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Applicability of molding procedures in laboratory mix tests for quality control and assurance of the deep mixing method

Masaki Kitazume[a], Massimo Grisolia[b], Enrico Leder[b], Ignazio Paolo Marzano[b], Antonio Alberto S. Correia[c], Paulo J. Venda Oliveira[c], Helen Åhnberg[d], Mattias Andersson[d]

[a]*Tokyo Institute of Technology, Japan*
[b]*Sapienza University of Rome, Italy*
[c]*University of Coimbra, Portugal*
[d]*Swedish Geotechnical Institute, Sweden*

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Abstract

The deep mixing method (DMM) has been applied in many construction projects. The laboratory mix test is essential to the quality control and quality assurance (QC/QA) of deep mixing methods. The procedures used for the preparation of specimens in the laboratory mix test greatly affect the physical and mechanical properties of the stabilized soils. Different procedures are applied in different countries/regions. With the increasingly globalized DMM market, it is desirable that a common understanding of the nature of the laboratory mix test and internationally accepted guidelines to conduct it be established in order to guarantee the QC/QA of DMMs. As part of an international collaborative study, the influence of different molding techniques for the laboratory preparation of specimens was studied. Five different molding techniques were tested in four organizations. The results showed that the molding techniques considerably influenced the magnitude and variation of the unconfined compressive strength and the wet unit weight of the stabilized specimens. The applicability of the molding techniques was discussed in terms of their undrained shear strength and the liquidity index of the soil and binder mixture, and the usefulness of the techniques was demonstrated.

Keywords: Molding technique; Stabilized clay; Cement; Lime; Laboratory tests; Unconfined compressive strength; Deep mixing

1. Introduction

The deep mixing method (DMM), an in-situ admixture stabilization technique using cement and/or lime as a binder, has been applied in many construction projects for various improvement purposes (Kitazume and Terashi, 2013). The DMM was put into practice in Japan and the Nordic countries in the middle of the 1970s to improve soft deposits, and then spread into the USA, China, South East Asia and, recently, to other parts of the world.

The quality of deep-mixed soil (improved soil by in-situ mixing) depends upon a number of factors including the type and condition of the original soil, the type and amount of binder, and the production process. The practice of quality control and quality assurance (QC/QA), which focuses upon the quality of deep-mixed soil, was originally established in Japan and the Nordic countries and has been accepted worldwide for more than three decades. It is comprised of a laboratory mix test, field trial installation, monitoring and control of construction parameters during production and verification by measuring the engineering characteristics of

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the deep-mixed soil either by unconfined compression tests on core samples or by sounding. The diversification of application, soil type, and execution system, together with an improved understanding of the behavior of deep-mixed ground over the past two decades have made a revision of the current QC/QA practice necessary. A previous literature review and International Collaborative Study have revealed the similarity and differences in the QC/QA procedures employed in different parts of the world (Kitazume and Terashi, 2009; Kitazume et al., 2009a; 2009b).

Laboratory mix tests are essential to the QC/QA of deep mixing methods. The procedures used for the preparation of specimens in the laboratory mix test greatly affect the physical and mechanical properties of the stabilized soils. Different procedures are applied in different countries/regions (e.g. Japanese Geotechnical Society, 2009; EN 14679, 2005; EuroSoilStab, 2001; Carlsten and Ekström 1997; Åhnberg and Holm, 2009). In an increasingly globalized DMM market, it is desirable that a common understanding of the nature of the laboratory mix test and internationally accepted guidelines to conduct it be established, in order to guarantee the QC/QA of DMMs.

As part of an international collaborative study, the influence of different molding techniques for the preparation of specimens has been studied. This is one of the major themes currently being studied with the purpose of establishing common understanding of the key issues involved in the QC/QA of deep mixing works (Terashi and Kitazume, 2009; 2011). This part of the collaborative study was undertaken in four organizations, the Tokyo Institute of Technology, the Sapienza University of Rome, the University of Coimbra and the Swedish Geotechnical Institute, referred to as TIT, UR, UC and SGI, respectively, hereinafter.

The laboratory mix tests were carried out on regional soils with regional binders which were available in the collaborating organizations. The soil and binder mixtures with different initial water content and binder amounts, which changed their consistency, were molded using five molding techniques. Unconfined compression tests were performed on the specimens produced. The results showed that the molding techniques considerably influenced the magnitude and variation of the unconfined compressive strength and the wet unit weight of the stabilized specimens. The applicability of the molding techniques was analyzed by using two indices: the undrained shear strength and the liquidity index of the soil and binder mixture. The study showed that these indices may be useful tools to evaluate the applicability of the techniques. The test results have been partially presented earlier by each collaborator (Kitazume, 2012; Grisolia et al., 2012, 2013, Marzano et al., 2012, Åhnberg and Andersson, 2011, Miguel, 2011; Venda Oliveira et al., 2012). A more general picture covering a variety of soils and binders is presented and discussed in this paper in order to evaluate the applicability of the indices.

2. Testing program

The collaborating organizations, the Tokyo Institute of Technology, the Sapienza University of Rome, the University of Coimbra and the Swedish Geotechnical Institute, prepared stabilized soil samples using their own materials, binders and facilities and molded by some of the five molding techniques, namely tapping (*TP*), rodding (*RD*), dynamic compaction (*DC*), static compaction (*SC*) and no compaction (*NC*). The soil, binder and testing procedure adopted by each collaborating institution are briefly presented in the following sections.

Table 1
Geotechnical properties of Kaolin Clay.

Specific gravity, G_s	2.61
Liquid limit, w_L(%)	77.5
Plastic limit, w_P(%)	30.3
Plasticity index, I_P	47.2
Compression index, C_c	0.56
Swelling index, C_s	0.10
K_0	0.6
c_u/σ'_{vo}	0.24

2.1. Tokyo Institute of Technology (TIT)

2.1.1. Soil materials and binder

A Kaolin clay was stabilized and tested in unconfined compression, with ordinary Portland cement (OPC) (Japanese Industrial Standard, 2009) as a binder. The geotechnical properties of the Kaolin clay tested are summarized in Table 1.

2.1.2. Test procedure and program

In preparing the samples of stabilized soil, the soil was first homogenized thoroughly with the prescribed initial water content, $w_i = 120\%$. The dry form of the binder was then mixed with the soil for 10 min to make a uniform mixture. Immediately after mixing, the water content of the mixture was measured, and the undrained shear strength of the mixture was also measured using the hand vane apparatus. The stabilized clay was placed into plastic molds (cylindrical shape, 50 mm in diameter and 100 mm in height) in 3–6 layers. Four different molding techniques were used, as shown in Fig. 1:

(1) Tapping (*TP*) (see Fig. 1(a))
For each layer, the mold was tapped about 50 times against the floor, which followed the standard specified by the Japanese Geotechnical Society (2009).
(2) Rodding (*RD*) (see Fig. 1(b))
Performed using an 8 mm diameter steel rod and consisted in slowly tamping down (30 times) the mixture with the rod for each layer and, if necessary, pushing down the material attached to the rod.
(3) Dynamic compaction (*DC*) (see Fig. 1(c))
Each layer was compressed by the weight of a rod (1.6 kg) and compacted by a falling weight (0.6 kg) using a special apparatus. The fall height was set to 10 cm, and the number of blows to 5.
(4) Static compaction (*SC*) (see Fig. 1(d))
Each layer was statically compressed by the weight (4.82 kg, corresponding to a vertical pressure of 25 kPa) for 10 s using a heavy rod.

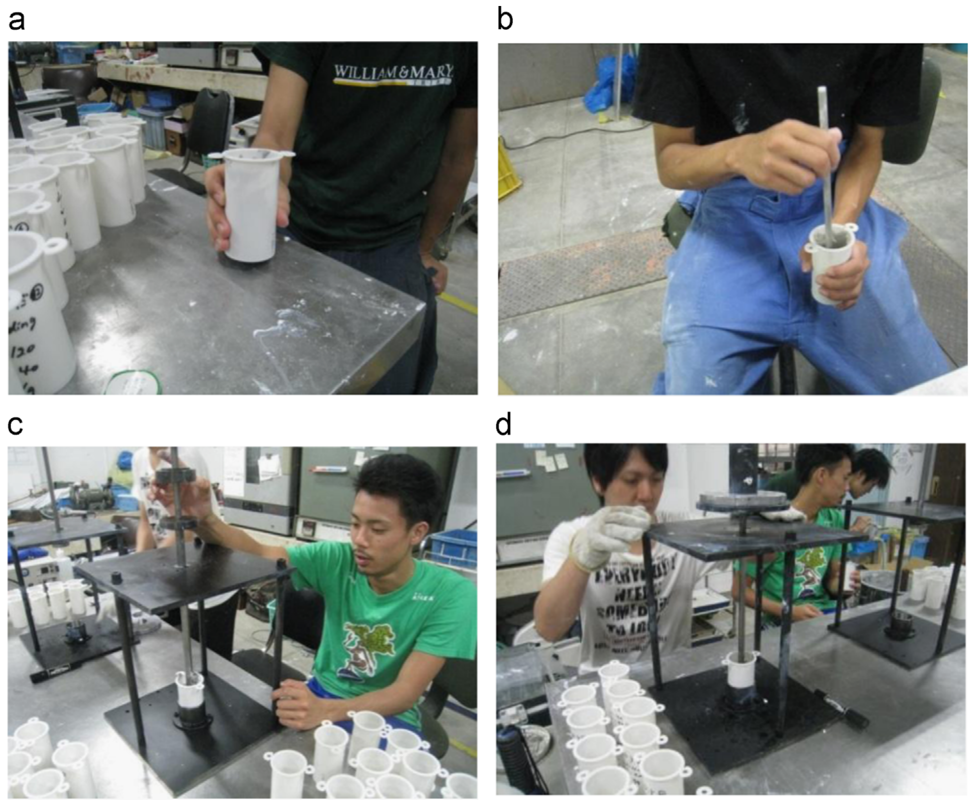

Fig. 1. Molding techniques (in TIT) (a) Tapping, (b) Rodding, (c) Dynamic compaction and (d) Static compaction.

Table 2
Soil properties.

