_2O	Na_2O	L.O.I
%	43.38	14.66	2.55	4.02	11.36	11.55	1.51	1.12	10.03

L.O.I – Loss on ignition.

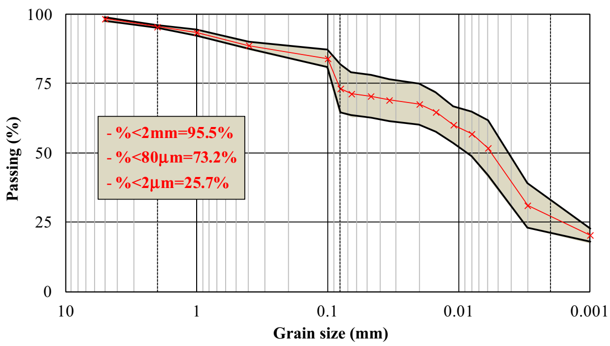

Fig. 1 Grain size distribution curve of Sidi-Hadjrès clay (wilaya of M'sila, Algeria).

distribution curve. Fig. 2 shows their X-ray diffraction test results.

These low dispersed values for the carried out sampling seem to indicate a homogeneous soil massif. The grain size distribution curve of soil samples tested indicates that they are composed of 1.9% gravel, 24.9% sand, 47.5% silt and 25.7% clay. According to USDA textural classification system, they are classified as clay loam. According to French classification [45], compatible to the Unified Soil Classification System (USCS), they are classified as high plastic (CH) and very consistent (I_c > 1) clay with important activity of its clayey fraction (A_c > 1.25; presence of calcic montmorillonite). This clay is classified as overconsolidated, low permeable and very low sensitive to creep [6]. Its overconsolidation is due to the phenomenon of shrinkage resulting from a more-or-less thorough desiccation. Chemical analysis conducted on this clay shows that the dominating elements are silica, carbonates and alumina. X-ray diffractogram shows that the silica is crystallized in quartz form (21%) and the carbonates are crystallized in calcite form (79%). According to the French classification for fine-grained soils and evolutionary rock materials [46], this clay belongs to A4 subclass (I_p > 40 or MBV > 8) and it is considered as low fragmentary (FR < 7) and low damaged (DG < 5). On the other hand, the modifications of its water content are accompanied by shrinkage or swelling. Casagrande plasticity chart adapted to expansive soils shows that this clay is characterized by a high swelling potential according to Dakshanamurthy and Raman classification [47] and by a high-to-very high swelling potential according to Chen classification [10] (Fig. 3). Seed et al. [48], Ranganatam and Santyanarayana [49], Williams and Donaldson [50] and Bigot and Zerhouni [51] classifications also indicate a very high swelling potential. In addition, BRE-UK classification [52] led to a very high shrinkage potential.

Experimental program and test procedures

In addition to identification tests, the experimental program comprises normal Proctor compaction tests, methylene blue tests, California bearing ratio tests and undrained direct shear tests performed in accordance with Algerian standards [53] comparable to French standards. These tests were carried out on untreated soil (control sample) and on treated soil with various cement and lime contents. The used composed Portland cement is locally manufactured in Lafarge's company of Hammam Dalâa (wilaya of M'sila, Algeria). Extinct lime used comes from ERCO's company of Hassasna (wilaya of Saïda, Algeria). Tables 3 and 4 give the physico-chemical properties of these two stabilizers.

