Elsevier Editorial System(tm) for Soils and Foundations
Manuscript Draft

Manuscript Number: SANDF-D-14-00165

Title: Applicability of molding procedures in laboratory mix test for quality control and assurance of deep mixing method

Article Type: Technical Paper

Keywords: molding technique; stabilized clay; cement; lime; laboratory tests; unconfined compressive strength; deep mixing

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Abstract: The deep mixing method (DMM) has been applied in many construction projects for various improvement purposes. Laboratory mix test is essential to quality control and quality assurance (QC/QA) of deep mixing methods. The procedures used for the prep-aration of specimens in the laboratory mix test greatly affect the physical and mechani-cal properties of the stabilized soils. Different procedures are applied in different coun-tries/regions. With the increasingly globalizing DMM market in the background, it is desired to establish common understanding of the nature of laboratory mix test and in-ternationally accepted guidelines to conduct them, in order to guarantee the QC/QA of DMMs. As part of an international collaborative study, the influence of different mold-ing techniques for the laboratory preparation of specimens was studied. Five different molding techniques were tested in four organizations. The results showed the molding techniques considerably influenced the magnitude and variation of the unconfined com-pressive strength and the wet density of the stabilized specimens. The applicability of the molding techniques was discussed by two indices, the undrained shear strength and the liquidity index of soil and binder mixture, which usefulness was demonstrated.

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

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ABSTRACT

The deep mixing method (DMM) has been applied in many construction projects for various improvement purposes. Laboratory mix test is essential to 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 globalizing DMM market in the background, it is desired to establish common understanding of the nature of laboratory mix test and internationally accepted guidelines to conduct them, 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 the molding techniques considerably influenced the magnitude and variation of the unconfined compressive strength and the wet density of the stabilized specimens. The applicability of the molding techniques was discussed by two indices, the undrained shear strength and the liquidity index of soil and binder mixture, which usefulness was demonstrated.

Key words: 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 Nordic countries in the middle of 1970s to improve soft deposits, and then spread into USA, China, South East Asia, and recently to the 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 original soil, the type and amount of binder, and the production process. The quality control and quality assurance (QC/QA) practice which focuses upon the quality of deep-mixed soil was originally established in Japan and Nordic countries and has been accepted worldwide for more than three decades. It comprises laboratory mix test, field trial installation, monitoring and control of construction parameters during production and the verification by measuring the engineering characteristics of deep-mixed soil either by unconfined compression tests on core samples or by sounding. Diversification of application, soil type, and execution system, together with the improved understanding on the behavior of deep-mixed ground in the past two decades require the revision of the current QC/QA practice. The literature review and the International Collaborative Study 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 test is essential to 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). With the increasingly globalizing DMM market in the background, it is desired to establish common understanding of the nature of laboratory mix test and internationally accepted guidelines to conduct them, 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 QC/QA of deep mixing works (Terashi and Kitazume, 2009; 2011). This part of the collaborative study has been undertaken in four organizations, Tokyo Institute of Technology, Sapienza University of Rome, University of Coimbra and Swedish Geotechnical Institute, respectively referred as TIT, UR, UC and SGI hereinafter.

The laboratory mix tests were carried out on regional soils with regional binders which are available in the collaborating organizations. The soil and binder mixtures with different initial water content and amount of binder, changing their consistency, were molded using five molding techniques. Unconfined compression tests were performed on the specimens produced. The results showed the molding techniques considerably influenced the magnitude and variation of the unconfined compressive strength and the wet density of the stabilized specimens. The applicability of the molding techniques was discussed by two indices; the undrained shear strength and the liquidity index of soil and binder mixture. The study revealed that the indices can be potential parameter to evaluate the applicability of the techniques. Parts of the test results have been 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). In this paper a more general picture covering a variety of soils and binders is presented and discussed in order to evaluate the applicability of the indices.

2. Testing program

In this study, 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 with 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 institutions are briefly introduced in the following sections.

2.1. Tokyo Institute of Technology (TIT)

(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.

Table 1 Geotechnical Properties of Kaolin Clay

(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 binder in dry form was then mixed with the soil, and they were mixed for 10 minutes to make a uniform mixture. Immediately after the mixing, the water content of the mixture was measured, and the shear strength of the mixture was also measured by 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 to 6 layers. In particular four different molding techniques were used, as shown in Figure 1:

(1) Tapping (*TP*) (see Figure 1(a))

For each layer, the mold was tapped against floor about 50 times, which followed the standard specified by the Japanese Geotechnical Society (2009).

(2) Rodding (*RD*) (see Figure 1(b))

Performed using a 8 mm diameter steel rod; consisted in slowly tamping (30 times) the mixture with the rod for each layer and eventually push down the material attached to the rod.

(3) Dynamic Compaction (*DC*) (see Figure 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. Fall height was set to 10 cm, and number of blows to 5.

(4) Static Compaction (*SC*) (see Figure 1(d))

Each layer was statically compressed by the weight (4.82 kg, corresponding to a vertical pressure of 25 kPa) for 10 seconds using a heavy rod.

Figure 1 Molding techniques (in TIT)

In this test series, the binder contents, a_c (defined as the ratio of the dry weight of binder to the dry weight of soil), used were 10, 20, 30 and 40% for each molding technique. Ten soil specimens were prepared for each mixing condition and molding technique, and the total of 160 specimens were prepared. At 28 days 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 referred 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 consistency 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 was used to produce nine soil-cement mixtures with different consistency. For each of the other soils, three different mixtures were produced, varying the initial water content and keeping constant the binder content, a_c (10 %).

Table 2 Soil properties

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. Before adding the binder the soil was homogenised by mixing. 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 ten minutes according to 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 follow. The stabilized clay was placed in plastic molds (cylindrical shape, 50 mm in diameter and 100 mm in height) in three layers. In particular five different molding techniques were used:

(1) Tapping (*TP*)

For each layer, the mold was tapped against floor 50 times (taken as standard value).

(2) Rodding (*RD*)

Performed using a 8 mm diameter steel rod; consisted in slowly tamping (30 times) the mixture with the rod for each layer and eventually push 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 seconds by using a heavy rod, 49 mm in diameter. A pressure of 25 kPa was applied.

(5) No Compaction (namely *NC*)

Simply consisted in filling the mold by either pouring or placing in the case of higher consistency mixture.

To prevent water evaporation from the specimen each mold was covered with a sealant and stored in a special curing room at 95 % relative humidity. To reduce the effects of hydration between the time of mixing with the binder and the completion of molding related with the mixture consistency, all the stabilized soils were molded in less than 45 min. after the binder was added, according to e.g. Kitazume and Nishimura (2009),. 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 was conducted on triplicate samples for each case (soil type and molding procedure) analysed. The details of the test program and test results are referred in the literature (Grisolia *et al*. 2012, 2013, Marzano *et al*. 2012).

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 whole 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, being classified as an organic silty-clayed soft soil with high plasticity, OH (ASTM D

2487, 1998)

Table 3 Baixo Mondego soil properties

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 (on a weight proportion of 75/25, Portland cement/slag) in the dry state to obtain a uniform binder. Finally, this uniform binder in a content 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 Euro-SoilStab (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%, correspondent to a liquidity index equal to 1.35) to water contents, w_i, of 89.6, 98.2, 105.9 and 113% (associated to liquidity indexes of 1.66, 1.96, 2.24 and 2.49, respectively). When it was necessary to increase the water content (for the study of the consistency of the soil), the water to be added to the soil was first mixed with the dry uniform binder producing a slurry, which was mixed with the soil. Immediately after the mixing, the shear strength of the mixture was measured by 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 has a thin film of grease. At the bottom of the mold it was placed a porous disc made of non-woven geotextile. The uniform paste was introduced in 6 layers (with a thickness/diameter ratio equal to 0.5). The paste of 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 seconds and finally, the surface was lightly scarified and another layer was introduced. After the 6 layers have been introduced, a porous disc of non-woven geotextile was placed at the top, above which it was applied a curing vertical pressure of 24 kPa. Immediately after, the mold with the sample was stored under water (temperature = 20±2ºC) during the curing time (28 days).

The molding technique with static compaction (100 kPa applied during 10 seconds on each of the 6 layers), was not applied on the samples with water contents greater than 89.6%, because there was soil lost during 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 sample with ± 140 mm high, and the remaining height mold is used as a guide (equilibrates) for the dead load correspondent to the vertical pressure of 24 kPa. The mold has two holes near the top in order to allow the submersion of the sample.

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 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 referred 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 laboratory characterisation of the test soils are presented in Table 4.

The binder used was a combination of cement and quicklime in proportion 50:50 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.

Table 4 Properties of Kattleberg clay and Munkedal clay.

2.4.2 Test procedure and program

For preparing the stabilized samples, the soil was first homogenized thoroughly and the dry binders were then mixed into the soil for five minutes. 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 exception for the molding methods used, the specimens of stabilized soils were prepared in accordance with common procedures for stabilized soil in Sweden (Carlsten and Ekström 1997;, EuroSoilStab 2001). In order to get an indication of the consistency of the soil-binder mixtures during moulding, the plastic limit, liquid limit, water content and the undrained shear strength of the materials were determined before the start of moulding The shear strength of the mixture was measured by the fall cone apparatus. The liquidity index taking into account the reduced water content after adding binders in relation to the w_P and w_L of the soil, was 1.35, 0.68 and 0.81 and the shear strength 7, 58 and 48 kPa in the mixtures with Kattleberg natural clay, Kattleberg partially dried clay and Munkedal clay respectively.

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

(1) Tapping (*TP*)

Tapping of the mould was performed 30 times for each of about 30 mm thick layer of soil-binder mixture filled into the mould. The filling was performed in four layers.

(2) Rodding (*RD*)

A rod was used by hand to evenly compact/smooth out each 20-30 mm thick layer of the soil-binder mixture.

