Evaluation of mechanical properties of jet-grouting columns using different test methods

Evaluation des propriétés mécaniques des colonnes de jet grouting au moyen de différentes méthodes d'essais

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ABSTRACT

This paper evaluates the mechanical properties of jet-grouting columns used for soil improvement. This technique was used to create a slab for the excavation of the one subway station in Barcelona, Spain. Before field treatment of the very soft clayey soil, a field trial was built with some jet-grouting columns in order to define the correct grouting parameters and to determine the mechanical properties of the soil-cement mixture by collecting some samples from the columns. These samples were obtained with two different techniques: (1) as core samples, the traditional method in which the samples are collected in situ at a certain age and then tested in the laboratory; and (2) as fresh jet material, a new technique developed by the contractor for collecting the material in a fresh state, right after the grouting application, and then curing the sample in a controlled laboratory environment. At the same time, a laboratory-based formulation study of soil-cement was developed using samples of the clayey soil and the same kind of cement employed in the field trial. Afterwards, the mechanical properties, strength and modulus of the soil-cement mixture made in laboratory were compared with those of the field samples, for the same of specimen ages. An attempt was made to establish correlations between the mechanical properties obtained by the different test methods, for the different types of soil-cement mixtures.

RÉSUMÉ

Ce document évalue les propriétés mécaniques de colonnes de jet grouting pour l'amélioration de sols. Cette technique d'amélioration a été employée pour créer une dalle pour l'excavation de l'une station de métro à Barcelone, Espagne. Avant le traitement sur le terrain du sol argileux très mou, quelques colonnes expérimentales ont été construites afin de définir les paramètres d'injection corrects et déterminer les propriétés mécaniques du mélange de sol-ciment en prélevant quelques échantillons des colonnes. Ces échantillons ont été obtenus avec deux techniques différentes: (1) comme carottes, la méthode traditionnelle dans laquelle les échantillons sont carottés in situ à un certain âge et alors essayés dans le laboratoire; et (2) comme matériau frais de jet grouting, nouvelle technique développée par l'entrepreneur pour prélever le matériau dans l'état frais, immédiatement après l'application du jet grouting, et avoir puis soumis l'éprouvette à des conditions de cure contrôlées dans le laboratoire. En outre, une étude basée sur une étude de formulation de sol-ciment en laboratoire a été développée utilisant des échantillons du sol argileux et le même type de ciment utilisé dans la réalisation des colonnes expérimentales. Après, les propriétés mécaniques, la résistance et le module, du mélange de sol-ciment préparée dans le laboratoire ont été comparés à ceux des échantillons provenant des colonnes expérimentales, pour le même temps de cure. Une tentative a été faite d'établir des corrélations entre les propriétés mécaniques obtenues par les différentes méthodes d'essai, pour les différents types de mélanges de sol-ciment.

Keywords : Jet grouting, mechanical properties, fresh field samples, unconfined compression tests

1 INTRODUCTION

At the design stage of jet grouting, there are still a relatively degree of uncertainties because there are no reliable methods that allow to predict the diameters and the mechanical properties of the soil-cement elements (Croce & Florat 2000 and Kirsch & Sondermann 2001). As a good practice, prior to the definitive application of this technique, preliminary field tests are carried out to define the optimal parameters for the jetting process, and are also produced laboratory mixtures of soil-cement. The laboratory mixtures allow to encompass the grouting parameters used in the field trials, as result of the mechanical performance of the different types of tested laboratory formulations.

Testing of jet-grouting field elements consist of traditional core samples, in which the samples are collected *in situ* at a certain age and then tested in the laboratory after the hardening process; and fresh samples, resulting from a new technique for collection of the material in a fresh state, right after the grouting application, and then curing in a controlled laboratory environment.

This paper aims to establish empirical relationships between the mechanical properties of the various soil-cement samples collected from *in situ* columns (fresh samples and core samples) and laboratory mixtures. These correlations are of great practical interest due to the fact that, after establishing these relationships, knowing one of the studied properties will make it possible to estimate the remaining ones.