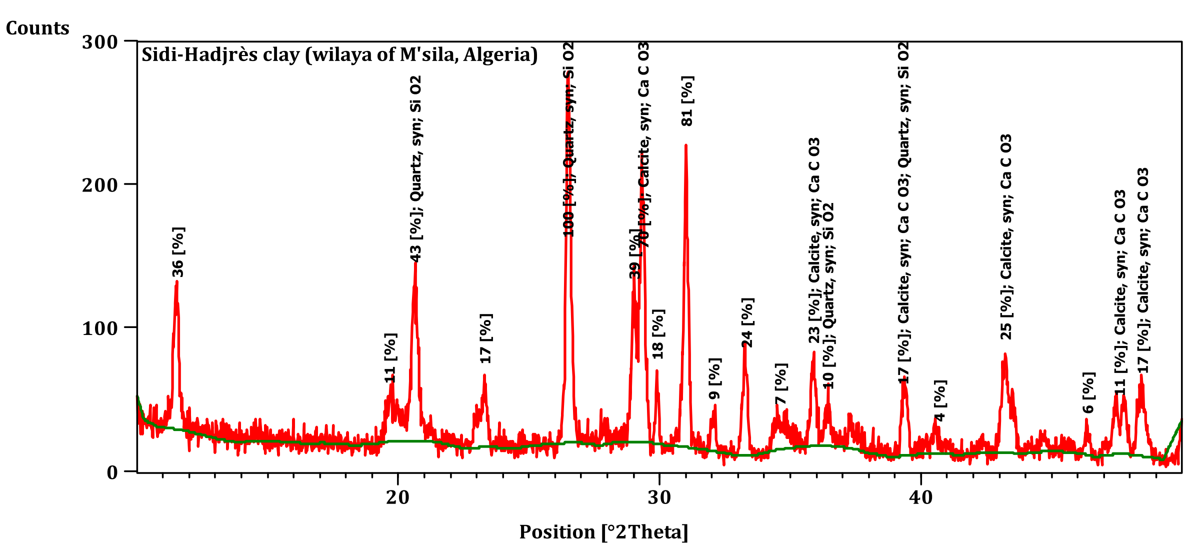

Fig. 2 X-ray diffractogram of Sidi-Hadjrès clay (wilaya of M'sila, Algeria).

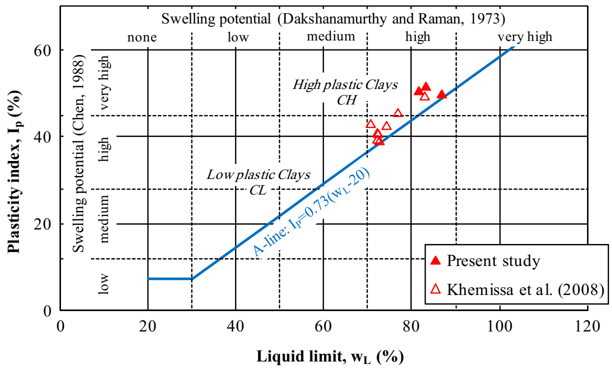

Fig. 3 Classification of Sidi-Hadjrès clay (wilaya of M'sila, Algeria).

Table 3 Physico-chemical properties of M'sila's composed Portland cement (Algeria).

Designation	CEM-II/B 42.5 N NA 442 – MATINE	
Physical properties	Normal consistency of the cement paste	25–28.5
	Blaine fineness	4150–5250 μm/m
	Initial setting	140–195 min
	End setting	195–290 min
	Shrink at 28 days of age	< 1000 μm/m
	Expansion	0.3–2.5 mm
	Compressive strength at 28 days of age	⩾42.5 MPa
Chemical composition	Loss on ignition	7.5–12%
	Soluble residues	0.7–2%
	Sulfates	2–2.7%
	Magnesium oxide	1–2.2%
	Chlorides	0.01–0.05%
	Tricalcic silicates	55–62%
	Alkalis	0.5–0.75%

Table 4 Physico-chemical properties of Saïda's extinct lime (Algeria).

Designation	NHL	
Physical properties	Bulk density	600–900 g/l
	Absorption coefficient	< 5
	Sensitivity to freezing	< 30
	Volume of extinction	2.73 cm^3
	Over 630 μm	0%
	Over 90 μm	< 10%
Chemical composition	CaO	> 83.3%
	MgO	< 0.5%
	Fe_2O_3	< 2%
	Al_2O_3	< 1.5%
	SiO_2	< 2.5%
	SO_3	< 2.5%
	Na_2O	< 4.7–0.5%
	CO_2	< 5%
	$CaCO_3$	< 10%
	Insolubles in HCl	< 1%

The considered stabilizer contents (cement or lime) are 0% for untreated sample (control sample), 2%, 4%, 6%, 8%, 10% and 12% by dry soil weight for treated samples. The soil samples were made starting from a mixture of the necessary quantity of finely crushed dried soil to desired stabilizer content; the whole being intimately mixed at dry then humidified with optimum water content w_{opt} (i.e. maximum dry density $\gamma_{d\text{-}max}$). The paste was remixed thoroughly before performing the compaction. All tests were conducted at room temperature. Experimental procedures followed in each test type were in conformity as much as possible with the usual testing methods in accordance with the corresponding standard. Interpretation techniques of the test results are mainly inspired from the knowledge obtained on clayey soils throughout the world. Fig. 4 presents the normal Proctor compaction test results conducted on the clay treated with various cement or lime contents under optimum Proctor conditions ($\gamma_{d\text{-}max}$ and w_{opt} given on untreated soil). It is noticed that these results constitute a pledge of good repeatability of the compaction test and indicate a good reconstitution of the soil under the necessary conditions to which the soil massif is expected to be subjected in the field.

Test results and discussion

Only the principal results interesting the object of this paper are exposed hereafter, i.e. influence of the cement and lime treatment on the deformability and strength properties of compacted expansive clay.