(3) Static compaction (*SC*)

A static pressure of 100 kPa was applied for 5 seconds to compress and squeeze out air pockets from each about 30 mm thick layer of soil-binder mixture. This is common procedure for moulding of stabilized clay in Sweden.

The moulding of the specimens for the different test series was completed within 30 minutes after mixing. The stabilized soils were cured for 28 days in a climate controlled room at a temperature of 7 °C before testing. The specimens were tested with regard to the unconfined compressive strength. The unconfined compression tests were performed at an axial strain rate of 1.5 %/min. The density 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

Here, some of the test results obtained in each collaborating organizations are briefly introduced, followed by comparisons and discussions of the data in the next chapter. All stabilized specimens presented here have 28 days of curing time. Focus will be given to the molding technique nevertheless the fact that, independently of the molding technique, as the binder content increases or the water content decreases the density and the unconfined compressive strength increases.

3.1. Observation of specimens

Figure 2 shows typical examples of the specimens produced by various molding techniques for various organizations. The uniformity of specimen are variable depending on the molding techniques, the soil type and mixing conditions.

Figure 2 Observations of Specimens

3.2. Tokyo Institute of Technology (TIT)

3.2.1 Wet density

Figure 3 shows the density 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 of 120 %. The figure shows that the highest density is found in the tapping technique irrespective of the binder content. The static compaction technique gives the smallest density which is in agreement with the observation of the specimens (Figure 2a).

Figure 3 Influence of molding technique on wet density (TIT)

3.2.2 Unconfined compressive strength

The unconfined compressive strength, q_u, of the specimens is plotted in Figure 4. A clear hierarchy is observed, with the tapping technique giving the highest strength as long as the binder content is lower than 40%. This phenomenon is consisted with the wet density of the samples as shown in Figure 6. In the case of the binder content of 40 %, however, the rodding technique gives 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, results that are not in accordance with the wet density and the observations of the specimens. The results clearly show that for such amount of binder (40%) there is a change on the fabric of the stabilized material, which is no longer a soil fabric with binder, beginning to be a soil fabric completely welded by the binder or similar to a binder paste (Horpibulsuk, 2001; Correia, 2011). The figure shows a strength development for all techniques except tapping.

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

3.3. Sapienza University of Rome (UR)

The results presented in this section are referred to the Kawasaki clay and to the test series where the initial water content is changed (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 on the next chapter.

3.3.1 Wet density

Figure 5 shows an example of the effect of molding technique on the density of the sample. The density is not so different irrespective of the molding technique except for the no compaction technique. The figure shows that the highest density 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 density decreases with the increment of the initial water content because the density of the water is lower than for solid particles.

Figure 5 Influence of molding technique on wet density (UR)

3.3.2 Unconfined Compressive Strength

Figure 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 density as shown in Figure 7. The no compaction technique gives the smallest strength and approximately the same strength irrespective of the initial water content. The unconfined compressive strength values are in accordance with the findings of Horpibulsuk 2001; Lorenzo and Bergado, 2004 and 2006; Horpibulsuk *et al*., 2003 and 2011; Correia, 2011; Correia *et al*., 2013 for stabilized soils at 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 of density).

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

3.4. University of Coimbra (UC)

3.4.1 Wet density

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

Figure 7 Influence of molding technique on wet density (UC)

3.4.2 Unconfined Compressive Strength

Figure 8 shows the unconfined compressive strength, q_u, in order to clarify the influence of the molding technique. 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 density of the samples was almost the same.

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

3.5. Swedish Geotechnical Institute (SGI)

3.5.1 Wet density

Figure 9 shows the measured density of the specimens of stabilized clays (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 mean density for specimens of this clay prepared with the different molding techniques, with the highest mean density 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 mean density than the other two methods. This may partly be an effect of a slight loss in water content in compaction of this material with the latter methods. For the Munkedal clay (series 2), the difference in mean density was small when using the different methods.

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

3.5.2 Unconfined compressive strength

Figure 10 shows the measured compressive strength 28 days after stabilization using the different molding techniques. For the Kattleberg natural, non-dried, clay-binder mixtures (series 1a), the mean 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 mean strength was highest when using the rodding technique. The use of static compaction technique resulted in about the same or only slightly lower mean strength as when using the rodding technique in the Munkedal clay and the Kattleberg natural wet clay.

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

4. Discussion

As shown in Figures 2 to 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. In order to discuss a general picture covering a variety of soils and binders, the density ratio and strength ratio in respect to that of the tapping technique are discussed in this section instead of their absolute magnitudes.

4.1. Relationship between density ratio and strength ratio

Figure 11 shows the relationship between the strength ratio and the density ratio of the stabilized soil prepared by 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 density ratio irrespective of the organization. The increment of the strength ratio against the density ratio in the rodding technique is larger than the other two techniques. In the case of the no compaction, the strength ratio and the density ratio are almost always smaller than unity, and the strength ratio increases with the density ratio but at a smaller ratio than the other three techniques.

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

Figure 12 shows all the data for comparing the effects of molding technique on the relationship between the strength ratio and the density ratio. Again, although there is a large scatter in the data, the strength ratio increases with the density 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.

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

4.2. Effect of undrained shear strength of mixture

According to previous studies (Grisolia *et al*. 2012, 2013, Marzano *et al*. 2012), the consistency of the soil and binder mixture is one of critical factors to take into account in evaluating the applicability of molding technique. In this section, the undrained shear strength of the mixture was selected for evaluating the consistency. The undrained shear strength of the mixture was measured immediately after the mixing of soil and binder by one of two methods: hand vane apparatus in TIT, UR and UC, and fall cone apparatus in SGI. Here, the effect of the the undrained shear strength of the mixture is discussed as an index of consistency of the mixture.

4.2.1 Wet density

Density ratio

Figure 13 shows the relationship between the wet density and the undrained shear strength of stabilized samples (with 28 days of curing time) for the tapping technique. The wet density is almost within the range 14 to 17 kN/m^3 depending on the type of soil and type and amount of binder. A general increase in density with increasing shear strength of mixture could be observed for specimens containing the same type of soil 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 mixture shear strength from about 15 to 30 kPa.

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

Figure 14 shows the relationship between the density ratio and the undrained shear strength of 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 ratio of SGI shows only small changes in density ratio with a slightly lower density compared to tapping at low mixture shear strength and somewhat higher at high 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 binders in the soil. In the dynamic compaction technique, the density ratio is around 1.0 with a relatively large scatter as long as the undrained shear strength is lower than about 15 kPa, but increases linearly with the undrained shear strength as similar 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 to 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 density ratio seems to decrease to about 0.8 with a slight increment of the undrained shear strength of the mixture, keeping always less than 1.0.

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

It is observed that, in general, for undrained shear strengths lower than about 15 kPa the density is of the same magnitude (± 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 of the UR soil with high binder contents, the density ratio increases linearly with the undrained shear strength (up to 10 %). A somewhat higher density 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 gave somewhat lower ratios. For the no compaction technique, in general the density is lower than tapping (up to 20%) and seems to decrease with the increment of the undrained shear strength.

Coefficient of variation in density

Figure 15 shows the relationship of the coefficient of variation (COV) of the wet density with the undrained shear strength of the mixture. For the tapping and rodding techniques, the COV remains quite small, less than 2% and 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 mixture strength of about 15 to 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.

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

4.2.2 Unconfined compressive strength

Strength ratio

Figure 16 shows the relationship between the unconfined compressive strength of samples and the undrained shear strength of soil binder mixtures for the tapping technique. It can be seen that the strength, q_u, is quite different depending on the type of soil and mixing conditions (type and amount of binder). The same pattern as for the density can be observed, with an increasing strength with the undrained shear strength of mixture (for specimens containing the same type of soil with varying binder content and water content), and a diverting decrease in strength for the UR specimens of mixture strengths between 15 and 30 kPa.

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

Figure 17 shows the relationship between the strength ratio of 28 day cured samples and the undrained shear strength of mixtures. In the rodding technique, the strength ratio has a large scatter as far as the undrained shear strength of mixture remains lower than about 10 kPa, but increases almost linearly with the undrained shear strength, for the UR specimens as high as up to about 2.0. In the dynamic compaction technique, the strength ratio is around 0.5 when the undrained shear strength of mixture 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 linearly decreases with the increment of the undrained shear strength of the mixture. The strength ratio has a quite small value, of the order of 0.25, when the undrained shear strength of mixture is greater than 10 kPa.

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

Coefficient of variation of unconfined compressive strength

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

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

As shown above, the density and unconfined compressive strength are considerably influenced by the molding technique as well as the undrained shear strength of the soil binder mixture. 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, for assuring the design strength requirements in the field. Therefore the laboratory test procedure for preparation of 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 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 there are many issues to evaluate regarding 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”. Here, the applicability and reliability of the molding technique are discussed from the point of view of the density and strength, according to their proposal.

4.3.1 Undrained shear strength of soil binder mixture as an index

Figure 19 shows the effect of the molding technique on the ratio and the coefficient of variation of the wet density and of the unconfined compressive strength from the view point of the undrained shear strength of the soil binder mixture.

(a) Density ratio
(b) Strength ratio
(c) Coefficient of variation in wet density
(d) Coefficient of variation in unconfined compressive strength
Figure 19 Comparison of molding techniques.

(1) In the case of the undrained shear strength of mixture lower or equal to 10 kPa

The density ratio is around 1.0 in the rodding and dynamic compaction techniques but is scattered in the static and the no compaction techniques. There is a large scatter in the strength ratio, the dynamic irrespective of the molding technique, being the lowest strength ratio obtained with the no compaction technique. The COV in the wet density 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 result suggests that the applicability of the tapping and the rodding techniques can be the highest from the point of view of the wet density and the unconfined compressive strength.

