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Prediction methods in soil-lime mixture design

Méthodes de prévision dans la conception de mélanges terrain-chaux

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ABSTRACT: Geotechnical engineering can contribute to the recycling of excavated soils via selecting ways to reuse them. The properties of fine-grained soils can be improved by adding lime as a stabilizing agent to get proper material characteristics. This technique is sustainable and widely applied in Italy and worldwide. Given the great number of factors that affect soil-lime properties, the design of soil-lime mixtures involves an extensive laboratory testing. Screening criteria to optimize this mix design procedure are therefore very useful. Quicklime or hydrated lime were added, in different proportions, to several soils with different characteristics. Determination of consistency limits, Proctor compaction and direct shear and triaxial tests were performed on lime treated soils. The modification of plasticity index and of the compaction characteristics due to lime addition were studied in order to identify useful correlations with the characteristics of soil to be treated. Results also show correlations among the shear strength parameters of soil-lime mixtures and the main variables of lime treatment. These correlations contribute to the evaluation of the opportunity of the application of lime treatement and, in several cases, to preliminary identify the lime amount for the treatment knowing the characteristics of the soil to be treated and the minimum project requirement (e.g. shear strength parameters, desired plasticity), reducing the number of lab tests to be performed in the design phase.

RÉSUMÉ: La géotechnique peut contribuer au recyclage des terrains excavés en choisissant des façons pour les remployer. Les propriétés des sols à grains fins peuvent être améliorées en ajoutant de la chaux comme agent stabilisant pour obtenir les caractéristiques appropriées des matériaux. Cette technique est soutenable et appliquée amplement en Italie et dans le monde entier. Étant donné le grand nombre de facteurs qui affectent les propriétés dusol-chaux, telles mélanges supposent des tests approfondis en laboratoire. C‘est pour cela que les critères de sélection qui permettent l‘optimisationde ce procéde de conception de mélange sont très utiles. On a ajoutée de la chaux vive ou hydratée a été, selon des proportions différentes, à plusieurs terrains avec des caractéristiques différentes.On a effecué la détermination des limites de consistance, le compactage de Proctor et les tests de cisaillement direct et triaxial ont été effectués sur des terrains traités à la chaux. Afin d'identifier des corrélations utiles avec les caractéristiques du terrain à traiter on a etudié la transformation de l'indice de plasticité et des caractéristiques de compactage à cause de l'addition de chaux. Les résultats montrent aussi des corrélations entre les paramètres de résistance au cisaillement des mélanges terrain-chaux et les variables fondamentales du traitement à la chaux. Ces corrélations contribuent à faire prendre en considération l‘opportunité d‘appliquer le traitement à la chaux et, dans plusieurs cas, à identifier au préalable la quantité de chaux à traiter, apres avair connù les caractéristiques du terrain à traiter et les exigences minimales du projet (paramètres de résistance au cisaillement, plasticité souhaitée), cela réduit le nombre de tests de laboratoire à effectuer au stade d‘elaboration.

Keywords: Soil; Lime; Compaction, Plasticity, Shear strength

1 INTRODUCTION

The reuse of excavated soil after its improvement is a possible way to reuse and recycle soil in a sustainable perspective. In recent years the soil sustainable management of materials has become a priority. Increase in reuse and consequent decrease in disposal amount of excavated soils will contribute to fulfil this priority and this is a task of the reseaarch in the field of geotechnical and geoenvironmental engineering (Katsumi et al., 2019).

The properties of fine-grained soils can be improved by stabilizing them with lime addition to get proper characteristics. The factors able to affect soil-lime properties include the type and amount of lime (Garzón et al 2016), the grain size distribution and plasticity of the soil to be treated (TRB 1987), the mixing and compaction procedures (Osinubi and Naiwu 2006, Di Sante et al 2015) and the curing time, temperature and moisture conditions (Al-Mukhtar et al 2010; Di Sante et al 2014). Given this great number of different factors, different soil-lime proportions should be tested in the laboratory design phase of soil-lime mixtures. A screening criterion with the aim of prior identification of a optimum lime content (OLC) is therefore very useful to limit the number of tests in the design phase. In fact, the search for correlations has recently become one of the main issues (e.g. Ghobadi et al 2014; Consoli et al. 2015).

