Laboratory study on the molding techniques for QC/QA process of a Deep Mixing work

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KEYWORDS: Deep mixing, laboratory procedures, molding techniques, QC/QA process

ABSTRACT: An international collaborative study has been undertaken to establish common understanding of the key issues involved in Quality Control/Quality Assurance of Deep Mixing (DM) technique. Testing stabilised specimens is one of the core activities of the QC/QA process. A large laboratory testing program was undertaken to study the effect of different molding techniques on the mechanical and physical properties of stabilised specimens. The laboratory analysis were carried out on four types of natural soils, as found in Rome, stabilised with Portland cement. Twelve soil-binder mixtures were prepared by changing the initial water content of the soils and keeping the binder amount and the water/cement ratio constants. Three different molding techniques were employed namely Tapping, Rodding and No compaction. Unconfined compressive strength, q_u, and hydraulic conductivity tests have been carried out systematically at different curing times. Results show that the choice of the molding technique has considerable influence on the properties of the stabilised specimens for all analysed mixtures except for the liquid type ones were the effects are minor. The results represents a useful data set for the correct selection of the molding technique for different kinds of mixtures. This study underlines the importance of the definition of a guideline for the stabilised specimens test procedures, which greatly affect the QC/QA process.

1 INTRODUCTION

The deep mixing method blends binder materials with in-situ soil to improve the engineering properties of the ground. (Terashi, 1997; CDIT, 2002). The effectiveness of the construction process strongly depends on the fulfilment of Quality Control/Quality Assurance procedures. Laboratory testing of stabilised soils is a fundamental part of the QC/QA procedures and must be carried out during the entire process, from the preliminary bench scale tests to the pre-production and construction stage (Larsson, 2005). As part of a larger international collaborative study (Terashi & Kitazume, 2009), the effect of different molding techniques on the mechanical and physical properties of stabilised specimens was investigated. Four types of natural soils, as found in Rome, were used. Keeping the binder content constant three mixtures with different consistency were prepared for each soil by varying the water content. Laboratory vane test readings were used as indication of the mixture's consistency. Three different molding techniques were employed namely No compaction, Tapping and Rodding. Unconfined compressive strength, q_u, and hydraulic conductivity tests were carried out on the stabilised specimens at pre-set curing times. Considerations about the applicability of each molding technique with the consistency are presented in function of the "*Normalised q_u strength and wet density*" (q_{uN} and γ_N respectively) and "*q_u strength and wet density relative errors*" (E_{q_u} and E_γ respectively)(Grisolia et al., 2012).

Hydraulic properties of the treated soils were also analysed for the numerous geo-environmental applications linked to DM technology, such as the construction of low-permeability cut-off walls

(Al-Tabbaa et al., 2009). Lower permeability values were also related to the applicability of a molding technique for a specific soil-binder mixture.

2 LABORATORY INVESTIGATION

A large laboratory testing program on several soil-binder mixtures was undertaken to investigate the influence of different molding techniques on the engineering properties of treated soils such as unconfined compressive strength q_u, wet density γ, secant modulus E_{50} and hydraulic conductivity, k. More than 200 laboratory tests were carried out.

2.1 Materials

Four different natural soils typical of Rome's geological environment, namely Man made silty deposit (M), Clayey silty Sand (SC), Sand and Gravel (SG) and Pliocene Clay (PLC) Table 1) with different initial water content w_n (%) were tested. Each soil was sieved through a 9.5 mm 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. Portland cement was used as binder with a water to cement ratio w/c equal to 1. A constant cement content (defined as the weight of the introduced dry cement divided by the dry weight of the soil to be stabilised), a_c equal to 10% was used. The properties of the twelve soil-binder mixtures analysed are shown in Table 2.

Table 1. Soil properties.

Soil type	Natural water content, w_n (%)	Liquid Limit, w_L (%)	Plastic Limit, w_P (%)	Plastic Index, I_P (%)	Gravel content (%)	Sand content (%)	Silt content (%)	Clay content (%)	*USCS*
M	30	37	19	18	18	24	34	24	CL
SC	30	49	21	28	22	40	20	18	CL/ML
SG	8	14	-	-	33	40	14	13	SM
PLC	60	38	19	19	-	-	64	34	CL

Table 2. Testing conditions.