2 CASE STUDY

This paper presents the mechanical study of different types of soil-cement samples related to the jet-grouting elements produced for a subway station in Barcelona, Spain. Natural soil samples were collected from the location for physical characterization and were used in the production of a laboratory formulation of soil-cement. The physical characterization and classification of the soil for engineering purposes are presented in Table 1.

At the construction site, jet grouting columns were produced on a field trial with variable jetting parameters (formulations), namely the quantity of injected cement by volume of treated material (kg/m^3) and the water/cement ratio (w/c). The different formulations are stated in Table 2 for the relevant column types. Core samples were collected from these column types along with fresh samples, later mechanically characterized. All the

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field samples studied in this paper were collected from columns manufactured with the type 2 jet-grouting process.

Table 1. Soil physical properties and classification.

Parameters	Values
Liquid limit (ω_L)	24%
Plastic limit (ω_P)	15%
Plasticity index (IP)	9%
Classification (ASTM D 2487-00)	Organic Clay (OL)
Water content (ω)	33%
Organic content	1,8%

Table 2. Main jetting parameters used in the columns for the field trial at the construction site.

Columns formulations	kg/m^3	w/c
Columns A	797	0.91
Columns B	600	0.91
Columns C	794	1.00
Columns D	904	1.00
Columns E	652	1.00
Columns F	765	1.00

At the same time, a laboratory mixture was produced, made of cement slurry with the soil sample collected from the studied location. The mixing procedure adopted generally consists of mixing a cement grout with soil in the natural state for 5 minutes, and then molding the mix without compaction. For comparison with the field samples, the laboratory mixtures were produced with nearly the same formulation (quantity of cement and w/c) as the field columns: 950 kg/m^3 and w/c=1.00.

All the soil-cement samples were tested to determine the uniaxial compressive strength (q_{ult}) and the modulus tangent to 50% of the ultimate strength ($E_{tg50\%}$). The modulus is obtained by measuring the local deformations of the samples with LDTs (Local Deformation Transducers, Goto et al. 1991) as shown in Figure 1 (Gomes Correia et al. 2006).

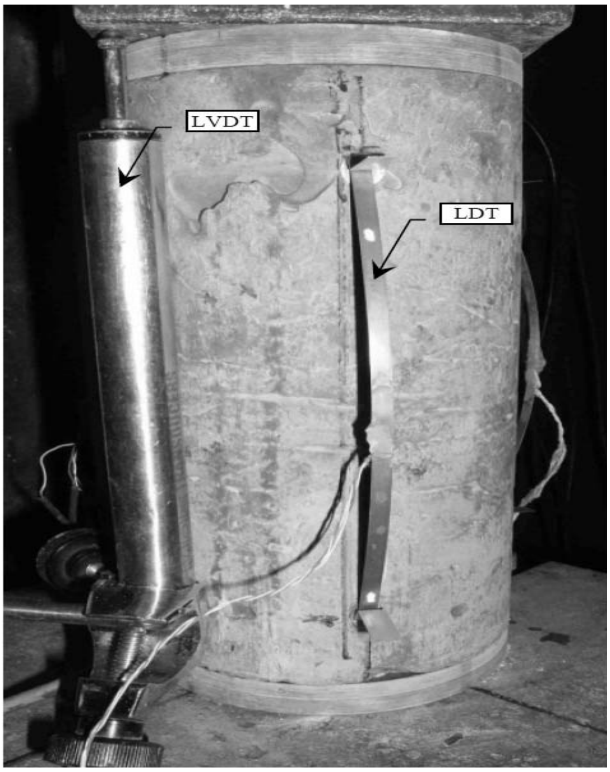

Figure 1. Specimen of the laboratory mixture instrumented with LDT and LVDT

Previous investigations, dating from the 1980s (Jardine et al. 1984; Symes & Burland 1984; Gomes Correia 1985 and Tatsuoka 1988), have shown the imprecision of evaluating the moduli by the use of the external measurement of the deformation of the samples. This fact is addressed in Figure 2, where the result of the modulus tangent to 50% of the ultimate strength ($E_{tg50\%}$) is very distinct when the the stress-strain and modulus-strain curves are plotted with local and external measurement (via LVDT - linear variable differential transformer) of the sample deformation. For the example shown, the ultimate strain obtained with the external measurement device is about three times as high as the local measurement and the $E_{tg50\%}$ determined with the local measurement is about three times as high as the $E_{tg50\%}$ determined with the external measurement. The core samples collected from the columns produced in the field were tested for curing periods ranging from 14 days to more than 2 months, and the fresh samples for curing periods until 3 to 4 months. The samples produced from the laboratory mixtures were tested after curing until 2 or 3 months.

