Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-45

ECSMGE 24
XVIII EUROPEAN CONFERENCE
ON SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

Mechanical features of stabilized soils with low cement content

Caractéristiques mécaniques des sols faiblement traités au ciment

M.A. Castaneda-Lopez*, T. Lenoir, L. Thorel
Université Gustave Eiffel, Bouguenais, France

J.-P. Sanfratello
Colas SA, Magny-les-Hameaux, France

**mario-alexander.castaneda-lopez@univ-eiffel.fr*

ABSTRACT: Soil chemical stabilization with cement is a common technique to enhance the engineering and mechanical properties of in situ soils according to stress rates imposed by civil engineering projects. Usually, moderate quantities of cement are used, around 5 to 10% of the dry material. However, cement manufacturing is one of the biggest sources of greenhouse gas emissions, specifically carbon dioxide. For this reason, reducing cement content by a few percent in geotechnical structures built with cement stabilized soils (CSS) has a high environmental interest, particularly in view of the involved volumes of material. This work aims to contribute to a better understanding of the mechanical characteristics of stabilized soils with low cement contents. First, the mechanical behavior of a soil treated with 3% cement was studied for several curing times. Next, measured fracture parameters were correlated. Finally, these measurements were used to characterize the Mohr-Coulomb (MC) failure criterion. Results showed a high correlation between compressive and MC parameters. An alternative method for estimating MC parameters for CSS based on tensile and compressive properties was successfully checked. The proposed approach can be used to determine design parameters for geotechnical structures.

RÉSUMÉ: Dans les projets de Génie Civil, le traitement des sols au ciment est une technique courante pour améliorer les propriétés techniques et mécaniques des sols en place. En général, les quantités de ciment utilisé sont modérées, de l'ordre de 5 et 10 % du matériau sec. Toutefois, la fabrication du ciment est l'une des sources d'émission les plus importantes de gaz à effet de serre et en particulier de dioxyde de carbone. C'est pourquoi, réduire de quelques pourcent la teneur de ciment dans les structures géotechniques réalisées avec des sols traités présente un intérêt environnemental certain, notamment en raison des volumes de matériau impliqué. Ce travail vise à contribuer à une meilleure compréhension des caractéristiques mécaniques des sols faiblement traités. Pour commencer, le comportement mécanique d'un sol traité avec 3% de ciment a été étudié pour plusieurs temps de cure. Ensuite, les liens entre les différents paramètres de rupture mesurés ont été établis par corrélation. Enfin, ces mesures ont permis de caractériser le critère de rupture de Mohr-Coulomb. Les résultats ont montré une forte corrélation entre les paramètres de compression et les paramètres de MC. Une méthode alternative d'estimation des paramètres MC pour le CSS basée sur les propriétés de traction et de compression a été vérifiée avec succès. L'approche proposée peut être mise en œuvre pour obtenir les paramètres de dimensionnement des structures géotechniques.

Keywords: Cement-stabilized soils; earthworks, correlation analysis, Mohr-Coulomb.

1 INTRODUCTION

Cement stabilization of soils is a common technique to enhance the engineering and mechanical properties of in situ soils according to stress rates imposed by civil engineering projects (Correia et al., 2019; Preteseille & Lenoir, 2016). Use of cement-stabilized soils (CSS) cover a wide range of civil engineering applications such as embankments, foundations, slope protection, pavements and rail construction (Consoli et al., 2007; Diambra et al., 2018).

CSS constitute an intermediate class of geomaterials whose mechanical behavior is at the boundary between soil and rock mechanics (Lenoir et al., 2021; Schnaid et al., 2001). Compressive and tensile strength are widely employed as indicators of stabilization. Whereas compressive strength is linked to granular packing and bonding compounds, tensile strength is more related to the amount of cementitious compounds (Consoli et al., 2001). However, these characteristics represent a defined state of stresses and don't necessarily match with the service state of stresses of structures.

It is generally accepted that the failure mode of CSS can be represented with the Mohr-Coulomb (MC) criterion (Schnaid et al., 2001). Use of compressive and tensile properties to determine MC parameters for design purposes is related in literature (Lenoir et al., 2021; Piratheepan et al., 2012; Sivakugan et al., 2014). Using direct and indirect measurements, the present work investigates the shear strength of a low-cement treated clayey soil.

