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On the mechanical behaviour of dredged submarine clayey sediments stabilized with lime or cement

Antonio Federico, Claudia Vitone, and Agnese Murianni

Abstract: This paper presents the preliminary results of experimental research into the stabilization of clayey sediments dredged from the Port of Taranto (Italy) with cement and (or) lime. First, the physical properties of the natural sediments are briefly described and compared with those of the same sediments when treated with different additives and cured up to 4 years. In particular, the effect of the treatment on the soil plasticity properties is originally analyzed in terms of plasticity paths. Then, the influence of the different stabilizing agents on the compression behaviour of the dredged soil is analysed and methods for quickly predicting the admixed-soil behaviour are presented.

Key words: soil stabilization, dredged clay, plasticity path, compression behaviour.

Résumé : Le présent article décrit les résultats préliminaires d'une étude expérimentale portant sur la stabilisation de sédiments argileux dragués dans le port de Taranto (en Italie) à l'aide de ciment ou de chaux. Dans un premier temps, les propriétés physiques des sédiments naturels sont brièvement décrites, puis comparées avec celles de ces mêmes sédiments une fois qu'ils ont été traités avec différents additifs et après une cure pouvant durer jusqu'à quatre ans. On analyse en particulier, d'une manière originale, les effets du traitement sur les propriétés plastiques du sol en examinant les droites de plasticité. Ensuite, l'influence des différents agents stabilisants sur l'état de compression du sol dragué est analysée et des méthodes de prédiction rapide du comportement du sol traité avec des additifs sont présentées. [Traduit par la Rédaction]

Mots-clés : stabilisation du sol, argile draguée, droite de plasticité, état de compression.

Introduction

Research into the behaviour of artificially stabilized clayey soils has become increasingly important and is developing along various lines to find the most effective ways to improve specific aspects of the behaviour of natural soils depending on the particular engineering problem to be solved. Since the early 1960s (e.g., Sherwood 1957, 1962; McDowell 1959; Taylor and Orman 1960; Mitchell and Hooper 1961; Dumbleton 1962; Herzog and Mitchell 1963; Eades and Grim 1966; Croft 1967; Broms and Boman 1977; Mitchell 1981; Terashi and Tanaka 1981; Locat et al. 1990, 1996; Smith 2005; Dalla Rosa et al. 2008; Cecconi et al. 2011; Russo and Croce 2011), soils have been treated with cementing agents to improve their mechanical behaviour. However, there has been only limited research into the prediction of changes in the plasticity properties and mechanical behaviour of dredged materials (e.g., Rajasekaran and Narashima Rao 1997; Tang et al. 2001; Tremblay et al. 2001; Burgos et al. 2007; Chiu et al. 2009; Grubb et al. 2010; Huang et al. 2011). In particular, although it has been observed that the addition of either cement or lime can produce significant effects on the soil index properties (e.g., Broms and Boman 1977; Brandl 1981; Buensuceso 1990 Locat et al. 1996; Russo and Croce 2011), no definite assessment of such modifications has been identified yet. This is also because the effect of the treatment depends on several factors, such as the quantity of additive, curing time, physical properties, grain size distribution, water chemistry, and, mainly, the soil mineralogical composition.

Due to its relative inexpensiveness, Portland cement is a commonly used cementing agent in geotechnical projects. Adding Portland cement to clayey soil results in a hydration reaction in the cement, followed by a pozzolanic reaction between the calcium hydroxide supplied by the cement and the silica in the soil (e.g., Herzog and Mitchell 1963; Croft 1967; Bergado et al. 1996). The products of the primary hydration reaction are calcium silicate hydrated (CSH), calcium aluminates, and hydrated lime. The subsequent secondary reactions occur as soon as hydrated lime is produced in the mixture, and they bring about the formation of additional CSH and calcium aluminate hydrates. The hydration reactions take place with a faster rate than the pozzolanic reactions and occur mainly in the space between the soil aggregates, forming a strong matrix enclosing the nonbonded particles and aggregates. Conversely, the pozzolanic reactions develop between the produced calcium hydroxide and the silica and alumina, dissolved from the clay surfaces, to bond the particles within the clay aggregates. These two forms of reactions combine to produce interaggregate and intraaggregate bridges, creating a strongly bonded fabric within the soil body.

Lime is another commonly used additive for soil stabilization or for improving soil properties[1]. When lime is used, the absence of a primary hydration reaction leads to a different microstructure than that produced by cement treatment (Chew et al. 2004). In particular, according to Locat et al. (1996), if enough lime is mixed with the clayey soil, the main chemical reactions are flocculation, which results from a large increase in the electrolyte concentra- Fn1

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[1]Use of lime is the oldest known method of chemical stabilization, used by Romans to construct the Appian Way (Winterkon and Pamucku 1991). By mixing quicklime with a clayey soil and adding water the Romans discovered that soil could be strengthened to provide a good foundation for road pavement (Smith 2005). Stretches of the Appian Way in Rome still sit on lime-stabilized soils that are two millennia old (Wheeler 2004).

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tion Ca^{++}, and the pozzolanic reactions. According to Mitchell and Soga (2005), the creation of a high pH environment (12.4 or greater) is essential for the effectiveness of lime stabilization of clays by means of pozzolanic reactions where CSH cementing materials are formed using silicate from broken down clay minerals.

In this paper, the effect of stabilization with cement and (or) lime of the clayey sediments that will be dredged from the Port of Taranto (Italy) is analysed. The study is part of a project aiming to improve and expand the infrastructure of the Port itself, which is located in a strategic area in the Mediterranean sea (Fig. 1). The extensive deepening of the seabed in the Port will require the disposal and (or) re-use of about 1.9×10^7 m^3 of dredged submarine sediments.

This paper presents the preliminary results of experimental research on the effects of artificial stabilization with cement and (or) lime on the physical properties and compression behaviour of dredged natural clayey sediments.

The physical properties of the natural high plasticity (CH) clay (classified according to the Unified Soil Classification System (USCS; ASTM 2011)) from the Port of Taranto are first compared with those of the treated clay. Then, the effect of treatment is analyzed and the experimental data originally interpreted in terms of plasticity paths. Moreover, the compression behaviour of the treated clay is investigated, taking into account the effect of both the percentage of additive and the curing time. In particular, the effect of the treatment on the clay structure is interpreted in light of the sensitivity framework, following the approach proposed in the literature for natural clays (Leroueil and Vaughan 1990; Cotecchia and Chandler 2000; Vitone and Cotecchia 2011). Finally, a strategy for quickly predicting the compression behaviour of the treated clay is outlined.

Submarine clayey sediments from Port of Taranto

During the first in situ investigation, carried out at site 1 in the Port of Taranto (Fig. 1), 14 continuous boreholes were drilled to depths of up to 30 m below the seabed and 74 undisturbed samples were taken (Cotecchia 2005; SGS – SELC 2009).

The submarine sediments in the area are mainly made up of so-called subapennine clays, which, being grey-blue to grey-green, are commonly known as blue clays. This Lower Pleistocene formation is in transgression over either the Gravina Calcarenite or the Altamura Limestone and its thickness, in the area under study, may be more than 100 m (Mastronuzzi et al. 1999).

