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ORIGINAL ARTICLE

Influence of mix uniformity on the induced solidification of dredged marine clay

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Abstract Ground improvement with soil solidification has been widely applied and has proven to be an effective pre-treatment of soft soil deposits. The solidification procedure usually involves addition and thorough mixing of hydraulic binders with in situ soils, consequently transforming the soft materials into a stronger and stiffer stratum for load bearing. Much has been done on the binder's effectiveness and resulting enhanced properties of the soils, but not as much has been reported of the factors governing in situ mixing efficiency in producing uniform mixtures. While advancement in machinery and computerization of operations have significantly improved soil mixing, individual factors contributing to the process can be further examined to refine the effectiveness. This paper describes a series of laboratory tests, mainly unconfined compressive strength tests complemented with X-ray computer tomography, conducted on cement-stabilized dredged Kawasaki clay of different uniformities. A number of factors affecting uniformity were examined, namely the water/cement (WC) ratios, number of cement layers in the initial state as well as the number of mixing cycles adopted. Test specimens were prepared based on a systematic combination of these factors to enable a comprehensive cross-analysis of the results. It was found that the clay's initial consistency was markedly altered by cement addition, which resulted in either enhanced or reduced workability of the mixture. While increased mixing vigor could apparently overcome poor distribution of binder in the mixture, the resulting strength remained very much affected by the WC ratio, suggesting dependency of the mixture's overall uniformity on a combination of the factors.

Keywords Solidification · Uniformity · Mixing · Unconfined compressive strength · X-ray computer tomography

Introduction

It was reported as far back as 1999 by the Japan Port and Harbour Association that the country produces 10–15 millions m^3 of dredged soils from maintenance of water channel and the construction of marine structures alone, yearly. The dredged material, considered as waste, has mostly been stored in specially built bulkheads together with other waste products. It made up nearly half the total storage, incurring construction costs of tens of billions Japanese Yen (10 billion Japanese yen is equivalent to approximately 130 million US Dollar). With increased maritime traffic and international trade via sea ports, the numbers can only be expected to escalate further. Nevertheless, this costly containment measure was necessary, considering that uncontrolled offshore dumping of dredged material can cause severe degradation of natural coastal or marine ecosystems (Kapsimalis et al. 2010). Irresponsible offshore disposal of dredged materials can result in irreversible and severe disruption to the sensitive marine food chain too (Harvey et al. 1998). Besides, Simonini et al. (2005) pointed out the risk of contamination by critical levels of heavy metals and hydrocarbon with such offshore dumping of dredged soils, where the release of these contaminants could result in long-term damaging pollution (Leotsinidis and Sazakli 2008).

Heightened environmental awareness as well as foresight for sustainable development has ushered in an era of

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dredged material reutilization. It was generally acknowledged that it is beneficial to the environment to re-introduce the dredged soil into the production cycle of secondary raw materials (Kan 2009). Lee and Sturgis (1996) termed these recycled materials 'manufactured soil', providing a long-term solution to the dredged soil. From the geotechnical engineering point of view, dredged soils are considered a very soft geomaterial with high water content, limited strength, and excessive compressibility. Their reuse would require certain pre-treatment such as solidification with chemical mixing. With the addition of binders, like cement, the originally poor properties of the material can be improved. This technique, since its inception in the 1960s, has been widely adopted for inland development of sites with poor underlying soil strata. The most appealing factor of the method is arguably the 'reuse' instead of 'replace' concept, which inadvertently gives a sustainable value to the engineering endeavor (Chan 2009; Lee and Chan 2008). There is no lack of research effort in that direction for dredged material too. For instance, Sun et al. (2010) successfully solidified dredged Nagoya Port clay with cement and gypsum by reducing the rate of structural decay, while Okumura et al. (2000) introduced air bubbles and expanded polystyrene beads into dredged soils to form the Super Geo Material (SGM), a lightweight treated soil suitable for backfilling retaining structures. These innovations have effectively given a second life to the dredged material, simultaneously containing possible contamination and creating usable geomaterials.