Aim of the present paper is to show several possibilities of prediction of charcteristics of soil-lime mixtures taking into account the previously discussed variables, as listed in the following:

- the variation of consistency limits due to lime addition, useful to improve the workability of the soil to be treated;
- the effects of lime addition to the shape of the Proctor compaction curve that define the range of water content that allows to obtain a sufficiently high dry unitweight of the mixture;
- the obtainable shear strength parameters (cohesion, c′ and peak shear resistance angle, Φ′) of compacted soil-lime mixtures, as a function of many variables.

In section 4 also an example of possible use of the proposed prevision methods is presented.

2 MATERIALS AND TEST METHODS

2.1 Materials

The soils used for the experimental test programs are those listed in Table 1. They are natural clayey soils of high and low plasticity.

Table 1. Characteristics of tested soils (w_L=liquid limit; w_P=plastic limit; PI=Plasticity Index).

	TESTED SOIL (Abbreviations)										
	MON	**SGT**	**TOR**	**FOS**	**PVB**	**PVG**	**PIA**	**TES**	**MSC**	**FAN**	**OSI**
sand (%)	16	3	4	10	12	10	5	1	2	9	9
fine (%)	84	97	93	90	88	90	95	99	97	90	90
clay (<2μm,%)	44	39	34	32	47	38	25	56	54	42	42
w_L (%)	62	40	49	42	55	50	52	63	57	50	50
w_P (%)	30	20	27	24	24	22	30	26	24	23	23
PI (%)	32	20	22	18	31	28	22	37	33	27	27
Activity (-)	0,73	0,51	0,65	0,56	0,66	0,74	0,88	0,66	0,61	0,64	0,64
USCS	CH	CL	CL	CL	CH	CH	CL	CH	CH	CH	CH
HL ICL* (%)	4	2	2.7	5	7	7	7	1.7	2.5	-	-
QL ICL* (%)	2	2	1.5	-	-	-	-	-	1.5	-	1

* ICL = Initial Consumption of lime ASTM C977-83

Also two artificial bentonites (sodium bentonite and calcium bentonite) are used for the study of the effects of lime on plasticity.

The lime used in the research is a fine calcic hydrated lime, classified as CL80-S (UNI EN 459-1) and a fine calcic quicklime classified as CL80-Q (UNI EN 459-01), completely passing through the ASTM 200 sieve (75 μm opening).

2.2 Test methods

The quantity of lime added is 5% by dry mass of soil for the consistency limits and for the compaction characteristics while different percentages are used to study the shear resistance. Lime and soil were mixed in wet state (tap water) with exception of the mixture for consistency limits obtained by dry mixing of soil and lime, followed by wetting with distilled water. Consistency limits (ASTM D4318-10) were performed after 24 hours since lime addidtion.

Compaction was carried out with Standard Proctor energy (ASTM D698-12).

Consolidated drained (ASTM D7181-11) or undrained (ASTM 4767-11) triaxial compression tests (TX) and direct shear tests (DS - ASTM D3080-98) were performed at different curing times on the specimens compacted at different water contents to obtain the Mohr-Coulomb peak failure envelopes in drained conditions, since high values of permeability are typical for lime treated soils compacted near optimum water content (e.g. Goswami & Mahanta, 2007). Anyway a low horizontal displacement rate was applied to ensure drained conditions during the direct shear tests.

3 EXPERIMENTAL RESULTS

3.1 *Lime modification: plasticity of soil-lime mixtures*

If lime modification is desired, a prediction of the extent of the reduction of the plasticity index, PI, after lime addition is useful. Lime modification is the development of short term reactions only, with the improvement in soil workability and the reduction of water affinity. PI is given by the difference between the liquid, w_L, and the plastic limit, w_P. With lime addition, value of w_P usually increases, while w_L does not always decrease. In some cases, this can compromise the reduction of the plasticity index (value in red in Table 2) and we observed that this occurrance is linked to the absence (or the presence in small amount) of the swelling minerals (Di Sante, 2016). Given the fact that the X-Ray diffraction is not a quick test to be performed, this observation can‘t be an easy to use prediction method.