	Kawasaki clay (KC)	Man made silty deposit (SD)	Silty clayey sand (SS)	Sand and gravel (SG)	Pliocene clay (PC)	Black Pozzolana (BP)	Red Pozzolana (RP)	Argillified Tuff (AT)
Specific gravity, G_s (dimensionless)	2.676	–	–	–	–	–	–	–
Natural water content, w_n (%)	57.0	30.0	30.0	8.0	60.0	30.0	32.0	52.0
Liquid limit, w_L (%)	48.6	37	49	–	38.0	–	–	34.0
Plastic limit, w_P (%)	29.6	19	21	–	19.0	–	–	25.0
Plasticity index, I_P (%)	19.0	18	28	–	19.0	–	–	9.0
Gravel content (%)	0	18.0	22.0	33.0	0.0	8.0	11.0	2.0
Sand content (%)	14.0	24.0	40.0	40.0	0.0	49.0	58.0	47.0
Silt content (%)	42.0	34.0	20.0	14.0	64.0	38.0	24.0	39.0
Clay content (%)	44.0	24.0	18.0	13.0	34.0	5.0	7.0	12.0

The binder contents, a_c (defined as the ratio of the dry weight of binder to the dry weight of soil), were 10%, 20%, 30% and 40% for each molding technique in this test series. Ten soil specimens were prepared for each mixing condition and molding technique; therefore, a total of 160 specimens were prepared. At 28 days of curing, the soil specimens were subjected to the unconfined compression test, in which the axial strain rate was 1%/min. The details of the test program and test results are described in the literature (Kitazume, 2012).

2.2. Sapienza University of Rome (UR)

2.2.1. Soil materials and binder

Eight types of soil were used in the study, a Japanese marine clay, identified as Kawasaki clay, and seven different natural Italian soils typical of Rome's geological environment. The soil properties are presented in Table 2. A total of 30 mixtures with different consistencies were tested. Specifically, Kawasaki clay with different initial water contents, w_i (72%, 66%, 60%, 54%

and 49%), was mixed with ordinary Portland cement in three binder contents, a_c (5%, 20% and 30%), and used to produce nine soil–cement mixtures with different consistencies. For each of the other soils, three different mixtures were produced, varying the initial water content and keeping the binder content, a_c (10%), constant.

2.2.2. Test procedure and program

A Hobart type mixer apparatus was adopted for the soil–binder mixing. After placing the natural soil in the mixer, the water content was adjusted to the desired value by adding water. The soil was homogenized by mixing, before adding the binder. The grout made of ordinary Portland cement (OPC) and water or the OPC in dry form was then added to the soil and mixed for 10 min in accordance with the Japanese Geotechnical Society (2009).

The hand vane shear strength and the water content of the mixture were measured just before the molding phase. The stabilized soil was then placed into plastic molds and compacted using the molding techniques as follows. The stabilized clay was placed in plastic molds (cylindrical shape, 50 mm in diameter and 100 mm in height) in three layers. Five different molding techniques were used:

(1) Tapping (*TP*)
For each layer, the mold was tapped 50 times (taken as a standard value) against the floor.
(2) Rodding (*RD*)
Performed using a 8 mm diameter steel rod and consisted in slowly tamping down (30 times) the mixture with the rod for each layer and, if necessary, pushing down the material attached to the rod.
(3) Dynamic compaction (*DC*)
Each layer was compacted by a falling weight (1.5 kg) using a special apparatus. Fall height was set to 10 cm, and the number of blows to 5.
(4) Static compaction (*SC*)
Each layer was statically compressed for 10 s by using a heavy rod, 49 mm in diameter. A pressure of 25 kPa was applied.
(5) No compaction (*NC*)
Simply consisted in filling the mold by either pouring or placing in the case of mixtures with a higher consistency.

Each mold was covered with a sealant and stored in a special curing room at 95% relative humidity to prevent water evaporation from the specimen. All the stabilized soils were molded in less than 45 min after the binder was added, according to, e.g., Kitazume and Nishimura (2009), in order to reduce the effects of hydration between the time of mixing with the binder and the completion of molding related with the mixture's consistency. After 28 days of curing time, the specimens were removed from the molds and then subjected to unconfined compression tests at an axial strain rate of 1.0%/min. Unconfined compression tests were conducted on triplicate samples for each case (soil type and molding procedure) analysed. The details of the test program and test results are referred to in the literature (Grisolia et al., 2012, 2013, Marzano et al., 2012).

Table 3
Baixo Mondego soil properties.

Specific gravity, G_s	2.57
Unit weight, γ (kN/m^3)	14.8
Natural water content, w_n (%)	80.9
Organic matter content, OM (%)	7.0
Liquid limit, w_L (%)	72.2
Plastic limit, w_P (%)	41.7
Liquidity index (%)	1.35
Sand content (%)	22.0
Silt content (%)	72.0
Clay content (%)	64.0
pH	3.7

2.3. University of Coimbra (UC)

2.3.1. Soil materials and binder

The soil used in this study is a Portuguese soft soil located in the center of Portugal at the estuary of the river Mondego (a region known as the “Baixo Mondego”, near Coimbra). At the sampling site the soft soil deposit has a thickness of 23 m, presenting a more or less uniform grain size distribution, with silt being the dominant fraction. The organic matter found in the entire thickness of the deposit has a major influence on its characteristics and behavior (Coelho, 2000; Venda Oliveira et al., 2010; Correia, 2011). At a depth of 2.5 m, the natural soil exhibits the characteristics presented in Table 3; it is classified as an organic silty-clayed soft soil with high plasticity, OH (ASTM D 2487, 1998).

The binder used in the study was a mixture of Portland cement type I 42.5R and ground granulated blast furnace slag. This binder composition was defined by Correia (2011) as one of the most suitable (mechanically and economically) for the chemical stabilization of the soil studied. These two binders were thoroughly mixed (in a weight proportion of 75/25, Portland cement/slag) in the dry state to obtain a uniform binder. Finally, this uniform binder, at a content rate of 15%, was mixed with the soil to produce the stabilized samples.

2.3.2. Test procedure and program

The molding technique adopted follows the laboratory procedure presented in EuroSoilStab (2001) with the modifications proposed by Correia (2011). The soil and the binder were thoroughly mixed using a mechanical mixer (Hobart, model N50) to obtain a uniform paste. The mixing time was set for 3 min and the mixing speed chosen was 136 rpm (Correia, 2011).

For each of the two molding techniques, the consistency of the soil was changed from the natural state (w_n = 80.9%) to water contents, w_i, of 89.6%, 98.2%, 105.9% and 113%. When it was necessary to increase the water content (to study the consistency of the soil), the water added to the soil was first mixed with the dry uniform binder producing a slurry, which was then mixed with the soil. Immediately after the mixing, the undrained shear strength of the mixture was measured using the hand vane apparatus.

The introduction and compaction of the uniform paste in the mold was done as described next. The inner surface of the mold had a thin film of grease. A non-woven geotextile porous disc was placed at the bottom of the mold. The uniform paste was introduced in 6 layers (with a thickness/diameter ratio equal to 0.5). The paste in each layer was tapped by hand, subjected to vibrations by the application of a hand drill with a steel bar near the inner surface of the mold, compacted or not with 100 kPa for 10 s and finally, the surface was lightly scarified and another layer was introduced. After the 6 layers were introduced, a non-woven geotextile porous disc was placed on the top, upon which a vertical curing pressure of 24 kPa was applied. Immediately after, the mold with the sample was stored under water (temperature$=20\pm2$ °C) during the curing time (28 days).

The molding technique with static compaction (100 kPa applied for 10 s on each of the 6 layers) was not used on the samples with water contents greater than 89.6%, because there was soil loss during the compaction of each layer.

The mold is made from polypropylene random copolymer (PP-R) pipes, with an internal diameter of 50.8 mm. The mold has a height of 330 mm, which accommodates a $\pm$140 mm high sample and the remaining height of the mold serves as a guide for the dead load, corresponding to a vertical pressure of 24 kPa. The mold has two holes near the top in order to allow the sample to be submersed. The study involved the production of 5 specimens for each test condition. In total, 35 specimens were tested, 10 for the molding technique with static compaction (*SC*), and 25 for the molding technique with tapping (*TP*).

At 28 days of curing, the soil specimens were subjected to the unconfined compression test at an axial strain rate of 1%/min. The details of the test program and test results are described in the literature (Miguel, 2011; Venda Oliveira et al., 2012).

2.4. Swedish Geotechnical Institute (SGI)

2.4.1. Soil materials and binder

Two types of clay were used in the laboratory tests. One of the clays was from Kattleberg, east of the Göta river valley in the western part of Sweden, and the other was from Munkedal, in the province of Bohuslän on the west coast of Sweden. The Kattleberg clay is a quick clay with a liquid limit of about 66% and a natural water content, w_n, of 102%. The Munkedal clay is a low plastic clay with a liquid limit of about 40% and a natural water content, w_n, of 44%. Results from the laboratory characterization of the test soils are presented in Table 4.

The binder used was a combination of cement and quicklime in a 50:50 proportion by weight. The amount of binder mixed into the soils corresponded to 90 kg/m^3 ($a_c=9\%$ and 12%) in the Kattleberg clay and 80 kg/m^3 ($a_c=4\%$) in the Munkedal clay.

2.4.2. Test procedure and program

The soil was first homogenized thoroughly and the dry binders were then mixed into the soil for 5 min to prepare the stabilized samples. To study the effect of the consistency of one of the clays, part of the homogenized Kattleberg clay was air dried to a lower water content of 61% before adding the binder. With the exception of the molding methods used, the stabilized soil specimens were prepared in accordance with common procedures for stabilized soil in Sweden (Carlsten and Ekström, 1997; EuroSoilStab, 2001). The plastic limit, liquid limit, water content and the undrained shear strength of the materials were determined before initiating the molding to obtain an indication of the consistency of the soil–binder mixtures during molding. The undrained shear strength of the mixture was measured using the fall cone apparatus. Taking into account the reduced water content, after adding the binders, in relation to the w_P and w_L of the soil, the liquidity index was 1.35, 0.68 and 0.81 and the undrained shear strength was 7, 58 and 48 kPa in the mixtures with Kattleberg natural clay, Kattleberg partially dried clay and Munkedal clay, respectively.