Grout properties: *w/c*=1; Cement content: a_c=10%.					
Group	Mixture	Angle of Torque (°)	Soil type	Mixture water content, w_m (%)	Cement/Mixture water, C/w_m(%)
Group 1	m1	0.8	M	48.34	19.2
	m2	1.0	SC	51.51	18.8
	m3	1.5	PLC	71.75	12.8
	m4	2.0	SG	16.24	55.1
Group 2	m5	3.3	SC	44.27	20.4
	m6	3.5	PLC	61.41	14.6
	m7	4.0	M	37.18	24.0
	m8	4.4	SG	15.09	59.3
Group 3	m9	8.3	SG	14.69	62.0
	m10	9.0	PLC	51.00	19.0
	m11	9.5	SC	39.38	22.8
	m12	15.0	M	26.01	34.6

Laboratory vane (ASTM D4648-00) readings were used as indications of the mixtures' consistency before the molding phase. The device used for the tests shown in Figure 3a has the vane shaft attached through the hollow upper shaft to a resettable pointer, which indicates the

"angle of torque" on a dial graduated in degree. For some mixtures, it was observed that the readings were affected by the presence of sandy or gravelly particles.
By changing the water content it was possible to produce for each soil three mixtures having different consistencies. The mixtures were then divided into three Groups according to the angle of torque values, as shown in Table 2. The effective total mixture water content, w_m (%) was also evaluated just before the molding phase. Cement to mixture water ratio, C/M_w (%) (ratio of the weight of dry cement to the weight of the total mixture water) was measured as well.

2.2 Laboratory procedures and testing methods

The stabilised soil was placed in plastic molds (cylindrical shape, 100 mm in height and 50 mm in diameter) in three layers. Three different molding techniques were employed, as shown in Figure 1:
_ *No Compaction, N.C.:* It simply consisted in placing the stabilized soil into the mold with a spoon.
_ *Tapping, TA.*: For each layer, the mold was tapped against the floor 50 times.
_ *Rodding, RO.:* It consisted in tamping each layer with a 8mm diameter steel rod and eventually pushing down the material attached to the rod. Number of poking per layer was set to 30.

A common kitchen mixer apparatus was adopted. The water content of the natural soil was adjusted to the prefixed value after which the soil was made homogeneous by mixing. The grout made by Portland cement and water was then added to the soil and they were mixed for 10 minutes, according to JGS 0821 (2000). The angle of torque and the effective total mixture content were determined just after these mixing operations. Afterwards the stabilised soil was placed into plastic molds and compacted using the molding techniques described before. The specimens produced were stored in special curing tanks at 95 % relative humidity and kept in a room at a controlled curing temperature of 20 °C. After curing times of 7 and 28 days, Unconfined compression and hydraulic conductivity tests were carried out.

(a) (b) (c) (d)

Figure 1. (a) Laboratory vane; (b) molding phases with No Compaction; (c) Tapping and (d) Rodding.

3 RESULTS

3.1 Unconfined compressive strength

The average q_u strength values obtained using different molding techniques for the investigated mixtures are shown in the Figures below. Duplicate samples were used for testing after curing time of 7 days, whereas triplicate samples for testing after 28 days. The ratio of q_u strength at 28 days to q_u strength at 7 days is between 1 and 2.4.

For Group 1 mixtures the strength gap between different molding techniques is significantly low and ranges from 5% to 12 % at 7 days and from 5% to 26% at 28 days (Figure 2). It can also be observed that for m1 and m2 mixtures the *N.C.* technique unexpectedly gave the higher q_u strength. This might be due to the segregation processes of gravel and sand particles that takes place for liquid type mixtures as a consequence of the compaction. This phenomenon as expected appears to be more evident for the *RO.* and *TA.* compacted specimens rather than for those molded with *N.C.* technique.