Consistency limits and swelling parameters

Casagrande plasticity chart adapted to expansive soils in accordance with Chen [10] and Dakshanamurthy and Raman [47] classifications can be used to analyze their behavior after treatment. Fig. 5 presents the Atterberg limit test results obtained for Sidi-Hadjrès (wilaya of M'sila, Algeria) expansive clay treated with various considered cement and lime contents. It can be noted that the plasticity index and liquid limit decrease with increasing stabilizer content, but more with lime than with cement. It results in a reduction of the clay's plasticity, i.e. reduction of its swelling potential from high to low. So, the clay becomes less sensitive to water, therefore not very expansive and better compactable. The swelling's reduction of the treated clay gets certain stability with respect to the deformations due to seasonal variations of water content and, consequently, a durable behavior of the compacted clay with respect to the wear of particles generating fine plastic particles.

Some correlations were established between index properties and swelling parameters of expansive clays, among which:

-for the swelling pressure σ_s:

- $\log(\sigma_s) = 0.0208w_L + 0.00665\gamma d - 0.0269w_{nat} - 2.132$ [54], (1)
- $\log(\sigma_s) = (0.65w_L + \gamma_d - 139.5)/19.5$ [55], (2)
- $\sigma_s = 0.25(I_p)^{1.12}(C_{2\mu m}/w_{nat})^2 + 25$ [56], (3)
- $\sigma_s = 290.015\gamma d + 5.178MBV - 457.817$ [57]; (4)

-for the free swelling ε_{fs}:

- $\varepsilon_{fs} = 2.16.10^{-5}(I_p)^{2.44}$ [48], (5)
- $\varepsilon_{fs} = 2.77 + 0.131w_L - 0.27w_{nat}$ [58], (6)
- $\varepsilon_{fs} = 0.2558e^{0.0838Ip}$ [10], (7)
- $\varepsilon_{fs} = 37.076\gamma d + 0.524MBV - 57.965$ [57]; (8)

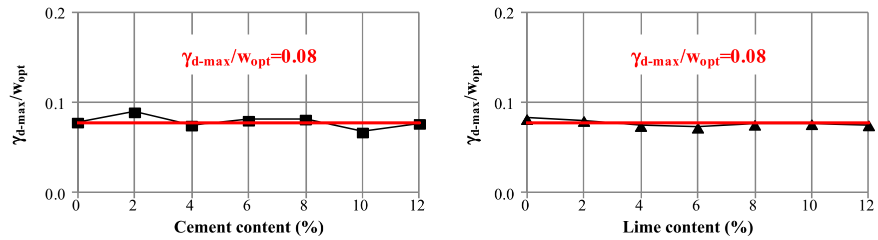

Fig. 4 Normal Proctor compaction test results for various cement and lime contents.

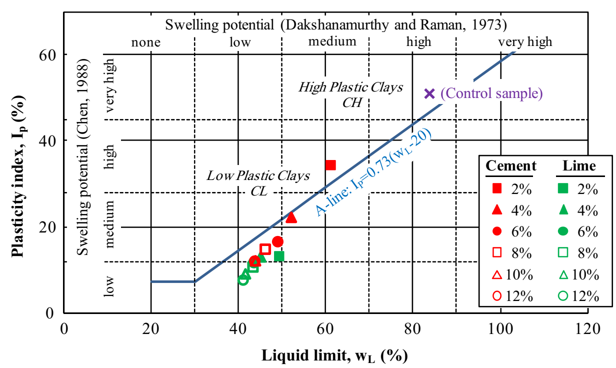

Fig. 5 Treated clay classification according to its consistency limits.

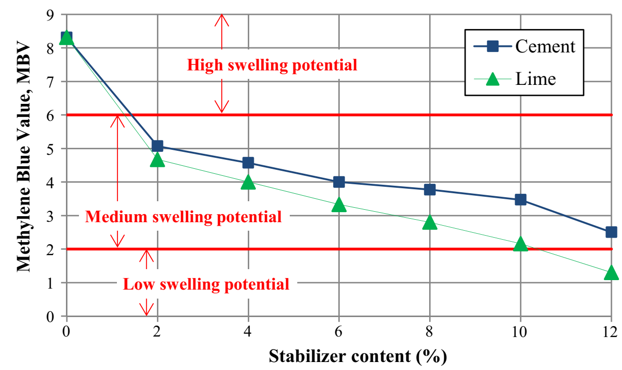

Fig. 7 Treated clay classification according to its methylene blue value.