The clay samples are fairly homogeneous in terms of both physical and mechanical properties, so they may be considered as belonging to a single geological unit. The high carbonate content (20%–35%) of these clays may be ascribed to carbonatic cementation. The constituent clay minerals are mainly represented by illite followed by chlorite, montmorillonite, and kaolinite. The organic content of the clay is low, and it decreases with depth from 2.2% for the shallow samples (i.e., up to 6 m below the seabed) to 1% for the deeper ones (Cotecchia 2005; SGS – SELC 2009). According to the literature (Keller 1982; Booth and Dahl 1986; Huang et al. 2012), below a minimum content threshold of about 3%–4%, the organic matter is too small to interfere during the cementing process when a cementing agent is added to the soil, so that, for the purpose of the present study, this clay can be considered as inorganic clay.

The grading spindle (Fig. 2) shows that the clay fraction, CF, is between 25% and 50%, and the silt fraction, MF, varies from 30% to 70%. The consistency index (CI) does not show a clear trend with depth, and it is either below or about 1 (Federico et al. 2013, 2014). According to the Casagrande (1948) plasticity chart (Fig. 3), the samples can be classified as clay of medium to high plasticity (CL–CH).

Fig. 1. Port of Taranto and its location in the Mediterranean Sea. Site 1: first in situ campaign; site 2: sampling site for the present study.

Fig. 2. Grading spindle of submarine sediments from Port of Taranto (modified from Cotecchia 2005 and SGS – SELC 2009).

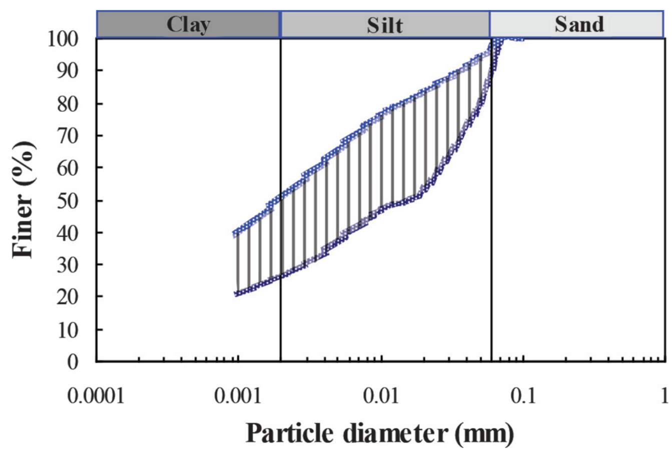
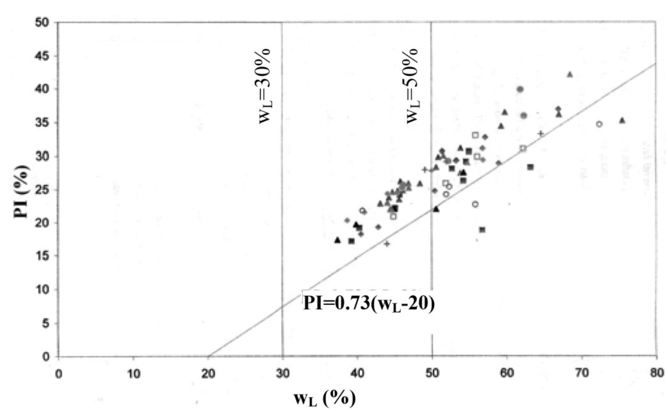


Fig. 3. Casagrande plasticity chart of submarine sediments from Port of Taranto (data from Cotecchia 2005 and SGS – SELC 2009).



Effect of stabilization on physical properties

Materials and methods

The soil used was taken from two submarine boreholes drilled in site 2 (Fig. 1) within 10 m below the seabed. Similarly to the

Table 1. Physical and plasticity properties of reconstituted and treated clay.

Additive	Additive content (%)	Curing time (days)	W_L (%)	W_P (%)	PI (%)	γ (kN/m^3)	G_s	e_0
—	0	—	55	26	29	15.32	2.67	2.203
Lime (L)	2	2	65	34	31	nd	nd	nd
		7	66	34	32	nd	nd	nd
		28	73	33	40	15.35	2.68	2.120
		1460	50	27	23	nd	nd	nd
	4	2	67	40	27	nd	nd	nd
		7	70	39	31	nd	nd	nd
		28	83	38	45	15.60	2.70	2.095
		1460	71	40	31	15.66	2.75	1.976
	8	2	50	36	13	nd	nd	nd
		7	55	39	16	nd	nd	nd
		28	76	51	25	15.99	2.65	1.828
		1460	65	45	20	16.04	2.81	1.822
	10	28	nd	nd	nd	nd	nd	1.818
Cement (C)	2	2	71	35	36	nd	nd	nd
		7	69	33	36	nd	nd	nd
		28	59	28	31	15.50	2.70	2.269
		1460	55	27	28	nd	nd	nd
	4	2	78	43	35	nd	nd	nd
		7	73	40	33	nd	nd	nd
		28	52	30	22	15.40	2.73	2.21
		1460	56	27	29	15.23	2.66	2.031
	8	2	70	43	27	nd	nd	nd
		7	69	44	25	nd	nd	nd
		28	66	45	21	15.60	2.75	1.953
		1460	63	44	19	15.58	2.79	1.823
	10	28	nd	nd	nd	nd	nd	1.932
		1460	nd	nd	nd	16.05	2.74	1.852
Cement/lime (C/L)	2	2	73	36	37	nd	nd	nd
		7	73	37	36	nd	nd	nd
		28	74	42	32	15.60	2.64	2.161
	4	2	62	31	31	nd	nd	nd
		7	65	33	32	nd	nd	nd
		28	75	43	32	15.70	2.65	2.014
	8	2	69	49	20	nd	nd	nd
		7	72	51	21	nd	nd	nd
		28	84	56	28	15.80	2.67	1.917

Note: G_s, XXXX; nd, XXXX.

shallower submarine sediments of site 1, it is a clayey silt (CF = 33%, MF = 52%, SF = 15%) of high plasticity (liquid limit w_L = 55%, plasticity index PI = 29%), so that it can be classified as CH.

The soil was cut into small pieces, dried at room temperature, and then finely pulverized into a powder passing the No. 40 sieve (0.425 mm). The clay powder was mixed with sea water (unit weight γ_w = 10.05 kN/m^3) to form a slurry with a water content (w) of 82.5%, i.e., about 1.5 times the liquid limit (w_L). The slurry was mixed in a mechanical mixer until a uniform paste was achieved.

Different cementing agents, namely CEM II/A-S 42.5 Portland cement (C), quicklime (L), and a mixture of 75% cement and 25% quicklime (C/L) were used in different quantities (i.e., 2%, 4%, 8%, and 10% by dry weight). They were added to the slurry and thoroughly mixed by means of a mechanical mixer. Thereafter, several specimens were prepared from each mixture using cylindrical polyvinyl chloride (PVC) moulds. The full moulds were then placed into a temperature-controlled room to be cured in sea T1 water. As summarized in Table 1, the physical and plasticity properties of the treated soils were determined after curing times of 2, 7, and 28 days. Further determinations were carried out after 1460 days (i.e., about 4 years).

F4 Figure 4 shows the plot of after-curing water content, w, versus additive content (A_w hereafter) at varying curing times. The decrease of the after-curing water content with increasing additive content is mainly attributable to the increased amount of water reduction from the hydration process of the additives. Also, as the additive content and the curing time increased, the increasing amount of cementing products resulting from the pozzolanic reactions eventually increased the weight of soil solids per unit volume (Table 1). This would justify the decrease of the water content with curing time (Fig. 4).