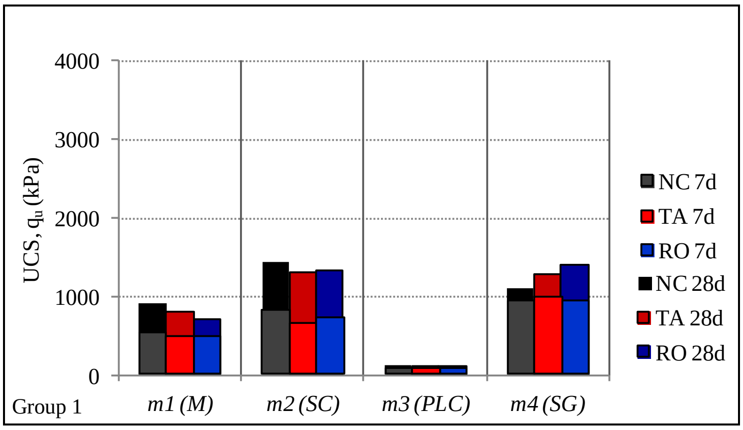


Figure 2. q_u strength vs Group 1 mixture for different molding techniques

The differences in the q_u strength between specimens molded with *N.C.* and those prepared with *TA.* or *RO.* increase with the consistency of the mixtures, passing from Group 2 to Group 3 mixtures, as shown in Figure 3 and Figure 4.

For Group 3 mixtures such differences after 28 days ranges from the 70% of the m9 mixture to about 200% of the m12 mixture. Similar differences were obtained for the same mixtures after 7 days.

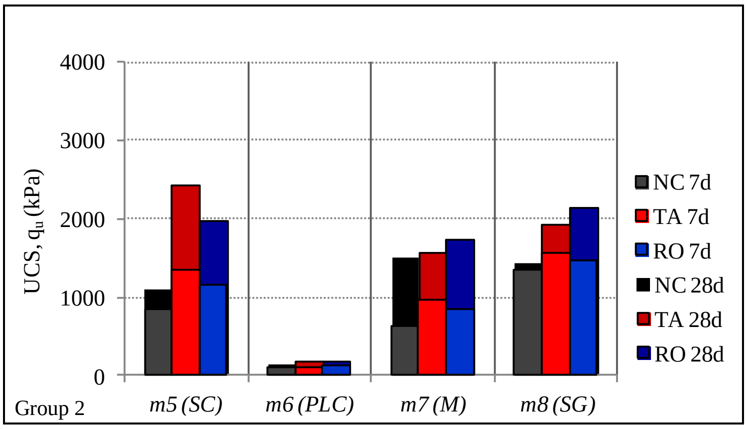


Figure 3. q_u strength vs Group 2 mixture for different molding techniques

Consistently with the results obtained by other authors (Taki and Yang, 1991; Bruce and Bruce, 2003) it was observed for the cohesive PLC soil, a considerably low q_u strength if compared to the ones obtained for other soils, which have a sand and gravel fraction higher than 40 %, thus giving higher strength.

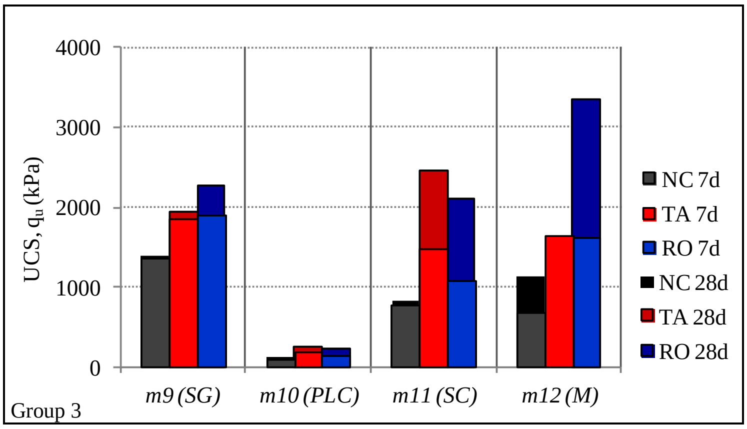


Figure 4. q_u strength vs Group 3 mixture for different molding techniques

3.2 Normalized q_u strength and wet density

It was considered that the suitability of a molding technique is related to the obtained mechanical properties of the specimens produced (highest q_u and wet density values). The q_u strength and wet density results for each molding technique were then normalised by the maximum measured values for the mixture (m#), as described in eq. (1) and (2):