where γ_d represents the dry unit weight, w_{nat} the natural water content, $C_{2\mu m}$ the clay content, w_L the liquid limit, I_p the plasticity index and MBV the methylene blue value. Application of these relations on various expansive natural clays [2,4,59–60] seems to give satisfactory results. Their application on Sidi-Hadjrès (wilaya of M'sila, Algeria) expansive clay seems to show that the treatment with lime as well as with cement influences its computed swelling parameters (Fig. 6). So, it can be noted that the swelling pressure of this clay and the corresponding free swelling decrease in an appreciable way with stabilizer content, but more with lime than with cement. However, for this clay, they are Nayak and Chiristensen [56] and Seed et al. [48] relations, which seem better adapted to compute respectively the swelling pressure and the corresponding linear swelling. Thus, according to Seed et al. classification [48], the linear swelling passes from very high ($\varepsilon_{fs} > 25\%$) to low ($\varepsilon_{fs} < 1.5\%$). This mitigation is due to the soil stabilization by the effect of cementing and of pozzolanic reactions, which seems to indicate that the clay becomes insensitive to swelling. This result confirms the same observation made on a bordering natural clay of comparable geotechnical characteristics, the Sidi-Aissa (wilaya of M'sila, Algeria) clay, which was treated with another composed Portland cement (CEM-II/B 32.5 R NA 442 – CHAMIL) also locally manufactured in Lafarge's company of Hammam Dalâa (wilaya of M'sila, Algeria) [32]. In addition, for the untreated soil, it can be noted that the experimental swelling pressure and the corresponding free swelling values frame well their computed values.

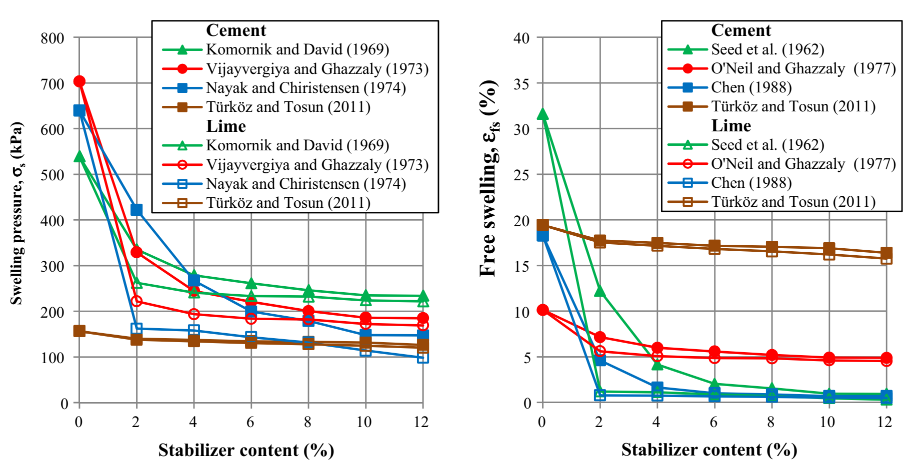

Fig. 6 Swelling pressure and free swelling computed for various cement and lime contents.

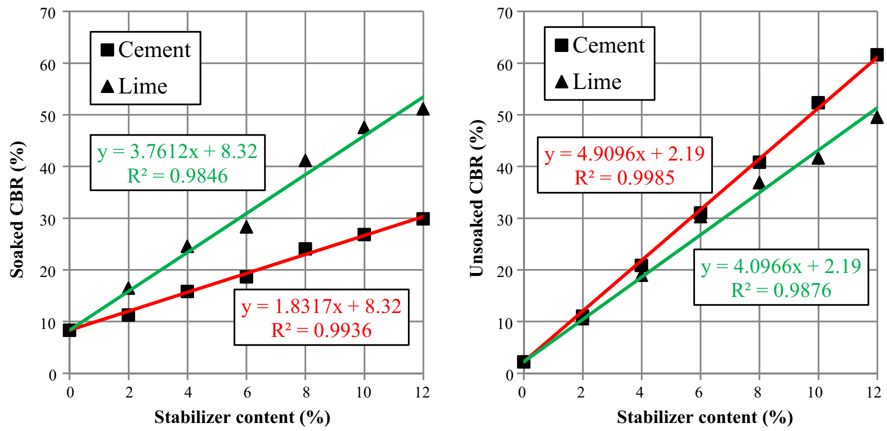

Fig. 8 Soaked and unsoaked CBR evolution for various cement and lime contents.

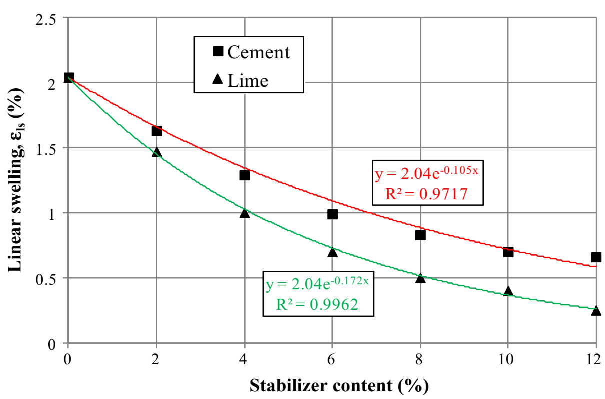

Fig. 9 Linear swelling evolution for various cement and lime contents.