While the binders, dosages as well as mixing methods, have gained tremendous advancement over the years, there remains the question of how much mixing is necessary to attain the target strengths. This is especially relevant in terms of time, energy, and money wastage for overdoing things on site. No report has been made to date, as far as the author is aware of, specifically on the mix uniformity aspect of induced solidification. Some of the more recent related work is included here though. Åhnberg and Holm (2009) examined the effect of time lapse between mixing and compaction of the mixture and reported anomalies in the strength measured. The time lapse effect may be offset by higher water content of the mixtures, where the retarded structural change allowed 'healing' of the mixed material (Hammond 1981). Marzano et al. (2009) found that the initial water content of a mixture has an inverse relationship with the unconfined compressive strength and secant Young's modulus (E_{50}). In compiling the data from an international collaborative study of lab-mixed specimens, Kitazume et al. (2009) drew several insightful conclusions: (1) prolonged mixing up to 2 h has no significant influence on the resulting solidified strength; (2) tapping and rodding are preferable to static and dynamic compaction to ensure homogeneity of the mixture; (3) maturity, a function of curing temperature and time, was found to be dependent on the soil type, binder type, and dosage in solidified clayey soils.

The present study examines the relationship between mixing quality of cement-treated dredged clay and the unconfined compressive strength. This aspect is of particular importance in mass solidification works of shallow depths (not exceeding 5 m), where backhoes are commonly used to mix the materials. As uniformity of the mixture is well known to have a significant effect on the resulting improved properties, the scooping motion of a backhoe may have limitations which can be aided by initial conditions of the materials, i.e., water/cement (WC) ratio, mixing water content, and distribution of cement powder. For this purpose, the study has been conducted with the dredged Kawasaki clay at a range of WC between 4 and 15, with varying cement dosages, mixing water contents, mixing frequency, and number of cement layers introduced initially. Interaction between the factors was examined in relation to the unconfined compressive strength, a parameter widely used in the assessment of solidified soils. Complementary images from the X-ray CT scans were also included for better illustration of the mix uniformity under the different conditions.

Experimental work

Test materials

The soil used in the present study was originally dredged from the shipping channels of Kawasaki Port in Japan. The dredged clay was removed of any foreign materials, such as pebbles, shell, and drift wood fragments and then wet-sieved to obtain only the soil particles. Properties of the soil can be found in Table 1. Note that silt constituted approximately half of the soil's composition. Mixing water content used in preparing the specimens was based on multiples of the liquid limit, LL = 55.2 %. As the natural water content was beyond that of LL, the clay was in liquefied form prior to mixing. Ordinary Portland cement was added to the clay as the binder ($G_s = 3.15$).

Preparation of test specimens

The clay was remolded in a conventional kitchen mixer a day prior to mixing. This was mainly to identify the actual water content of the clay so that the correct cement dosage and quantity of additional water required could be determined. The measured out distilled water was added to the clay to achieve the consistency of 1.5LL, 2.0LL, 2.5LL, or 3.0LL, respectively. The cement powder was oven-dried at 105 °C to remove any entrapped moisture, then added to

Table 1 Properties of soil used in the study

Properties	Values
Natural water content, w_{nat}	73.5 %
Specific gravity, G_s	2.702
Consistency limits	
Liquid limit, LL	55.2 %
Plastic limit, PL	24.4 %
Plasticity index, PI	30.8 %
Particles size distribution	
75 μm–2 mm	16.4 %
5–75 μm	49.7 %
<5 μm	33.9 %

the clay at dosages (C) of 8–41 %, corresponding to water/cement ratios (WC) ranging from 4 to 15. Table 2 gives a summary of the specimens and mix ratios. The cement was placed either in single (S), double (D) or triple (T) layers in the specimens at equal distances. Disposable plastic molds measuring 50 mm in diameter and 135 mm in height were used to form the specimens, which were trimmed to 100 mm height upon demolding.

Mixing was carried out using a small spatula in scooping motions, mimicking field shallow mixing with a backhoe. The mixing frequency was fixed at 5, 50, and 100 cycles, to simulate a low-to-high agitation level of the soil–cement mixture for attaining uniformity. The mold containing the mixture was finally tapped 50 times to avoid formation of large voids due to entrapped air, excessive adherence of materials on the interior wall and an overly undulating top surface. Both the number of cement layers and mixing cycles were considered primary factors affecting the mixing quality, while the mixing water contents as well as cement dosages served as the initial conditions of mixing environment. All specimens were cured in an airtight container at controlled room temperature of 20 °C and relative humidity of 70 %.