2 MATERIALS AND METHODS

2.1 Materials

2.1.1 Soil

Studied material (A) was collected from the covering soil of an aggregate quarry at Soignies, Belgium (50° 34’ 25.759’’ N, 4° 2’ 16.476’’ E). The grain size curve is shown in Figure 1.

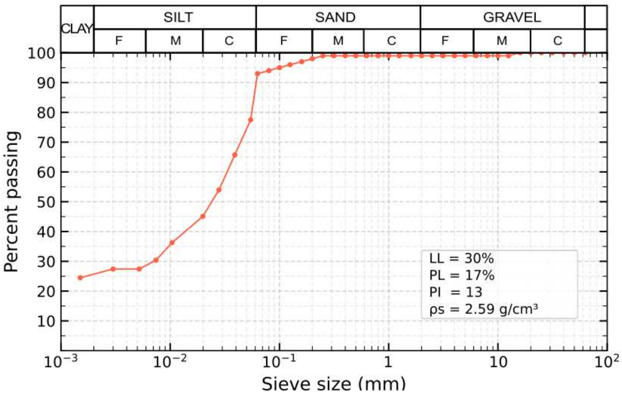


Figure 1. Particle-size distribution. F: fine, M: medium, C: coarse. PL: plastic limit, LL: liquid limit, PI: plastic index and ρ_s specific mass.

The soil is classified as A-6 (11), CL and A2 following the AASHTO (M 145-91), USCS (ASTM D2487-17) and GTR (NF P11-300) classification systems. The clay activity (A) is low A = PI/clay content = 0.29, which suggest a not significant swelling potential. Natural moisture content is below the PI (liquidity index < 0).

2.1.2 Soil treatment

Soil was treated with 3% of Portland-limestone cement (weight of dry material) CEM II/A-LL 42.5 R (NF EN 197-1). Main constituents of the binder are clinker (80-94%) and limestone (6-20%). The Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) were determined following the standard Proctor compaction tests (NF P94-093): OMC = 15.5%, MDD = 1.79 g/cm^3. Reference values for sample preparation are 96% of MDD at OMC.

Samples were tested after several curing times (CT): 7, 28, 90, 180 and 360 days. For curing, samples were stored in a room with temperature controlled at 20 °C in plastic bags to keep constant moisture content.

2.2 Experiments

Experimental program is summarized in Table 1. For Unconfined Compression Strength test (UCS), Direct Tensile Strength test (DTS) and Indirect Tensile Strength test (ITS), tests are carried out on a Zwick/Roell Z150 press. Crosshead speed was 0.1 mm/min for UCS and DTS and 0.3 mm/min for ITS.

2.2.1 UCS

Tests followed the standard EN 13286-41:2021. Principle of testing is presented in Figure 2 (a). The maximum load registered, corresponding to the failure load, is equal to the UCS. Due to it is a compressive load, its value is positive.

2.2.2 DTS

Tests followed the standard EN 13286-40. As vertical load is a traction load, its value is negative (Figure 2 (b)). Minimal value corresponds to the DTS.

2.2.3 ITS

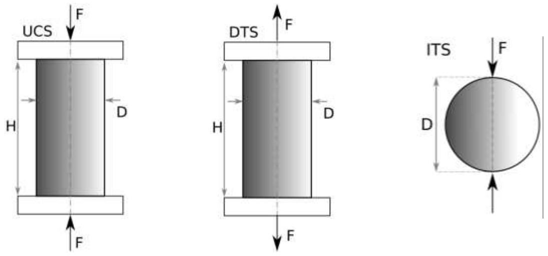
Tests followed the standard NF EN 13286-42. Principle of test is displayed in Figure 2 (c). Analytical solution of stresses at the center of the specimen during ITS test is used to construct the stress tensor (Piratheepan et al., 2012; Preteseille et al., 2014; Thompson, 1966).

