# Standardization of the molding procedures for stabilized soil specimens as used for QC/QA in Deep Mixing application

## Normalisation des procédures pour la production d'éprouvettes de sols stabilisés utilisées dans les processus de QC/QA pour des applications de « Deep Mixing »

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ABSTRACT: An international collaborative research has been undertaken to establish common understanding of the key issues involved in Quality Control/Quality Assurance (QC/QA) of Deep Mixing technique and propose international standards on design, execution and execution control. The aim of the study is to investigate the influence of the laboratory procedures on the mechanical properties of stabilised soil specimens and develop an innovative method to select the appropriate molding technique. A large laboratory testing program was carried out on seven types of heterogeneous natural soils, as found in Rome, and on Kawasaki clay stabilised with Portland cement. Thirty soil-binder mixtures with different workability were prepared using five different molding techniques, varying initial water content of the soils, water to cement ratio and binder amount. Unconfined compression tests have been carried out systematically on over 800 specimens. The applicability of different molding techniques in function of the workability of the mixture has been investigated and from the results it was possible to define an "applicability index" and therefore the range of applicability for each technique in function of the mixture's workability.

RÉSUMÉ: Une étude internationale a été entreprise dans le but de définir des orientations communes pour les procédures QC/QA liés aux travaux effectués par « Deep Mixing » et proposer des normes internationales relatives à la conception, l'exécution et le contrôle des opérations. Le but de cette étude est d'étudier l'effet des procédures de laboratoire pour la réalisation des éprouvettes de sols stabilisés et de développer une méthode innovante pour sélectionner à chaque fois la technique de réalisation appropriée. Un vaste programme d'essais en laboratoire a été réalisé en analysant plus de trente mélanges différents de ciments et sols à partir de huit sols naturels de Rome et Tokyo. Cinq techniques de réalisation ont été utilisées pour la confection d'éprouvettes testées avec des essais de compression simple.. L'applicabilité des différentes techniques de réalisation a été étudiée selon l'usinabilité du mélange. A partir des résultats, il a été possible de définir un index d'applicabilité et donc un champ d'application de chaque technique en fonction de l'usinabilité du mélange..

KEYWORDS: Deep mixing, workability, laboratory procedures, operational abaci.

## 1 INTRODUCTION

The Deep Mixing Method is a widely spread in situ ground improvement technique using different kind of binders to enhance mechanical and physical properties of soils (Terashi 1997; CDIT 2002).

Laboratory mixing tests are essential to QC/QA processes and performed to obtain the mechanical and physical properties of stabilized soil samples. The laboratory test results provide crucial information for the estimation of the mix design and in-situ properties to utilize in the geotechnical design. (Bruce et al. 2000; Larsson 2005; Marzano et al. 2009; Terashi and Kitazume 2011; Filz et al. 2012). At the moment many laboratories produce and test soil-binder specimens without a standard procedure, therefore the results for the same soil-binder mixture could be very different and not usefully compared. In fact molding techniques have a great influence on the mechanical and physical properties of the stabilized soil specimens (Grisolia et al. 2012; Marzano et al. 2012). This influence is strictly correlated to the workability of the soil-binder mixture defined as the property of the mixture of being easily mixed in the bowl and placed in the mold. High workability refers to liquid type mixtures (easier to place and handle), while low workability to sticky and stiff type ones.

Workability represents diverse characteristics of fresh mixture that are difficult to measure quantitatively, because a soil-binder mixture is a complex material with a wide range of particle sizes and time-dependent properties. The definition of a parameter representative of the mixture's workability and an univocal method for the evaluation of the mixture's workability are currently not available (Koehler and Fowler, 2003) even if such parameter could be well related to consistency when considering mixtures made up of cohesive soils.

A new method for the evaluation of the mixture's workability was introduced and applied in the study. It is based on the measure of the torque required to turn an impeller in soil-binder mixture through a commercial device which is applied directly on the mixer. This method has the advantage to provide the possibility of measuring the workability for each mixable mixture, independently on the type of the materials used.

Furthermore, the study develops a procedure to select, through an "applicability index" function of the initial mixture workability, the molding technique that provides densest specimens with highest strength and results repetitiveness in order to obtain very useful reference values to set specification limits to be achieved in field applications (ratio between laboratory and field target strength is reported for instance by JGS 0821-2000 and EuroSoilStab 2002).