Table 2 Details of specimens

$W/C = 10$ ($C = 8$–16 %)	$W/C = 4$ ($C = 21$–41 %)	$C = 11$ % ($W/C = 7.5$–15.0)
1.5LL-8*C*-5*S/D/T*	1.5LL-21*C*-5*S/D/T*	1.5LL-11*C*-5*S/D/T*
1.5LL-8*C*-50*S/D/T*	1.5LL-21*C*-50*S/D/T*	1.5LL-11*C*-50*S/D/T*
1.5LL-8*C*-100*S/D/T*	1.5LL-21*C*-100*S/D/T*	1.5LL-11*C*-100*S/D/T*
2.0LL-11*C*-5*S/D/T*	2.0LL-28*C*-5*S/D/T*	2.0LL-11*C*-5*S/D/T*
2.0LL-11*C*-50*S/D/T*	2.0LL-28*C*-50*S/D/T*	2.0LL-11*C*-50*S/D/T*
2.0LL-11C-100*S/D/T*	2.0LL-28*C*-100*S/D/T*	2.0LL-11*C*-100*S/D/T*
2.5LL-14*C*-5*S/D/T*	2.5LL-35*C*-5*S/D/T*	2.5LL-11*C*-5*S/D/T*
2.5LL-14*C*-50*S/D/T*	2.5LL-35*C*-50*S/D/T*	2.5LL-11*C*-50*S/D/T*
2.5LL-14*C*-100*S/D/T*	2.5LL-35*C*-100*S/D/T*	2.5LL-11*C*-100*S/D/T*
3.0LL-16*C*-50*S/D/T*	3.0LL-41*C*-50*S/D/T*	3.0LL-11*C*-50*S/D/T*
3.0LL-16*C*-5*S/D/T*	3.0LL-41*C*-5*S/D/T*	3.0LL-11*C*-5*S/D/T*
3.0LL-16*C*-100*S/D/T*	3.0LL-41*C*-100*S/D/T*	3.0LL-11*C*-100*S/D/T*

Example: 1.5LL-8*C*-50*S* represents specimen mixed at 1.5 times the clay's liquid limit (1.5LL), with 8 % cement addition by dry weight of the clay (8*C*), subjected to 5-cycle mixing (5) and had an initial single layer of cement (*S*)

Test methods

The unconfined compressive strength (UCS) test was conducted when the specimens reached the age of 28 days, following the standard procedure of JIS A 1216–1993 (Japanese Standard Association 1993). As a popular and widely adopted test method for stabilized soils, it was also considered appropriate for assessing the effect of uniformity as it measures the representative strength of a specimen, which is a measurement of the average compression resistance. Complementary observations of the specimens' uniformity were also carried out using X-ray CT (computerized tomography) scans. The Shimidzu scanner employed for the purpose had a cone-shape X-ray irradiation angle of 60° and was equipped with micro-focus function (minimum focus size, 4 μm) for capturing high-resolution images of very small parts in a specimen.

Results and discussions

Initial and final water contents

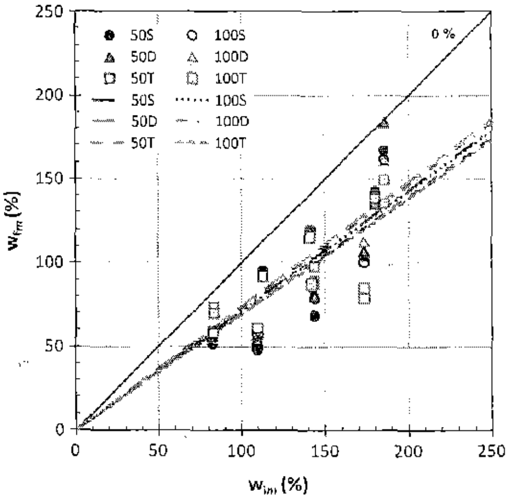
The measured initial and final water contents, w_{in} and w_{fin}, are compiled and shown in Fig. 1. A line of equality (labeled 0 %) was included in the plots to represent no change in the water contents, where all data can be expected to fall below the line. Notwithstanding the scatter of the data, linear regression lines were fitted to the individual data sets with coefficients of correlation (R^2) ranging between 0.5882 and 0.7646 in Fig. 1 (see accompanying table). Gradient of the regression lines is defined as factor A, which is the ratio between w_{in} and w_{fin}. The effects of number of cement layers (N_{C}) as well as mixing cycles (M_{X}) on the uniformity of mixtures can be inferred from this plot, where they are defined by taking the ratio between A factors of specimens D/S and $100/50$, respectively. First, factor A for specimens with the same mixing cycles over those with a single cement layer, i.e., $50D/50S = 1.03$, $50T/50S = 0.97$, $100D/100S = 1.03$, and $100T/100S = 0.97$, did not show significant differences. The very small differences were negligible, taking into consideration possible errors arising from evaporation and sample disturbance. As such, N_{C} was found to be 1.00, taken as average of the four sets of data. An apparent observation was made though, that with increased mixing cycles, w_{fm} underwent greater reduction, indicating less bleeding and a more well-mixed soil mass with more extensive cementation. Second, factor A for specimens with the same number of cement layers over those with 50-cycle mixing, i.e., $100T/50T = 0.989$ and $100D/50D = 0.990$, again showed very negligible differences. This gives an average M_X value of 0.988. The marginal differences were attributed to the same reasons mentioned above for N_C.