2.2.4 Direct Shear test (DS)

Tests were carried out in a machine Sheartest VJT following the standard NF EN ISO 17892-10. Shear rate was 0.12 mm/min. The contact area used to calculate the normal (σ) and shear stress (τ) is corrected following the procedure proposed by (Skuodis & Tamošiūnas, 2014). Levels of normal stress varied between 2 and 250 kPa.

Table 1. Experimental program.

Test	**Standard**	**D (mm)**	**H (mm)**	**CT (days)**	**Number of Samples**	**Number of Samples, total**
UCS	EN 13286-41:2021	100	200	7, 28, 90, 180, 360	3	15
DTS	NF EN 13286-40	100	200		3	15
ITS	NF EN 13286-42	100	100		4	19
DS	NF EN ISO 17892-10	60	35		15	75



(a) *(b)* *(c)*

Figure 2. Characteristics of mechanical tests employed: (a) UCS, (b) DTS, (c) ITS.

3 RESULTS AND DISCUSSION

For UCS, DTS and ITS, mean values and standard deviation (SD) are presented in

Table 3. For DS, conventional linear regressions parameters *c* (cohesion) and *φ* (friction angle) corresponding to the MC criteria are presented for each CT with the coefficient of determination, R^2. R^2 is higher than 0.93 for 3 out of 5 CT studied, which suggest the suitability of this model to represent the failure characteristics of the studied material.

Linear regressions are used to represent UCS, DTS, ITS and cohesion as a function of CT (Xuan et al., 2012) following the eq. (1). Results, shown in

Table 3, reveal a good agreement between traction gain and CT. For UCS and *c*, unexpectedly, a poor correlation with CT is identified, with higher values for CT = 90 days. For *φ*, regressions also revealed a poor correlation (R^2=0.15).

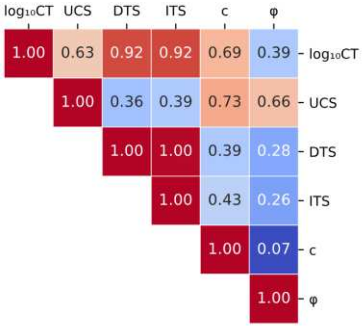
$$y = a\,log_{10}(CT) + b \tag{1}$$

Table 2. Regression models for experimental results.

Test	a	b	R^2
UCS (MPa)	0.338	1.281	0.403
DTS (MPa)	0.077	0.053	0.840
ITS (MPa)	0.063	0.074	0.842
c (MPa)	0.050	0.238	0.473

A comprehensive correlation between studied parameters was done (Figure 3). Results agree with the linear correlation between Log_{10}CT and the tensile strength enhancement (Table 2).

DTS and ITS are highly correlated ($R_{DTS\text{-}ITS}$ = 1.00). The ratio DTS/ITS is 1.04±0.09. For practical purposes this ratio is assumed as 0.8 (SETRA & LCPC, 2000). A moderate correlation is also identified between UCS and MC parameters ($R_{UCS\text{-}c}$ = 0.73 and $R_{UCS\text{-}\phi}$ = 0.66). Correlation between the tensile strength (either DTS or ITS) and the MC parameters are moderated, with higher coefficients for cohesion ($R_{DTS\text{-}c}$ = 0.39, $R_{ITS\text{-}c}$ = 0.43).



log₁₀CT	UCS	DTS	ITS	c	φ	
1.00	0.63	0.92	0.92	0.69	0.39	log₁₀CT
	1.00	0.36	0.39	0.73	0.66	UCS
		1.00	1.00	0.39	0.28	DTS
			1.00	0.43	0.26	ITS
				1.00	0.07	c
					1.00	φ

Figure 3. Correlation matrix of the dataset

Mean results after 7 days of cure are displayed in a $\{\sigma - \tau\}$ space in Figure 4. Here, principal stresses in the failure, i.e., the couple (σ_3, σ_1), are used to represent Mohr semi-circles for UCS $(0, UCS)$, DTS $(DTS, 0)$ and ITS $(ITS, -3ITS)$ (Jaeger et al., 2007). Direct shear results are depicted as both the couple (σ, τ) of individual tests (scatterplot) and the MC envelope (linear regression).