Table 4
Properties of Kattleberg clay and Munkedal clay.

	Kattleberg clay	Munkedal clay
Depth (m)	4.5	5
Unit weight (Mg/m^3)	1.45	1.83
Specific gravity (Mg/m^3)	2.68	2.72
Water content (%)	102	44
Plastic limit (%)	26	19
Liquid limit[a] (%)	66	40
Undrained shear strength[a] (kPa)	10	25
Sensitivity	150	30
Organic content[b] (%)	0.8	1.8
Clay content (%)	70	46
Clay mineralogy	Illitic	Illitic
pH	8.6	8.3

[a]Determined by the fall cone test (ETC5. 1998; SIS 2007).
[b]Determined by colorimetric method (Swedish standard, 1990).

Five specimens of each type were prepared. The molds used were plastic tubes commonly used for piston sampling in Sweden, with a diameter of 50 mm and a height of 170 mm. The molding of stabilized specimens was varied:

(1) Tapping (*TP*)
Tapping of the mold was performed 30 times for each of the approximately 30 mm thick layers of soil–binder mixture put into the mold. The filling was performed in four layers.
(2) Rodding (*RD*)
A rod was used to evenly compact/smooth out each 20–30 mm thick layer of the soil–binder mixture by hand.
(3) Static compaction (*SC*)
A static pressure of 100 kPa was applied for 5 s to compress and squeeze out air pockets from each approximately 30 mm thick layer of soil–binder mixture. This is common procedure for molding stabilized clay in Sweden.

The molding of the specimens for the different test series was completed within 30 min after mixing. The stabilized soils were cured for 28 days in a climate controlled room at a temperature of 7 °C before testing their unconfined compressive strengths. The unconfined compression tests were performed at an axial strain rate of 1.5%/min. The wet unit weight and the water content of the specimens were also determined. The test program and test results are described in more detail by Åhnberg and Andersson (2011).

3. Test results

Some of the test results obtained at each collaborating organizations are briefly described here and are followed by comparisons and discussions of the data in the next section. All stabilized specimens presented here were cured for 28 days. Focus is given to the molding technique despite the fact that, independently of the molding technique, as the binder content increases or the water content decreases the wet unit weight and the unconfined compressive strength increase.

3.1. Observation of specimens

Fig. 2 shows typical examples of the specimens produced by the various molding techniques at the various organizations. The uniformity of the specimens is variable depending on the molding techniques, the soil type and mixing conditions.

3.2. Tokyo Institute of Technology (TIT)

3.2.1. Wet unit weight

Fig. 3 shows the wet unit weight of the stabilized soil for four different molding techniques. In this test case, the binder content was changed, while the initial water content was kept constant at 120%. The figure shows that the highest wet unit weight is found in the tapping technique, irrespective of the binder content. The static compaction technique gives the smallest wet unit weight, which is confirmed by observation of the specimens (Fig. 2a).

3.2.2. Unconfined compressive strength

The unconfined compressive strength, q_u, of the specimens is plotted in Fig. 4. A clear hierarchy is observed, with the tapping technique registering the highest strength as long as the binder content is lower than 40%. This phenomenon is consistent with the wet unit weight of the samples as shown in Fig. 3. However, in the case of the binder content of 40%, the rodding technique registers the highest strength, while the strength of the dynamic compaction and static compaction techniques are almost of the same order as for the tapping technique; these results are not in accordance with the wet unit weight and the observations of the specimens. The results clearly show that for such an amount of binder (40%) there is a change in the fabric of the stabilized material, which is no longer a soil fabric with binder, but the beginnings of a soil fabric completely welded by the binder or similar to a binder paste (Horpibulsuk, 2001; Correia, 2011). The figure shows the strength development for all techniques except tapping.

3.3. Sapienza University of Rome (UR)

The results presented in this section refer to the Kawasaki clay and to the test series where the initial water content is changed (w_i=72%, 66% and 60% for A-m1, A-m2 and A-m3, respectively), while the binder content was kept constant (a_c=5%). The results for the other soils are presented and discussed in the next section.

3.3.1. Wet unit weight

Fig. 5 shows an example of the effect of the molding technique on the sample's wet unit weight. The wet unit weight is not so different irrespective of the molding technique, except for the no compaction technique. The figure shows that the highest wet unit weight is found in Test series A-m3 (w_i=60%), with the exception of the dynamic compaction technique for which the highest density is found in Test series A-m2 (w_i=66%). As expected for saturated samples, the wet unit weight decreases with the increment of the initial water content because the density of the water is lower than for solid particles.

3.3.2. Unconfined compressive strength

Fig. 6 shows the unconfined compressive strength in order to clarify the influence of the molding technique. The figure shows that the highest strength is found in the tapping technique irrespective of the initial water content. It is interesting to note that the dynamic compaction technique provided comparatively small q_u values even if the Test series A-m2 has the highest wet unit weight as shown in Fig. 5. The smallest strength is obtained from the no compaction technique and it may also be observed that the strength is almost independent of the initial water content. The unconfined compressive strength values are in accordance with the findings of e.g. Horpibulsuk, 2001; Lorenzo and Bergado, 2004, 2006; Horpibulsuk et al., 2003, 2011; Correia, 2011; Correia et al., 2013 for stabilized soils with a high water content ($\geq w_L$), i.e., for a constant binder content, a_c, the q_u decreases as the initial water content increases and the added total amount of binder, in kg/m^3, decreases (as a consequence of the decrease in wet unit weight).

3.4. University of Coimbra (UC)

3.4.1. Wet unit weight

Fig. 7 shows an example of the effect of the molding technique on the wet unit weight of a stabilized soil. In this test series, the initial water content is changed, while the binder content was kept constant at 15%. The wet unit weight of the sample produced by the static compaction technique is almost the same as those by the tapping technique, irrespective of the initial water content.

3.4.2. Unconfined compressive strength

Fig. 8 shows the unconfined compressive strength, q_u, in order to clarify the influence of the molding technique. The figure shows that the q_u of the static compaction is somewhat smaller than that of the tapping technique in the case of the initial water content of 80.87% but slightly higher in the case of 89.56%, while the wet unit weight of the samples was almost the same.

3.5. Swedish Geotechnical Institute (SGI)

3.5.1. Wet unit weight

Fig. 9 shows the measured wet unit weight of the stabilized clay specimens (identified as series 1a, 1b and 2, respectively, for Kattleberg natural clay, Kattleberg partial dried clay and Munkedal clay). There is a clear difference in the wet unit

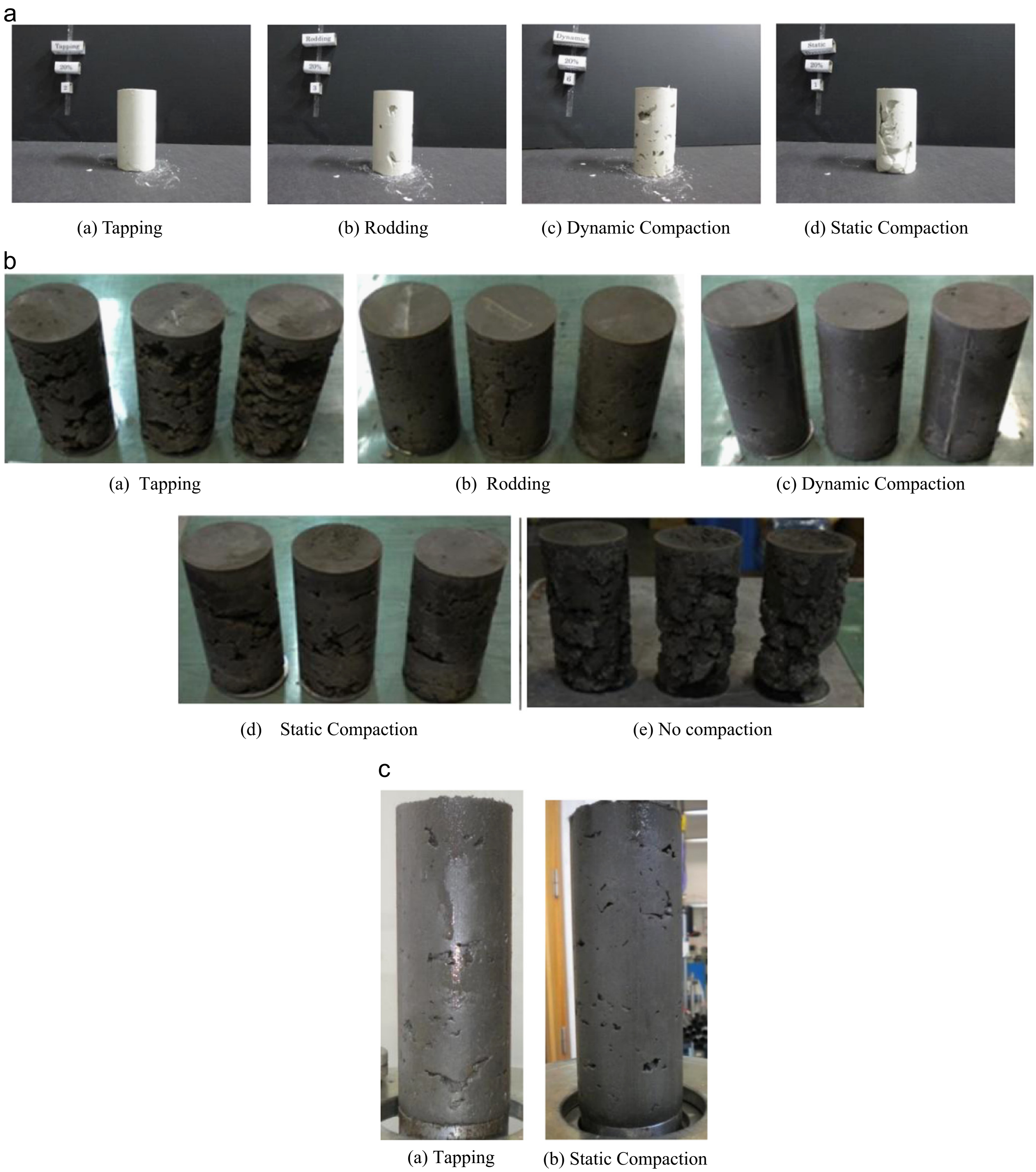

Fig. 2. Observations of specimens (a) Kaolin clay, $w_i = 120\%$, $a_c = 10\%$ (TIT), (b) Kawasaki clay, $w_i = 54\%$, $a_c = 30\%$ (UR) and (c) Baixo Mondego soil, $w_i = 80.9\%$, $a_c = 15\%$ (UC)

weight for specimens of the partially dried Kattleberg clay (series 1b) prepared with the different molding techniques, with the highest wet unit weight achieved by using the rodding technique. For the natural, non-dried Kattleberg clay (series 1a), the use of a rod resulted in a slightly lower wet unit weight than the other two methods. However, this phenomenon may partly be due to the effect of a slight loss in water content during the compaction of this material with the latter methods. For the Munkedal clay (series 2), the difference in wet unit weight was small when using the different methods.