Unconfined compressive strength (q_u)

Taking the specimens with the same cement content (C), i.e., 11C, a graph of unconfined compressive strength (q_u) versus mixing water content (w_{mix}) was plotted (Fig. 2). These specimens were chosen as they represented a full range of mixtures with varying w_{mix} but a fixed C. The data were further differentiated as those subjected to 50- or 100-cycle mixing. It can be quickly noticed that q_u decreased with increased water added for mixing initially. Also, as the base clay became more liquefied with higher w_{mix}, the effect of mixing frequency diminished, where at w_{mix} over 180 %, increased agitation of the mixture produced no difference in q_u. While higher w_{mix} enabled easier mixing, insufficient agitation of the mixture could cause the cement powder to either distribute unevenly within the specimen, or form cement-coated lumps of clay, both leading to poor uniformity and compromised overall strength. This is evident from similar q_u values recorded for the 15WC–3.0LL specimens in Fig. 2. Besides, 50-cycle mixing at lower w_{mix} was clearly detrimental to uniformity of the specimens as shown by the uniformly lower q_u values for specimens with 7.5–12.5WC.

In Fig. 3, the data presented were those of specimens mixed at WC = 4 and 10, respectively. For both cases, strength (q_u) dropped with increased cement content (C) and mixing water content (w_{mix}), though the 10WC specimens showed distinct clustering of the data points with q_u not exceeding 900 kPa. The cement content in the 10WC specimens were clearly much lower, which could account for the low q_u recorded. The mixing cycles also showed less significant effect on q_u as C increased, but this is attributed to the higher w_{mix} of the specimens. Considering that both the specimen groups of 4 and 10WC had the same mixing water contents but varying cement dosages, the cementation effect is bound to be more significant in the former group, which contained on average 2.55 times more binder than the latter group. This highlights the overwhelming effect WC has on the performance of the solidified soil.

Following the discussion above, while certain pattern can be observed of the q_u–w_{mix} and q_u–C relationship, it is apparent that both w_{mix} and C are fundamental parameters that govern the solidification effectiveness. This is not novel though, as pointed out by Horpibulsuk et al. (2005) and Miura et al. (2001), who formulated a predictive model for similar treated soils based on Abram's law, a well-established equation used in the studies of cement. Nonetheless, there are a couple of arguments which the author would like to put forth referring to the work of the aforementioned researchers. First, well-mixed solidified soils



Specimen	$A = w_{fm}/w_{im}$	R^2
50S	0.718	0.6423
100S	0.713	0.6702
50D	0.742	0.6685
100D	*0.732*	*0.7646*
50T	0.699	0.6186
100T	0.691	0.5882

Fig. 1 Measured final (w_{fm}) and initial water contents (w_{im}): effects of number of cement layers (N_C) and mixing cycles (M_X)

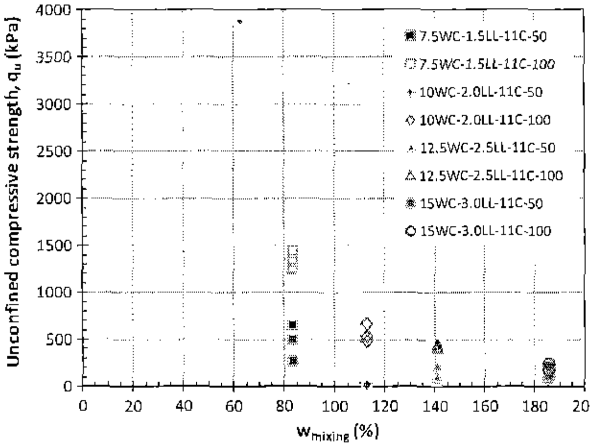


Fig. 2 Unconfined compressive strength (q_u) against mixing water content (w_{mixing}) plots