(2) In the case of the undrained shear strength of mixture ranging from 10 to 20 kPa

The rodding, the dynamic compaction and the static compaction techniques provide a wet density 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 shear strength of mixture. For the unconfined compressive strength ratio, the rodding technique provides 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 mixture increases, showing values less than 10% except for the no compaction technique. The result suggests that the applicability of the rodding techniques can be the highest in terms of density and strength.

(3) In the case of the undrained shear strength of mixture ranging from 20 to 30 kPa

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

(4) In the case of the undrained shear strength of mixture larger than 30 kPa

The data for mixture strengths higher than 30 are limited to the results from the two SGI clays having low water contents. The shear strength of mixture strength was quite high, although the absolute values may be regarded as 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 having the highest mixture strength. The results showed that rodding provided a better molding results than tapping and static compaction in these cases.

4.3.2 Liquidity index of soil binder mixture as an index

In this section, the liquidity index of the mixture was selected for evaluating the consistency. The water content of the mixture was measured immediately after the mixing of soil and binder to calculated the liquidity index of the mixture. Here, the effect of the the liquidity index of the mixture is discussed as an index of consistency of the mixture. Figure 20 shows the relationship between the liquidity index and the undrained shear strength of mixture. There is a large scatter depending on the collaborating organizations probably due to the difference in the soil type and type and amount of binder as well as the testing apparatus of shear strength. It can be seen in the TIT and UR that the shear strength of mixture decreases rapidly with the liquidity index as long as the index is lower than about unity and decreases gradually when the index is higher than about unity.

Figure 20 Relationship between liquidity index and shear strength of mixture

Figure 21 shows the effect of the molding technique on the ratio and the coefficient of variation of the wet density and of the unconfined compressive strength from the view point of the liquidity index of the soil binder mixture.

(1) In the case of the liquidity index larger than 1.0

The density 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 density is small, less than 5%, being the tapping and the rodding techniques the ones presenting consistently lower COV values. The COV in the strength is around 10% in the tapping and the rodding, but larger in the dynamic, static and the no compaction techniques. The result suggests that the applicability of the tapping and the rodding techniques can be the highest.

(2) In the case of the liquidity index ranging from 0.5 to 1.0

The rodding, the dynamic compaction and the static compaction techniques provide a wet density 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.

(3) In the case of the liquidity index smaller than 0.5

The rodding, the dynamic compaction and the static compaction techniques provide high wet density ratio with small COV. For the unconfined compressive strength ratio, the rodding and the dynamic compaction techniques provide high strength which increases with 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.

(a) Density ratio of sample
(b) Strength ratio of sample
(c) Coefficient of variation in wet density
(d) Coefficient of variation in unconfined compressive strength
Figure 21 Comparison of molding techniques.

5. Conclusions

As part of a large international study, the influence of different molding techniques for the preparation of specimens has been studied in four collaborating organizations. The tests were carried out on regional soils and binders which are available in the collaborated organizations. The soil and binder mixtures with different consistency were molded 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 density of stabilized soils irrespective of the difference of the soil type and the type and amount of binder.

Two indices of the consistency of soil binder mixture are proposed, the undrained shear strength and liquidity index. As far as 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, but the rodding technique is applicable in the case of the undrained shear strength ranging than 10 to 20 kPa or liquidity index ranging from 0.5 to 1.0. In the case of the 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 was carried out, the applicability and reliability of the two indices presented can't be evaluated precisely notwithstanding its potential have been demonstrated. Further study will be necessary to discuss their applicability and reliability in detail. This scientific work is a step forward in order to establish international guidelines to conduct laboratory deep mixing tests.

Acknowledgement

The authors thank the Japan Society for the Promotion of Science for financial support as Grants-in-Aid for Scientific Research, No. 22360190. The SGI investigation has been supported by grants from Cementa AB and Nordkalk AB, and by internal research funds at the Swedish Geotechnical Institute. The UC investigation has been financially supported by FCT (PTDC/ECM/101875/2008). The UC researchers express their gratitude to Cimpor for supplying the binders.

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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

Table

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 -	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

Table

Table 3 Baixo Mondego soil properties

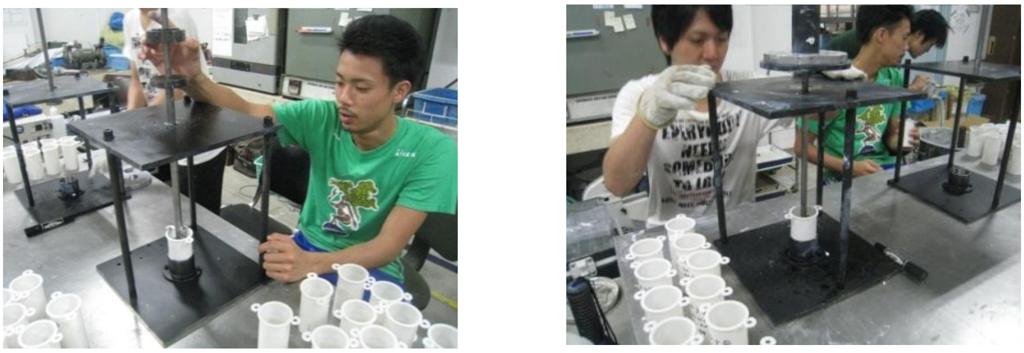
Specific gravity, G_s	2.57
Unit weight, γ (kN/m^3)	14.8
Natural water content, w_n (%)	80.9
Organic matter content, OM (%)	7.0
Liquid limit, w_L (%)	72.2
Plastic limit, w_P (%)	41.7
Liquidity index (%)	1.35
Sand content (%)	22.0
Silt content (%)	72.0
Clay content (%)	64.0
pH	3.7

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[1] (*%*)	66	40
Undrained shear strength[1] (kPa)	10	25
Sensitivity	150	30
Organic content[2] (*%*)	0.8	1.8
Clay content (*%*)	70	46
Clay mineralogy	Illitic	Illitic
pH	8.6	8.3

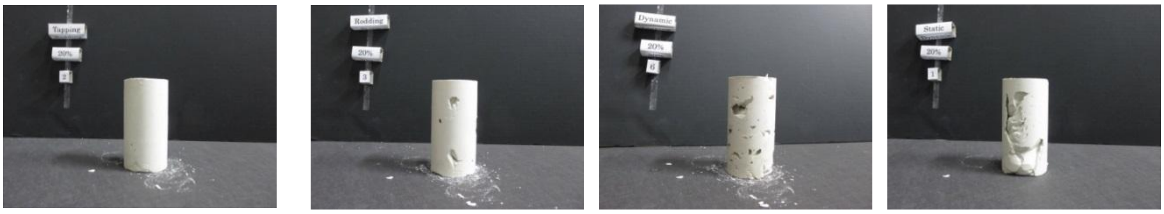
[1]Determined by the fall cone test (ETC5. 1998; SIS 2007). [2]Determined by colorimetric method (Swedish standard, 1990).

(a) Tapping (b) Rodding



(c) Dynamic compaction (d) Static compaction

Figure 1 Molding techniques (in TIT)



(a) Tapping (b) Rodding (c) Dynamic Compaction (d) Static Compaction

(a) Kaolin clay, w_i = 120%, a_c = 10% (TIT)

(a) Tapping (b) Rodding (c) Dynamic Compaction

(d) Static Compaction (e) No compaction

(b) Kawasaki clay, w_i = 54%, a_c = 30% (UR)

(a) Tapping (b) Static Compaction

(c) Baixo Mondego soil, w_i = 80.9%, a_c = 15% (UC)

Figure 2 Observations of Specimens

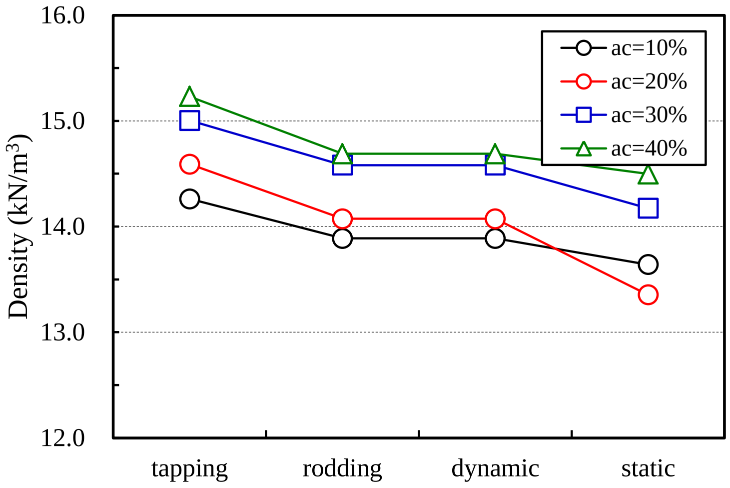


Figure 3 Influence of molding technique on wet density (TIT)

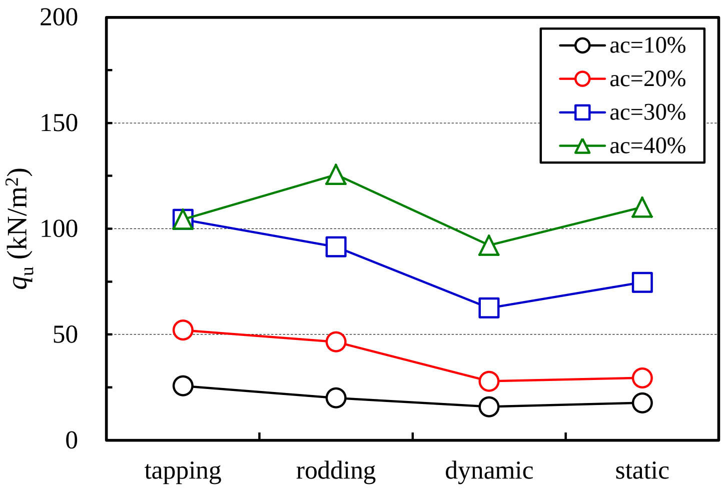


Figure 4 Influence of molding technique on unconfined compressive strength (TIT)