3.5.2. Unconfined compressive strength

Fig. 10 shows the measured compressive strength 28 days after stabilization using the different molding techniques. For

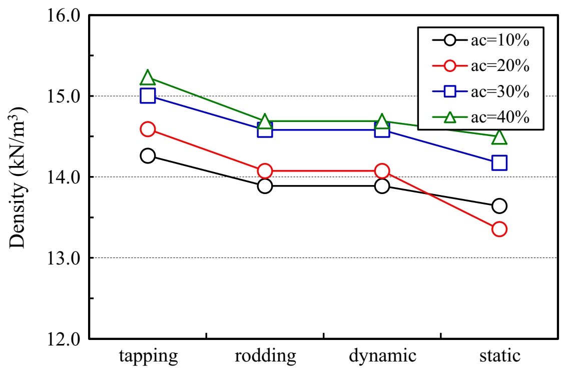

Fig. 3. Influence of molding technique on wet density (TIT).

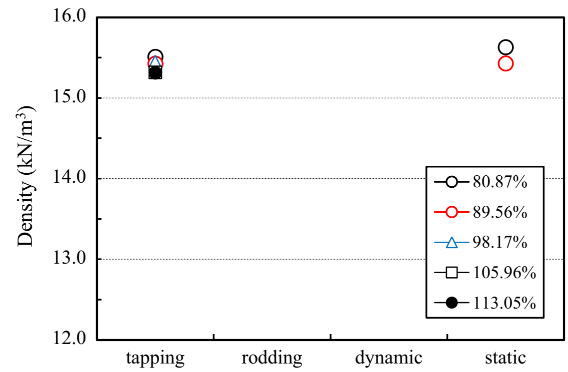

Fig. 7. Influence of molding technique on wet density (UC).

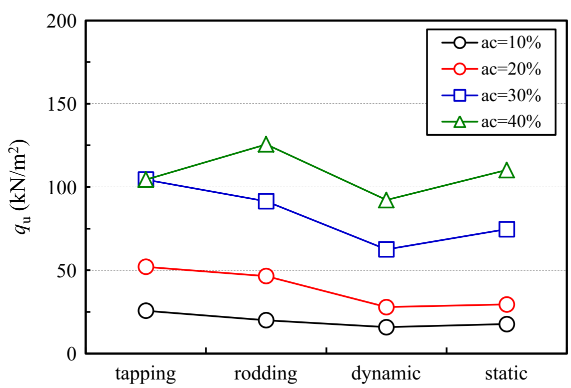

Fig. 4. Influence of molding technique on unconfined compressive strength (TIT).

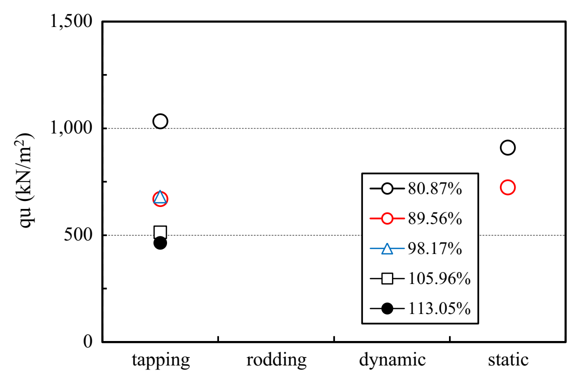

Fig. 8. Influence of molding technique on unconfined compressive strength (UC).

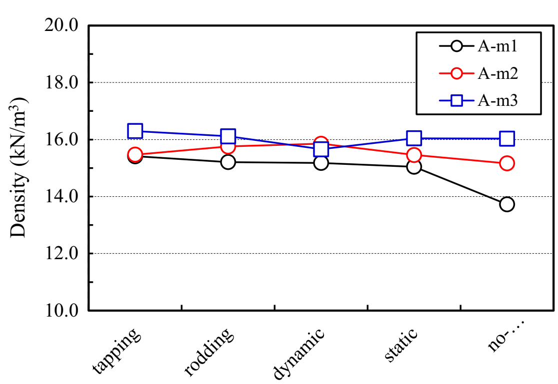

Fig. 5. Influence of molding technique on wet density (UR).

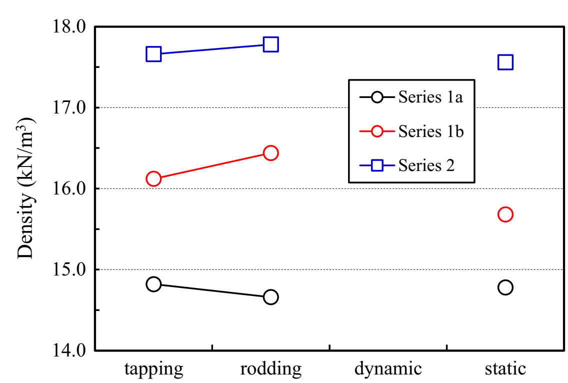

Fig. 9. Influence of molding technique on wet density (mean values) (SGI).

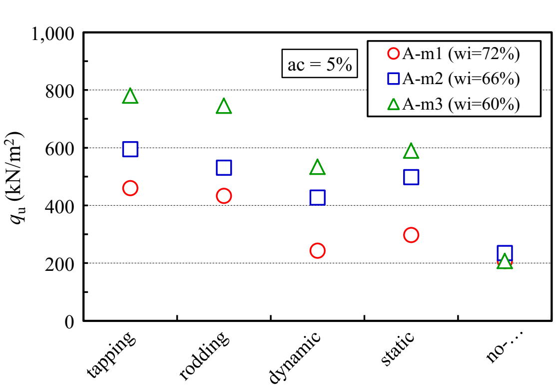

Fig. 6. Influence of molding technique on unconfined compressive strength (UR).

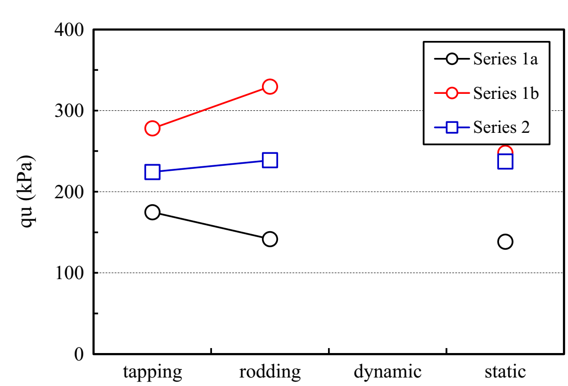

Fig. 10. Influence of molding technique on unconfined compressive strength (mean value) (SGI).

the natural, non-dried, Kattleberg clay–binder mixtures (series 1a), the strength was highest when preparing specimens by tapping. For the Kattleberg clay–binder mixture with reduced water content (series 1b), as well as the Munkedal clay–binder mixture (series 2), the strength was the highest when using the rodding technique. Using the static compaction technique resulted in about the same, or only slightly lower strength, as when using the rodding technique in the Munkedal clay and the Kattleberg natural wet clay.

4. Discussion

As shown in Figs. 2–10, the improvement induced by the cement-based stabilization varies considerably among the cooperating organizations, since the soil type and binder type studied are quite different. The wet unit weight ratio and strength ratio, with respect to that of the tapping technique, are discussed in this section instead of their absolute magnitudes for a general analysis covering the variety of soils and binders.

4.1. Relationship between wet unit weight ratio and strength ratio

Fig. 11 shows the relationship between the strength ratio and the wet unit weight ratio of the stabilized soil prepared using the various molding techniques in the four organizations. In the cases of the rodding, dynamic and static compaction techniques, the strength ratio increases almost linearly with the wet unit weight ratio, irrespective of the organization. The increment of the strength ratio against the wet unit weight ratio in the rodding technique is somewhat larger than the two other techniques. In the case of no compaction, the strength ratio and the wet unit weight ratio are almost always smaller than 1, without a clear trend, which clearly indicates the poor quality of the specimens and the inadequacy of the molding technique.

Fig. 12 shows all the data for comparing the effects of the molding technique on the relationship between the strength ratio and the wet unit weight ratio. Again, although there is a large scatter in the data, the strength ratio increases with the wet unit weight ratio, irrespective of the molding technique, but the increment ratio is slightly different depending on the molding technique; the largest increment can be seen in the rodding technique.

