Prediction of the unconfined compressive strength in soft soil chemically stabilized

Prévision de la résistance à la compression non confinée dans sols mous chimiquement stabilisés

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ABSTRACT: The chemical stabilization of soils is a ground improvement technique consisting on the mechanical mixing of the in situ natural soil with binders. The chemical stabilization of soils can be applied with either slurries (wet method) or powder (dry method) binders. When the stabilizing binders are mixed with the soil, physico-chemical interactions take place and are responsible for the stabilization effect, which has a major influence on the mechanical behaviour of the improved material. This stabilizing effect is dependent on a range of parameters which should be analysed through a long and extensive laboratory and field trial test program, as stated in the european standard (EN 14679:2005). In order to minimize the number of tests during the optimization process, this paper presents a simple method to predict the unconfined compressive strength, which is independent of the binder content and state (powder or slurry). The method is successfully applied to a wide range of soils, showing its versatility (Correia, 2011). Applying the generalised relationship of the method, it is possible to predict the unconfined compressive strength for any binder content and state from one single unconfined compression test.

RÉSUMÉ : La stabilisation chimique de sols est une technique de l'amélioration des sols qui consiste en le mélange mécanique dans situ du sol naturel avec liants. La stabilisation chimique de sols peut être appliquée avec coulis (méthode mouillée) ou poudre (méthode sec) liants. Quand les liants stabilisateurs sont mélangés avec le sol, ils produisent interactions physique-chimique lesquels sont responsables pour l'effet de la stabilisation, qui a une influence majeure sur le comportement mécanique du matériel améliorée. Cet effet stabilisateur est dépendant d'une gamme de paramètres qui devraient être analysés à travers d'un long et étendu programme d'essais en laboratoire et sur terrain, comme énoncé dans la norme européenne (EN 14679:2005). Pour minimiser le nombre d'essais pendant le processus de l'optimisation, cet article présent une méthode simple de prédire la résistance à la compression simple, qui est indépendant du contenu de liant et état (poudre ou coulis). Le méthode est appliquée avec succès à une grande gamme de sols, montrant sa versatilité (Correia, 2011). Appliquant la version généralisée du méthode, c'est possible prédire la résistance à la compression simple pour tout contenu de liant et état basé d'une seule essais à la compression simple.

KEYWORDS: chemical stabilization, unconfined compression test, soft soils, strength prediction.

1 INTRODUCTION.

Over the last few decades, infrastructure requirements and land occupation policies have demanded construction on soils with poor geotechnical properties (in particular, soft soils). These soils are usually characterized by low strength and high compressibility, demanding from geotechnical engineers new and challenging solutions to overcome these undesirable engineering characteristics. One of the ground improvement techniques that have been used with success in practice is the chemical stabilization, where the natural soil is mechanically mixed in situ with binders (usually called Mass Stabilization, or, Deep Mixing when applied in depth). This technique has given good results when applied to soft soils, becoming a prominent subject nowadays, rapidly growing and wide spreading around the world due to its technical and economical benefits when compared with other ground improvement techniques.

At first the chemical stabilization of soils used the quicklime as the hardening agent. Later on, the use of Portland cement has permanently been outpacing the use of quicklime, not only because Portland cement is readily available at reasonable cost but also because cement is more effective than quicklime (Horpibulsuk et al 2011, Åhnberg 2006, Lorenzo and Bergado 2004, Kitazume and Terashi 2002). However, additives such as granulated blast furnace slag, fly ash, gypsum and silica dust, among others, may be used specially for the improvement of soft soils with high water content or organic soils (Kitazume and Terashi 2002, Edil and Staab 2005).

The chemical stabilization of soils can be applied with either slurries (wet method) or powder (dry method) binders. When the stabilizing binders are mixed with the soil, physico-chemical interactions take place and are responsible for the stabilization effect, which has a major influence on the mechanical behaviour of the improved material. This stabilizing effect is dependent on a range of parameters which should be analysed through a laboratory and field trial test program, as stated in the european standard (EN 14679:2005).