Normalised q_u strength: $$q_{uN} = \left(\frac{q_u}{q_{u\max}}\right)_{m\#} \qquad 0 < q_{u_N} < 1 \qquad (1)$$

Normalised wet density: $$\gamma_N = \left(\frac{\gamma_u}{\gamma_{\max}}\right)_{m\#} \qquad 0 < \gamma_N < 1 \qquad (2)$$

These parameters are shown in Figures 5 for each mixture at 28 days.

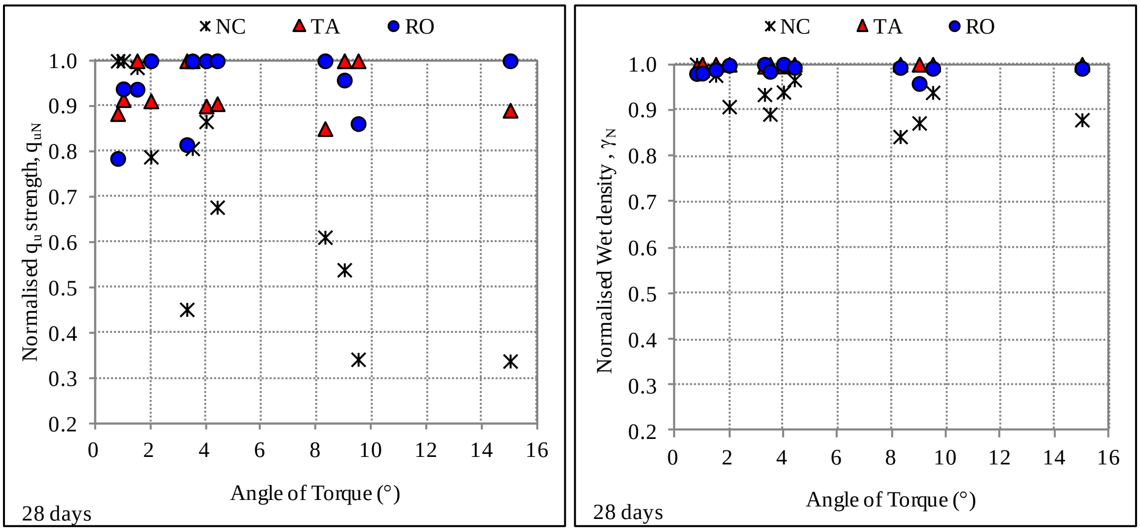


Figure 5. (a) Normalised q_u strength and (b) Normalised wet density for each mixture.

From Figure 5(a) it was possible to see some trends of the q_{uN} with the measured angle of torque. *RO.* and *TA.* technique are most applicable for all the mixtures, having q_{uN} values generally higher than 0.9. The *N.C.* technique is considered applicable only for the liquid type mixtures, since the q_{uN} values dramatically decreases for angle of torque higher than 1.5°. Figure 5(b) also shows that the molding technique has a lower influence on the wet density than that on the strength since all data obtained, excluding the *N.C.* results, are closer to 1. In general *TA.* and *RO.* techniques gave the highest results.