4.2. Effect of the undrained shear strength of the mixture

According to previous studies (e.g. Grisolia et al., 2012, 2013, Marzano et al., 2012), the consistency of the soil and binder mixture is one critical factor to take into account when evaluating the applicability of a molding technique. In this section, the undrained shear strength of the mixture (c_u) is selected to evaluate the consistency. The undrained shear strength of the mixture was measured immediately after mixing the soil and binder by one of the two methods: the hand vane apparatus in TIT, UR and UC, and

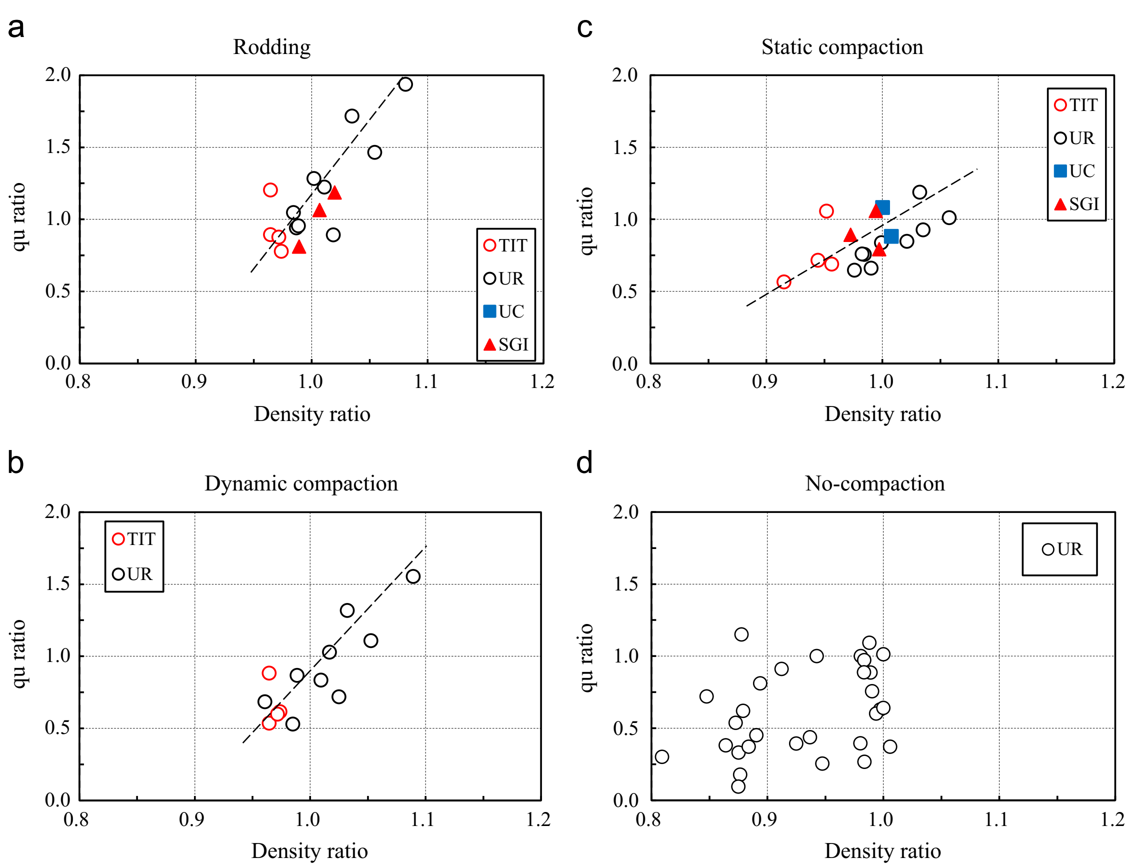

Fig. 11. Relationship between the strength ratio and the density ratio. (a) Molded by rodding technique, (b) molded by dynamic compaction technique, (c) molded by static compaction technique, and (d) molded by no compaction technique.

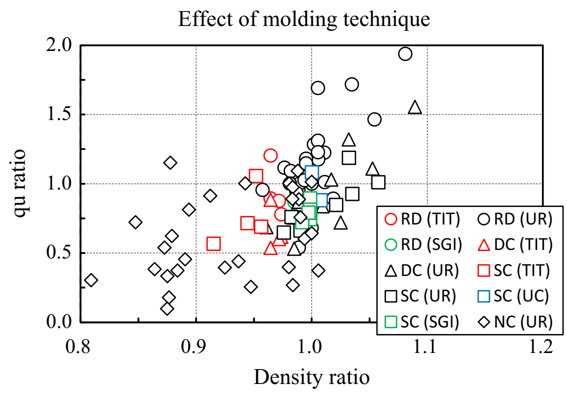

Fig. 12. Relationship between the strength ratio and the density ratio (all data).

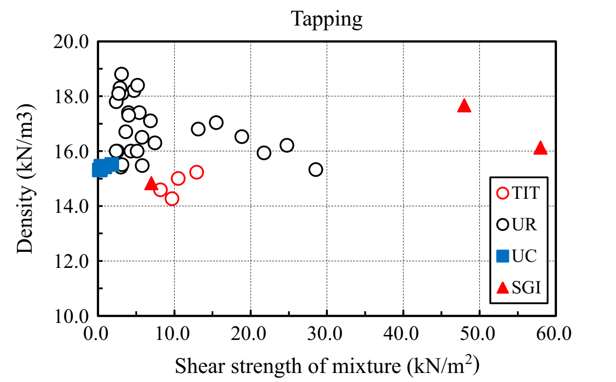

Fig. 13. Relationship between wet density of sample and undrained shear strength of mixture for the tapping technique.

the fall cone apparatus in SGI. Here, the effect of the undrained shear strength of the mixture is discussed as an index of the mixture's consistency.

4.2.1. Wet unit weight

4.2.1.1. Density ratio. Fig. 13 shows the relationship between the wet unit weight and the undrained shear strength of the mixtures for the tapping technique. The wet unit weight is almost within the range of 14–17 kN/m^3, depending on the type of soil and the binder type and quantity. There is a general increase in density with the increasing mixture's shear strength for the specimens containing the same soil type with varying binder content and water content, as might be expected if homogeneously molded. A slightly less effective molding is indicated for the UR specimens with the higher undrained shear strength of about 15–30 kPa.

Fig. 14 shows the relationship between the wet unit weight ratio and the undrained shear strength of the soil binder mixture. In the rodding technique, the ratio slightly decreases to about 0.95 at the undrained shear strength of about 10.0 kPa but then increases almost linearly to about 1.1 with the undrained shear strength. However, the SGI ratio shows only small changes in the wet unit weight ratio with a slightly lower wet unit weight, compared to tapping at low undrained shear strength, but somewhat higher at high undrained shear strength values. It should be noted that the shear strength values in this case are approximate values evaluated from the fall-cone method, which is an indirect method commonly used for natural clays, here used without corrections for any possible effects of the binders in the soil. In the dynamic compaction technique, the wet unit weight ratio is around 1.0 with a relatively large scatter when the undrained shear strength is lower than about 15 kPa, but increases linearly with the undrained shear strength, in a similar way to the rodding technique. In the static compaction technique, similar phenomenon to the rodding technique can be seen, but now the ratio decreases to about 0.9–0.95 at the undrained shear strength of about 10 kPa, increasing linearly again with the undrained shear strength. In the case of the no compaction technique, the wet unit weight ratio seems to decrease to about 0.8 with a slight increment of the undrained shear strength of the mixture, always remaining less than 1.0.

It is observed that, generally, for undrained shear strengths lower than about 15 kPa the wet unit weight is of the same magnitude ($\pm$5%) or slightly lower for the rodding, dynamic and static compaction techniques compared to the tapping, while for higher undrained shear strength values between 15 and 30 kPa (UR soil with high binder content), the wet unit weight ratio increases linearly with the undrained shear strength (up to 10%). A somewhat higher wet unit weight is seen for the rodding technique, compared to that of the tapping, at high mixture strengths of the SGI low water content soils, whereas the static compaction technique displays somewhat lower ratios. In general, the wet unit weight is lower than tapping (up to 20%) for the no compaction technique, and seems to decrease with the increment of the mixture's undrained shear strength.

4.2.1.2. Coefficient of variation in density. Fig. 15 shows the relationship of the coefficient of variation (COV) of the wet unit weight with the undrained shear strength of the mixture. For the tapping and rodding techniques, the COV remains quite small, less than 2% and is almost constant irrespective of the undrained shear strength. For the dynamic compaction technique, the COV is higher when the undrained shear strength is less than about 10 kPa, but decreases to about 1%, or lower, at a mixture strength of about 15–30 kPa. For the static compaction and no compaction techniques, the COV is quite large, irrespective of the undrained shear strength value, reflecting the non-homogeneity of the specimens produced by such molding techniques.

4.2.2. Unconfined compressive strength

4.2.2.1. Strength ratio. Fig. 16 shows the relationship between the unconfined compressive strength and the undrained shear strength of the soil binder mixtures for the tapping technique in each of the samples. Considerable differences can be seen in the strength, q_u, depending on the type of soil and mixing conditions (type and amount of binder). The same pattern as that for the wet unit weight can be observed; the strength increases with the undrained shear strength of mixture (for specimens containing the same soil type with varying binder content and water content). This

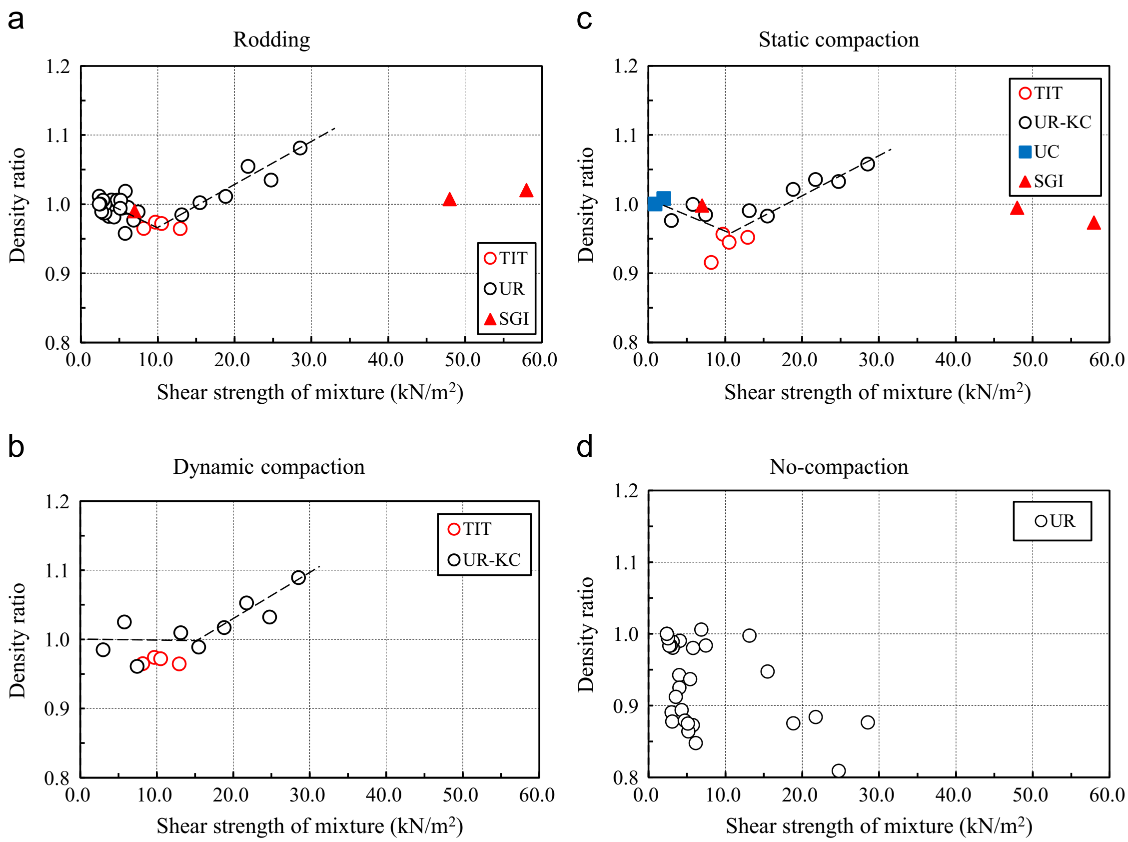

Fig. 14. Relationship between density ratio of sample and undrained shear strength of mixture. (a) Molded by rodding technique, (b) molded by dynamic compaction technique, (c) molded by static compaction technique, and (d) molded by no compaction technique.

trend is inverted with a decrease in strength for mixture strengths between 15 and 30 kPa (UR soil with high binder content).