The fundamental mechanical properties of cement based admixed soft soils have been experimentally investigated by many researchers (Correia 2011, Åhnberg 2006, Hernandez-Martinez 2006, Lorenzo and Bergado 2006 and 2004, Horpibulsuk et al 2004, Kamruzzaman 2002, Horpibulsuk 2001, Miura et al 2001, Uddin et al 1997, Locat et al 1996). Most of these previous investigations mainly focus on the influence of the water content and binder content, as well as on the ratio between them. Based on some of these parameters, Horpibulsuk et al (2003 and 2011) and Lorenzo and Bergado (2006) have introduced phenomenological models for predicting laboratory strength development in cement based stabilized soft soils. This paper presents a new simple model which aims to predict the laboratory strength (expressed by the unconfined compression test) for various combinations of water content and cement content. This model intents to minimize the number of laboratory tests needed to specify the quantity of cement and water to be admixed with the soft soil. Although the model is developed for a particular soft soil, its versatility is demonstrated for a wide range of soils. A generalized strength equation is presented, which allows the strength prediction based, at lower limit, on a single unconfined compression test.

2 EXPERIMENTAL TESTS

2.1 *Materials*

Table 1 presents the geotechnical and chemical properties of the soft soil deposit of "Baixo Mondego" (located near Coimbra city, Portugal), used in the study. In general, the soil is predominantly clayey-silt with a high organic matter content, which has a strong influence on some characteristics of the soil, namely, low unit weight, high plasticity, high natural water content, high void ratio, low undrained shear strength and high compressibility although this fact is not consistent with the grain size distribution, particularly due to the low clay content, (Coelho 2000, Venda Oliveira et al. 2010).

Table 1. Principal properties of the soft soil of "Baixo Mondego".

Natural water content, w_{nat} (%)	80
Unit weight, γ_{sat} (kN/m^3)	14.6
Natural void ratio, e_{nat} (-)	2.1
Clay fraction (%)	8-12
Silt fraction (%)	71
Sand fraction (%)	17-21
Density, G (-)	2.55
Organic matter content, OM (%)	9.3
Liquid limit, w_L (%)	71
Plastic limit, w_P (%)	43
Undrained shear strength, c_u (kPa)	< 25
CaO (%)	0.74
SiO_2 (%)	62
Al_2O_3 (%)	16
Fe_2O_3 (%)	4.8
MgO (%)	1.1
pH (-)	3.5

The binders used in the present study to produce stabilized "Baixo Mondego" soft soil samples were a Type I Portland cement, designated CEM I 42.5 R (EN 197-1 2000), and a blast furnace granulated slag, here simply designated as SLAG. These two binders, on a dry weight proportion of 75/25 as proposed by Correia (2011), were thoroughly mixed to obtain a uniform binder. The binder added to the soil was defined by the parameter binder content, a_w (ratio of the dry weight of binder used in the mixture to the dry weight of the soil). The composition and the specific surface of the binders are presented in Table 2.

Table 2. Composition and specific surface of the binders.

	CEM I 42.5R	SLAG
CaO (%)	63.02	37.02
SiO_2 (%)	19.70	38.74
Al_2O_3 (%)	5.23	11.59
Fe_2O_3 (%)	2.99	0.85
MgO (%)	2.38	6.75
Specific surface, S (m^2/kg)	321.5	363.0

2.2 *Chemical stabilization of the soft soil of "Baixo Mondego"*

In order to evaluate the influence of the water content and binder content on the chemical stabilization of the soft soil of "Baixo Mondego", several samples were prepare for various water contents (equivalent to a liquidity index I_L of 1.35, 1.96 and 2.49) and binder contents (from 9 to 27, step 3). The laboratorial procedure to produce stabilized samples followed the laboratory procedure presented in EuroSoilStab (2001) with the modifications proposed by Correia (2011). During the curing time, fixed as 28 days, all samples were subjected to a vertical pressure of 24 kPa and stayed submerged in a water tank at a controlled temperature (20±2ºC). After this period, the samples were submitted to the unconfined compression test in order to evaluate its strength ($q_{u\,max}$).

Tabel 3 and Figure 1 summarizes the main results of the chemical stabilization of the soft soil of "Baixo Mondego". The results show that, as expected, the unconfined compressive strength increases with the binder content and with the decreasing of the water content (or liquidity index). As the binder content increases, more binder is admixed with the soil allowing the construction of a stronger skeleton matrix. As the water content increases the void ratio also increases, promoting the particles' spacing with obvious reflects on the fabric of the stabilized soil and on its strength.

Table 3. Unconfined compressive strength results of the chemical stabilization of the soft soil of "Baixo Mondego".