Anyway, the reduction of plasticity index is one of the available criteria used for the determination of the OLC; the Oklahoma procedure is based on plasticity reduction and Rogers et al. (1996) extensively studied variation of consistency limits due to lime addition. Therefore we searched for correlation between plasticity reduction and characteristics of the untreated soil easy to determine.

Consistency limits, determined before and after 5% lime addition, are listed in Table 2 for natural soils and bentonites. Also data retrieved from literature are displayed in Table 2 in grey background.

Table 2. Variation of consistency limits before and after 5% lime addition – Experimental results and literature data (grey background).

		Soil			**Soil+5%lime**		
Source		**w_L** (%)	**w_P** (%)	**I_p** (%)	**w_L** (%)	**w_P** (%)	**I_p** (%)
Experimental determinations (natural soils)	**MON**	62	30	32	**55**	33	22
	TOR	49	27	22	**44**	31	13
	FOS	42	24	18	**41**	30	11
	PVB	55	24	31	57	35	22
	PVG	50	22	28	56	37	19
	PIA	52	30	22	57	31	26
	TES	63	26	37	61	36	25
	SGT	40	20	20	46	31	15
Experimental determinations (bentonites)	**Sodium B.**	320	60	260	**273**	77	196
	Calcium B.	160	56	104	**155**	63	92
Bell,1996	Upper boulder clay	30	14	16	40	22	18
	Tees laminated clay	58	26	32	**52**	33	19
	Kaolinite	72	41	31	98	42	56
	Montmorillonite	100	62	38	**83**	69	14
	Quartz	52	38	14	71	45	26
De Brito Galvao et al.,2004	Tropical Soil 1	35	21	14	38	24	14
	Tropical Soil 2	58	30	28	**53**	31	22
Guney et al.,2007	**70% Bent+30% Kao**	385	35	350	**290**	53	237
	30% Bent+70% Kao	168	28	140	**147**	42	105
	Turkmen clay	115	45	70	**103**	50	53
Thompson,1967	AASHO road test	25	14	11	27	22	5

In order to have an estimation of the plasticity reduction, we searched for correlations between the ΔPI = [PI before lime addition – PI after lime addition] and: the clay fraction, CF, the PI , the w_L and the soil activity, A of the untreated soil. We found the best correlation coefficient

($R^2 = 0.89$) with this last soil characteristic (see Figure 1). Activity combines the consistency with the grain-size characteristics of the soil, the good linear trend confirms the need of both these requirements for a successful lime treatment, at least for what concerns the short term improvement in workability.

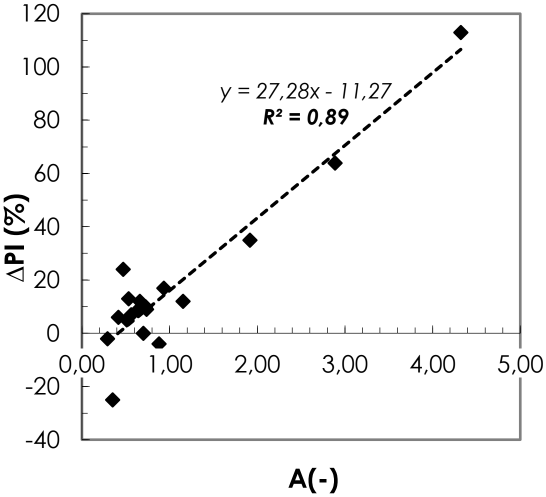

Figure 1. Relations between the soil activity of untreated soils and the PI reduction of soils treated with 5% HL.

For two of the soils in Table 1 (SGT and TES) consistency limits were determined also after the addition of 3,7 and 10% of HL. Results are shown in Figure 2.