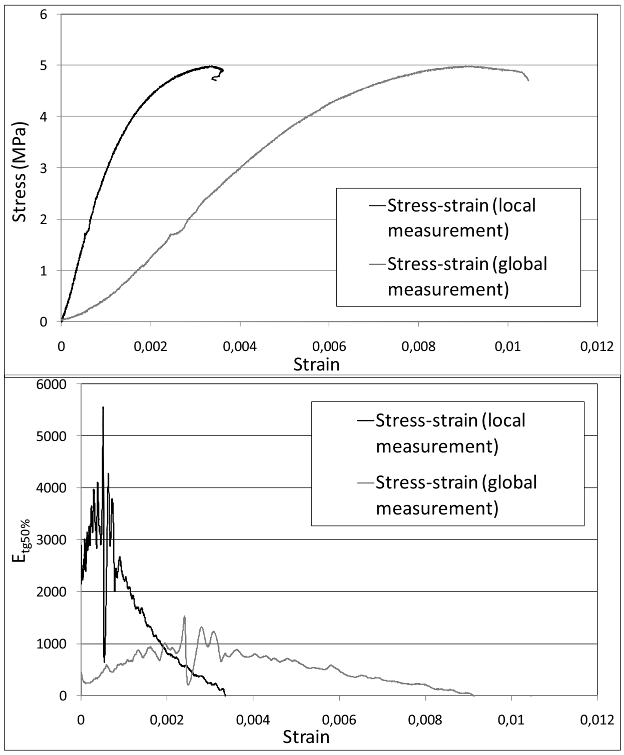

Figure 2. Comparison of the stress-strain and modulus-strain curves for a fresh sample

3 RESULTS

This paper presents the results of the uniaxial compressive strength tests on soil-cement samples representative of jet-grouting columns and laboratory mixtures, based on the local measurement of sample deformations, in order to assess the modulus tangent ($E_{tg50\%}$) to 50% of the ultimate strength (q_{ult}).

Figure 3 presents the average of the mechanical properties of the different field samples and laboratory mixtures from the case study, whose formulations are identical. Thus, the laboratory mixture was compared with the core samples and fresh samples from columns type D. The comparison shown in Figure 3 was obtained after normalization of the experimental data for a curing period of 28 days using the Eurocode 2 (EN 1992-1-1 2004) theoretical model intended for estimating the variation in concrete mechanical properties over time. Previous studies (Valente et al. 2008) have stated that the adaptation of the Eurocode 2 theoretical model results in a reasonable adjustment to the soil-cement mechanical behavior.

As demonstrated in Figure 3, all types of samples from field had similar performance. The two types of field samples had