Moreover, the data in Table 1 show that the after-curing void ratio decreases with increasing the additive content for a given curing time. In particular, irrespective of the additive used, after 28 days of curing, the void ratio decreases if more than 2% of additive is used, and it seems to stabilize for an additive content higher than 8%. Similar results are reported in the literature for cement-treated soft Bangkok clay (Bergado et al. 2006) and submarine dredged clayey sediment from Shenzen in China (Chiu et al. 2009).

Plasticity paths of the treated clays

Figures 5–7 show the positions in the Casagrande plasticity F5-F7 chart of the natural clay and the clay treated with cement, lime, and cement–lime mixture, respectively. For each percentage of additive, the plasticity points are shown in the figures with symbols of size proportional to the curing time. The first general consideration that can be made is that, regardless of both the typology and percentage of additive used, the plasticity points in Figs. 5–7 after 2, 7, 28, and 1460 days (i.e., points AX, BX, CX, and DX) appear to be almost aligned. Also, the results show that, if 8% additive (either lime, cement or cement–lime) is used, two days of curing are sufficient to transform the untreated clay (U in the figures) from CH to MH soil, according to USCS classification (ASTM 2011).

AX-DX paths in Fig. 5 show that, irrespective of the cement content, curing time from two days up to about 4 years makes the

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Fig. 4. Water content of treated samples after 28 days (empty symbols) and 1460 days (full symbols) of curing. Rec, ~~water~~ reconstituted sample.

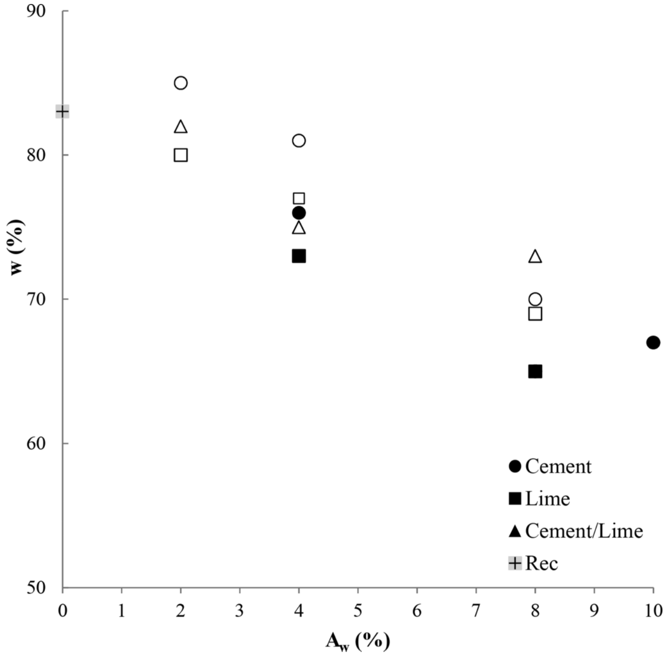


Fig. 5. Plasticity paths of clay treated with cement. Symbol size is proportional to curing time (i.e., small symbols AX: 2 days, medium symbols BX: 7 days, and large symbols CX and DX: 28 and 1460 days, respectively).

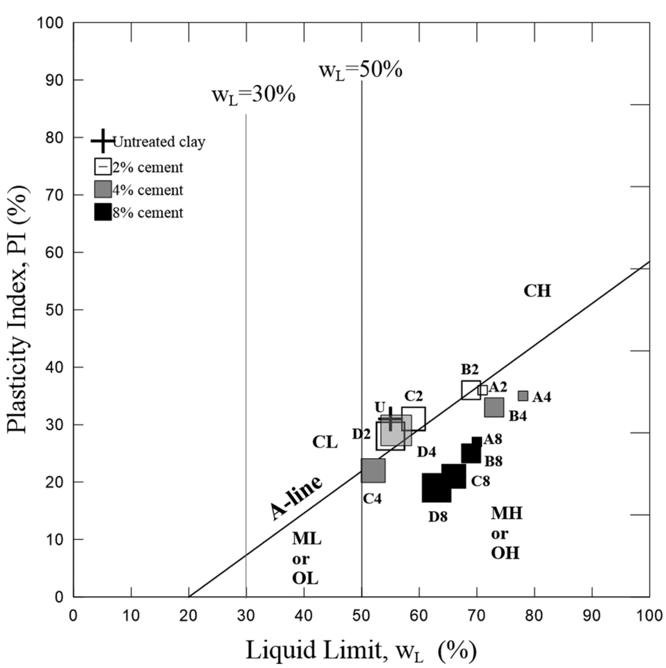


Fig. 6. Plasticity paths of clay treated with lime. Symbol size is proportional to curing time (i.e., small symbols AX: 2 days, medium symbols BX: 7 days, and large symbols CX and DX: 28 and 1460 days, respectively).

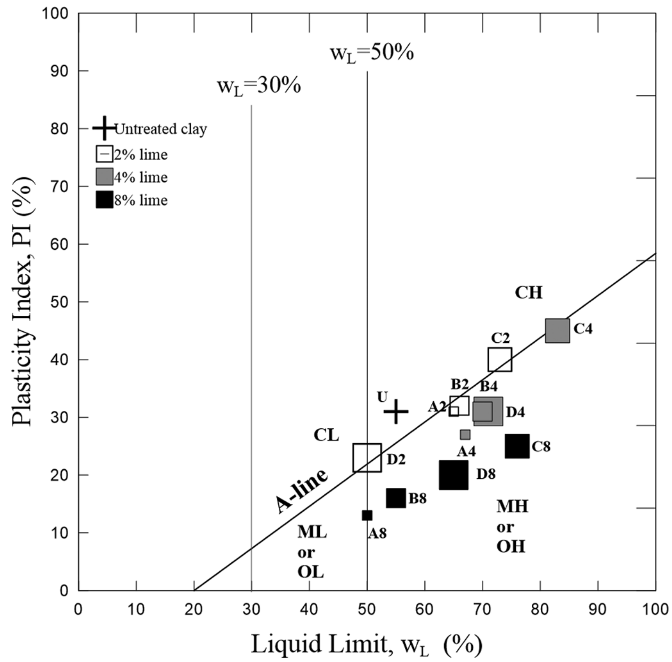
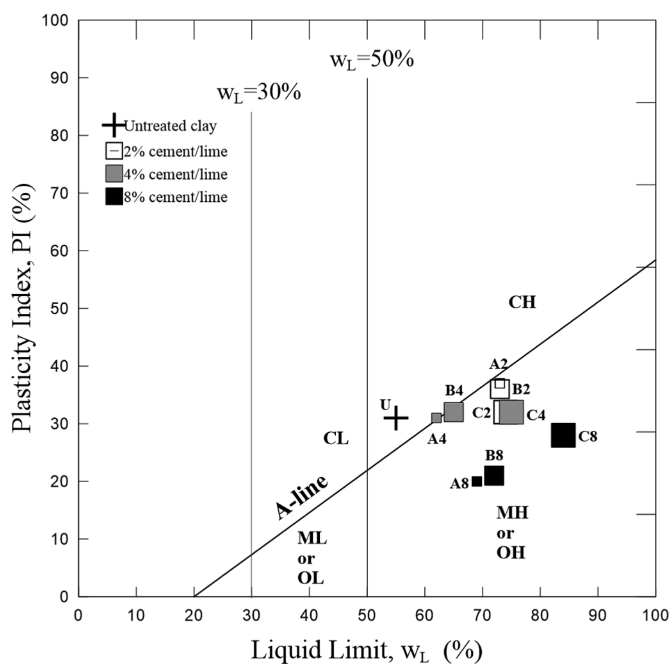


Fig. 7. Plasticity paths of clay treated with cement–lime mixture. Symbol size is proportional to curing time (i.e., small symbols AX: 2 days, medium symbols BX: 7 days, and large symbols CX: 28 days).



plasticity points move downwards and to the left in the chart (i.e., a reduction in both w_L and PI is recorded).

