Prediction of shear strengths parameters and its application in soil-lime mixture design

Prévision des paramètres de résistance au cisaillement et son application dans le projet des mélanges terre-chaux

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ABSTRACT: The paper presents useful correlations between the shear strength parameters of compacted soil-lime mixtures and the main variables of lime treatment: moisture content, lime amount, curing time, clay fraction and plasticity index of the untreated soil. A case study addressing the reliability of this prediction is shown. The correlations were derived by multiple regression analysis from a database of 35 triaxial compression or direct shear tests on seven soils treated with different amounts of quicklime or hydrated lime. Tests were carried out at different curing times on soil-lime samples compacted at different water contents. The obtained correlations allow to assess the feasibility of the lime treatment and to preliminarily identify the optimum lime type and amount on the basis of the characteristics of the soil to be treated and the required shear strength parameters. The case study concerns the design of embankments for service roads of a landfill constructed along a slope. It shows that the correlations can be a key strategy to select the proper construction method and that they allow reducing the number of laboratory tests to be performed in the design phase.

1 INTRODUCTION

A way to contribute to the target of recycling rate posed at 70% by the European Union directive 2008/98/CE within the year 2020 is the reuse of excavated soil after its improvement.

The mechanical properties of fine-grained soils can be improved by adding lime as a stabilizing agent to get proper characteristics. The factors that can 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 the great number of variables, the laboratory design phase includes different soil-lime proportions to be tested. In this regard, it is very useful to identify a screening criterion, which allows optimizing the mix-design procedure. To this purpose, the search for correlations has become one of the main issues (e.g. Mooney and Toohey 2010; Ghobadi et al 2014; Consoli et al. 2015).

Aims of the present note are: (1) to present useful correlations between the shear strength parameters (cohesion, c′ and peak shear resistance angle, Φ′) of compacted soil-lime mixtures and the main variables of lime treatment and (2) to assess the reliability of this prediction by showing a case study.

2 CORRELATIONS, METHODS AND RESULTS

The correlations were derived by multiple regression analysis from a database of 35 triaxial compression or direct shear tests on seven soils (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, 2017 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 variable plays a significant role in lime treatment.

The statistical significance of the correlations (Table 2) was verified by Fisher's exact test. 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.

Table 1. Main characteristics of the soils tested.

characteristics	TESTED SOILS (Abbreviations)						
	MON	TOR	SGT	MSC	OSI	FAN	TES
sand (%)	16	4	3	2	7	9	1
fine (%)	84	93	97	97	92	90	99
clay (<2μm,%)	44	34	39	54	48	42	56
Liquid limit (%)	62	49	40	57	53	50	63
Plasticity index (%)	32	22	20	33	27	27	37
Soil Activity (-)	0.73	0.65	0.51	0.61	0.56	0.64	0.66
USCS classification	CH	CL	CL	CH	CH	CH	CH
$Ca(OH)_2$ ICL* (%)	4	2.7	2	2.5	-	-	1.7
CaO ICL* (%)	2	1.5	2	1.5	1	-	-

* ICL = Initial Consumption of lime (ASTM C977-83)

Table 2. List of derived correlations.

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

3 USE OF THE CORRELATIONS

The correlations were applied to a case study concerning a berm of lime-stabilized soil and the predictions were compared with results of experimental tests carried out in the laboratory on soil-lime specimens.

3 .1 *Site and project description*

The soil-lime berm will be located next to a service road that will enclose, in the uphill part, a controlled landfill to be built along a slope (Fig. 1). The subsoil (Fig. 1) 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 units will be excavated to locate the waste, the use of both soils has been evaluated to construct the berm.

Both soils resulted to be suitable for lime treatment (UNI EN 14227-11:2006). The berm internal stability requires high shear strength parameters as its maximum slope reaches 60°.

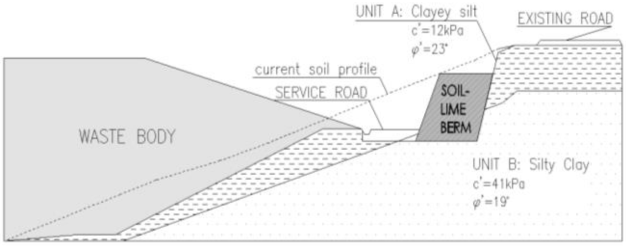

Figure 1. Cross sectional view with maximum slope.

3 .2 *Internal stability*

Before starting the laboratory design phase, a prevision was carried out by means of the "safe" correlations (Table 2). In particular, 3% QL was supposed for the treatment. A cautionary value of curing time of 7 days and a compaction at 6% wet of optimum were considered. The correlations were applied to the soil "A" (given its lower CF) resulting in c′ = 37 kPa and Φ′ = 26°. The ultimate limit state of internal stability was verified using the A2+M2+R2 combination of actions, soil parameters and resistances, as per Italian Regulations. Therefore, the minimum safety factor, SF was 1.1. The analysis was carried out using the Morgenstern-Price method of limit equilibrium. The code used for the analysis allows evaluating the internal stability of the berm. The minimum SF resulted = 2.01, confirming the feasibility of the 3% QL treatment.