Fig. 17 shows the relationship between the strength ratio of 28 day cured samples and the mixtures' undrained shear strength. With the rodding technique, the strength ratio has a large scatter when the undrained shear strength of the mixture remains lower than about 10 kPa, but increases almost linearly with the undrained shear strength (UR soil with high binder content) up to about 2.0. In the dynamic compaction technique, the strength ratio is around 0.5 when the mixture's undrained shear strength is less than about 10 kPa, and increases almost linearly with the undrained shear strength. In the static compaction technique, the strength ratio slightly decreases from 1.0 to 0.5 with the increment of the undrained shear strength of mixtures up to 10 kPa but for higher undrained shear strength of mixtures, the strength ratio increases almost linearly to about 1.0. In the case of the no compaction technique, the strength ratio sharply decreases linearly with the increment of the mixture's undrained shear strength. The strength ratio has a quite small value, in the order of 0.25, when the undrained shear strength of mixture is greater than 15 kPa.

4.2.2.2. Coefficient of variation of the unconfined compressive strength. Fig. 18 shows the coefficient of variation of the unconfined compressive strength after 28 days and the mixtures' undrained shear strength. In the tapping and rodding techniques, the COV remains comparatively small (less than about 18% and 15%, respectively) and almost constant, irrespective of the mixtures' undrained shear strength. In the dynamic compaction technique, the COV is relatively large, in the order of 20%, for the low undrained shear strength of the mixtures (less than about 10–15 kPa), decreasing to values in the order of 5% for the higher undrained shear strength of the mixtures. In the static compaction technique, the COV is in the order of up to 10%, irrespective of the mixture's undrained shear strength, except for some TIT test data. In the no compaction technique, the COV is quite large, in the order of 20–30%, and seems to decrease slightly with the increment of the undrained shear strength of the mixtures.

4.3. Applicability and reliability of the molding technique in preparing the stabilized soil sample

As shown above, the wet unit weight and unconfined compressive strength are considerably influenced by the molding technique as well as the mixture's undrained shear strength. From the point of view of the quality control/quality assurance of the deep mixing method, the laboratory mix testing program is conducted to determine the mixing condition, namely the type and amount of binder, to ensure it fulfills the strength requirements of the design in the field. Therefore, the laboratory test procedure to prepare stabilized soil samples should, in principle, be the same as those in the field. However, as the field strength is considerably influenced by the mixing

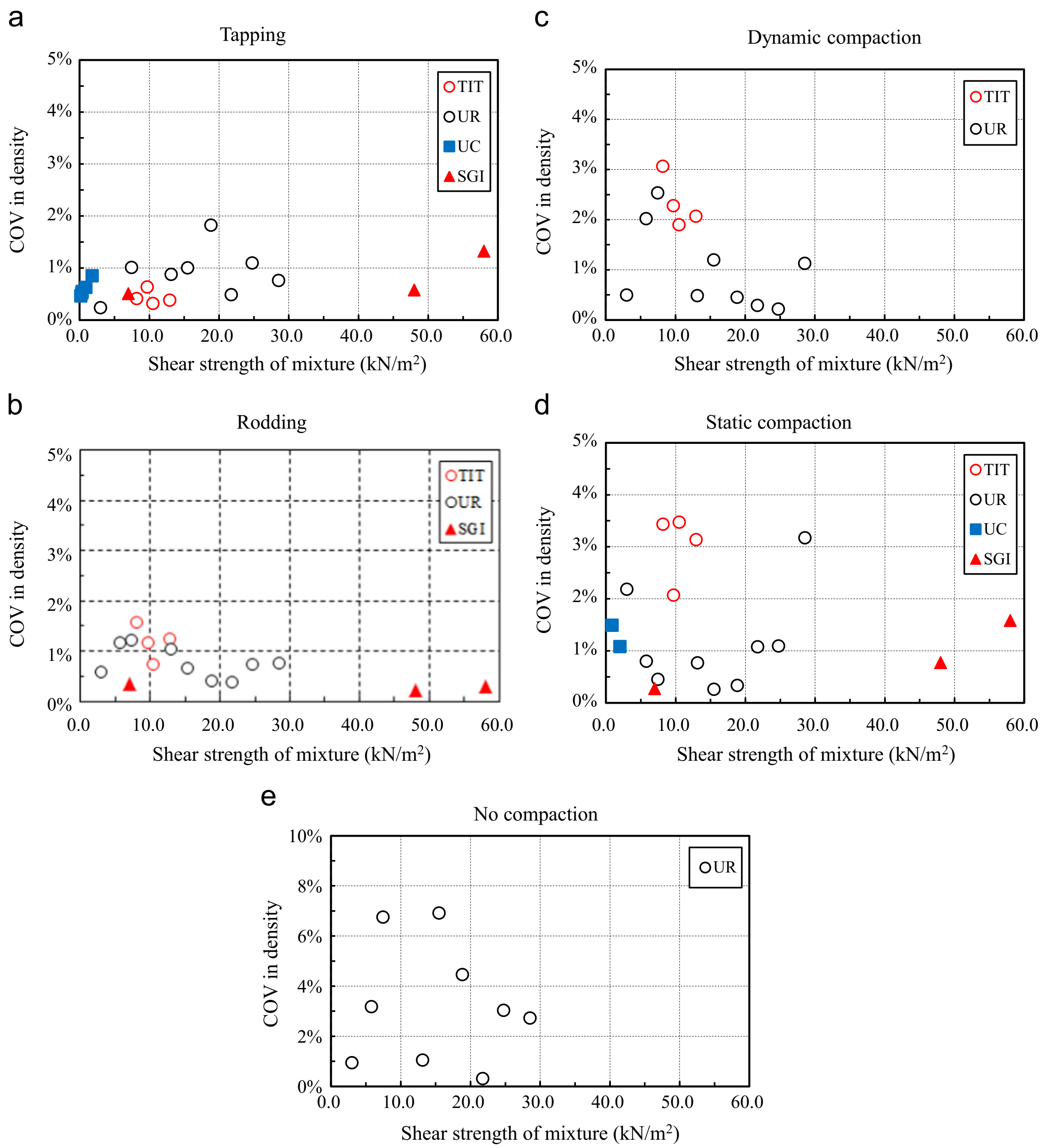

Fig. 15. Relationship between coefficients of variation of wet density of sample and undrained shear strength of mixtures. (a) Molded by tapping technique, (b) molded by rodding technique, (c) molded by dynamic compaction technique, (d) molded by static compaction technique, and (e) molded by no compaction technique.

technology adopted (type of machine and mixing procedure) as well as the in situ stresses, temperatures and variability of the soil characteristics, it is very difficult to simulate the real field mixing and curing conditions in the laboratory mix-testing program.

The authors believe that evaluation is required for many of the factors which potentially affect the applicability and reliability of the laboratory mix test. Grisolia et al. (2013) proposed the "applicability index" for evaluating the applicability of a molding technique, which is related to "densest specimens with the highest strength" and "results repetitiveness". The applicability and reliability of molding techniques are discussed here from the perspective of the wet unit weight and strength, according to their proposal.

4.3.1. The mixture's undrained shear strength as an index

Fig. 19 shows the effect of the molding technique on the ratio and the coefficient of variation of the wet unit weight and of the unconfined compressive strength, considering the mixture's undrained shear strength.

(1) Undrained shear strength of mixtures lower or equal to 10 kPa

The wet unit weight ratio is around 1.0 in the rodding and dynamic compaction techniques but it is scattered in the static and the no compaction techniques. There is a large scatter in the strength ratio, irrespective of the molding technique, with the lowest strength ratio obtained with the no compaction technique. The COV in the wet unit weight is small, irrespective of the molding technique except some data in the tapping and no compaction techniques. The COV in the strength is lower than around 15% in the tapping, rodding and static compaction techniques, increasing for larger values in the dynamic and the no compaction techniques. The results suggest that the applicability of the tapping and the rodding techniques may be the highest, from the point of view of the wet unit weight and the unconfined compressive strength.

(2) Undrained shear strength of mixtures ranging from 10 to 20 kPa

The rodding, the dynamic compaction and the static compaction techniques provide a wet unit weight ratio that is somewhat lower than, or about equal to, 1.0 with a COV of about 2.5% decreasing to about 1% with the increment of the mixture's shear strength. For the unconfined compressive strength ratio, the rodding technique results in a high strength, while the dynamic and the static compaction techniques provide low strength. The COV in the strength decreases sharply as the shear strength of the mixture increases, showing values of less than 10%, except for the no compaction technique. The results suggest that the applicability of the rodding techniques may be the highest in terms of density and strength.