After 28 days of curing with cement, plasticity paths U-CX show that only when adding more than 2% cement, the treated clay has a lower PI than the untreated clay. However, after about 4 years (i.e., 1460 days) the effect on the clay plasticity induced by adding 4% cement has been almost entirely cancelled out, such that point D4 is coincident with point U in Fig. 5. It follows that a permanent reduction in PI has been obtained only when 8% cement (path U-D8) is added.

When lime is used, points AX-CX in Fig. 6 appear to follow paths that are opposite to those of the cement-treated clay in Fig. 5: the longer the curing time, the further the process develops, such that the plasticity points continuously shift further away from point U as time passes. However, for longer curing time, paths CX-DX, irrespective of the percentage of additive, still follow aligned

Table 2. Oedometer tests carried out on undisturbed, reconstituted, and treated clay specimens. ~~Test typology: loading–unloading (L-U).~~

Type	Test	Loading sequence, σ'_v (kPa)
Clay	Und	12.25-4900-294
Lime	Li0	12.25-196-24.5
	Li2	12.25-392-24.5
	Li4	12.25-392-12.25
	Li4*	12.25-3138-12.25
	Li8	12.25-392-12.25
	Li8*	12.25-3138-12.25
	Li10	12.25-392-12.25
Cement	Ce0	12.25-196-24.5
	Ce2	12.25-196-12.25
	Ce4	12.25-392-12.25
	Ce4*	12.25-1569-12.25
	Ce8	12.25-392-12.25
	Ce8*	12.25-3138-12.25
	Ce10	12.25-392-12.25
	Ce10*	12.25-3138-12.25
Cement + lime	CL0	12.25-196-24.5
	CL2	12.25-196-12.25
	CL4	12.25-392-12.25
	CL8	12.25-392-12.25

*Test after 4 years.

Fig. 8. Undisturbed, reconstituted (Ce0), and cement-treated (Ce2, Ce4, Ce8, Ce10) clay samples: oedometer compression curves. Numbers refer to percentage of cement used; asterisk (*) is used for 1460 days of curing.

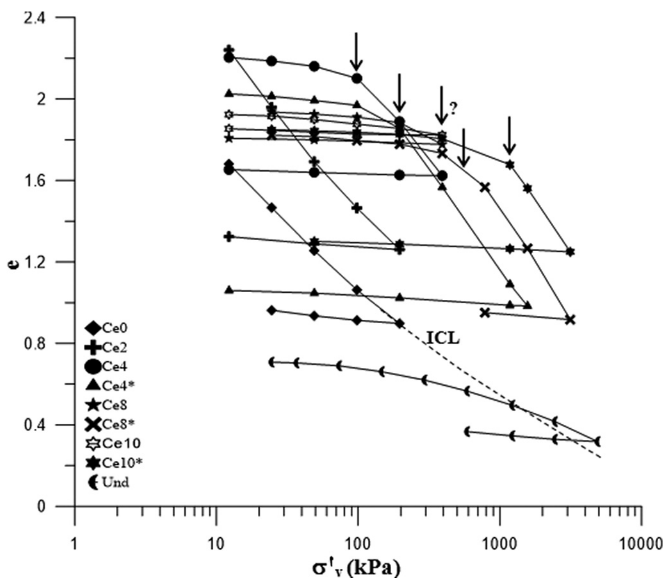


Fig. 9. Undisturbed, reconstituted (Li0), and lime-treated (Li2, Li4, Li8 and Li10) clay samples: oedometer compression curves. Numbers refer to percentage of lime used; asterisk (*) is used for 1460 days of curing.

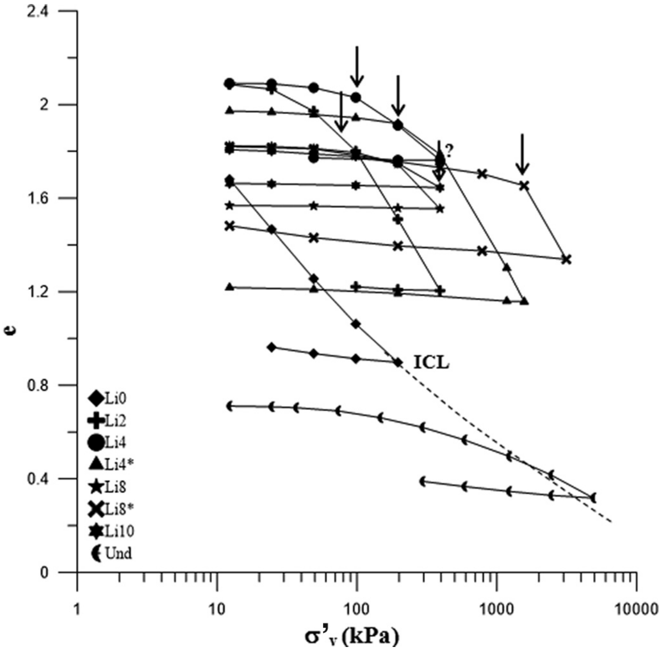
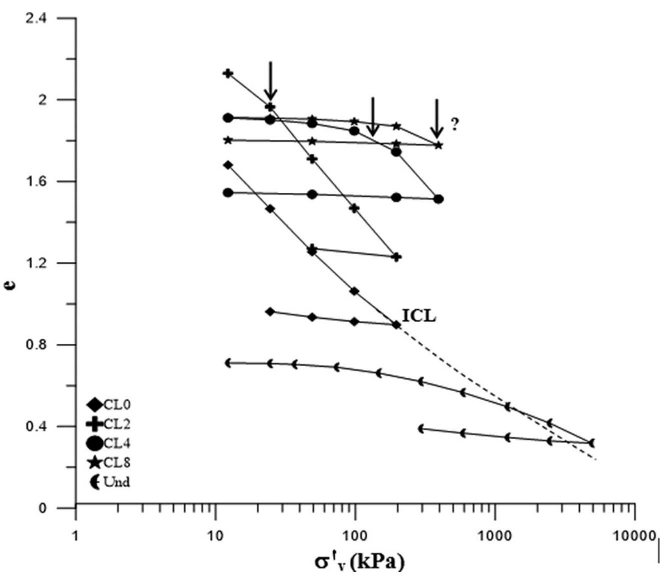


Fig. 10. Undisturbed, reconstituted (CL0), and cement–lime-treated (CL2, CL4, CL8) clay samples: oedometer compression curves. Numbers refer to percentage of mixture used.



paths but with opposite verse (i.e., the same of the cement-treated clay). The plasticity paths U-DX also show that a net PI reduction is recorded only after 1460 days of curing (paths U-D2 and U-D8).

The plasticity paths AX-CX of the cement–lime mixture (i.e., 75% cement and 25% lime) are similar to those of the lime-treated clay only when 8% mixture is added (Fig. 7). Moreover, only when 8% of mixture is used, after 28 days of curing the PI of the treated clay becomes lower than that of the untreated clay (path U-C8).