Methylene blue value (MBV) and specific surface area (SSA)

Methylene blue test may be performed on each soil for which the fine fraction exceeds 15–20%. Methylene blue quantity (i.e. methylene blue value or MBV) necessary to be absorbed by the clayey particles depends on their specific surface area and of the nature of minerals which constitute them. Considered as identification and classification parameter of soils, the methylene blue value can thus be used to estimate the swelling potential of fine-grained soils. For Sidi-Hadjrès (wilaya of M'sila, Algeria) expansive clay characterized by 25.7% of clayey particles, Fig. 7 presents the evolution curve of the methylene blue value (i.e. the corresponding specific surface area SSA = 21MBV) determined for various considered stabilizer contents. According to Bigot and Zerhouni classification [51], it can be noted that the swelling potential of this clay decreases with stabilizer content, but more with lime than with cement, to pass from high (MBV > 6) to medium (2 < MBV < 6), even to low (MBV < 2). In addition, the mitigation of its specific surface area seems to indicate that its treatment with cement or lime reduces its swelling potential by modification of its texture.

California bearing ratio (CBR) and linear swelling

The CBR tests can be used to evaluate the bearing pressure of geotechnical structures (embankments, pavement base layers). Fig. 8 presents the soaked and unsoaked California bearing ratio values corresponding to soil samples tested before and after their soaking according to the considered stabilizer contents. Fig. 9 presents the evolution curve of the corresponding linear swelling. It can be noted that the treatment of Sidi-Hadjrès (wilaya of M'sila, Algeria) expansive clay compacted under the optimum Proctor conditions increase its CBR values, but more with lime than with cement for unsaoked CBR and reciprocally for soaked CBR. This is translated, in both

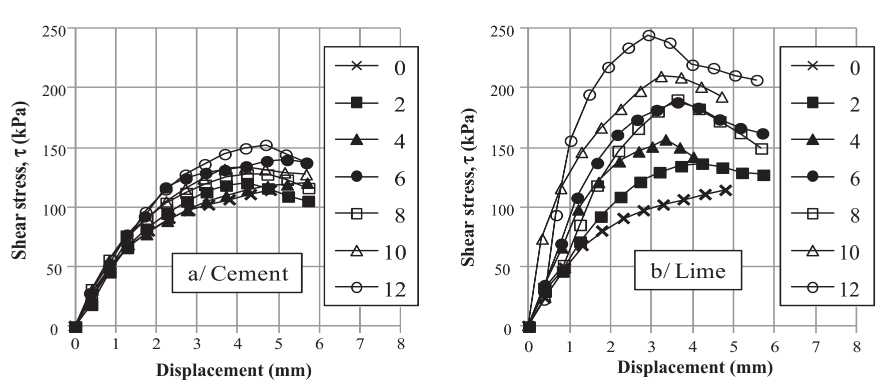

Fig. 10 Undrained shear curves for various cement and lime contents.

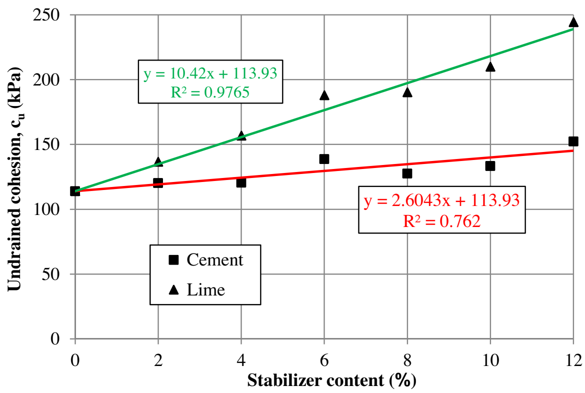

Fig. 11 Undrained cohesion evolution for various cement and lime contents.

cases, by a clear improvement of bearing capacity of this compacted clay and a very sensitive lowering of its deformability resulting from an excessive humidification after its compaction under the optimum Proctor conditions.

Undrained shear strength

Soil undrained cohesion is a parameter of short-term foundation design. It is defined by the maximum undrained shear strength deduced starting from the undrained-unconsolidated direct shear curves. Fig. 10 presents the direct shear curves of Sidi-Hadjrès (wilaya of M'sila, Algeria) expansive clay treated with various considered cement and lime contents. Fig. 11 presents the evolution curve of the corresponding undrained cohesion values. It can be noted that the shear strength of this clay (i.e. the corresponding undrained cohesion) compacted under the optimum Proctor conditions increases with increasing the stabilizer content, but more with lime than with cement. This is translated, in both cases, by a clear improvement of the bearing capacity of this compacted clay.

Summary and conclusions

This paper has the aim of characterizing the behavior of an expansive overconsolidated clay treated with a locally manufactured stabilizers (composed Portland cement and extinct lime) for its use in the road works as roadway foundation (base and subbase courses). The choice of Sidi-Hadjrès urban site (wilaya of M'sila, Algeria) was justified because of its extension toward zones at risk, where significant damages frequently appear in the road infrastructures and in the light structures.