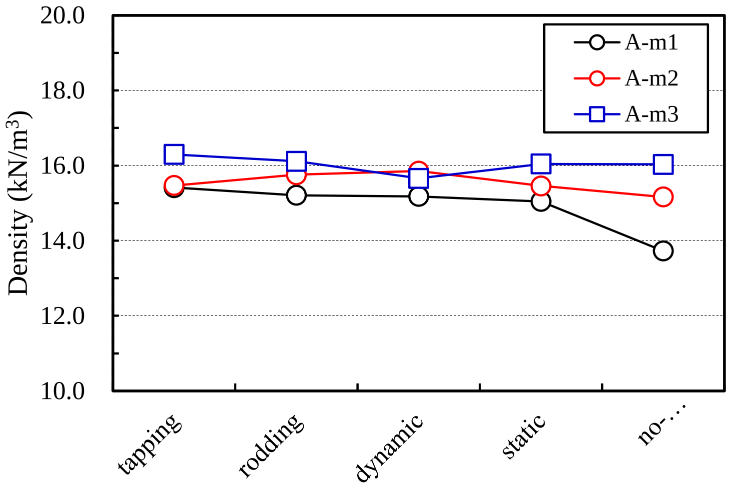


Figure 5 Influence of molding technique on wet density (UR)

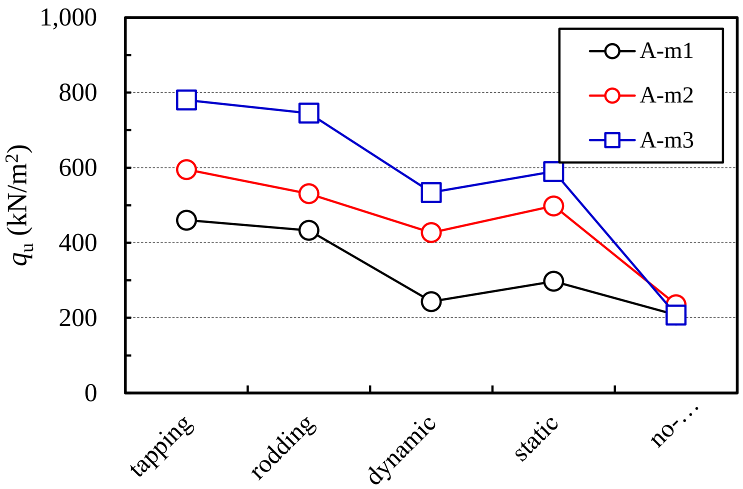


Figure 6 Influence of molding technique on unconfined compressive strength (UR)

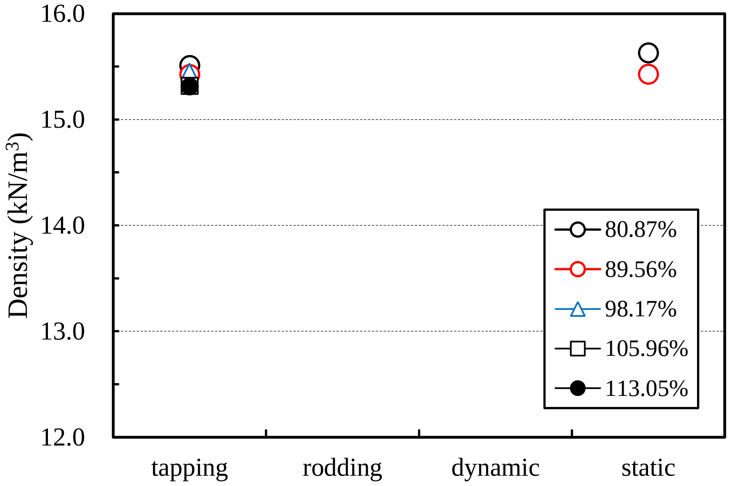


Figure 7 Influence of molding technique on wet density (UC)

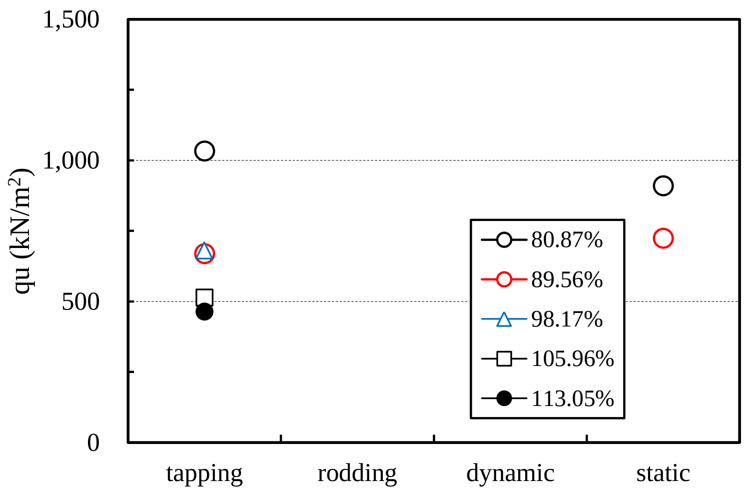


Figure 8 Influence of molding technique on unconfined compressive strength (UC)

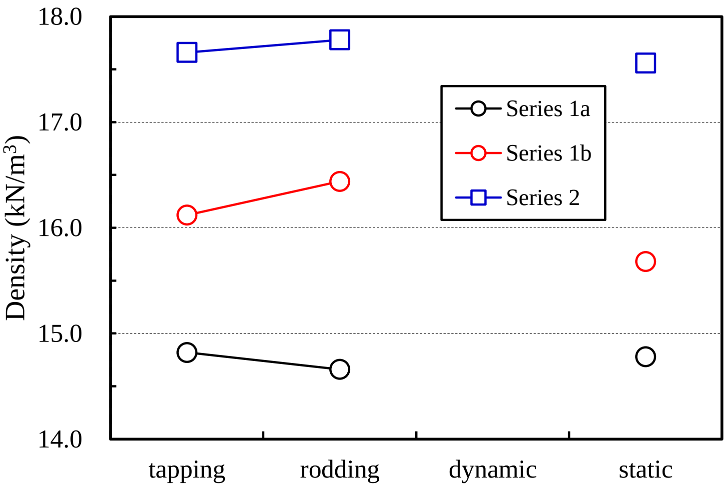


Figure 9 Influence of molding technique on wet density (mean values) (SGI)

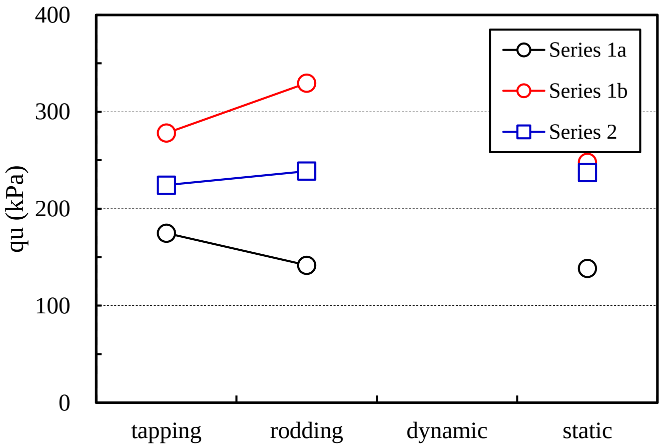
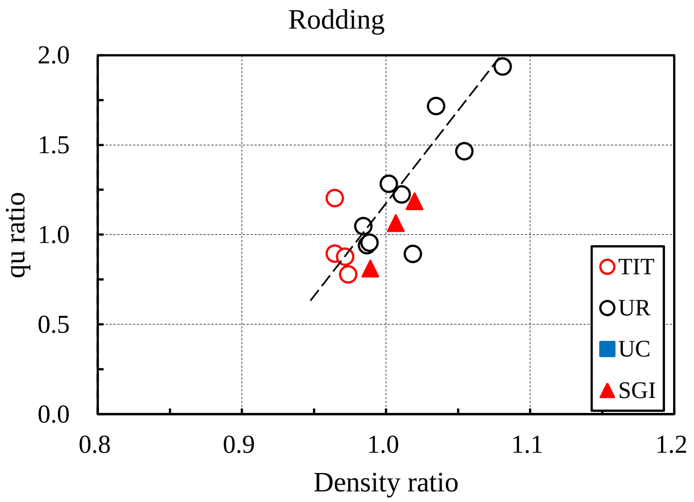
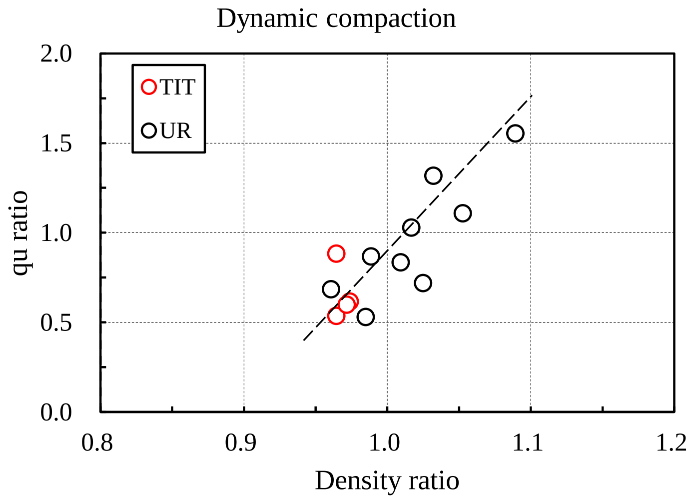