Effect of stabilization on one-dimensional compression behaviour

T2 Table 2 summarizes the oedometer tests carried out on the undisturbed, reconstituted, and treated clay. The base material was prepared according to the procedure suggested by Burland (1990) for reconstituted clay, as already mentioned, by mechanically mixing the soil at a water content of about 1.5 times the liquid limit (i.e., w_0 = 82.5%) and, thereafter, by stirring it with the different additives ranging from 2% to 10% of the dry weight. The material was then placed into plastic moulds 58 mm in diameter and 50 mm in height. The full moulds were cured into marine water and maintained in a temperature-controlled room at 20 °C. The oedometer specimens were trimmed from the full moulds after 28 days of curing. Moreover, additional tests were carried out after curing for 1460 days.

Figures 8–10 show the results of oedometer tests carried out on specimens stabilized with cement, lime, and the cement–lime F8-F10

Fig. 11. Effect of additive content, A_w, and curing time on the (*a*) compression and (*b*) swelling index. Asterisk (*) and full symbols refer to 1460 days of curing.

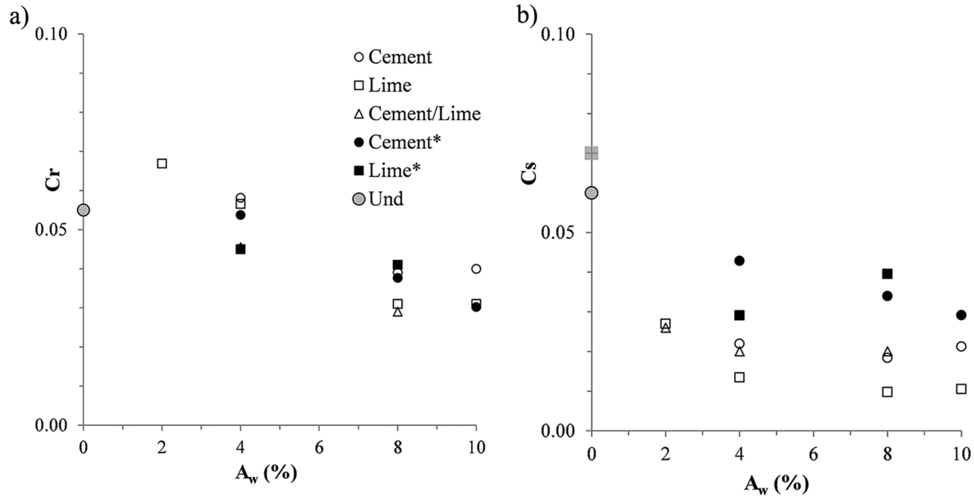
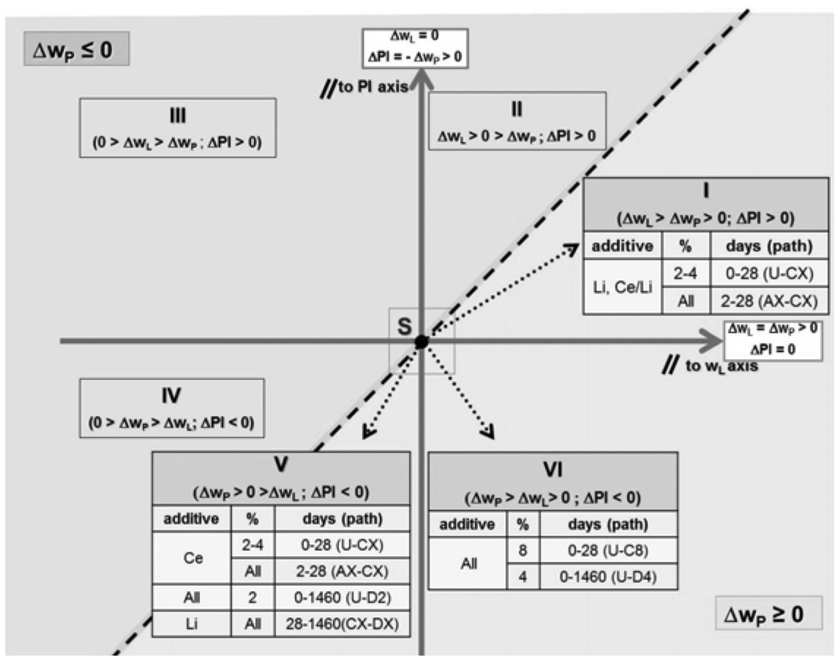


Fig. 12. Chart of plasticity paths resulting from data in Figs. 5–7.



mixture, respectively, along with those relevant to the reconstituted clay and the undisturbed natural clay. The first consideration that can be made is that, irrespective of the quantity and typology of additive used, the compression curves of the treated clay lie always on the right of the normal compression line of the reconstituted sample (i.e., the intrinsic compression line (ICL) (Burland 1990), being characterized by much higher void ratios for the same σ'_v values, where σ'_v is the vertical effective stress). Moreover, the much lower void ratios of the undisturbed clay make its compression curve be located on the right of the ICL only from medium-high pressures. It is evident that, because of the cementation, treated clays are stable at higher void ratios than untreated clay (either natural or reconstituted) subject to the same consolidation pressure.

Figure 8 shows that for 2% cement content, the compression curve is still similar to that of the reconstituted specimen, but shifted towards higher void ratios. This result is consistent with the plasticity paths of the cemented clay: within the chart in Fig. 5, point C2 is in fact almost coincident with point U, which represents the plasticity point of the untreated clay.

For cement contents higher than 2% (i.e., 4%, 8%, and 10%), the yield stress state (arrows in the Figure) becomes easily recognizable along the compression curves (Fig. 8). Moreover, a post-yield compression behaviour can be identified where the cemented clay begins to develop large strains.

Consistent results have been found by Bushra and Robinson (2010), who performed oedometer tests on untreated specimens and specimens of a marine clay (w_L = 56%, PI = 31%, CF = 44%, MF = 47%) quite similar to that of the present study, when treated (and cured for 28 days) with different quantities of ordinary Portland cement. The authors found that more than 2.5% of cement has to be added to make the pozzolanic reactions initiate and make the pre-yield behavior distinguishable from the post-yield behaviour along the compression curve.

Figures 9 and 10 show that a mild curvature at yield stress (arrows in the figures) is instead already visible when the soil is

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treated with 2% of either lime or the cement–lime mixture. This is consistent with the fact that in Figs. 6 and 7, points C2 are not coincident with point U. It can be inferred that the yield stress state is still not pronounced along the curve because, following from Locat et al. (1996), quantities of less than 3% of hydrated lime are not sufficient to activate pozzolanic reactions at the base of the formation of secondary CSH minerals, and only flocculation occurs.

F11 In Figs. 11*a*–11*b* the compression index, C_c, and the swelling index, C_s of the treated specimens are plotted versus the additive content, A_w. The compression index, C_c, of the treated clay does not seem to follow a clear trend after 28 days of curing. This is probably due to both the limited number of data and the fact that in some cases they are not fully representing normally consolidated states. The higher C_c values exhibited by the admixed clay after 1460 days of curing time seem to remain almost unchanged for different percentages of lime or cement. Moreover, C_c values of all the treated specimens are higher than those of the untreated clay (either natural or reconstituted). After 28 days of curing, the C_s of the lime-treated clay is almost always the smallest one (Fig. 11*b*). For longer curing time this is not always the case. Moreover, for the same quantity of additive, an increase in C_s is recorded if curing time increases. The C_s values of the treated clay are always lower than those of the untreated clay (either undisturbed or reconstituted).