(3) Undrained shear strength of mixtures ranging from 20 to 30 kPa

The rodding, the dynamic compaction and the static compaction techniques provide a high wet unit weight ratio with a small COV. For the unconfined compressive strength ratio, the rodding and the dynamic compaction techniques provide high strength, which increases with the mixture's undrained shear strength. The COV in the strength remains relatively small in all the techniques except for no compaction. The test result suggests that the applicability of the rodding and the dynamic compaction techniques can be the highest in terms of wet unit weight and strength. The no-compaction technique, on the other hand, shows quite a small wet unit weight and q_u with high COV values, which suggests the low applicability of the technique.

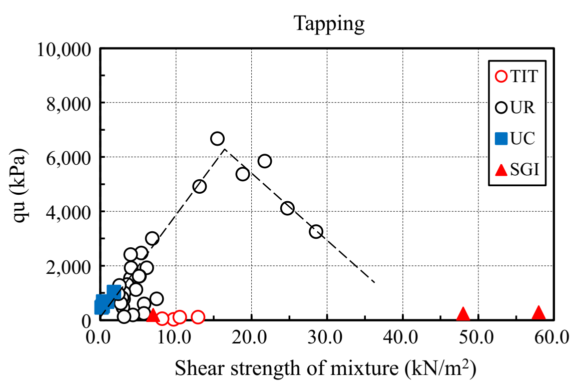

Fig. 16. Relationship between unconfined compressive strength of sample and undrained shear strength of mixtures for tapping technique.

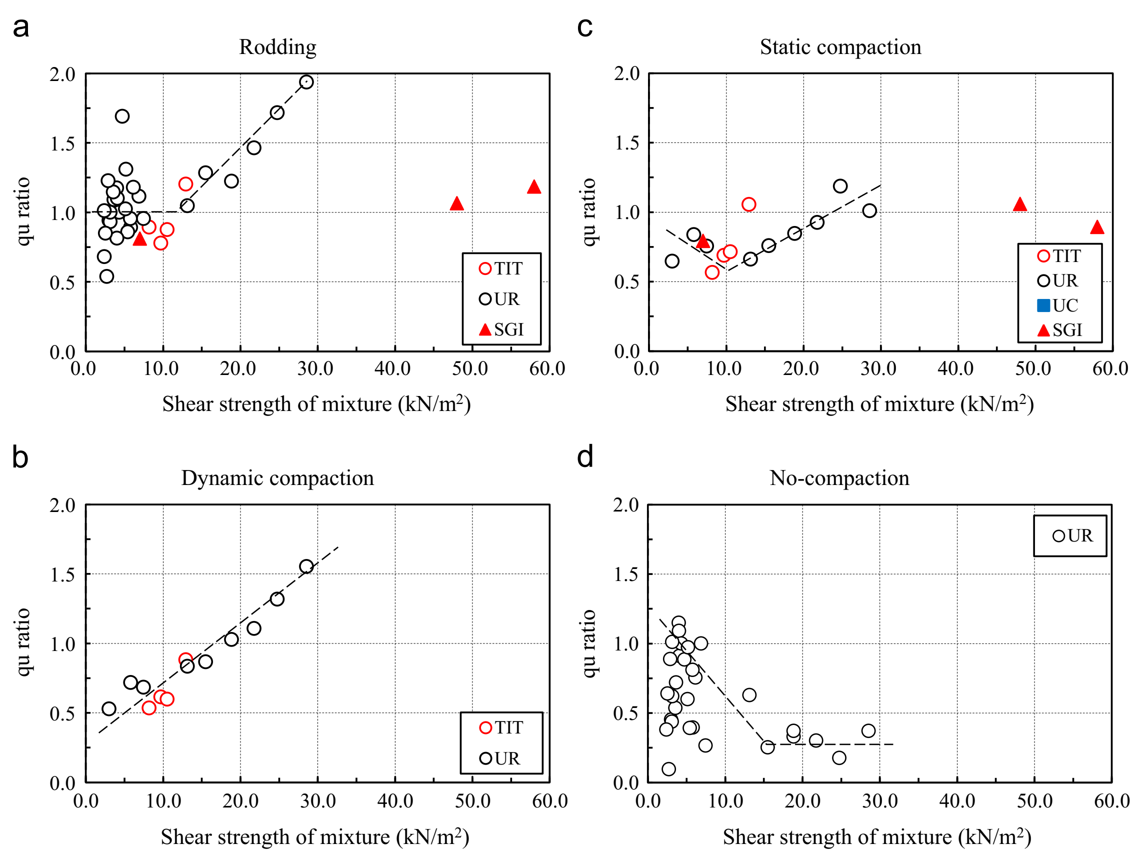

Fig. 17. Relationship between strength ratio of sample and undrained shear strength of mixture. (a) Molded by rodding technique, (b) molded by dynamic compaction technique, (c) molded by static compaction technique, and (d) molded by no compaction technique.

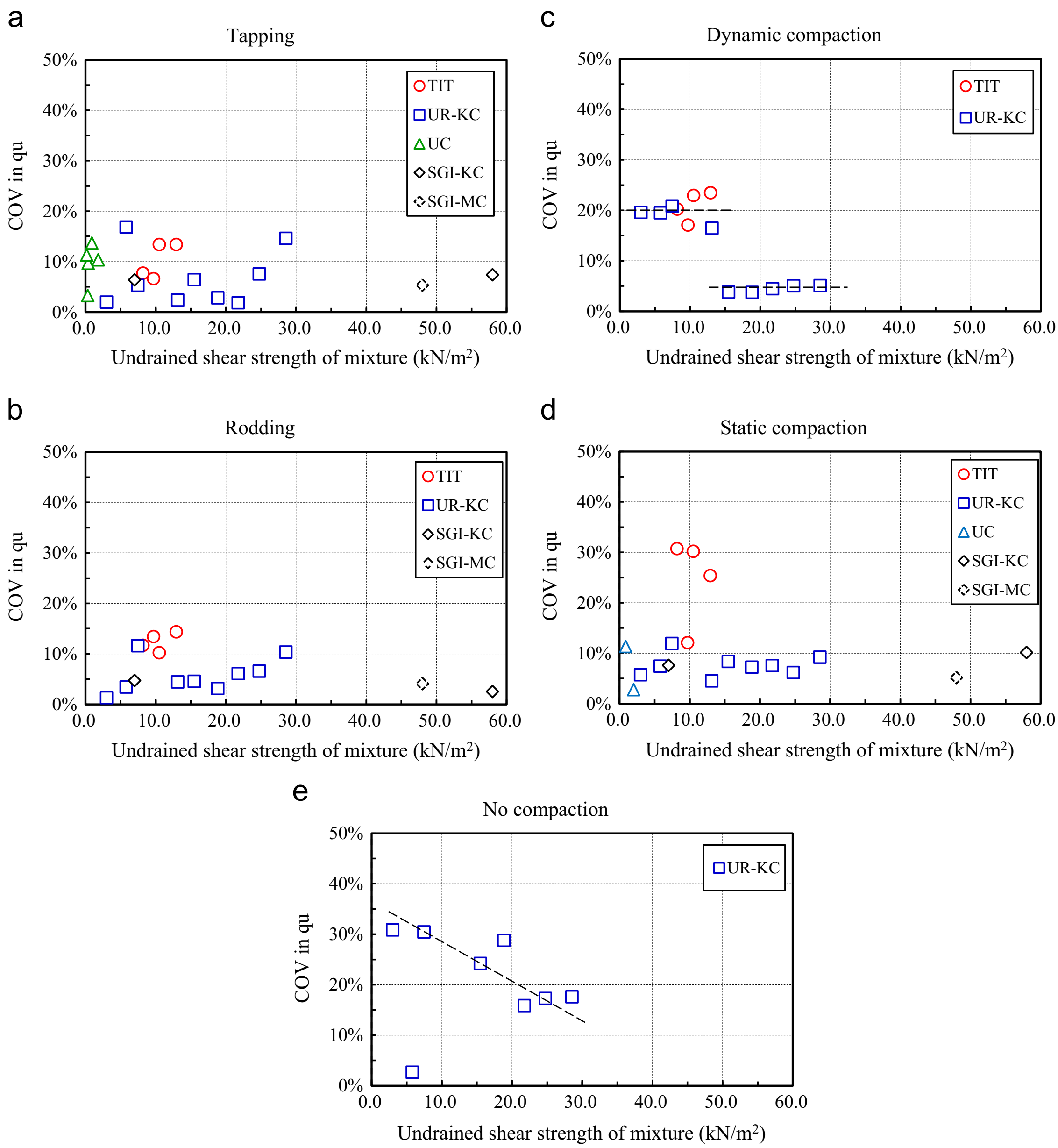

Fig. 18. Relationship between coefficients of variation of the unconfined compressive strength and undrained shear strength of mixture.(a) Molded by tapping technique, (b) molded by rodding technique, (c) molded by dynamic compaction technique, (d) molded by static compaction technique, and (e) molded by no compaction technique.

(4) Undrained shear strength larger than 30 kPa

The data for mixture strengths higher than 30 are limited to the results from the two SGI clays with low water contents. The undrained shear strength of the mixture was quite high, although the absolute values should be regarded as only approximate, as commented on earlier in Section 4.2.1. The dynamic and no compaction techniques were not tested in these soils. The differences were small between the results from the other techniques used, i.e. tapping, rodding and static compaction, for the clay with a low natural water content and a mixture strength of 48 kPa, whereas it was larger for the partially dried clay with the highest mixture strength. The results showed that rodding provided a better molding result than tapping and static compaction in these cases.