The tested soil samples were identified as high plastic clay. Various classifications based on the geotechnical properties show that this one is characterized by a very high swelling potential; swelling being to some extent due to the mineralogical structure of soils (high percentage of montmorillonite) and to the variations of their water content (cycles of desiccation-humidification of soils).

The obtained tests results make it possible to show a sensitive improvement of the mechanical properties of this expansive clay treated with lime and cement and compacted under the optimum Proctor conditions. Moreover, it can be noted that the treatment allows:

- to decrease the plasticity index and the methylene blue values with lime than with cement, clay becomes no expansive and better compactable;
- to increase the unsaoked and soaked CBR values, allowing this fact of increasing the bearing pressure of clay and reduction of its expansibility;
- to increase the shear strength of clay, therefore of its bearing capacity.

Performances acquired by this expansive clay treated with cement and lime get stability, durability and better resistance.

References

[1] A.A. Al-Rawas, Preface, in: A.A. Al-Rawas, M.F.A. Goosen (Eds.), Expansive Soils: Recent Advances in Characterization and Treatment, Taylor & Francis Group, 2006, pp. xi–xii.
[2] Z. Derriche, M. Kebaili, Prévision du gonflement des argiles d'In-Aménas, Bulletin des Laboratoires des Ponts et Chaussées France 218 (1998) 15–23.
[3] A. Hachichi, J.M. Fleureau, Caractérisation et stabilisation de quelques sols gonflants d'Algérie, Revue Française de Géotechnique 86 (1999) 37–51.
[4] A. Djedid, A. Bekkouche, S.M. Aissa Mamoune, Identification et prévision de quelques sols de la région de Tlemcen (Algérie), Bulletin des Laboratoires des Ponts et Chaussées France 233 (2001) 67–75.
[5] A. Hachichi, S.A. Bourokba, J.M. Fleureau, Stabilisation chimique de deux sols gonflants de la région d'Oran, Revue Française de Géotechnique 118 (2007) 3–11.
[6] M. Khemissa, L. Mekki, N. Bakir, Comportement oedométrique des argiles expansives de M'sila (Algérie), in: J.P. Magnan, R. Cojean, Y.J. Cui (Eds.), SEC 2008: Symposium International Sécheresse et Constructions, Presses du Laboratoire Central des Ponts et Chaussées France, 2008, pp. 229–234.
[7] M. Khemakhem, M. Ben Jdidia, Z. Bouarada, Identification des paramètres de gonflement d'un sol de Bir Ali ben Khalifa (Tunisie), in: J.P. Magnan, (ed.) PARAM 2002: International symposium on identification and determination of soil and rock parameters for geotechnical design. Presses de l'Ecole Nationale des Ponts et Chaussées France, 2002, pp. 133–144.
[8] H. Ejjaaouani, J.P. Magnan, V. Shakhirev, S. Mowgli, Comportement des sols gonflants à Ouarzazate, in: M. Sahli, L. Bahi, R. Khalid (Eds.), The Involvement of Geotechnical Engineering in Infrastructure Development in Africa, Marrakech, 2003, pp. 363–369.
[9] G. Philipponnat, Désordres dus à la présence des sols gonflants dans la région parisienne, Annales de l'Institut Technique du Bâtiment et des Travaux Publics France 364 (1978) 1–15.
[10] F.H. Chen, Foundations on Expansive Soils, Elsevier, Developments in Geotechnical Engineering, 1988.
[11] J.D. Nelson, J.D. Miller, Expansive Soils-Problems and Practice in Foundation and Pavement Engineering, John Willey and Sons, New York, 1992.
[12] Z. Derriche, L. Iguechtal, M. Tas, Comportement des ouvrages dans les argiles expansives d'In-Aménas, Revue Française de Géotechnique 89 (1999) 55–65.
[13] R. Bahar, S. Kenai, Désordres dus à l'infiltration des eaux: Cas de la ville d'El-Affroun, Revue Française de Géotechnique 101 (2002) 91–103.
[14] A.I. Al-Mhaidib, Swelling behavior of expansive shale: a case study from Saudi Arabia, in: A.A. Al-Rawas, M.F.A. Goosen (Eds.), Expansive Soils: Recent Advances in Characterization and Treatment, Taylor & Francis Group, 2006, pp. 273–287.