Discussion of results

Physical and plasticity properties of treated clays

The main results of the analysis of the plasticity paths in

F12 Figs. 5–7 are summarized in the chart in Fig. 12. The first general consideration that can be made is that all the plasticity paths in Figs. 5–7 are included into sectors I, V, and VI that are those characterized by an increase of the plastic limit, w_p. This implies (irrespective of the w_L variations) an increment of the consistency index (CI), if, as it is generally in this case, the after-curing water content reduces (Fig. 4). Only when lime is added, paths AX-CX are included into sector I (i.e., PI increases) for the first 28 days of curing. Longer curing time shows that plasticity points start moving in the opposite verse (paths CX-DX; sector V in Fig. 12), that is, similarly to the AX-CX paths of the cement-treated clay.

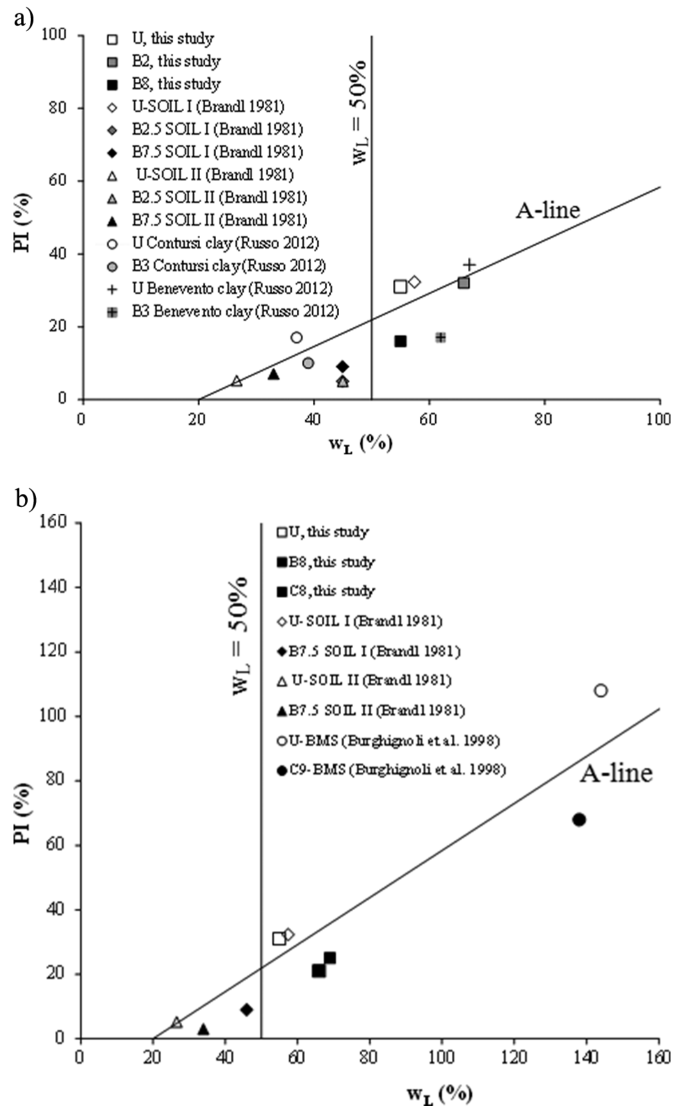
Moreover, 8% of additive (either cement, lime or cement–lime mixture) and 28 days of curing make the plasticity point move in sector VI (paths U-CX), where the reduction in PI is due to the much higher increase in w_p with respect to that recorded for w_L ($\Delta w_P > \Delta w_L > 0$, $\Delta PI < 0$). When 4% of additive is used, the same effect is recorded later (i.e., after 1460 days (paths U-DX)). When 2% of either lime or cement is added, only after 1460 days is a reduction in PI recorded (path U-D2). However, in this case, paths U-D2 are included in sector V (i.e., the reduction in PI is due to both a reduction in w_L and an increase in w_p (Fig. 12)).

The results of lime stabilization from the present study appear to be consistent with those from the literature (i.e., Broms and Boman 1977; Buensuceso 1990; Locat et al. 1996), as the addition of lime produced in general the PI reduction despite the increase of w_L (Paths U-C8 and U-D4, sector VI in Fig. 12). Some of the plasticity points of the clay treated with lime in the present study are com-

F13 pared with others from the literature in Fig. 13*a*. The data from Russo (2012) on Contursi clay (CF = 27%, MF = 50%) are still consistent with this framework. However, the figure shows that in some cases the reduction of PI can be accompanied by a reduction of w_L (sector V in Fig. 12). This is the case of soil I (CF = 25%, MF = 54%) and soil II (CF = 12%, MF = 73%) tested by Brandl (1981) after 7 days of curing using either 2.5% or 7.5% of lime (Fig. 13*a*).

Few data are available in the literature concerning the influence of cement on the index properties of treated soils. Again, the results from the present study are compared (Fig. 13*b*) with those of soil I and soil II after 7 days of curing using 7.5% of cement (Brandl 1981). It can be observed that only the most active soil I (*A* =

Fig. 13. Effect of (*a*) lime and (*b*) cement stabilization on soil plasticity properties: data from this study and from the literature.



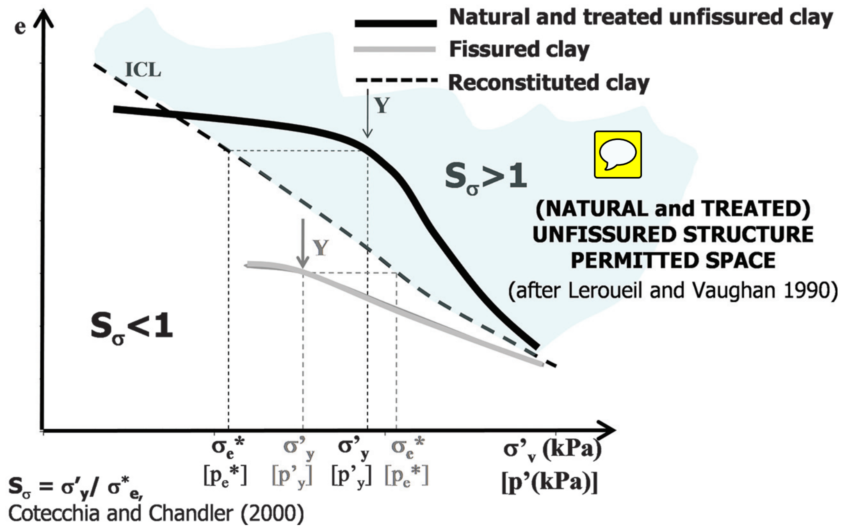
0.78) exhibits a reduction in both PI and w_L (sector V in Fig. 12). Similar results are also reported by Burghignoli et al. (1998) for a clay (CF = 36%, MF = 59%) treated with 6% of cement and cured for 28 days (Fig. 13*b*).

Behavioural trends in compression of treated clays

The natural micro to mesostructure of natural fissured and unfissured clays has been dealt with as an internal state variable adding to void ratio in controlling the clay response (e.g., Leroueil 1988; Burland 1990; Leroueil and Vaughan 1990; Nagaraj et al. 1998; Cotecchia and Chandler 2000; Vitone and Cotecchia 2011; Vitone et al. 2013*a*, 2013*b*). It has been found that, if unfissured, the natural structure (i.e., the combination of fabric and bonding) makes the clay enter the structure permitted space as recalled by Leroueil and Vaughan (1990), so that, at the same consolidation pressure, the natural unfissured clay can be stable at higher water content than the same clay when reconstituted in the laboratory (Fig. 14). Conversely, for the natural fissured clay, fissuring is det- F14 rimental for strength, so that the fissured clay is even weaker than the same clay when reconstituted (Vitone and Cotecchia 2011).