3 .3 *Design phase*

A laboratory study was conducted on soil treated with 3% of QL, compacted by the Standard Proctor procedure and tested for shear strength parameters. The optimum water contents were 22% and 19% for the soil "A" and "B", respectively. Direct shear and triaxial compression tests were carried out at different water contents and curing times. Fig. 3 shows the resulted cohesion and shear resistance angle compared with the predicted values (by eq. 3 and eq. 6 of Table 2).

The shear resistance angles are better predicted than cohesion values. In particular, 3 experimental values of c' out of 12 are significantly higher than the predicted values, while all the predicted Φ' values are conservative. Given this evidence, we repeated the stability analysis assigning to the soil-lime berm the couple of parameters obtained for the specimen marked by the grey arrow in Fig.2 (i.e. the lowest c'=10kPa and Φ'=42°). The analysis was carried out with the same criteria of the previous one (§3.2) and the obtained SF was 1.29, therefore acceptable.

For completeness, global stability was also evaluated, using the parameters in Fig.1 for the units A and B, both in static and dynamic conditions (pseudo-static determination of seismic actions), resulting in SF=1.33 and SF=1.27, respectively. The related failure surfaces are shown in Fig. 3.

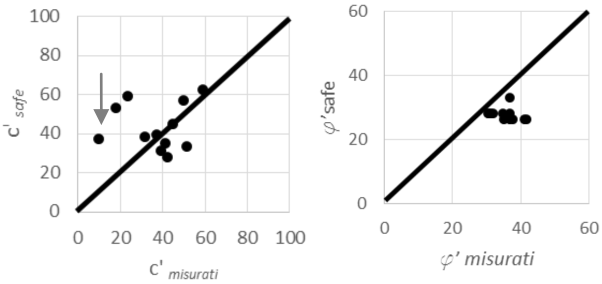

Figure 2. Quicklime treatment: calculated versus measured values of shear strength parameters.

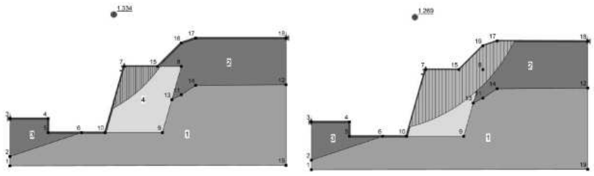

Figure 3. Critical slip surfaces in static and seismic conditions.

CONCLUSIONS

The prevision by the "Safe" correlations resulted to be fully conservative for shear reistance angles and suggested cautionary values of cohesion in 50% of cases. However, results of stability analyses demonstrates that despite the overestimation of c′ given by the correlation stability is ensured.

Thanks to the proposed correlations, the optimum lime amount can be preliminarily identified knowing the physical characteristics of the soil to be treated and the construction geometry. The approach allowed reducing the number of laboratory tests to be performed in the design phase.

4 REFERENCES

Al-Mukhtar M., Lasledj A., Alcover J.F. 2010. Behaviour and mineralogy changes in lime treated expansive soil at 50°C. *Appl. Clay Sci.*50, 199-203.

Consoli N.C., Da Silva Lopes L. jr, Consoli B.S., Festugato L., Di Sante M., Fratalocchi E., Mazzieri F. 2015. Discussion "Mohr-Coulomb failure envelopes of lime treated soils", *Géotechnique* 65, 866-868.

Di Sante M., Fratalocchi E., Mazzieri F., Brianzoni V. 2015. Influence of delayed compaction on the compressibility and hydraulic conductivity of soil-lime mixtures. *Eng. Geol.* 185, 131-138.

Garzón E., Cano M., O'Kelly B.C., Sánchez-Soto P.J. 2016. Effect of lime on stabilization of phyllite clays. *Appl. Clay Sci* 123, 329-334.

Ghobadi M.H., Abdilor Y. Babazadeh R. 2014. Stabilization of clay soils using lime and effect of pH variations on shear strength parameters. *Bull. Eng. Geol.Env.* 73, 611-619.

Mooney M.A. and Toohey N.M. 2010. *Accelerated curing and strength-modulus correlation for lime-stabilized soils*. Report n. CDOT-2010-1, Colorado Department of Transportation DTD.

Osinubi K.J. and Naiwu M. 2006. Compaction delay effects on properties of lime-treated soil. *J. Mat. in Civil Eng.*, 18(2), 250-258

Transportation Research Board 1987. *State of the art report 5: Lime stabilization*. Washington.

Di Sante M., Fratalocchi E., Mazzieri F., Pasqualini E. 2014. Time of reaction in a lime treated clayey soil and influence of curing conditions on its microstructure and behaviour. *Appl. Clay Sci*. 99, 100-109.