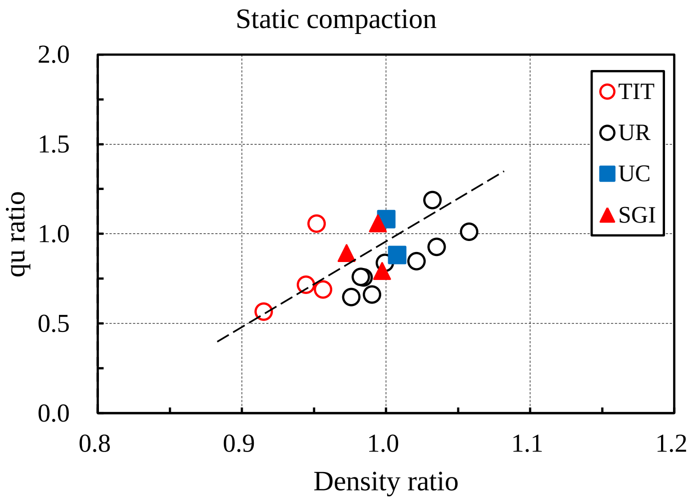
Figure 10 Influence of molding technique on unconfined compressive strength (mean value) (SGI)



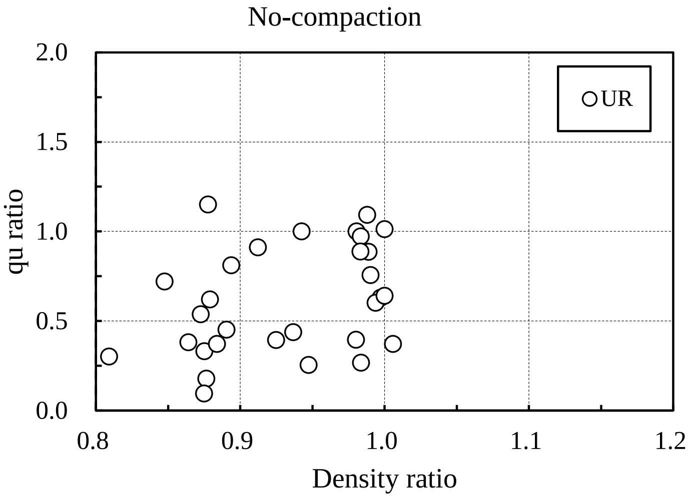
(a) Molded by rodding technique



(b) Molded by dynamic compaction technique



(c) Molded by static compaction technique



(d) Molded by no compaction technique

Figure 11 Relationship between the strength ratio and the density ratio

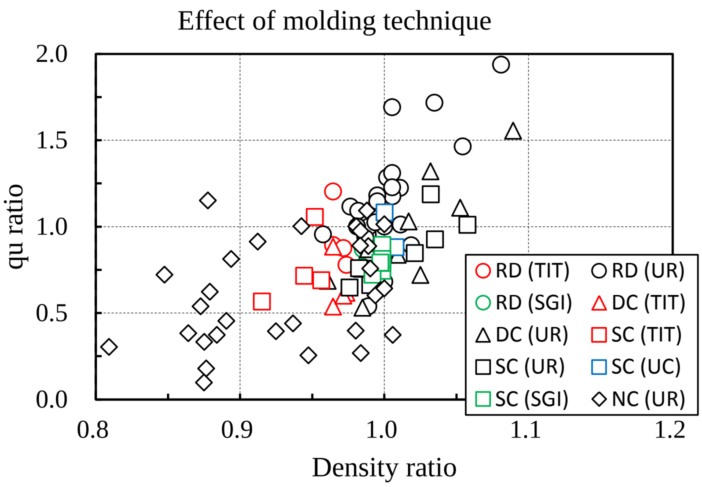


Figure 12 Relationship between the strength ratio and the density ratio (all data)

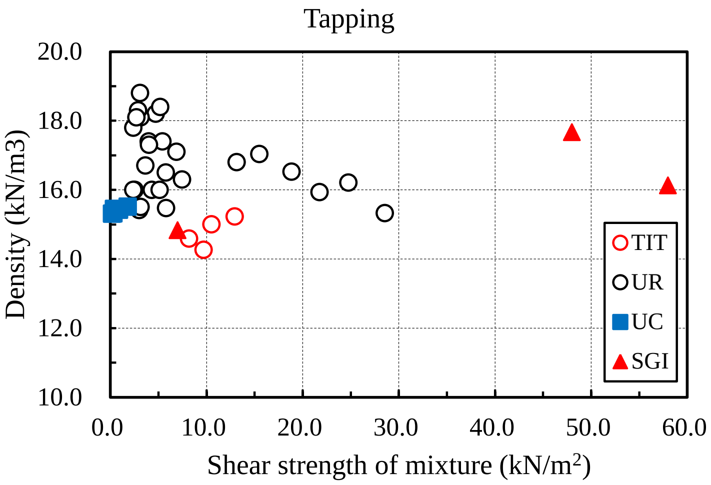
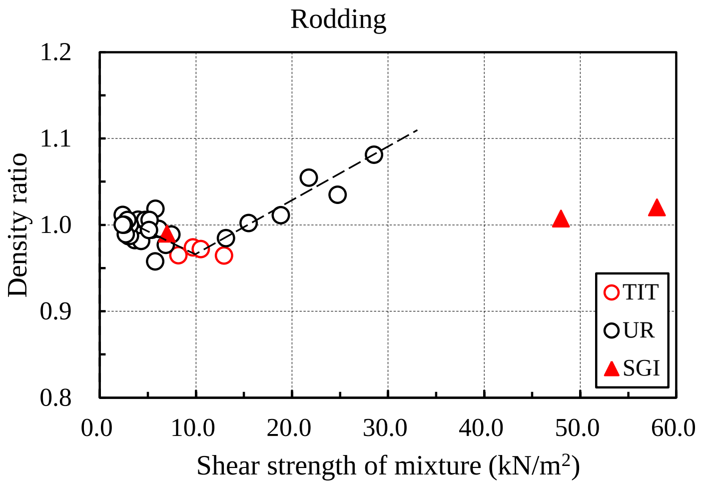
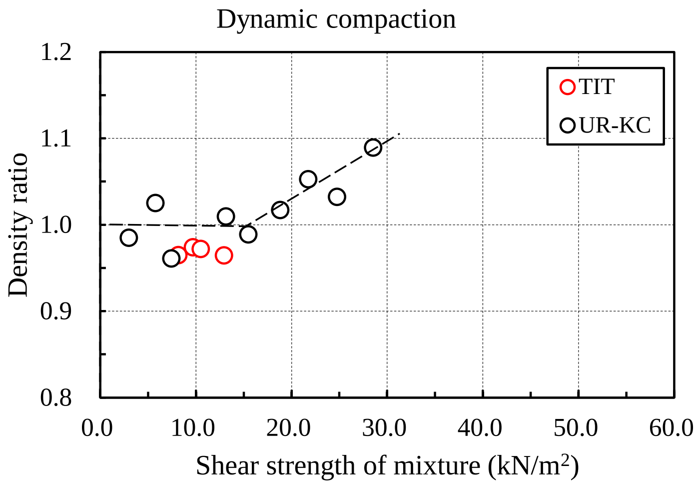


Figure 13 Relationship between wet density of sample and undrained shear strength of mixture for the tapping technique