4.3.2. Using the mixture's liquidity index as an index

The mixture's liquidity index was also selected to evaluate the consistency of the mixture. The water content of the mixture was measured immediately after mixing the soil and binder to calculate the mixture’s liquidity index with regard to the liquid limit and plastic limit of the original soil. Fig. 20 shows the relationship between the mixture’s liquidity index and the undrained shear strength. There is a large scatter depending on which collaborating organization’s results are considered, most likely due to the difference in the soil type

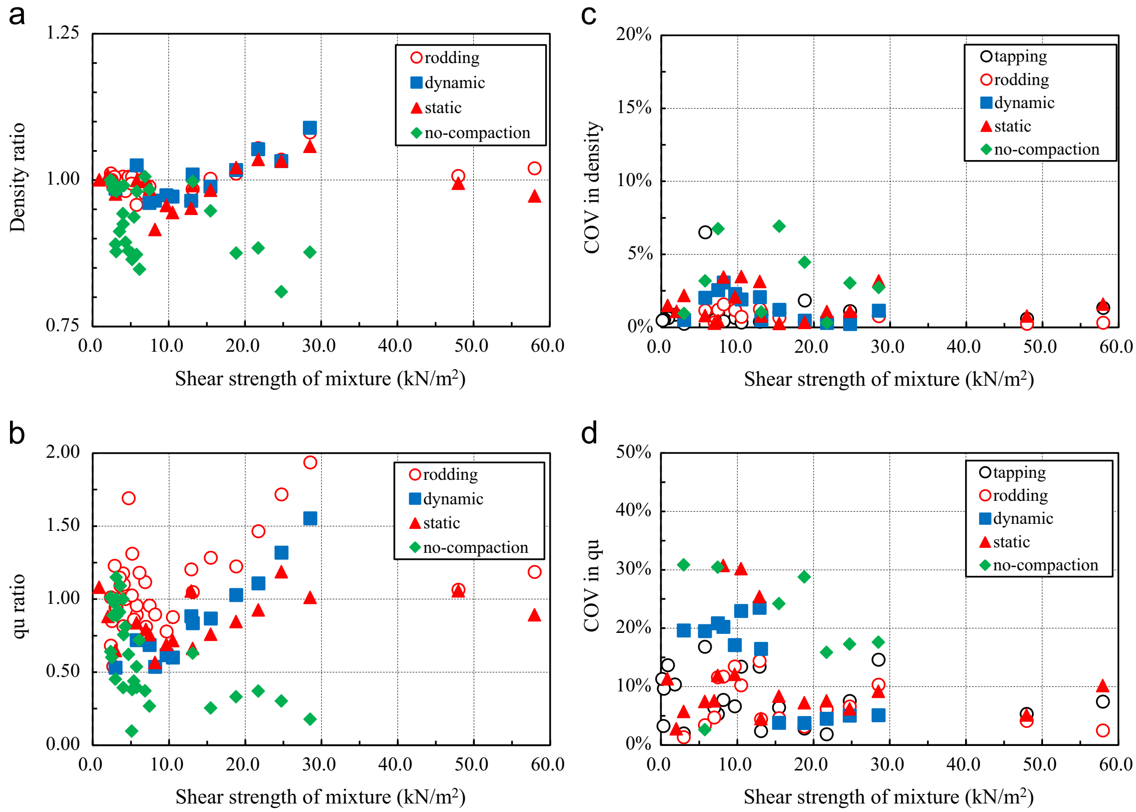

Fig. 19. Comparison of molding techniques. (a) Density ratio, (b) strength ratio, (c) coefficient of variation in wet density, and (d) coefficient of variation in unconfined compressive strength.

and type and amount of binder, as well as the testing procedures. The results demonstrate that the mixture's undrained shear strength decreases rapidly along with the liquidity index, exhibiting a similar behavior to that observed for unstabilized soils (e.g. Leroueil et al., 1983).

Fig. 21 shows the effect of the molding technique on the ratio and the coefficient of variation of the wet unit weight and of the unconfined compressive strength in relation to the liquidity index of the mixture.

(1) Liquidity index larger than 1.0

The wet unit weight ratio is around 1.0 in the rodding and dynamic compaction techniques. The static and no compaction techniques show low strength ratio, while the no compaction technique shows the lowest. The COV in the wet unit weight is small, less than 5%, with the tapping and the rodding techniques consistently presenting lower COV values. The COV in the strength is around 10% for tapping and the rodding, but larger in the dynamic, static and the no compaction techniques. The results suggest that the applicability of the tapping and the rodding techniques can be the highest.

(2) Liquidity index ranging from 0.5 to 1.0

The rodding, the dynamic compaction and the static compaction techniques provide a wet unit weight ratio of around 1.0 with a COV of about 2.5% or lower. For the unconfined compressive strength ratio, the rodding technique provides the highest strength. The COV in the strength is small in all the techniques except the no compaction technique. The result suggests the high applicability of the rodding technique.

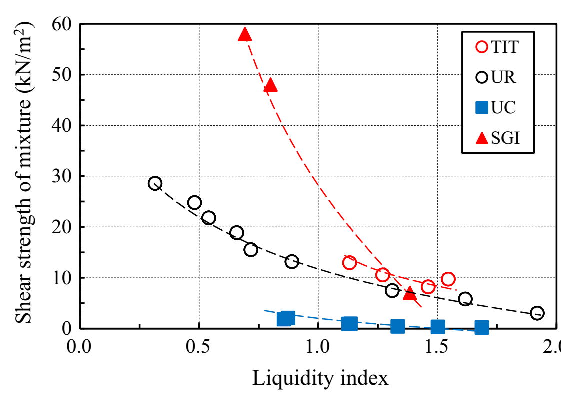

Fig. 20. Relationship between liquidity index and shear strength of mixture.

(3) Liquidity index smaller than 0.5

The rodding, the dynamic compaction and the static compaction techniques provide high wet unit weight ratio with a small COV. For the unconfined compressive strength ratio, the rodding and the dynamic compaction techniques provide a high strength which increases with the decreasing liquidity index. The COV in the strength remains relatively small in the rodding, dynamic and static compaction techniques. The test result suggests the high applicability of the rodding and the dynamic compaction techniques.

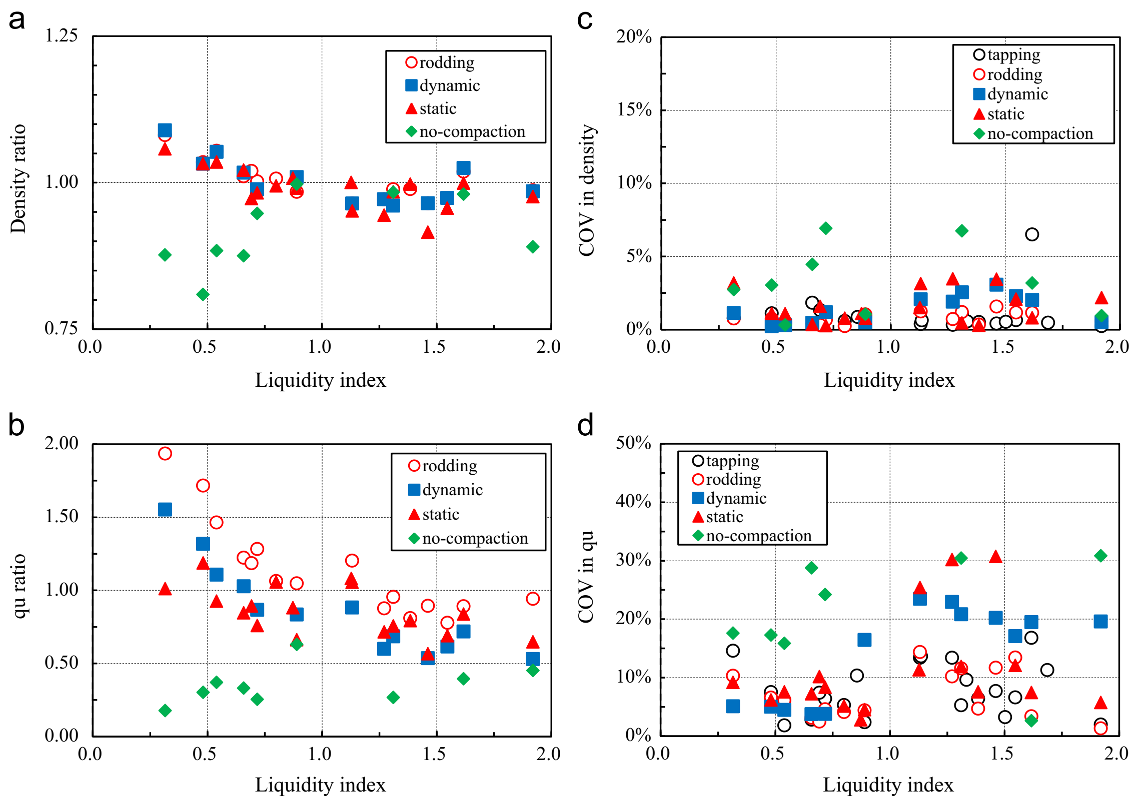

Fig. 21. Comparison of molding techniques. (a) Density ratio of sample, (b) strength ratio of sample, (c) coefficient of variation in wet density, and (d) coefficient of variation in unconfined compressive strength.

5. Conclusions

As part of a large international study, the influence of different molding techniques for the preparation of specimens has been studied by four collaborating organizations. The tests were carried out on the regional soils and the binders available to them. Soil and binder mixtures of different consistencies were prepared in the laboratory using five molding techniques, namely Tapping, Rodding, Dynamic Compaction, Static Compaction and No Compaction. Unconfined compression tests were performed on the specimens produced. The total number of stabilized soil samples were 620 (160 specimens in TIT, 380 in UR, 35 in UC and 45 in SGI), corresponding to a total of 12 soils and 5 binders.

The tests clearly revealed that the molding techniques considerably influenced the magnitude and variation of the unconfined compressive strength and the wet unit weight of the stabilized soils, irrespective of the difference of the soil type and the type and amount of binder.

Two indices for the consistency of the soil binder mixture are proposed, the undrained shear strength and liquidity index. The results have shown that both indices can be employed as a good index to identify the applicable mixing techniques. According to the test conditions in this study, the tapping and the rodding techniques are highly applicable in the case of the undrained shear strength smaller than 10 kPa or liquidity index larger than 1.0, and the rodding technique is highly applicable in the case of the undrained shear strength ranging from 10 to 20 kPa or a liquidity index ranging from 0.5 to 1.0. In the case of an undrained shear strength larger than 20 kPa or liquidity index smaller than 0.5, the rodding and the dynamic compaction techniques are highly applicable.

Although a large number of laboratory mix tests were carried out, the general applicability and reliability of the two indices presented cannot be evaluated precisely. However, their potential has been demonstrated. Further studies will be necessary to evaluate their applicability and reliability in more detail. This scientific work is a step forward in establishing international guidelines for conducting laboratory deep mixing tests.

Acknowledgments

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