## 2 MATERIALS AND METHODS

The experimental work consisted in a laboratory investigation on the effect of different molding techniques on the unconfined compressive strength, *UCS* (measured according to the JIS A 1216:2009) and wet density, $\gamma$ (defined as the specimen's weight divided by the volume of the mold) of cement stabilised soil specimens under various mixing conditions.

### *2.1 Materials*

Eight types of natural soils stabilised with Portland cement added in wet or dry form were used. The tests were performed on: Kawasaki Clay (*KC*), manmade Silty Deposit (*SD*), Silty clayey Sand (*SS*), Sand and Gravel (*SG*), Pliocene Clay (*PC*), Black Pozzolana (*BP*), Red Pozzolana (*RP*) and Argillified Tuff (*AT*). For each soil, different mixtures were produced, varying the initial water content and keeping constant the cement content, $a_c$ (defined as the weight of the introduced dry cement divided by the dry weight of the soil to be stabilized). Specimens with 5 cm diameter and 10 cm height were employed. Each soil was sieved through a 9.5mm sieve, so that the maximum grain size of the soil sample would be less than 1/5$^{th}$ of the inner diameter of the mold. The properties of the soil-binder mixtures analyzed are shown in Table 1.

Table 1. Soil properties and Testing conditions.

| Soil type | Gravel-Sand-Silt-Clay | Water content, $w_n$ (%) | Cementitious grout | Workability parameter, Torque, $M_t$ (Nm) |
|---|---|---|---|---|
| *KC* | 0-14-42-44 | 72 | w/c = 0<br>$a_c$ = 5% | 5,32 |
| | | 66 | | 8,47 |
| | | 60 | | 17,40 |
| | | 60 | $a_c$ = 20% | 29,00 |
| | | 60 | $a_c$ = 30% | 40,00 |
| | | 54 | $a_c$ = 20% | 61,00 |
| | | 54 | $a_c$ = 30% | 75,00 |
| | | 49 | $a_c$ = 20% | 96,00 |
| | | 49 | $a_c$ = 30% | 120,00 |
| *SD* | 18-24-34-24 | 20 | $a_c$ = 10%<br>w/c = 1 | 13,55 |
| | | 30 | | 4,81 |
| | | 40 | | 2,23 |
| *SS* | 22-40-20-18 | 35 | | 9,08 |
| | | 40 | | 4,88 |
| | | 45 | | 3,76 |
| *SG* | 33-40-14-13 | 6 | | 11,28 |
| | | 8 | | 5,11 |
| | | 10 | | 3,51 |
| *PC* | 00-00-64-36 | 50 | | 10,16 |
| | | 60 | | 5,76 |
| | | 70 | | 2,34 |
| *BP* | 08-49-38-05 | 25 | $a_c$ = 10%<br>w/c = 0,5 | 6,97 |
| | | 30 | | 2,37 |
| | | 35 | | 0,21 |
| *RP* | 11-58-24-07 | 20 | | 8,34 |
| | | 26 | | 1,60 |
| | | 32 | | 1,08 |
| *AT* | 02-47-39-12 | 44 | | 8,22 |
| | | 48 | | 0,60 |
| | | 53 | | 0,20 |

### *2.2 Laboratory procedures and testing methods*

A Hobart type mixer apparatus was adopted. After placing the natural soil in the mixer, the water content was adjusted to the desired value by adding water. Before adding the binder the soil was homogenised by mixing. The grout made of Portland cement (PC) and water or the PC in dry form was then added to the soil and mixed for ten minutes according to JGS 0821 (2000).

Using a commercial device applied directly on the kitchen mixer apparatus, it was measured the torque required to turn the impeller in a soil-binder mixture just before the molding phase. According to the proposed method the workability was expressed as a torque ($M_t$) applied to mix certain amount of soil-binder mixture ($V_m$) with set impeller shape ($S_h$) and rotational speed ($R_s$). In the study were assumed the following parameters: $V_{m0}$ = 3dm$^3$; $S_{h0}$ = "K" shape; $R_{s0}$ = 10rpm.