In the case of the clayey soil of low plasticity (SGT) PI reduces from 20% to 15% after addition of 3% of lime, no further PI reduction can be obtained adding a greater amount of binder; in this case the liquid limit increased after the addition of lime. For the clayey soil of high plasticity (TES) PI reduces (from 37% to 25%) the higher the binder amount until 5% lime and then holds steady; in this case, the reduction of the liquid limit contributed to reduce the soil plasticity.

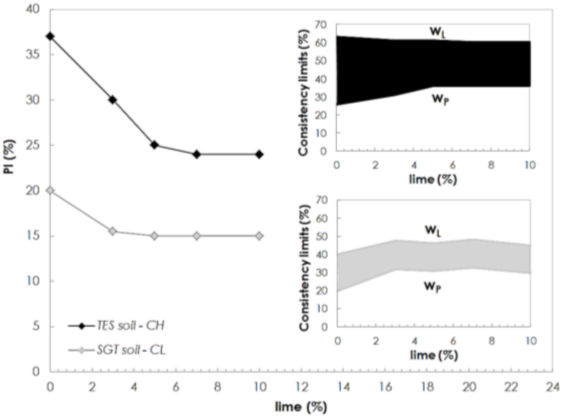

Figure 2. Variation of consistency limits and plasticity indexes for SGt soil and TES soil treated with different lime amounts.

3.2 Compaction characteristics

Lime induces modification of the Proctor compaction curve and therefore of the relative compaction characteristics (i.e. optimum water content, w_{opt}, and maximum dry unit weight, $\gamma_{d,max}$). In particular, a lower value of $\gamma_{d,max}$ is registered, if compared with that of the untreated compacted soil and a different, often higher, value of w_{opt} (e.g. TRB, 1987).

Another modification of the curve include its flattening. and this is probably the most interesting modification because the flattening allows to reach high values of $\gamma_{d,max}$ with a broader range of water contents. This is a clear advantage for the practice because the dry unit weight is the parameter used for field controls and in most technical specifications it should be higher than the 90-95% of the value of $\gamma_{d,max}$ determined in laboratory for lime treated samples.

In Figure 3 compaction curves for 4 untreated soils (characteristics in Table 1) and for the same soils compacted with 5% of hydrated lime are depicted.

A lower value of $\gamma_{d,max}$ due to lime addition $_{max}$ is obtained for each of the tested soils and w_{opt} is always equal or greater than the one of the untreated soil.