[15] H. Ejjaaouani, Désordres des bâtiments lors de l'humidification des sols sensibles, Revue Marocaine du Génie Civil 119 (2007) 2–16.
[16] LCPC-SETRA, Treatment of soils with lime and/or hydraulic binders, in: Application to the construction of pavement base layers, Technical Guide France, 2000.
[17] G. Morel, Etude en laboratoire du traitement à la chaux et au ciment des sols fins, Bulletin des Laboratoires des Ponts et Chaussées France 133 (1984) 63–70.
[18] F.G. Bell, Lime stabilization of clay soils, Eng. Geol. Environ. Springer 39 (1) (1989) 67–74.
[19] F.G. Bell, Lime stabilization of clay minerals and soils, Eng. Geol. Environ. Springer 42 (1996) 223–237.
[20] Z. Derriche, F. Lazzali, Analyse des mécanismes de stabilisation d'un sol gonflant apport de chaux sous différentes formes, Eng. Geol. Environ. Springer (1997) 79–84.
[21] R. Bahar, M. Benazzoug, S. Kenai, Performance of compacted cement stabilized soil, Cement Concrete Composites Elsevier 25 (6) (2004) 633–641.
[22] M.C. Tonoz, R. Ulusay, C. Gockceoglu, Effects of lime stabilization on engineering properties of expansive Ankara Clay, Eng. Geol. Infrastructure Plann. Europe 104 (2004) 466–474.
[23] M.C. Tonoz, C. Gockceoglu, R. Ulusay, Stabilization of expansive Ankara Clay with lime, in: A.A. Al-Rawas, M.F.A. Goosen (Eds.), Expansive Soils: Recent Advances in Characterization and Treatment, Taylor & Francis Group, 2006, pp. 317–339.
[24] U.S. Okyay, R. Manirakiza, G. Rault, L. Thorel, J.D. David, J.C. Auriol, Caractérisation d'un limon traité utilisé comme matelas de transfert de charges dans une fondation composite, in: A. Anagnostopoulos et al., (eds.) Proc. 15th Eur. Conf. Soil Mech. Geot. Eng. IOS Press, 2011, pp. 1031–1036.
[25] M. Mellas, A. Hamdane, D. Benmeddour, A. Mabrouki, Improvement of the expansive soils by the lime for their use in road works, in: Proc. 10th Int. Cong. Adv. Civ. Middle East Technical University Ankara Turkey, 2012, pp. 1–8.
[26] M. Afès, G. Didier, Stabilisation des sols gonflants: cas d'une argile en provenance de Mila (Algérie), Bull. Eng. Geol. Environ. Springer 59 (1) (2000) 75–83.
[27] A. Hachichi, A. Benaissa, S. Bourokba, M. Boudia, Etude de la stabilisation chimique des sols gonflants de la région d'Oran, in: M. Sahli, L. Bahi, R. Khalid (Eds.), The Involvement of Geotechnical Engineering in Infrastructure Development in Africa, Marrakech, 2003, pp. 371–379.
[28] A.A. Al-Rawas, A.W. Hugo, H. Al-Sarmi, Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman, Building Environ. Elsevier 40 (2005) 267–281.
[29] Z. Nalbantoglu, Lime stabilization of expansive clay, in: A.A. Al-Rawas, M.F.A. Goosen (Eds.), Expansive Soils: Recent Advances in Characterization and Treatment, Taylor & Francis Group, 2006, pp. 341–348.
[30] E.I. Stavridakis, Stabilization of problematic soils using cement and lime, in: A.A. Al-Rawas, M.F.A. Goosen (Eds.), Expansive Soils: Recent Advances in Characterization and Treatment, Taylor & Francis Group, 2006, pp. 385–397.
[31] M. Al-Mukhtar, A. Lasledj, J.F. Alcover, Behavior and mineralogy changes in lime treated expansive soil at 20 °C, Appl. Clay Sci. Elsevier 50 (2) (2010) 191–198.
[32] A. Mahamedi, M. Khemissa, Cement stabilization of compacted expansive clay, J. Sci. Technol. 3 (1) (2013) 33–38.
[33] F. Kaoua, Z. Derriche, N. Laradi, Contribution à l'étude de la stabilisation des sols gonflants par ajouts de sable, Algérie Equipement: Revue de l'Ecole Nationale des Travaux Publics 15 (1994) 12–15.
[34] M. Lamara, M.K. Gueddouda, B. Benabed, Stabilisation physico-chimique des argiles gonflantes (sable de dunes + sel), Revue Française de Géotechnique 115 (2006) 25–35.
[35] A.S. Muntohar, Prediction and classification of expansive clay soils, in: A.A. Al-Rawas, M.F.A. Goosen (Eds.), Expansive Soils: Recent Advances in Characterization and Treatment, Taylor & Francis Group, 2006, pp. 25–35.
[36] A. Bekkouche, F.Z. Azzouz, S.M. Aissa Mamoune, Stabilisation par les sels des sols gonflants de la région de Tlemcen, in: SOMAPRO'07: Colloque « sols et matériaux à problèmes ». ISET Sfax Tunisie, 2007, pp. 19–25.
[37] M.K. Gueddouda, M. Lamara, N. Aboubekr, I. Goual, Caractérisation et stabilisation des sols expansifs, in: SOMAPRO'07: Colloque « sols et matériaux à problèmes ». ISET Sfax Tunisie, 2007, pp. 27–34.
[38] T.L. Ramadas, N. Darga Kumar, G. Yesuratnam, Study of swelling and strength characteristics of expansive soil treated with stone dust and fly ash, in: A. Anagnostopoulos et al., (eds.), Proc. 15th Eur. Conf. Soil Mech. Geot. Eng. IOS Press, 2011, pp. 659–664.
[39] R.M. Brooks, Soil stabilization with Fly Ash and Rice Husk Ash, Int. J. Res. Rev. Appl. Sci. 1 (3) (2009) 209–217.
[40] K. Harichane, G. Ghrici, S. Kenai, K. Grine, Use of natural pozzolana and lime for stabilization of cohesive soils, Geotech. Geol. Eng. Springer 29 (2011) 759–769.
[41] H. Khabbaz, B. Fatahi, Chemical stabilization of closed landfill sites using chemical agents, in: A. Anagnostopoulos et al., (eds.), Proc. 15th Eur. Conf. Soil Mech. Geot. Eng. IOS Press; 2011, pp. 1777–1782.
[42] Y.E.A. Mohamedzein, A.A. Al-Rawas, Cement-stabilization of sabkha soils from al-auzayba, sultanate of Oman, Geotech. Geol. Eng. Springer 29 (2011) 999–1008.
[43] B. Louafi, R. Bahar, Sand: an additive for stabilization of swelling clay soils, Int. J. Geosci. 3 (2012) 719–725.
[44] N.K. Sharma, S.K. Swain, U.C. Sahoo, Stabilization of a clayey soil with fly ash and lime: a micro level investigation, Geotech. Geol. Eng. Springer 30 (2012) 1197–1205.
[45] J.P. Magnan, Classification géotechnique des sols: a propos de la classification LPC, Bulletin de liaison des Laboratoires des Ponts et Chaussées France 105 (1980) 49–52.
[46] LCPC-SETRA, Guide des terrassements routiers: réalisation des remblais et des couches de forme, Guide technique France (1992).
[47] V. Dakshanamurthy, V. Raman, A simple method of identifying an expansive soil. Soils and foundation, Jap. Soc. Soil Mech. Found. Eng. 13 (1) (1973) 97–104.
[48] H.B. Seed, R.J. Woodward, R. Lundgren, Prediction of swelling potential for compacted clays, J. Soil Mech. Found. Eng. Div. ASCE 88 (SM3) (1962) 53–87.
[49] B.V. Ranganatam, B. Santyanarayana, A rational method of predicting swelling potential for compacted expansive clays, in: Proc. 6th Int. Conf. Soil Mech. Found. Eng. Montreal, 1965, pp. 92–96.
[50] A.B. Williams, G.W. Donaldson, Developments related to building on expansive soils in South Africa: 1973–1980, in: Proc. 4th Int. Conf. on Exp. Soils. Denver, 1980, pp. 834–844.
[51] G. Bigot, M.I. Zerhouni, Retrait, gonflement et tassement des sols fins, Bulletin des Laboratoires des Ponts et Chaussées France 229 (2000) 105–114.
[52] BRE-UK, Building Research Establishment, United Kingdom, 1980.
[53] IANOR, Recueil des normes algériennes: secteur des travaux publics, Institut Algérien de Normalisation, 2010.
[54] J. Komornik, A. David, Prediction of swelling potential for compacted clays, J. Soil Mech. Found. Eng. Div. ASCE 95 (1) (1969) 209–225.