Cotecchia and Chandler (2000) introduced the parameter $S_\sigma = \sigma'_y/\sigma^*_e$ (where σ'_y is the vertical effective stress at yield and σ^*_e is the equivalent effective stress on the ICL at the same void ratio

Fig. 14. Framework of compression behaviour of natural clay (fissured and unfissured), reconstituted clay, and treated clay (modified after Vitone and Cotecchia 2011).



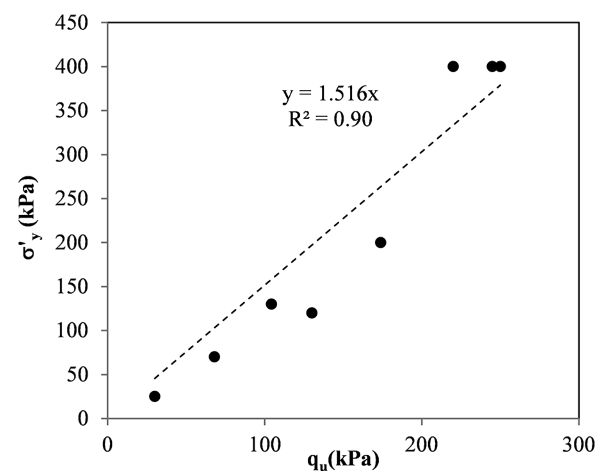
(Fig. 14), defined as stress sensitivity ratio, to quantify the influence of microstructure on the gross yield pressures. S_σ values higher than 1 were found in natural unfissured clays and attributable to the natural microstructure in comparison with that of the reconstituted, where $S_\sigma = 1$ by definition. Vitone and Cotecchia (2011) found values of $S_\sigma < 1$ for natural fissured clays. Therefore, the combination of fissuring with the clay microstructure was found to weaken the clay in comparison with the same clay when reconstituted, irrespective of the microstructural features.

The experimental results from this study show that, as expected, the compression behaviour of all the treated clay specimens here of reference appears to be always similar to that of natural unfissured clays. In particular, irrespective of the type and percentage of additive used, after 28 days of curing the normal compression line (NCL) of the treated clay is located on the right of the ICL (Figs. 8–10). This is because the pozzolanic reactions induced by the treatment bring about a *chemically induced* structure that is characterized by $S_\sigma > 1$. It can be concluded that this framework could provide insight into the behaviour and degree of structuring of chemically stabilized soils. Kang and Santagata (2006) and Bobet et al. (2011) seem to follow a similar approach when they used the intrinsic values of the untreated reconstituted soil to normalize the data of cement-treated soil.

Moreover, the results from this study show that the NCLs of the treated clay specimens are also located to the right of the normally-consolidated states of the natural clay, although in this case the NCL of the natural clay could not be clearly identified. From the above, it has to be expected that, for the treated clay, as for the natural clay, a relation exists between the magnitude of the effective stress at yield, σ'_y, and that of the unconfined compressive strength, q_u, also given their common dependency upon the percentage of additive.

F15 Despite the limited number of data, the test results in Fig. 15 confirm the linear relation between the yield stress, σ'_y (arrows in Figs. 8–10) and unconfined compressive strength, q_u, of the treated clay where the value of the gradient C is 1.52. It is worth to note that C values between 1.4 and 2.2 have been found for the cement-treated Bangkok clay (Bergado and Lorenzo 2001), Tokyo clay (Terashi et al. 1979), and Ariake clay (Horpibulsuk 2001; Horpibulsuk et al. 2004). These last authors found that for a cement-treated clay the compression index, C_c, depends only on cement content, irrespective of the water content, and that uncemented and cemented clays follow a single generalized compression line (GCL) in the e/e_{100} versus vertical effective stress, σ'_v, plot,

Fig. 15. Relation between unconfined compression strength and vertical effective stress at yield of treated clay after 28 days of curing.



where e_{100}, introduced by Burland (1990), is now the void ratio corresponding to σ'_v = 100 kPa of both the cemented and uncemented clays. Figures 16*a*–16*c* show that this approach can also be applied to the submarine sediments here of reference both untreated and treated not only with cement, but also with lime and cement–lime, after different curing times (i.e., either 28 days or 1460 days). Moreover, all the data in the normalized plot (e/e_{100})-σ'_v follow a single GCL (Fig. 17) that is described by the equation F16 F17

$$e/e_{100} = -0.385 \log\sigma'_v + 1.767 \tag{1}$$

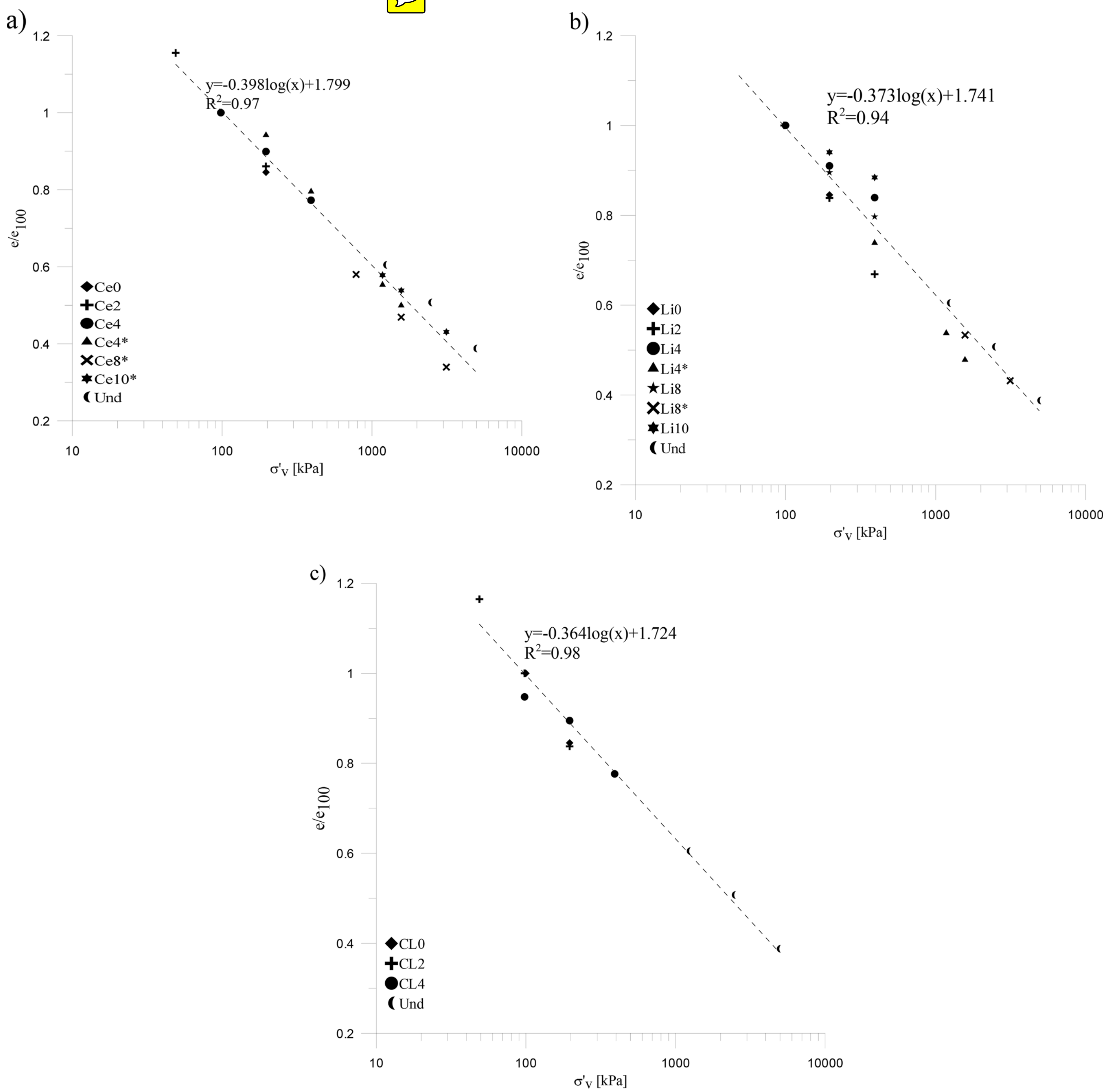
showing a very good correlation (R^2 = 0.96) for vertical effective stress values between 49 and 4900 kPa.