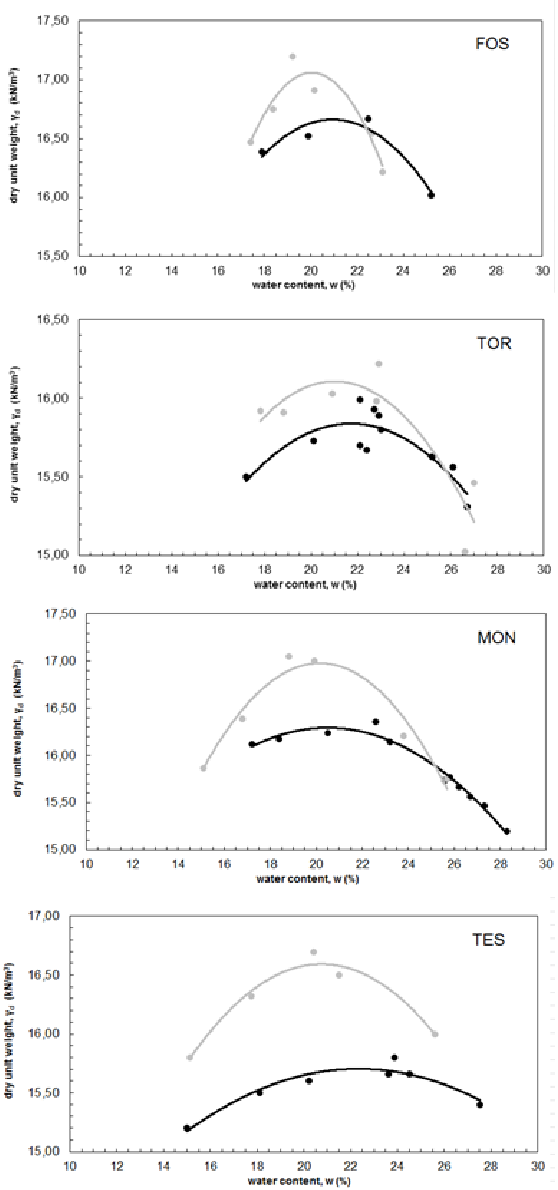

Figure 3. Proctor compaction curves for untreated soils (in grey) and for soils compacted with 5% of hydrated lime (in black) for each graph the abbreviation of the tested soil is reported at the top left.

In order to quatify the flattening, the difference between the optimum water content of the curve corresponding to the treated soil ($w_{opt,SL}$) and the minimum water content corresponding to 97% of the maximum dry density of the same curve ($w_{97\%\ \gamma dmax\ DRY}$) is calculated; this value represents half of the range of water contents that allows to have the 97% of the $\gamma_{d,max}$. In fact, the flatter the curve becomes, this difference (whose abbreviation is FLAT in Figure 4) is greater.

Also in this case we examined the possible correspondence of the FLAT value with characteristics of the untreated soil in order to have a preliminary indication of the entity of the reduction of water affinity due to the presence of lime.

A good correlation was found between the FLAT value of curves obtained after 5% HL treatment and the clay fraction of the untreated soil (Figure 4, R^2=0.97).

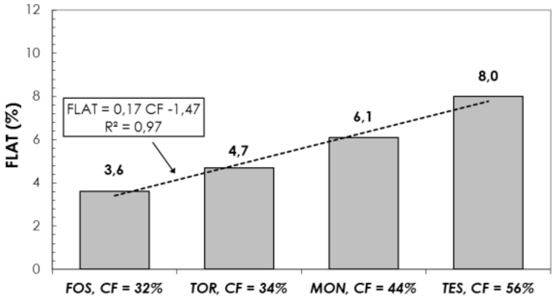

Figure 4. Soils treated with 5% HL: relations between the clay fractions of untreated soils and the FLAT value

MON soil was also treated with the same amount (5%) of quicklime (Figure 5).

In this case, lower value of $\gamma_{d,max}$ is obtained if compared with HL treatment but the FLAT value is similar to the one calculated for the HL treatment. For this soil, the type of lime seems to influence the γ_d only.

A preliminary estimation of the in-situ acceptable range of water content for 5%HL treatement can be obtained knowing the CF of the untreated soil and applying the correlation equation shown in Figure 4. This can be a possible way to evaluate the opportunity to apply a lime treatment to a soil prior to start the experimental work, especially when work has to be carried out in the fall-winter season, during which heavier rainfall can be expected.

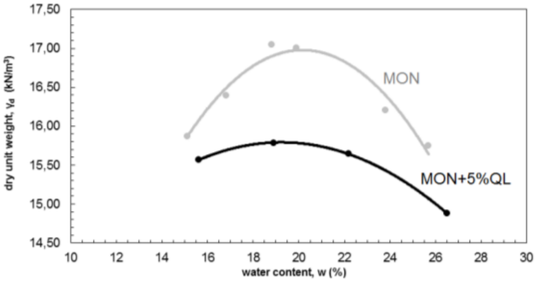

Figure 5. Proctor compaction curves for untreated soils (in grey) and for soils compacted with 5% of quickime (in black) for MON soil.

3.3 *Lime stabilization: shear strength*

Soil-lime systems in which pozzolanic reactions (i.e. long term reactions) developed are named "lime stabilized soil". These reactions improve strength, compressibility and durability of the soil to be treated. Shear strength is the focus for both slope stabilization application and embankment construction (e.g. road embankment, river banks or dams). Correlations between shear strength parameters and the main variables of lime treatment were derived by multiple regression analysis from a database of 35 triaxial compression or direct shear tests on seven of the soils listed in Table 1, treated with different amounts of quicklime (QL) or hydrated lime (HL). Tests were carried out at different curing times on soil-lime samples compacted at different water contents (details in Di Sante et al, 2019 and Fratalocchi et al., 2019, in press). The database was split in QL and HL. The selected independent variables are: (1) the relative moisture content, Δw, defined as the difference between the water content of the specimens and the optimum water content (standard Proctor compaction) of the relevant mixture; (2) lime amount, L, expressed by percentage (by dry weight) of soil; (3) curing time of the mixture, T; (4) clay fraction, CF, and (5) plasticity index, PI, of the untreated soil. Each of the variables was selected for the role espressely played in lime treatment.