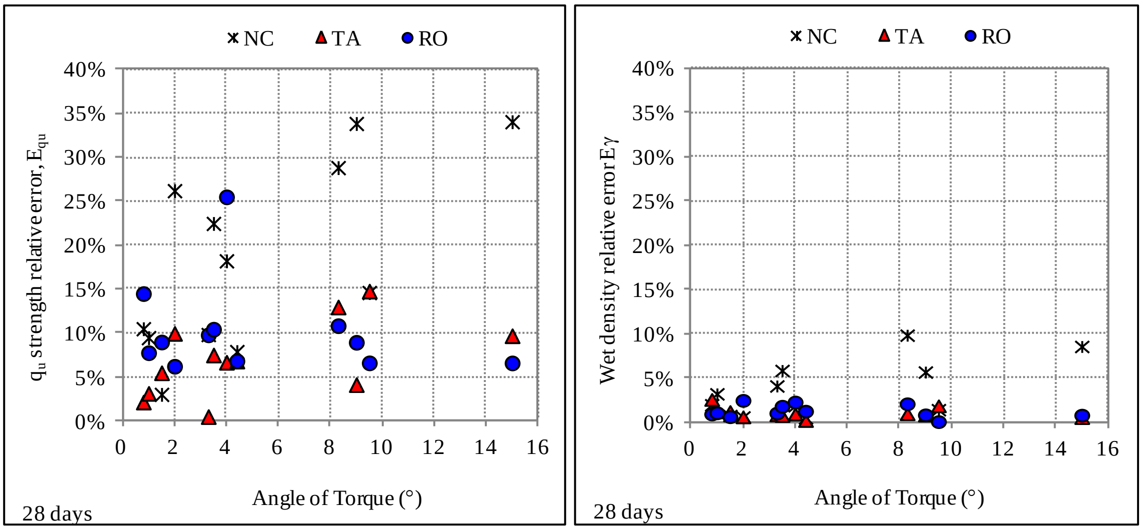
3.3 q_u strength and wet density relative errors

The q_u strength and wet density relative errors (E_{qu} and E_γ respectively) are defined as the difference between maximum and minimum values divided by the average ones, as shown in the following equations (3) and (4):

$$q_u \text{ strength relative error: } E_{qu} = \frac{q_{u\max} - q_{u\min}}{q_{uaverage}} \ (\%) \quad (3)$$

$$\text{Wet density relative error: } E_\gamma = \frac{\gamma_{\max} - \gamma_{\min}}{\gamma_{average}} \ (\%) \quad (4)$$

These parameters were used to evaluate the repetitiveness of the results in terms of minimum variation from the average value of the mechanical properties of the treated soil. E_{qu} and E_γ data are shown respectively in Figure 6 (a) and (b). *TA.* technique generally shows lower E_{qu} values for different mixtures. *TA.* and *RO.* techniques results are all below 15%. The unexpected high E_{qu} obtained for the *RO.* technique for the m7 mixture was probably due to operator error in the specimens preparation. E_{qu} obtained for the *N.C.* technique are generally higher, underlining the unsuitability of this technique especially in sticky mixtures. Small relative errors E_γ for all the employed molding techniques were registered, with *TA.* and *RO.* giving the lowest E_γ values.



(a) (b)

Figure 6. (a) q_u strength relative error and (b) Wet density relative error for each mixture.

3.4 Secant modulus E_{50}

The Secant modulus, E_{50}, defined as the ratio of 50 % of the failure stress to the corresponding strain, was also evaluated. The relationships between E_{50} and the q_u strength obtained for each Group of mixtures are shown in Figure 7 in relation to the different molding techniques. The data at 7 and 28 days are plotted. It was found the same overall relation, $40\ q_u < E_{50} < 170\ q_u$, for all Groups and techniques. This relation is consistent with those proposed for different soils by other authors such as Porbaha et al. (2000).