Since the kitchen mixer has a planetary motion, the test was undertaken continuously on the whole mixture therefore giving more reliable outputs. For each completed revolution it was possible to measure the Torque, and for the test it was decided to set the number or revolution to 10, to obtain more accurate measures.

Afterwards the stabilized soil was placed into plastic molds in three layers and compacted using several molding techniques (Figure 1):

_ No Compaction (namely *N.C.*): It simply consisted in placing the stabilized soil into the mold with a spoon.

_ Tapping, namely (*TA.*): For each layer, the mold was tapped against the floor 50 times.

_ Rodding, (namely *RO.*): It consisted in tamping each layer with a 8mm diameter steel rod for 30 times and eventually pushing down the material attached to the rod.

_Static Compaction (namely *S.C.25* and *S.C.50*): Each layer was statically compressed for 10 seconds by using a heavy rod, 49 mm in diameter. 25 or 50 kPa pressure were applied.

_Dynamic Compaction (namely *D.C.*): Each layer was compacted by a falling weight (1.5 kg) using a special apparatus. Fall height was set at 10 cm, number of blows at 5.

These techniques are those currently used in most of the laboratory all over the world (JGS 0821, 2000; EuroSoilStab, 2002; Kitazume et al. 2009).

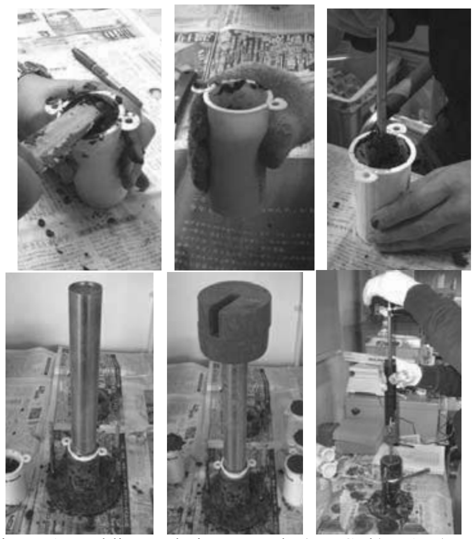

Figure 1. Molding techniques used: a) *N.C.*, b) *TA.*, c) *RO.*, d) *S.C.25*, e) *S.C.50*, f) *D.C.*

To prevent water evaporation from the specimen each mold was covered with the sealant and stored in special curing tanks at 95% relative humidity. To reduce the effect of the time of rest between the hydration of binder and completion of molding on the specimens properties, according to Kitazume et al. (2009), all the stabilized soil was molded in less than 45 minutes from binder hydration. After curing times of 28 days, the specimens were removed from the molds and then subjected to unconfined compression tests at a rate of 1.0 mm/min. Unconfined compression tests were conducted on triplicate samples for each case (mixture type and molding technique) analyzed.

## 3 RESULTS

The applicability of a molding technique was evaluated by the "Applicability index", which is related to "densest specimens with the highest strength" and "results repetitiveness".

For the same mixture a well made specimen has low cavities/bubbles/voids amount and therefore higher wet density ($\gamma$) if compared to a bad made one. Furthermore it was indeed observed that the specimens produced by different molding techniques could have similar wet density but very different unconfined compressive strength (*UCS*) values. For that reason the *N*-parameter was introduced to condense the indications given by both parameters, $\gamma$ and *UCS*, into one. *N* is defined as the mean of the normalized unconfined compressive strength ($UCS_N$) and the normalized unit weight ($\gamma_N$) as reported in the Eq. 1. The $UCS_N$ and $\gamma_N$ values for a given molding technique and mixture were calculated by dividing the UCS and γ by the maximum values ($UCS_{max}$ and $\gamma_{max}$) obtained from all the employed molding techniques. The normalizations are necessary to allow direct comparison between two parameters with different unit of measurements. According to the Eq. 1 the *N* parameter values range between 0 and 1. In order to define a criteria for the choice of the applicable techniques, it was set the acceptable limit of 0.9*N* considering a variation of 10 % from the maximum *N* value.

$$N = Average\left[\, UCS_N : \gamma_N \,\right] \quad (1)$$

The Figure 2 shows as example the *N* parameters vs. torque values obtained for all the analyzed soil-binder mixtures molded by the Rodding technique. From the figure clearly appears that for all the measured mixtures workability the *N* values are above the set limit as an expression of the high quality of the specimens realized by Rodding.