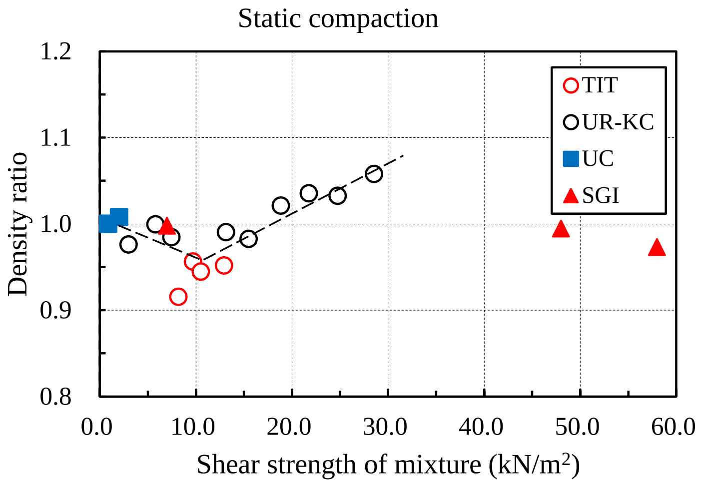
Figure



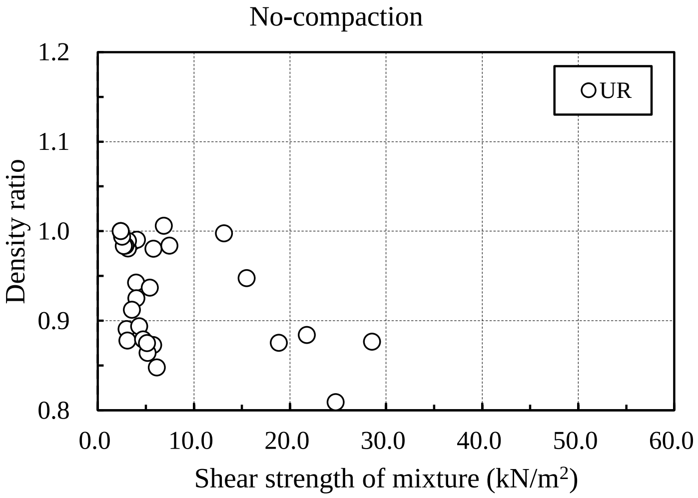
(a) Molded by rodding technique



(b) Molded by dynamic compaction technique

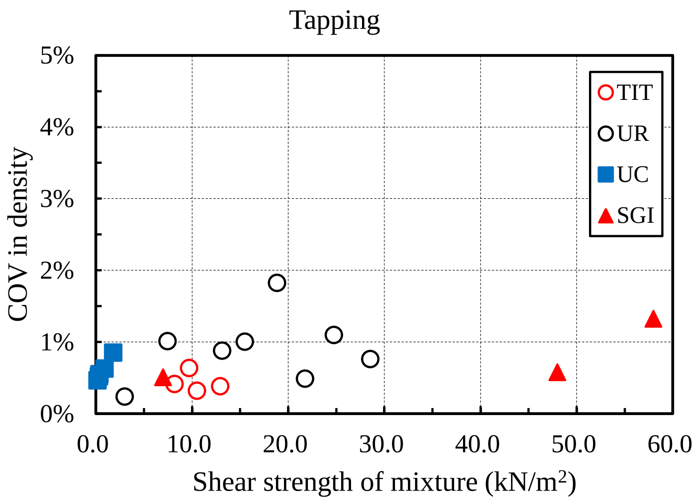


(c) Molded by static compaction technique

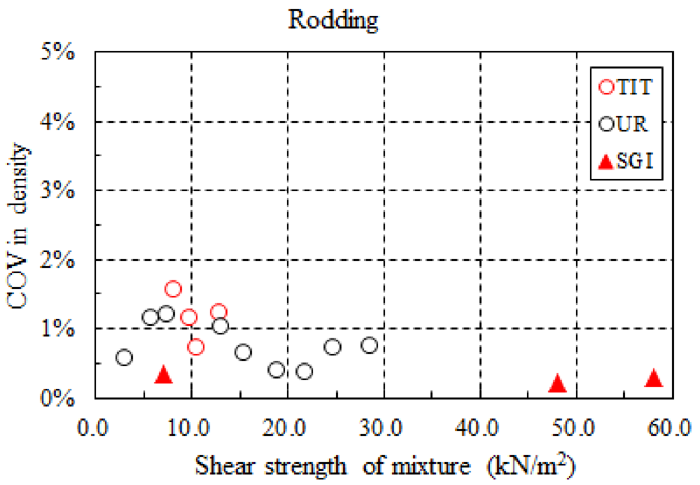


(d) Molded by no compaction technique

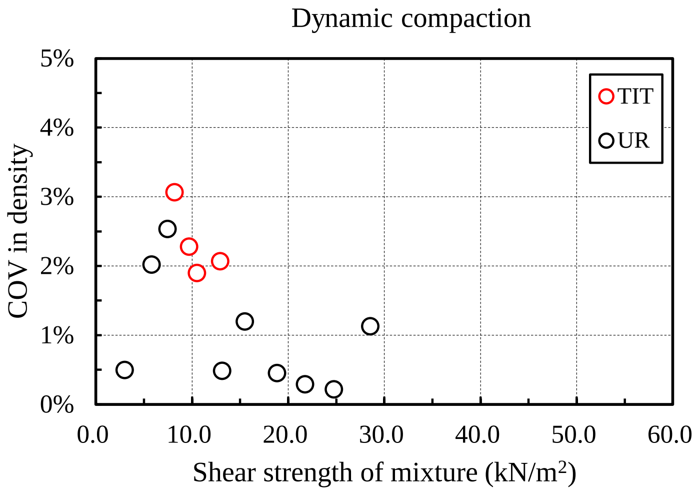
Figure 14 Relationship between density ratio of sample and undrained shear strength of mixture



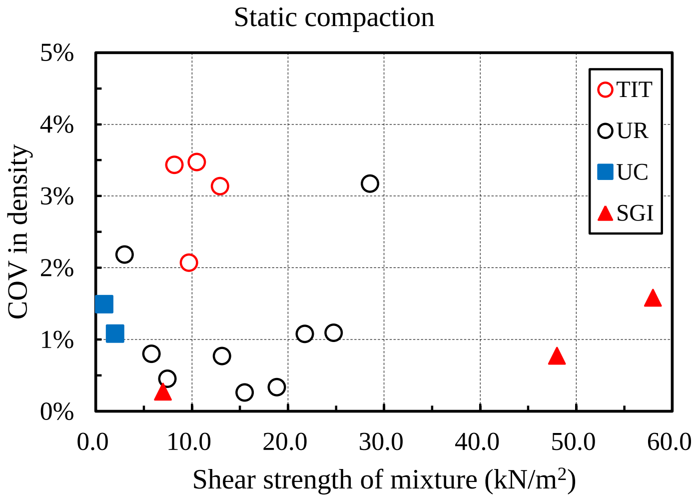
(a) Molded by tapping technique



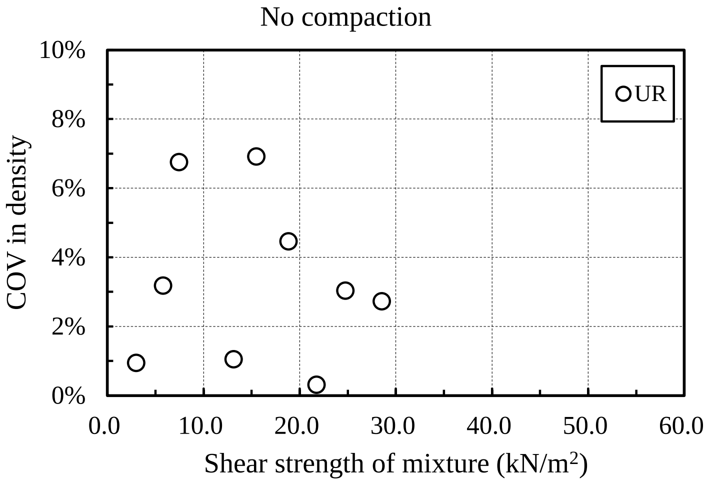
(b) Molded by rodding technique



(c) Molded by dynamic compaction technique



(d) Molded by static compaction technique



(e) Molded by no compaction technique

Figure 15 Relationship between coefficients of variation of wet density of sample and undrained shear strength of mixtures.

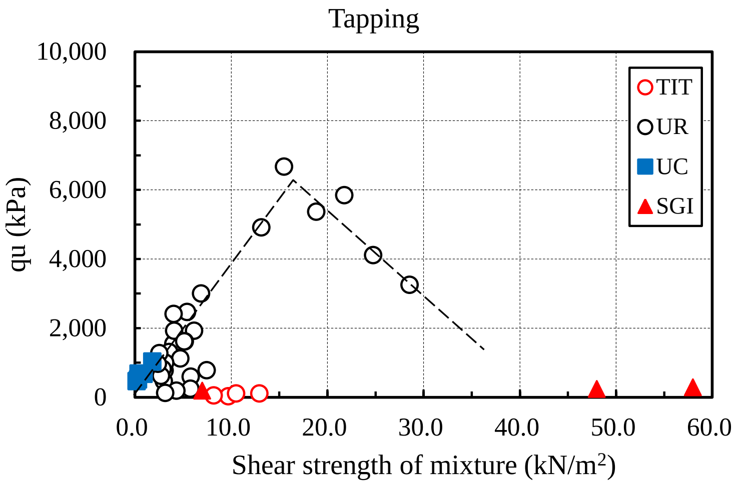
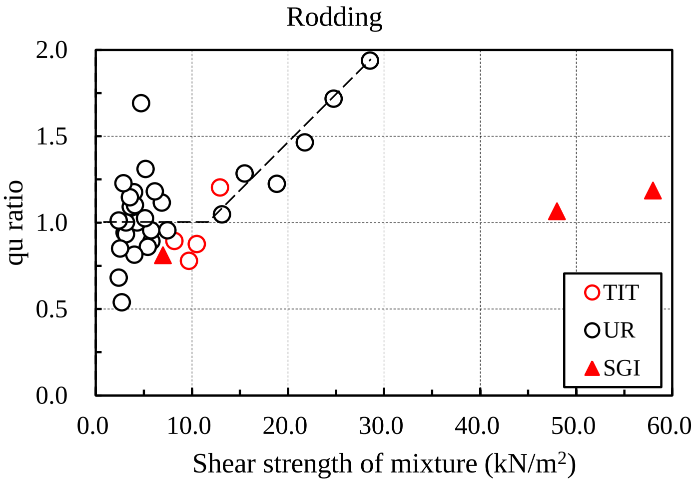
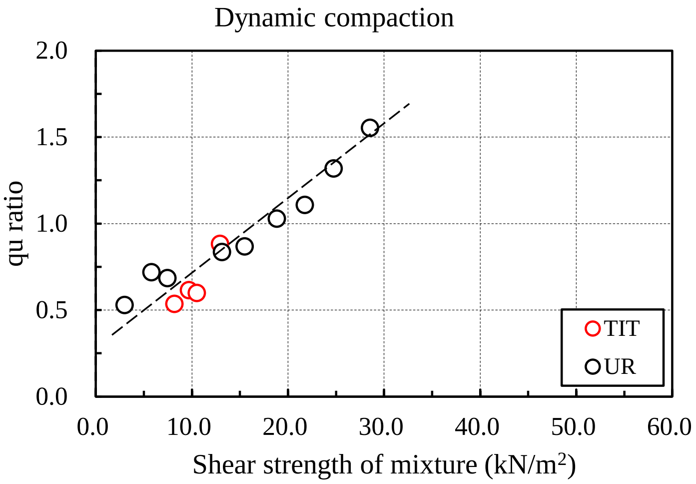


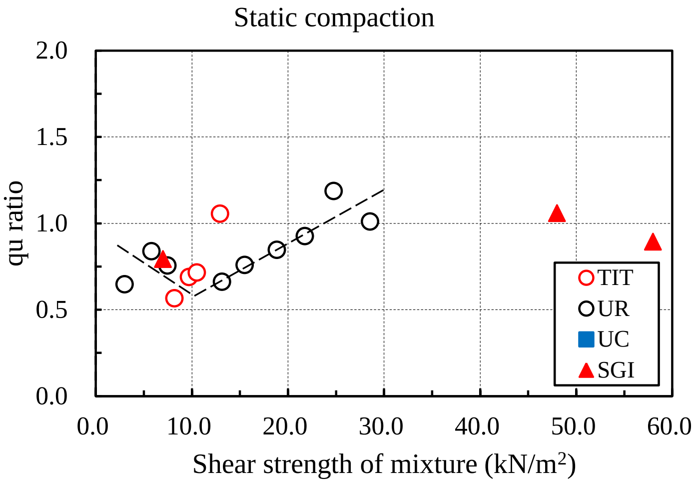
Figure 16 Relationship between unconfined compressive strength of sample and undrained shear strength of mixtures for tapping technique.