I_L (-)	a_w (%)	$q_{u\,max}$ (kPa)
1.35	9	209
	12	644
	15	1143
	18	1618
	21	1831
	24	1936
	27	1995
1.96	9	118
	15	694
	21	1266
	27	1383
2.49	9	90
	15	552
	21	965
	27	1032

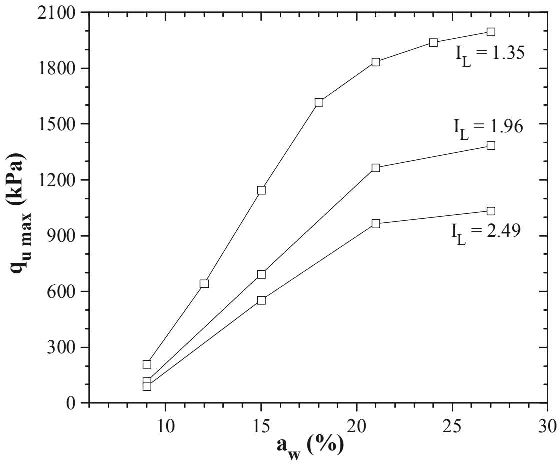


Figure 1. Unconfined compressive strength results of the chemical stabilization of the soft soil of "Baixo Mondego".

From Figure 1 it can be seen that the curves for different liquidity index exhibit a similar shape (are homothetic). Thus the unconfined compressive strength ($q_{u\,max}$) can be normalised by the liquidity index (I_L) multiplying both parameters ($q_{IL} = q_{u\,max} \times I_L$). Figure 2 presents these results which are well fitted by a linear logarithmical regression. This is a simple way to predict the unconfined compressive strength at 28 days of curing time for the cement based stabilized softy soil in study. As it is a linear regression it only requires two test data made for different binder contents.

In order to validate this simple method, it will be applied to other soft soils as presented in the next section.

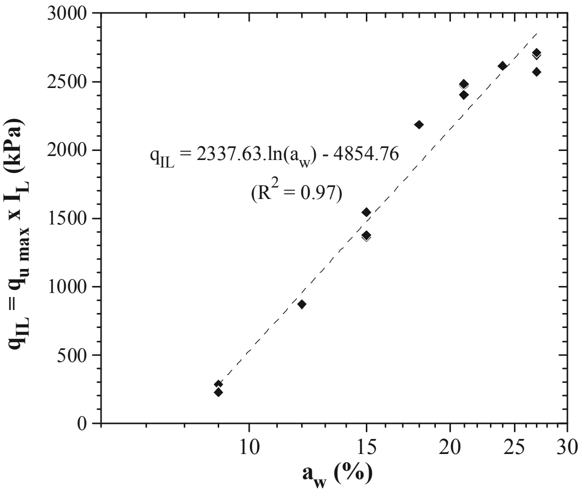


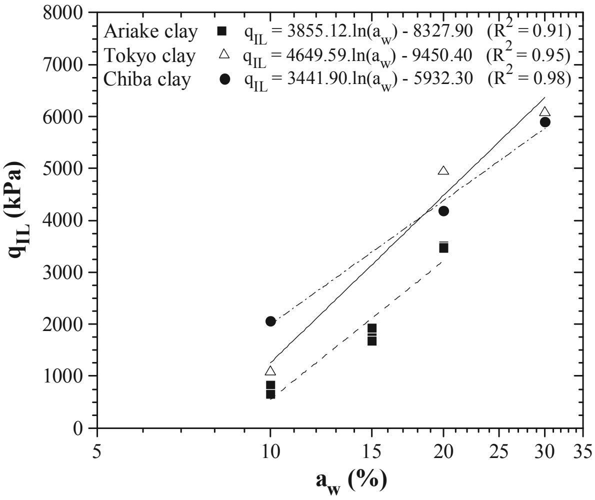
Figure 2. Normalized unconfined compressive strength results of the chemical stabilization of the soft soil of "Baixo Mondego".

3 DATA FROM OTHER CEMENT BASED STABILIZED SOFT SOILS

Table 4 presents the main results of 7 other cement based stabilized soft soils whose geotechnical properties are described in Horpibulsuk (2001) and Kawasaki et al (1981). Figure 3 presents the results of the unconfined compressive strength normalized by the liquidity index, from which it can be concluded that each cement based stabilized soft soil has its normalization (fitting curve). Thus the method here proposed is versatile as it is valid for other soft soils.

Table 4. Unconfined compressive strength results of cement based chemical stabilization of other 7 soft soils (Horpibulsuk 2001, Kawasaki et al 1981).