The statistical significance of the correlations (Table 3) was verified by Fisher's exact test.

Table 3. List of derived correlations.

QL Treatment	**Eq**	**Predictors**
$c'(kPa)=2.9\cdot CF(\%)-4.5\cdot PI(\%)+15.8\cdot L(\%)-2.4\cdot \Delta w(\%)+0.6\cdot T(days)$	(1)	All
$c'(kPa)=0.5\cdot CF(\%)+17.2\cdot L(\%)-2.7\cdot \Delta w(\%)$	(2)	BackWE
$c'_{safe}(kPa)=0.5\cdot CF(\%)+17.2\cdot L(\%)-2.7\cdot \Delta w(\%)-15$	(3)	Safe
$\Phi'(°)=0.3\cdot CF(\%)+0.2\cdot PI(\%)+5.1\cdot L(\%)+0.6\cdot \Delta w(\%)+0.2\cdot T(days)$	(4)	All
$\Phi'(°)=0.4\cdot CF(\%)+5.4\cdot L(\%)+0.23\cdot T(days)$	(5)	BackWE
$\Phi'_{safe}(°)=0.4\cdot CF(\%)+5.4\cdot L(\%)+0.23\cdot T(days)-5$	(6)	Safe
HL Treatment	**Eq**	**Predictors**
$c'(kPa)=1.3\cdot CF(\%)+1.65\cdot PI(\%)+7.8\cdot L(\%)-3.7\cdot \Delta w(\%)+0.3\cdot T(days)$	(7)	All
$c'(kPa)=0.3\cdot CF(\%)+7.5\cdot L(\%)$	(8)	BackWE
$c'_{safe}(kPa)=0.3\cdot CF(\%)+7.5\cdot L(\%)-15$	(9)	Safe
$\Phi'(°)=1.51\cdot CF(\%)-1.7\cdot PI(\%)+3.9\cdot L(\%)-2.2\cdot \Delta w(\%)+0.2\cdot T(days)$	(10)	All
$\Phi'(°)=0.5\cdot CF(\%)+3.8\cdot L(\%)$	(11)	BackWE
$\Phi'_{safe}(°)=0.5\cdot CF(\%)+3.8\cdot L(\%)-5$	(12)	Safe

After fitting the model with all the predictors ("All"), a procedure of backward elimination was applied to reduce the number of predictors ("BackWE"). To safely estimate the values of shear strength parameters, a fixed value was subtracted to the estimated one ("Safe").

The correlations were validated by data from literature, comparing the predictions with the published results (Di Sante et al, 2019 and Fratalocchi et al., 2019, in press).

4 EXAMPLE OF POSSIBLE USE OF THE PROPOSED CORRELATIONS

The correlations were applied to a case study concerning two types of soil from a site in which a landfill will be constructed along a slope and a service road had to be built. The in-situ subsoil comprises of two stratigraphic units: a clayey silt named “A” (CF = 34%; PI = 27%), 5 m thick in the upper part of the slope, and a silty clay (deep unit) named “B” (CF = 38%; PI = 21%). Since both stratigraphic units will be excavated to locate the waste body, the lime treatment of both soils was considered to construct the service road.

Both soils resulted to be suitable for lime treatment (UNI EN 14227-11:2006) and the proposed prevision methods were applied to have a preliminary idea of the type and the amount of lime for the treatment, to be confirmed by the laboratory study and by a test pad.

By using the correlation for the plasticity reduction, it turns out that 5%HL wolud have allowed to reduce the PI of 10%for the soil A and of 4% for the soil B.