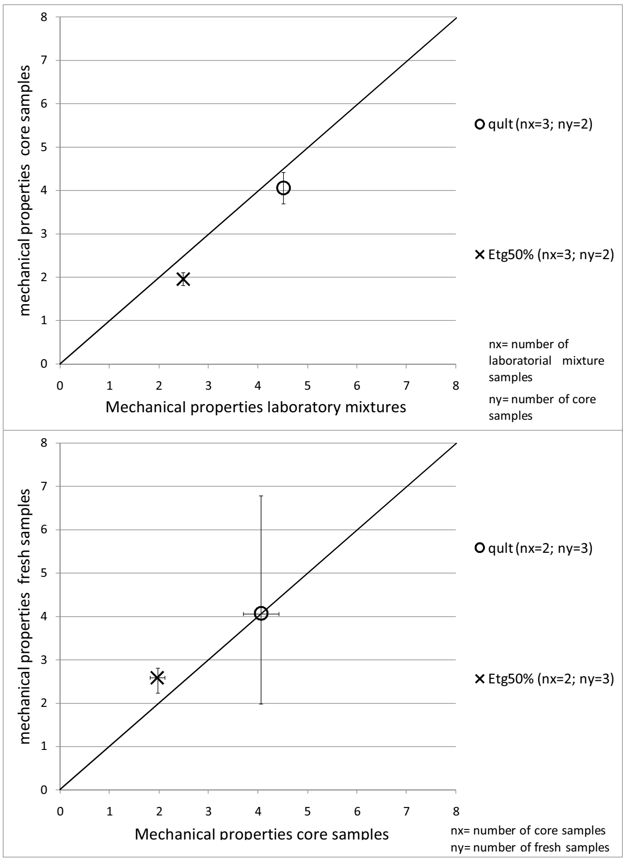

Figure 3. Comparison between the different types of samples, after normalization using Eurocode 2 theorethical model

slightly lower values of qult than the laboratory mixture, with a difference of 10%. The values for $E_{tg50\%}$ displayed the biggest differences in the studied mechanical properties of the samples; the fresh samples had a performance of about 1.32 times higher than the core samples and 1.04 times higher than the laboratory mixture.

The difference found in the laboratory mixture may result from the fact that the laboratory procedure cannot perfectly reproduce the original jet-grouting construction technique. Also, due to the discrepancy of the stiffness modulus and the similarity of the uniaxial compressive strength between the fresh and core samples, it is possible to infer that the core

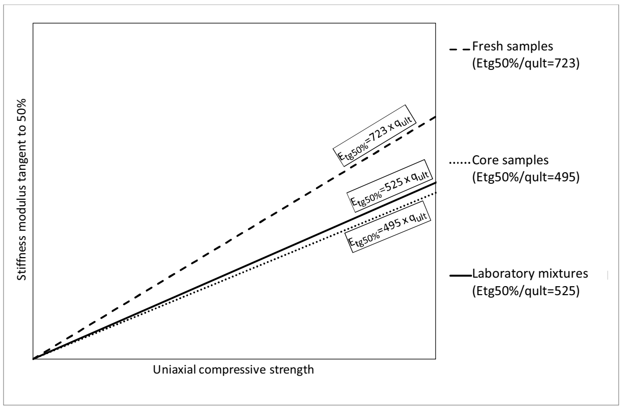

Figure 4. Comparison of the relations between the modulus tangent to 50% and the uniaxial compressive strength of the samples with similar formulations.

sampling process might have caused a disturbance in the samples during the extraction, such as cracking and/or micro-cracking, which particularly affect the stiffness modulus evaluation. This hypothesis is consistent with the empirical knowledge that the mechanical properties of the core samples represent a conservative approach to the real performance of the columns. As a result, it is possible to validate the utility of carrying the characterization of the fresh samples for quality-control procedures.

Figure 4 presents the relationship between $E_{tg50\%}$ and q_{ult} for the various samples with similar formulations. As can be seen, the ratios of core samples and the laboratory mixture are practically the same. The fresh samples have the highest ratios, a consequence of the finding presented in Figure 3.

4 CONCLUSIONS

This paper characterizes the different types of samples (core samples, fresh samples and laboratory mixtures) from a case study related to the construction of jet-grouting columns in a subway station in Barcelona, Spain.

The comparison between the mechanical behavior of the different types of samples collected and produced for the case study revealed a similar performance for all types of samples. In this case, the most notable difference occurred between the $E_{tg50\%}$ of the fresh samples and the core samples, whose ratio is about 132%. The fresh samples showed a very good agreement with the laboratory mixture, which reveals the utility of collecting fresh samples in order to compare column performance with previous laboratorial studies and for quality-control procedures, instead of collecting core samples. Moreover, the differences noted in the moduli of the core samples may be related to disturbance in the material (cracking and micro-cracking) during extraction of the samples. So, for mechanical evaluation, the use of fresh samples in quality-control procedures of jet-grouting columns represents a viable alternative to core samples, especially for the determination of the stiffness modulus where cracks have a higher influence than in the evaluation of the uniaxial compressive strength.

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