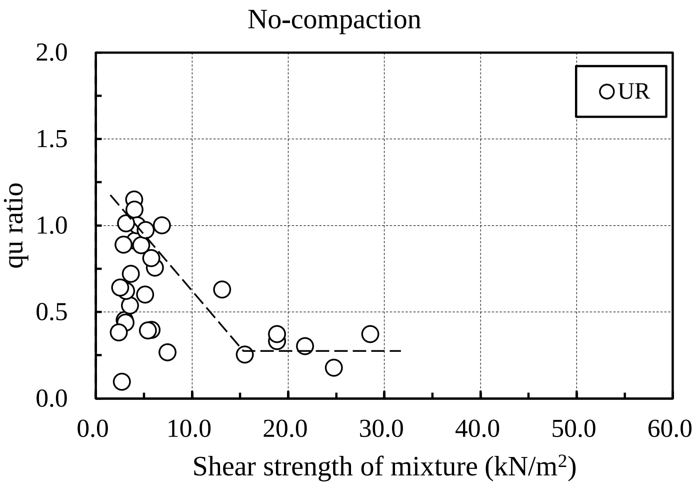
(a) Molded by rodding technique



(b) Molded by dynamic compaction technique



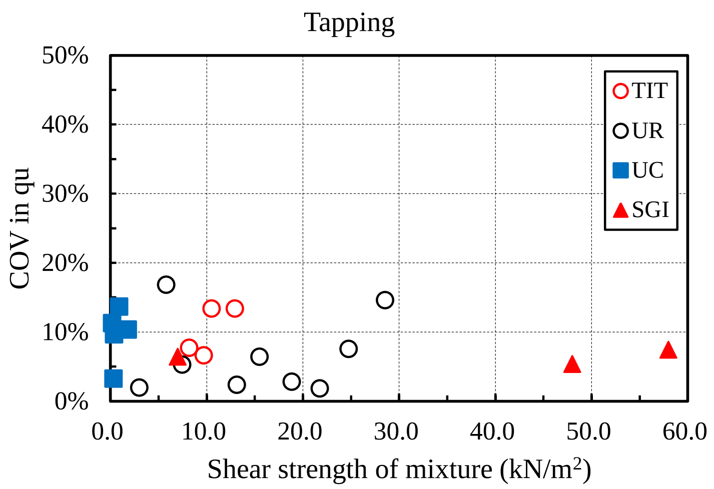
(c) Molded by static compaction technique



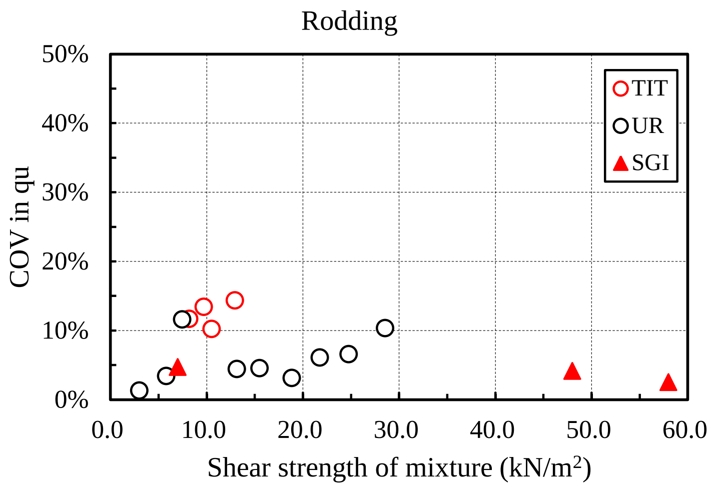
(d) Molded by no compaction technique

Figure 17 Relationship between strength ratio of sample and undrained shear strength of mixture.

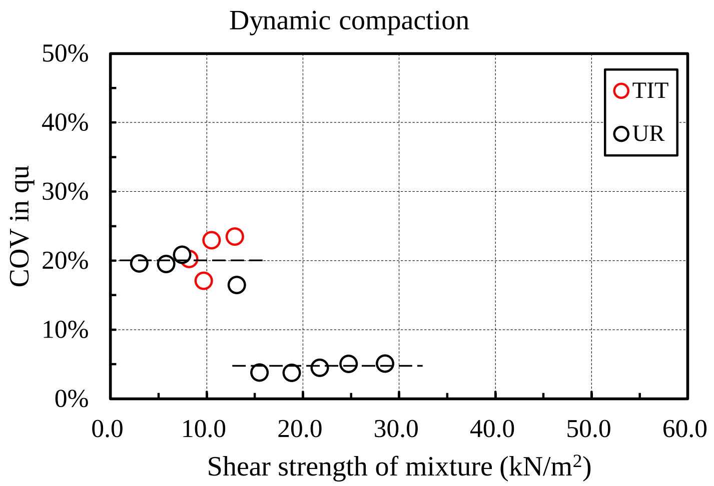
Figure



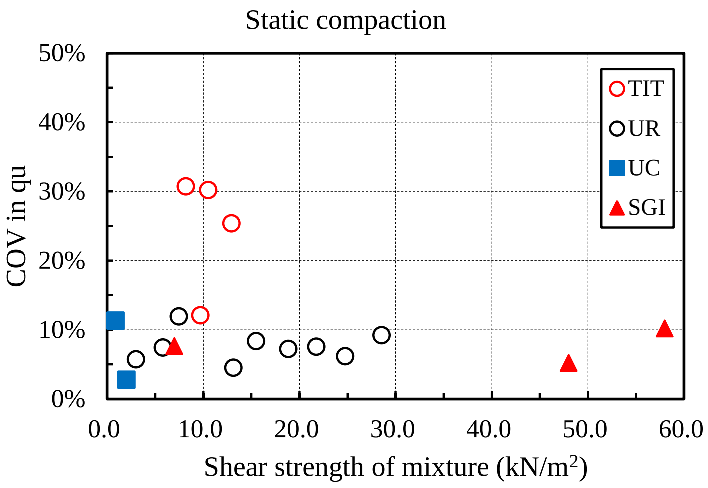
(a) Molded by tapping technique



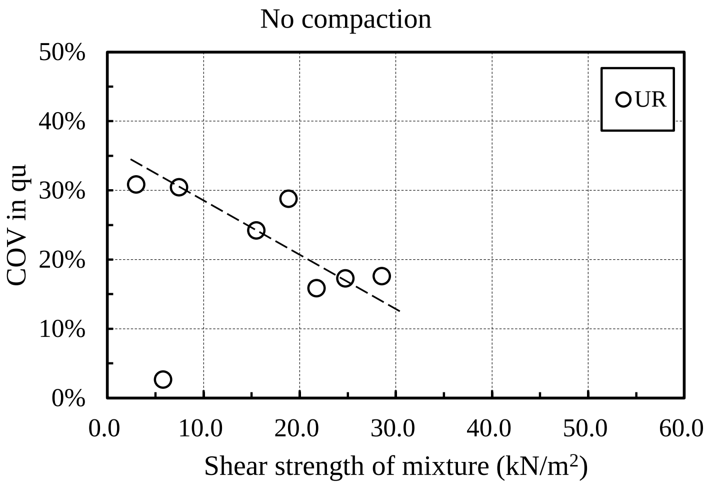
(b) Molded by rodding technique



(c) Molded by dynamic compaction technique



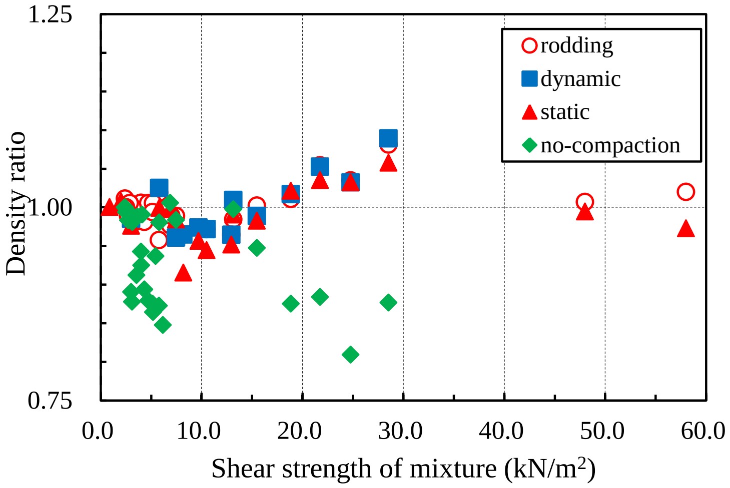
(d) Molded by static compaction technique



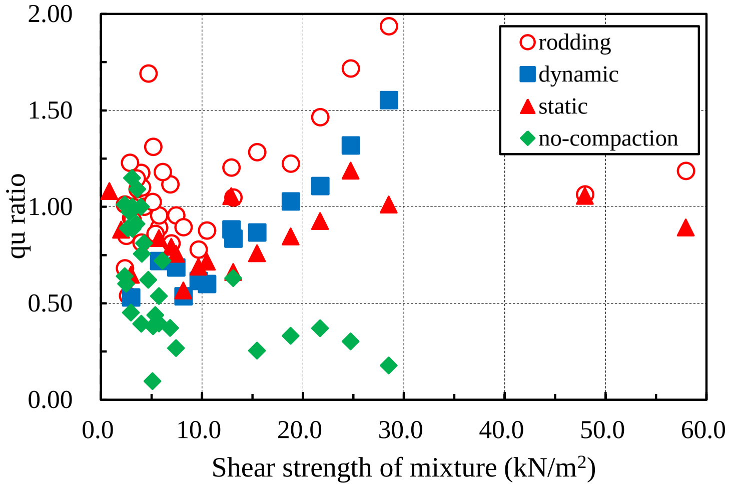
(e) Molded by no compaction technique

Figure 18 Relationship between coefficients of variation of the unconfined compressive strength and undrained shear strength of mixture.