Soft soil	I_L (-)	a_w (%)	$q_{u\,max}$ (kPa)
Ariake clay	1.0	10	833
		15	1798
	1.5	10	434
		15	1286
		20	2343
	2.0	15	839
		20	1736
Tokyo clay	1.0	10	1085
		20	4941
		30	6072
Chiba clay	1.0	10	2063
		20	4189
		30	5894
Kangawa clay	1.0	10	1068
		20	3120
		30	5047
Aichi clay	1.0	10	887
		20	1889
		30	2159
Osaka clay	1.0	10	595
		20	1707
		30	1976
Hiroshima clay	1.0	10	748
		20	2436
		30	3952



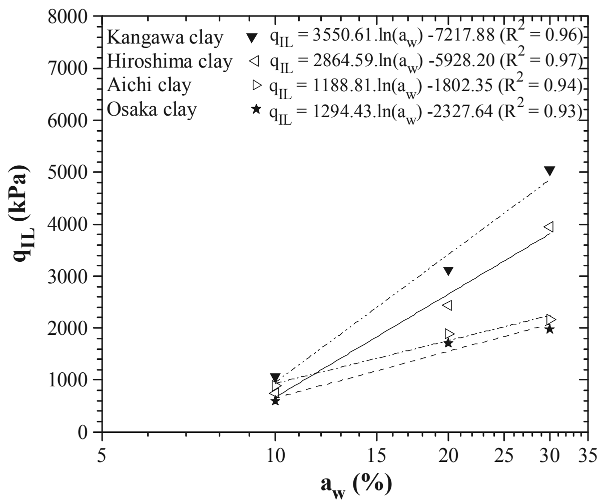


Figure 3. Normalized unconfined compressive strength for other cement based stabilized soft soils.

4 GENERALIZING THE PROPOSED METHOD

As it was observed in Figures 2 and 3, the method proposed can be applied satisfactory to a wide range of soft soils. However, each cement based stabilized soft soil has its own fitting parameters (see the equations for q_{IL} in Figures 2 and 3), different for each soil.

In order to find a generalized strength equation, independent of the soft soil, the q_{IL} data of a particular soft soil was normalized by the unconfined compressive strength defined for a liquidity index of 1.0 and for a constant binder content (it was considered the value 18% for all soft soils), $q_{IL=1\ (aw=18\%)}$. For each soft soil, this last value was evaluated from the fitting curves presented in Figures 2 and 3. All data are presented in Figure 4, where it can be seen that the values are in a narrow linear band, fitted relatively well by a linear logarithmical regression ($R^2 = 0.94$). Thus, the method proposed in this paper seems to be independent of the soft soil type, being valid for the prediction of the unconfined compressive strength at 28 days of curing time of cement based stabilized soft soils, which is helpful for the laboratory optimization process of the chemical stabilization. The number of unconfined compression tests required can be reduced to one if it is applied the generalized equation and the binder content chosen is 18%.

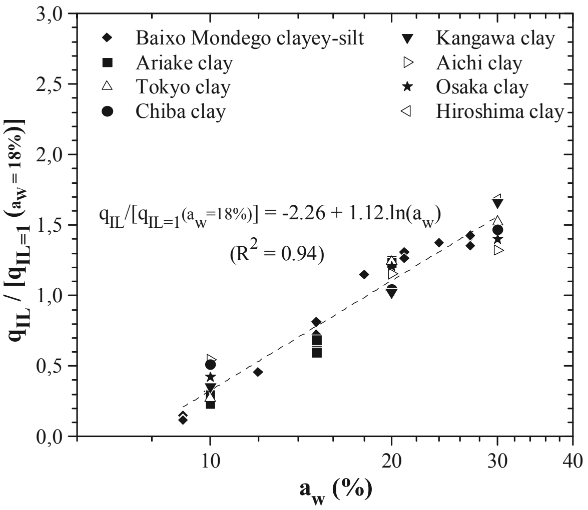


Figure 4. Generalized strength equation for the unconfined compressive strength of cement based stabilized soft soils.

5 CONCLUSION

The paper presents a new simple method to predict the unconfined compressive strength at 28 days of curing time of cement based stabilized soft soils, whatever be the water content and binder content. The method was initially developed for the soft soil of "Baixo Mondego" chemically stabilized, and then was sucessfully applied to a wide range of cement based stabilized soft soils. Thus, this new method seems to be independent of the soft soil, which allows the definition of a generalize relationship (presented in Figure 4). At limit, the number of unconfined compression tests required can be reduced to one if it is applied the generalized equation and the binder content chosen is 18%. The method proposed in this paper is helpful for the laboratory optimization process of the chemical stabilization at the pre-design stage.

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