[55] V.N. Vijayvargiya, D.I. Ghazzaly, Prediction of swelling potential for natural clays, in: Proc. 3rd Int. Conf. on Exp. Soils. Haifa, 1973, pp. 227–236.
[56] N.V. Nayak, R.W. Chiristensen, Swelling characteristics of compacted expansive clays, Clays Clay Minerals 19 (4) (1974) 251–261.
[57] M. Türköz, H. Tosun, The use of methylene blue test for predicting swell parameters of natural clay soils, Sci. Res. Essays 6 (8) (2011) 1780–1792.
[58] M.W. O'Neil, O.I. Gazzaly, Swell potential related to building performance, J. Geotech. Eng. Div. ASCE 103 (12) (1977) 1363–1379.
[59] A.S. Muntohar, Swelling characteristics and improvement of expansive soil with rice husk ash, in: A.A. Al-Rawas, M.F.A. Goosen (Eds.), Expansive Soils: Recent Advances in Characterization and Treatment, Taylor & Francis Group, 2006, pp. 435–451.
[60] B.R. Phanikumar, Prediction of swelling characteristics with free swell index, in: A.A. Al-Rawas, M.F.A. Goosen (Eds.), Expansive Soils: Recent Advances in Characterization and Treatment, Taylor & Francis Group, 2006, pp. 173–184.