It is worth noting that, although this equation was derived for clays treated with different stabilizing agents and different curing times, it is only slightly different from that found by Horpibulsuk et al. (2004) for cemented clays between 10 and 3000 kPa (Fig. 17), i.e.,

$$e/e_{100} = -0.422 \log\sigma'_v + 1.848 \tag{2}$$

From the above, it seems that, if the unconfined compressive strength and the after-curing void ratio are known, the yield stress

Fig. 16. Normalized normal-compression states of the natural, reconstituted, and (*a*) cement-treated clay, (*b*) lime-treated clay, and (*c*) cement–lime treated clay.



can be derived from the relation $\sigma'_y = Cq_u$ and e_{100} can be calculated from eq. (1). This allows for drawing the NCL of the treated clay assuming that C_s values are negligible.

Similar results are also obtained when the compression data are normalized with respect to both after-curing water content, w_0, and additive content (Fig. 18). The figure shows that the product w_0A_w can combine the effects of total clay water content, additive content, and curing time on the compressibility of the treated soil. Plotted together, all the data clearly follow a single compression line. An improved fitting can be obtained if all data are normalized also with respect to the liquid limit, w_L, as shown in Fig. 19. This allows an alternative general compression line (AGCL) to be determined, irrespective of the additive used.

Through the relation in Fig. 18, a preliminary assessment of the quantity of additive to be admixed to get a fixed value of the unconfined compressive strength could be made. The value of yield stress can be calculated through the relation in Fig. 15. If it is assumed that, up to the yield stress, the soil is almost uncompressible (i.e., no pre-yield compressibility), the corresponding A_w values can be derived from Fig. 18.

Concluding remarks and future research

This paper attempts to analyse the plasticity properties and the compressibility characteristics of clayey sediments treated with lime and (or) cement.

Fig. 17. Generalized compression line for untreated clay and clay treated with lime, cement, and cement–lime mixture.

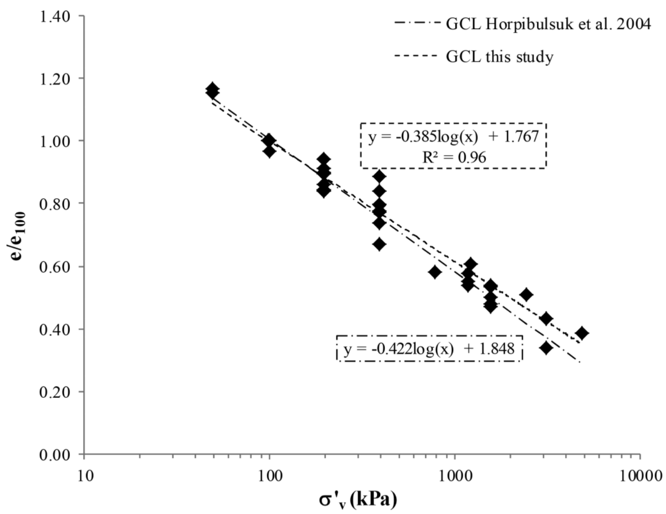


Fig. 18. Normalized compression line of treated clay (cement, lime, and cement–lime mixture).

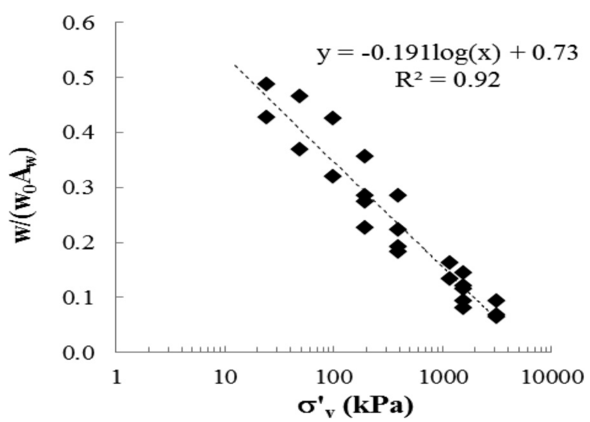
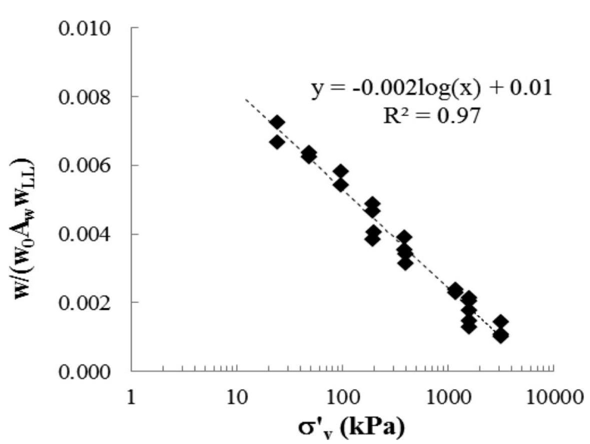


Fig. 19. Alternative general normalized compression line (AGCL) of admixed-clay (cement, lime, and cement–lime mixture).



In particular, the effects of stabilization on the plasticity of the clayey sediments dredged from the Port of Taranto (South of Italy) have been analyzed and interpreted for a rational interpretation of the plasticity modifications induced by the treatment.

With respect to the effect of the treatment on the clay plasticity properties, the following conclusions can be drawn: (*i*) irrespective of both the type and percentage of additive, clay treated for different curing times (up to about 4 years) follows aligned paths in the plasticity chart; (*ii*) all the plasticity paths (U-AX, U-BX, U-CX, U-DX) are characterized by an increase of w_p (sectors I and V–VI in the chart in Fig. 12), which implies an increment of the consistency index (CI) if, as in this case, the after-curing water content reduces; and (*iii*) 8% additive and 2 days of curing are sufficient to reduce PI and transform the soil from CH to MH according to USCS classification.

The compression behaviour of the treated clay is similar to that of natural untreated unfissured clays because, irrespective of the additive used, after 28 days of curing, the NCL of the treated clay is located to the right of the ICL of the reconstituted; the artificial structure (whatever the additive), that is the product of the pozzolanic reactions, is characterized by $S_\sigma > 1$.

Moreover, it has been found that additive content is the prime parameter governing the compression curve at the post-yield state. An AGCL is newly developed for untreated and treated clays. Moreover, new relations are provided for a preliminary assessment of the quantity of additive to be used to get a fixed value of unconfined compressive strength.

The next stage of the research is the study of the effects of cement and lime treatment on the plasticity properties of clays of different mineralogy (e.g., pure kaolinite and almost pure montmorillonite). Moreover, a laboratory testing programme aimed at studying the effect of stabilization on the clay shearing behaviour is still in progress.

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