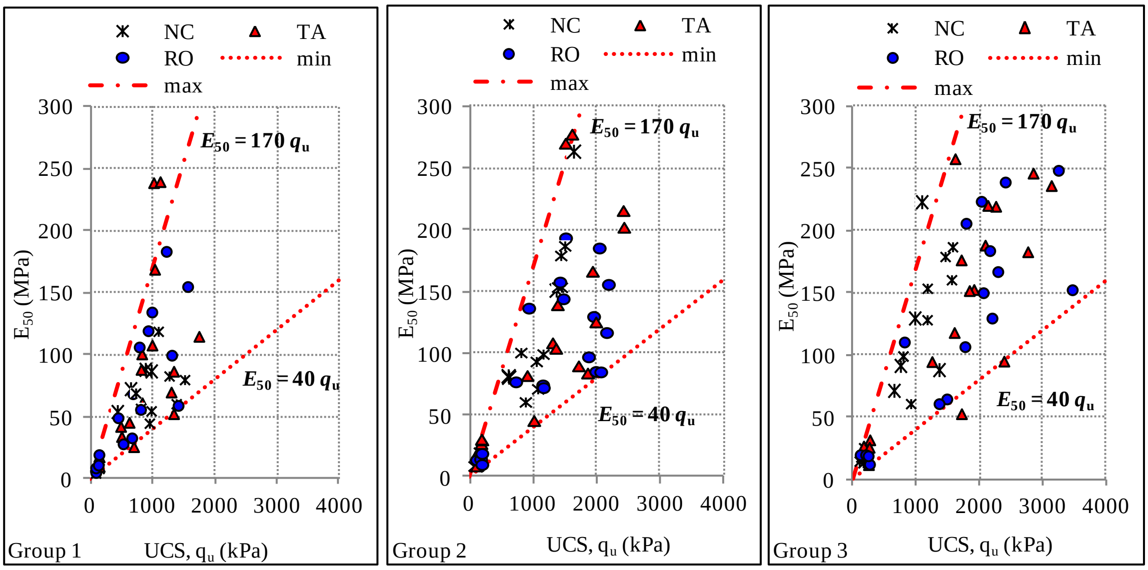
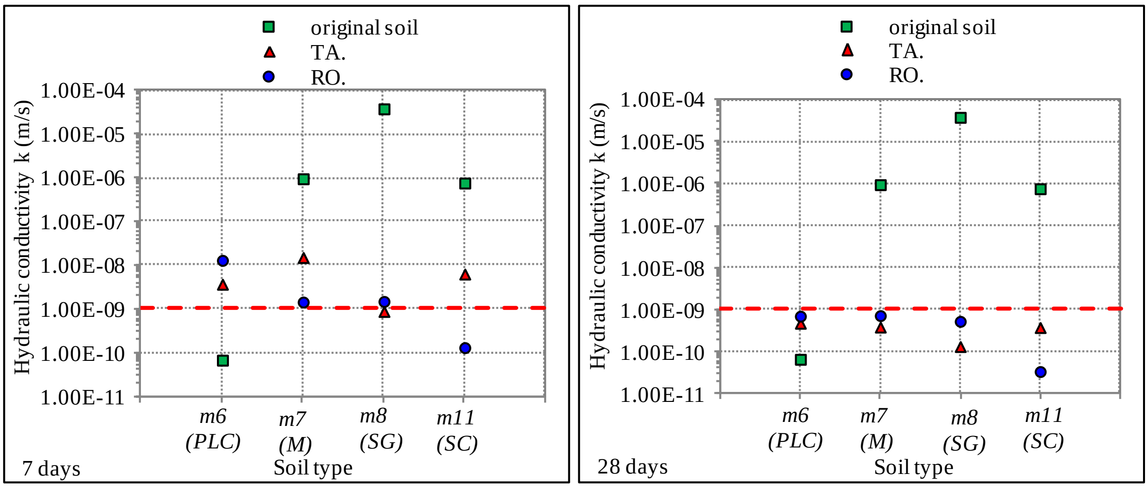


Figure 7. Relationships between E_{50} and q_u strength for the three Groups.

3.5 Hydraulic conductivity

The influence of the molding technique on the hydraulic conductivity was also investigated for the environmental applications of DM technology. A coefficient of permeability, *k*, of 10^{-9} m/s is generally required for permanent seepage control, i.e. waste and pollutant containment to prevent groundwater contamination. Hydraulic conductivity tests (ASTM D5084-00) were carried out on *TA.* and *RO.* specimens while those prepared with *N.C.* technique were not tested. Duplicate samples were used at both curing times. One mixture for each soil was tested at 7 and 28 days and coefficients of permeability obtained were compared with those of the original soil (Figure 8).