With the same type and amount of lime the value of the FLAT parameters were calculated:

- for soil A: FLAT = 4%, allowing a minimum acceptable range of water content of 8% straddling the w_{opt},
- for soil B: FLAT = 5%, allowing a minimum acceptable range of water content of 10% straddling the w_{opt}.

Shear strength parameters obtained with the proposed correlations were depicted in Figure 6. With 5%HL, values of c’ higher than 30kPa and values of Φ’ higher than 30° were calculated with the “safe” correlation for both soils.

Given that the site is located quite away from residential areas, the possibility of quicklime treatment is also envised, therefore we applied the correlation for 5%QL too, cautionary considering 7 days of curing and a compaction at 4% wet of optimum (limit suggested by FLAT parameter). Given the very high shear strength parameters attained with 5%QL (Figure 6) we decided to try to lower the quicklime amount, obtaining the prevision of peak shear envelopes shown in grey ink in Figure 6, almost overlapping the 5%HL line (continuous black line in Figure 6).

Given: (1) the shear strength prevision obtained with 3% QL, (2) the fact that quicklime is far more reactive than hydrated lime (i.e. given the good results of plasticity reduction and compaction characteristics obtained for 5%HL, in all likelyhood, they will be further improved using QL) and (3) the determined ICL value (=1.5%QL for soil “A” and 2%QL for soil “B”), it was worth fixing 3%QL (>ICL) as the percentage for the subsequent laboratory experimental program.

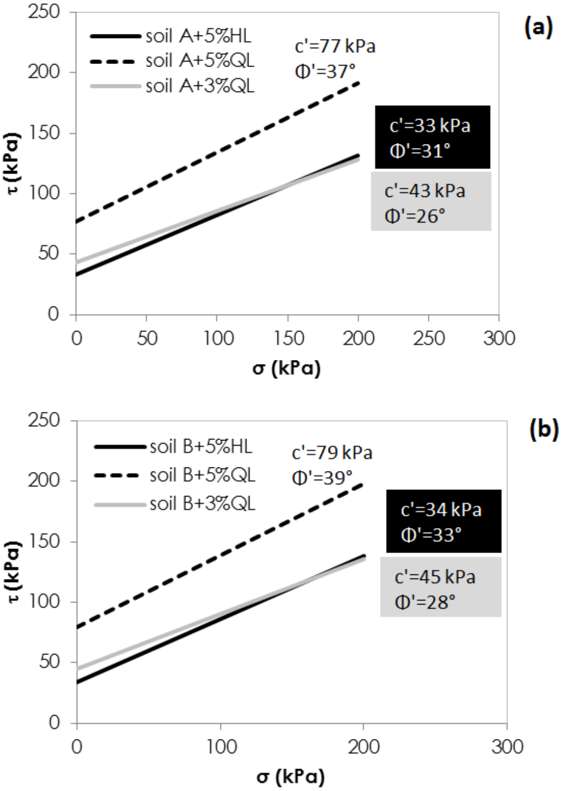

Figure 6. Peack shera strength envelopesdetermined with the “safe“ correlations (see Table 3) for (a) soil A and (b) soil B.

The good characteristics expected for the mixtures as suggested by the application of the prevision methods, were confirmed by experimental results (details in Di Sante et al., 2017).

5 CONCLUSIONS

The present paper presents several possibilities of prediction of charcteristics of soil-lime mixtures taking into account the main variables affecting the outcomes of lime treatment.

In particular, good correlations were obtained between the activity of the soil to be treated and the reduction of the plasticity index due to the addition of 5% of hydrated lime. A prevision of the flattening of the compaction curve due to the addition of the same lime amount was found to be related to the clay fraction of untreated soils. Shear strength parameters of soil lime mixtures can also be predicted by means of the presented (and verified) correlations.

The described case study demonstrates how a preliminary identification of the optimum lime amount is possible, knowing the physical characteristics of the soil to be treated and the project requirements. In this way, the laboratory experimental program can be optimized reducing the number of tests to be performed.

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