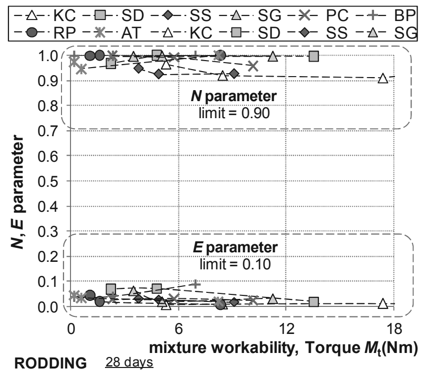


Figure 2. Applicability of Rodding technique considering the *N* and *E* parameters.

Despite the *N*-parameter is a good indicator of the applicability of a molding technique, to take into account that the applicability should be also related to the “repeatability” of the tests results the *E*-parameter was introduced. Repeatability means that the results related to the specimens produced by a specific molding technique should have a low “scatter” or relative error. Unconfined compression tests was conducted on triplicate samples for each case analyzed, therefore it was possible to evaluate the relative error on the unconfined compressive strength and wet density values for the different mixtures types and molding techniques. *E* is defined as the mean of the relative error on the UCS and γ values as reported from Eq. 2. According to its definition also this parameter ranges between 0 and 1. To set a criteria to select the applicable techniques, some literature works were taken into account. For the accuracy or repeatability of the experiments, Richards and Reddy (2010) claimed that a standard deviation of 10 % was not unheard of in geotechnical testing. Al-Tabbaa et al. (2012) also reported an error of 5 – 15% for laboratory mixed specimens tested with unconfined compression tests. Therefore even for the *E* parameter the acceptable limit was set equal to 10% of *E*.

$$E = Average\left[\, E_{UCS} : E_{\gamma} \,\right] \quad (2)$$

The results obtained from the specimens molded by the Rodding technique in terms of *E* vs. torque values are shown in Figure 2 as example. It can be clearly seen that also for the *E* parameter all the obtained values are below the set limit, expression once again of the high repeatability of the tests results obtained from the specimens molded by the Rodding technique.

In order to take into account the different aspects of a well made specimen, expressed by the *N* and *E* parameter, an index of applicability $I_A$ defined in Eq. 3 was introduced.

$$I_A = \frac{N}{1+E} \quad (3)$$

According to the Eq. 3 and to the *N* and *E* parameters definitions, also the $I_A$ values range between 0 and 1. To obtain a target value for the choice of the applicable techniques, the limit values given for the two different parameters *N* and *E* were introduced in the Eq. 3. A target value of $I_A$ = 0.82 was then obtained.

The Figure 3 shows an example of the $I_A$ vs. mixtures workability graph obtained for all the analyzed soil-binder mixtures molded by the Rodding technique.

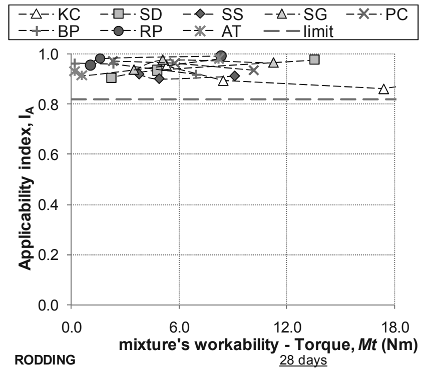


Figure 3. Applicability index of Rodding technique.

The figure show that Rodding is applicable for all the measured mixtures workability since $I_A$ values are all above the set target limit. From the results it is possible to see a very good trend of the $I_A$ despite the fact that data were obtained from mixtures based on different types of soil (cohesive and granular types), with different grout dosage and water contents. The results obtained also from other techniques show that the $I_A$ is strictly dependent on the workability of the mixture among other factors.

The results related to the No Compaction technique are shown in Figure 4. It clearly appears that this technique is applicable for $M_t$ < 3Nm and not applicable for $M_t$ > 6Nm. In the range $M_t$ = 3÷6Nm it is not possible to obtain univocal indication from the data, therefore this technique have been considered marginally applicable in this workability interval.