(a) (b)

Figure 8. Coefficient of permeability versus soil type at (a) 7 days and (b) 28 days.

Lower permeability values were related to the applicability of a molding technique for a specific mixture. It can be noticed that for m6, m7 and m8 mixtures, having similar angle of torque, *TA.* and *RO.*, techniques gave comparable results (within half order or magnitude) at 28 days, with *TA.* technique giving the lowest values and therefore the highest applicability. *RO.* technique has a better effect than *TA.* on hydraulic conductivity of the stiffer m11 mixture at both curing times.

The treatment increases the coefficient of permeability for the PLC soil compared to the initial value. This may happen because the usage of wet method in soil with high natural water content leads to an excessive amount of total water in the treated soil. Nevertheless, results show that the prescriptive *k* value of 10^{-9} m/s and less is achieved for all the soils and molding techniques after 28 days.

4 CONCLUSIONS

The influence of the molding technique on the mechanical properties of soil-binder mixtures was investigated. The technique associated to the highest strength and wet density values and to the highest repetitiveness was considered more applicable for a mixture. In general *TA.* and *RO.* techniques gave the highest applicability. The *N.C.* technique was never considered suitable for stiffer mixtures. It was found the same overall relationships between secant modulus and the q_u strength for all Groups and molding techniques. Hydraulic conductivity results pointed out that *TA.* and *RO.* techniques gave comparable results at 28 days for mixtures having similar angle of torque, while *RO.* technique had a better effect for the stiffer m4 mixture. Some preliminary indications on the selection of the correct molding technique to be employed for the stabilised soil specimens production were obtained. The study highlights the need to define a guideline for laboratory test procedures which are fundamental in the QC/QA process.

REFERENCES

Al-Tabbaa A., Barker P., Evans C.W. (2009) Innovation in soil mix technology for remediation of contaminated land. In Proceedings International Symposium on Deep Mixing & Admixture Stabilization, Okinawa, Japan, 19-21 May 2009. CD-ROM, IC-2.

ASTM D4648-00 (2000). Standard Test Method for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil. ASTM International, West Conshohocken, www.astm.org.

ASTM D 5084-00 (2000). Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter. ASTM International, West Conshohocken, www.astm.org.

Bruce, D. and Bruce M., (2003). The Practitioner's Guide to Deep Mixing. Proceedings of the Third International Conference on Grouting and Ground Treatment, New Orleans, ASCE Special Publication, Vol. 1, pp. 474-488.

Coastal Development Institute of Technology, CDIT (2002). The Deep Mixing Method - principle, design and construction, 123p.

Grisolia M., Kitazume M., Leder E., Marzano I.P., Morikawa Y. (2012). Laboratory study on the applicability of molding techniques for the preparation of cement stabilised specimens. International Symposium & short courses on Recent Research, Advances & Execution Aspects of ground improvement works, Brussels 2012.

JGS 0821-00 (2000). Practice for Making and Curing Stabilised Soil Specimens Without Compaction (Translated version). Geotechnical Test Procedure and Commentary, Japanese Geotechnical Society.

Larsson S. (2005), State of Practice Report – Execution, monitoring and quality control. Deep Mixing '05, volume 2.

Porbaha A., Shibuya S., Kishida T. (2000). State of the art in deep mixing technology. Part III: Geomaterial characterization. Ground Improvement, vol. 3, pp. 91-110.

Taki, O. and Yang, D. (1991). Soil Cement Mixed Wall Technique. Geotechnical Engineering Congress. American Society of Civil Engineers, New York, Special Publication 27, pp. 258-309.

Terashi, M. (1997). Deep Mixing Method – Brief State-of-the-Art. 14th International Conference on Soil Mechanics and Foundation Engineering, 4 pp. 2475-2478

Terashi, M. & Kitazume, M. (2009). Keynote Lecture: Current Practice and Future Perspective of QA/QC for Deep-Mixed Ground. In Proceedings International Symposium on Deep Mixing & Admixture Stabilization, Okinawa, Japan, 19-21 May 2009. CD-ROM, KL-3.