Results suggests a link between MC envelope and UCS and ITS values for a given CT as reported in the literature (Piratheepan et al., 2012). This approach states that the envelope of Mohr-Coulomb's failure corresponds to the tangent to the ITS and UCS semi-circles. Mathematically, it relies on either UCS or ITS, and the ratio $\xi = ITS/UCS$. This ratio varies within quite a narrow range 0.10 ± 0.02.

In Table 4, this approach is applied to the experimental dataset for a given CT and compared to the measured values from DS test. Results are in good agreement. When comparing the ratio between estimated and measured values, it varies between 0.84 and 1.22 with a mean of 1.07 for *c* and between 0.77 and 1.40 with a mean of 1.03 for φ.

It is interesting to remark that φ_ξ is close to a constant value (49.4±5.5°), which suggest that CT doesn't have effect on friction angle.

Table 3. Experimental results. Max and min values in bold

CT (days)	UCS (MPa)		DTS (MPa)		ITS (MPa)		DS		
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**c (MPa)**	***φ* (°)**	**R^2**
7	**1.53**	0.05	**0.13**	0.02	**0.14**	0.02	**0.24**	50.2	0.942
28	1.65	0.15	0.15	0.01	0.15	0.01	0.35	**36.3**	0.568
90	**2.41**	0.01	0.18	0.03	0.18	0.01	**0.37**	55.9	0.933
180	1.77	0.11	**0.26**	0.07	**0.23**	0.01	0.33	41.7	0.485
360	2.11	0.02	0.25	0.04	0.22	0.03	0.34	**62.0**	0.936

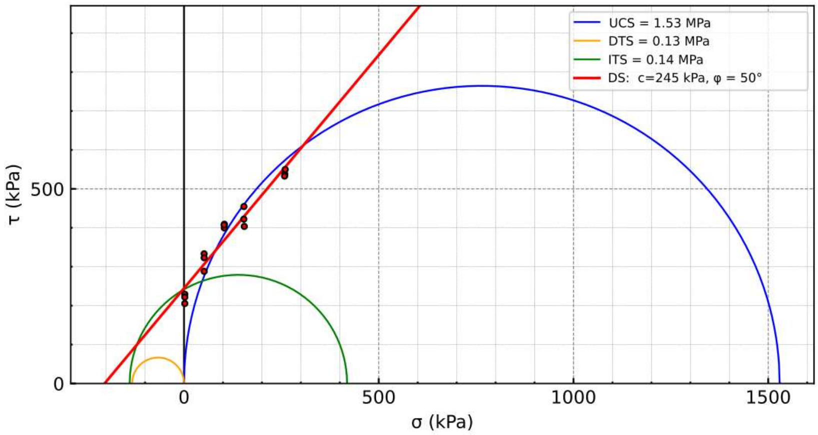


Figure 4. Mean results after 7 days of cure. UCS (blue), DTS (orange), ITS (green) and Direct shear (red).

Table 4. Measured (c, φ) and estimated (c_ξ, φ_ξ) MC param.

CT (days)	ξ	**Estimated**		$\frac{c_\xi}{c}$	$\frac{\varphi_\xi}{\varphi}$
		c_ξ kPa)	**φ_ξ (°)**		
7	0.09	271.0	51.0	1.11	1.02
28	0.09	293.4	50.9	0.84	1.40
90	0.07	368.8	56.0	0.99	1.00
180	0.13	402.9	41.0	1.22	0.98
360	0.10	405.0	48.0	1.18	0.77

4 CONCLUSIONS

This work shows that tensile properties are linearly correlated with curing time. Moreover, DTS≈ITS and DTS exhibit higher SD. The ITS/UCS ratio is 0.10.

For a given curing time, a good relationship is identified between UCS and MC parameters. The alternative method for estimating MC parameters for CSS based on ITS and UCS is successfully checked. Friction angle seems to be independent from CT.

ACKNOWLEDGEMENTS

The authors would like to thank the Gustave Eiffel University, Materials and Infrastructures Department (MAST) for the technical support and laboratory facilities to carry out this research.

REFERENCES

Consoli, N. C., Foppa, D., Festugato, L., & Heineck, K. S. (2007). Key Parameters for Strength Control of Artificially Cemented Soils. *Journal of Geotechnical and Geoenvironmental Engineering*, *133*(2), 197–205. https://doi.org/10.1061/(asce)1090-0241(2007)133:2(197).