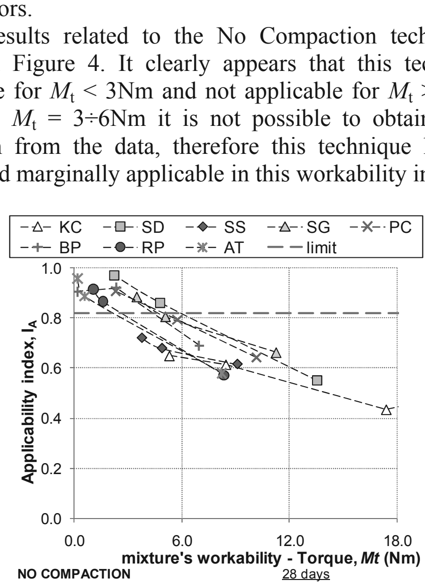


Figure 4. Applicability index of No Compaction technique.

Similar graphs to the ones shown in Figures 3 and 4 were also obtained for the other molding techniques used in the study. From these graphs it was possible to determine for each molding technique the ranges of workability in which they are applicable, marginally applicable and not applicable. The results are summarized in the operational abacus of Figure 5.

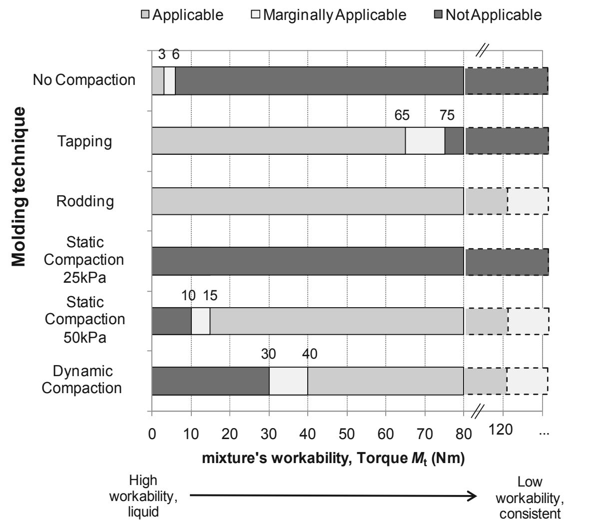


Figure 5. Ranges of applicability of the different molding techniques.

To allow the standardisation and the use of the method a "calibration curve" was elaborated by drawing the torque versus the water content (*w*) of an easily available kind of soil such as kaolin clay using the set of mixer related parameter $V_{m0}$, $S_{h0}$ and $R_{s0}$ (Figure 6).

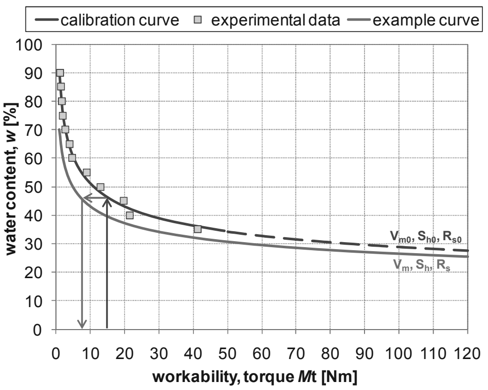


Figure 6. Calibration curve.

By using different set of parameters ($V_m$, $S_h$ and $R_s$), function of the mixer type and torque evaluation procedure, other curves can be drawn in the same graph. Therefore for each molding technique the range of applicability (expressed by torque values) corresponding to the used set of parameter can be graphically obtained from the calibration curve, as shown in Figure 6.

By mean of the abaci of Figures 5 and 6, it would be possible to select for every kind of mixable soil-binder mixture the molding technique that gives high quality specimens in a very quick and easy way only by measuring the workability of the material.

## 4 CONCLUSIONS

The results of the large laboratory study performed on eight types of natural soils confirm that the mixture's "workability" has a great influence on the mechanical and physical properties of the stabilised soil specimens. The results provide very useful operational abaci to select the molding technique that produces high quality specimens in function of the soil-binder mixture's workability.

The results obtained represent a useful data set for the correct selection of the molding technique for different kind of soils and mixing conditions headed for the international standardisation. This study represents a significant step forward towards the definition of highly required guidelines for the molding procedures of stabilised soil specimens as used in QC/QA processes for Deep Mixing applications.

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