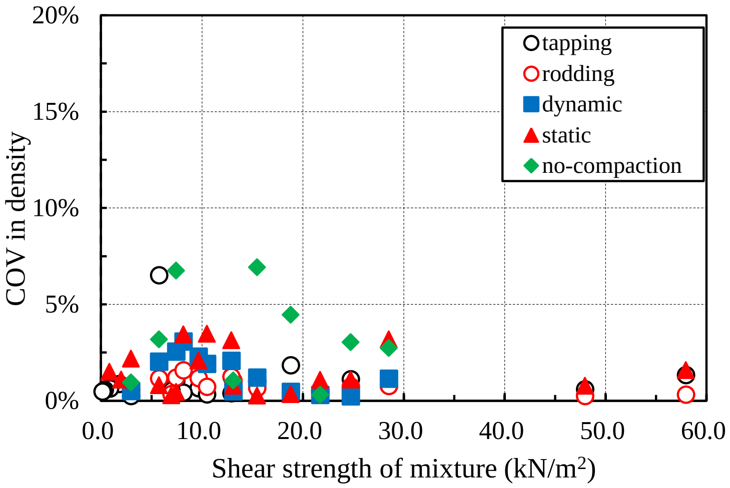
Figure



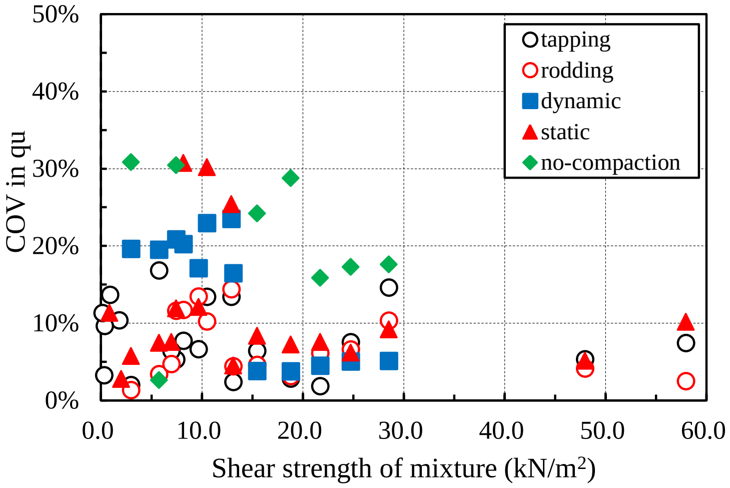
(a) Density ratio



(b) Strength ratio



(c) Coefficient of variation in wet density



(d) Coefficient of variation in unconfined compressive strength

Figure 19 Comparison of molding techniques.

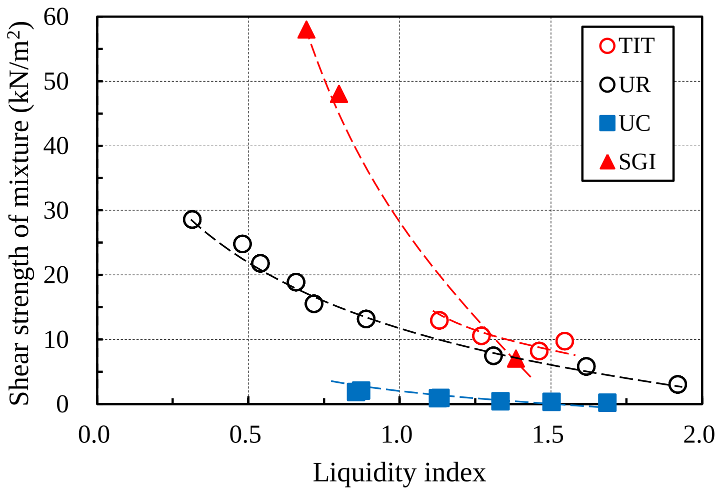
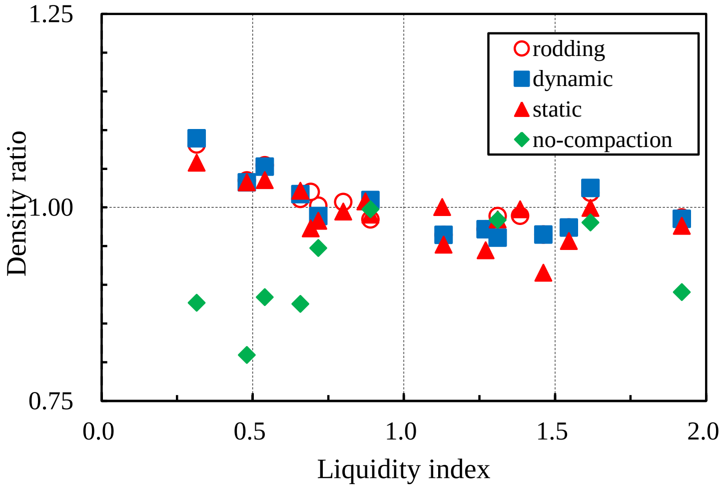
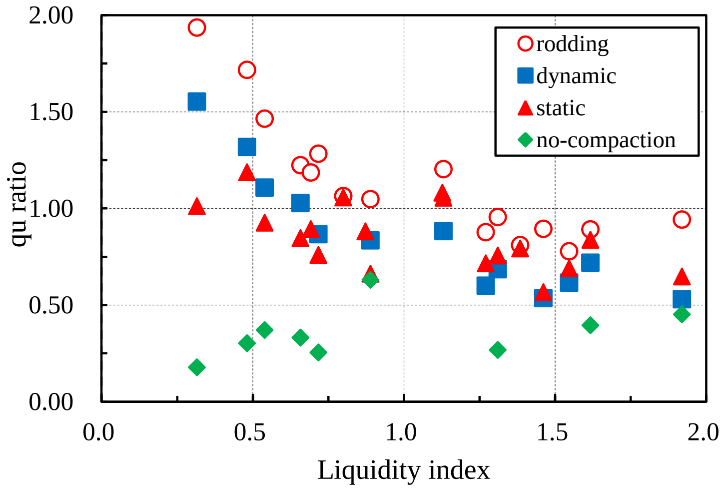


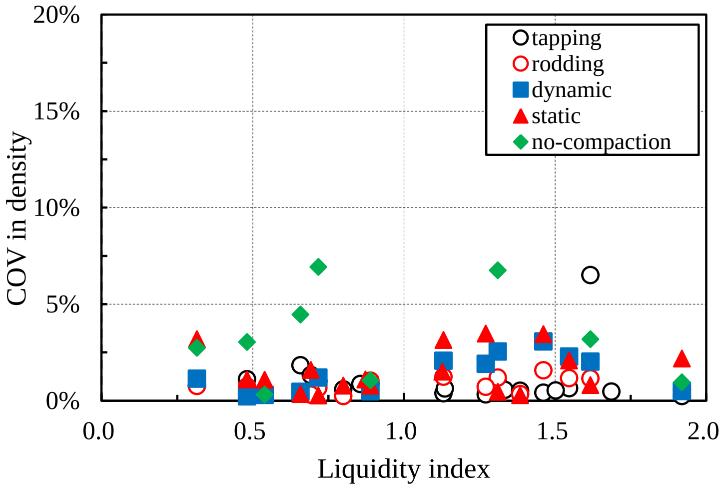
Figure 20 Relationship between liquidity index and shear strength of mixture.



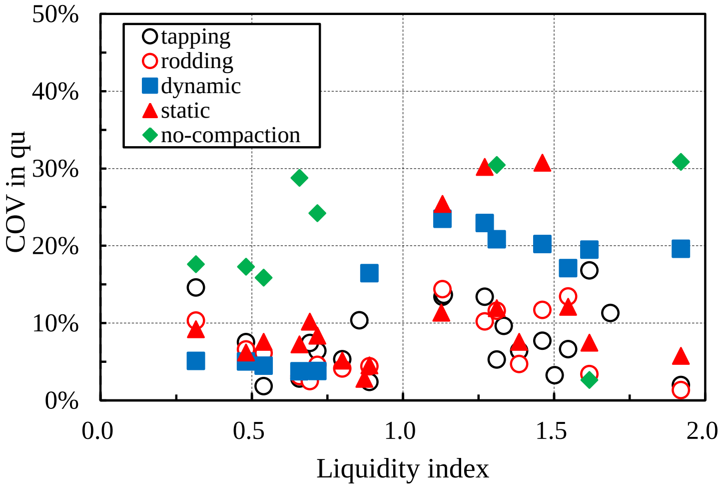
(a) Density ratio of sample



(b) Strength ratio of sample



(c) Coefficient of variation in wet density



(d) Coefficient of variation in unconfined compressive strength

Figure 21 Comparison of molding techniques.