Consoli, N. C., Prietto, P. D. M., Carraro, J. A. H., & Heineck, K. S. (2001). Behavior of Compacted Soil-Fly Ash-Carbide Lime Mixtures. *Journal of Geotechnical and Geoenvironmental Engineering*, *127*(9), 774–782. https://doi.org/10.1061/(ASCE)1090-0241(2001)127:9(774).

Correia, A. A. S., Venda Oliveira, P. J., & Lemos, L. J. L. (2019). Strength assessment of chemically stabilised soft soils. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, *172*(3), 218–227. https://doi.org/10.1680/jgeen.17.00011.

Diambra, A., Festugato, L., Ibraim, E., Peccin da Silva, A., & Consoli, N. C. (2018). Modelling tensile/compressive strength ratio of artificially cemented clean sand. *Soils and Foundations*, *58*(1), 199–211. https://doi.org/10.1016/j.sandf.2017.11.011.

Jaeger, J. C., Cook, N. G. W., & Zimmerman, R. (2007). *Fundamentals of Rock Mechanics* (4th ed.). Blackwell.

Lenoir, T., Dubreucq, T., Lambert, T., & Killinger, D. (2021). Safety factor calculation of a road structure with cement-modified loess as subgrade. *Transportation Geotechnics*, *30*(May), 100604. https://doi.org/10.1016/j.trgeo.2021.100604.

Piratheepan, J., Gnanendran, C. T., & Arulrajah, A. (2012). Determination of c and φ from IDT and Unconfined Compression Testing and Numerical Analysis. *Journal of Materials in Civil Engineering*, *24*(9), 1153–1164. https://doi.org/10.1061/(asce)mt.1943-5533.0000493.

Preteseille, M., & Lenoir, T. (2016). Mechanical Fatigue of a Stabilized/Treated Soil Tested with Uniaxial and Biaxial Flexural Tests. *Transportation Research Procedia*, *14*(December), 1923–1929. https://doi.org/10.1016/j.trpro.2016.05.159.

Preteseille, M., Lenoir, T., Gennesseaux, E., & Hornych, P. (2014). Structural test at the laboratory scale for the utilization of stabilized fine-grained soils in the subgrades of High Speed Rail infrastructures: Analytical and numerical aspects. *Construction and Building Materials*, *61*, 164–171. https://doi.org/10.1016/j.conbuildmat.2014.02.069.

Schnaid, F., Prietto, P. D. M., & Consoli, N. C. (2001). Characterization of Cemented Sand in Triaxial Compression. *Journal of Geotechnical and Geoenvironmental Engineering*, *127*(10), 857–868. https://doi.org/10.1061/(ASCE)1090-0241(2001)127:10(857).

SETRA, & LCPC. (2000). *Réalisation des remblais et des* *couches de forme (GTR)* (Cerema (ed.); 2nd ed.).

Sivakugan, N., Das, B. M., Lovisa, J., & Patra, C. R. (2014). Determination of c and Φ of rocks from indirect tensile strength and uniaxial compression tests. *International Journal of Geotechnical Engineering*, *8*(1), 59–65. https://doi.org/10.1179/1938636213Z.00000000053.

Skuodis, Š., & Tamošiūnas, T. (2014). Direct Shear Tests with Evaluation of Variable Shearing Area. *Mokslas – Lietuvos Ateitis*, *6*(5), 499–503. https://doi.org/10.3846/mla.2014.692.

Thompson, M. R. (1966). *Split Tensile Strength of Lime-Stabilized Soils*. 69–82. https://trid.trb.org/view/121697

Xuan, D. X., Houben, L. J. M., Molenaar, A. A. A., & Shui, Z. H. (2012). Mechanical properties of cement-treated aggregate material – A review. *Materials & Design*, *33*(1), 496–502. https://doi.org/10.1016/j.matdes.2011.04.055.

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 18th European Conference on Soil Mechanics and Geotechnical Engineering and was edited by Nuno Guerra. The conference was held from August 26th to August 30th 2024 in Lisbon, Portugal.