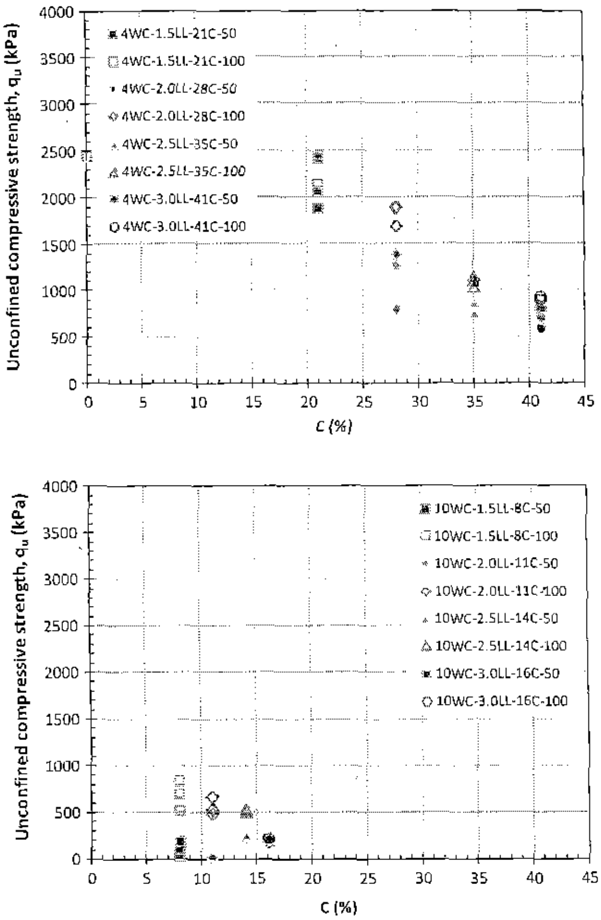


Fig. 3 Unconfined compressive strength (q_u) against cement content (C) plots

with the same WC do not necessarily display the same strength, suggesting that WC is not an exclusive signature for estimating the strength. Second, due to the diversified mineralogy and chemical composition of the base soils, a universal predictive model that suits all soils when subjected to chemical treatment is highly debatable. These are further highlighted in the following analysis and discussions of the present work.

Figure 4a compiles q_u of the specimens plotted against WC, where each plot represents specimens prepared with the same mixing water content (w_{mix}), i.e., 1.5, 2.0, 2.5, and 3.0LL. Within the WC range up to 10, it is apparent that gradient of the q_u–WC curves reduced with higher w_{mix}. Although the specimens with more liquefied base clay (i.e., higher w_{mix}) contained significantly higher cement dosages, the cementation effect did not prevail in the q_u measured. This indicated the overwhelming effect of initial 'wet' condition on the resulting solidification, despite the presence of greater quantities of cement. Furthermore, as mentioned earlier, the mixing cycles ceased to influence the solidified strength of the specimens as the ease of mixing was enhanced with higher w_{mix}. Consequently, it is suggestive that the compromised strength of the specimens was due to the non-uniformity of cementation within the specimens as a result of either (1) insufficient or (2) ineffective mixing. The former is evident in the strength disparity between specimens with 50- and 100-cycle mixing, particularly at lower w_{mix}. The latter, on the other hand, was caused by the cement powder coagulating and settling to the bottom of the more liquefied specimens. These extreme ends of initial mixing condition clearly play a dominant role in the uniformity of solidified soils. In practical terms, mixing under an overly dry condition requires higher energy consumption for mixing power and duration, while mixing in an overly wet condition can be outright futile regardless of the mixing vigor employed.

Figure 4b shows the combined plots of all the specimens, as derived by using natural log-based regression on the data sets in Fig. 4a. The log-based equations are presented in the same figure. In spite of the scatter of data, especially in the 1.5 and 2.0LL data sets (see Fig. 3), the plot reveals a unique mixture identity at WC = 10, where all the trend lines intersect at approximately 380 kPa. It appears that the solidified material will attain the same strength irrespective of the initial mixing conditions (i.e., as determined by w_{mix} and C), as long as WC is kept at 10. However, as a more liquefied soil needs a higher cement dosage to attain the optimal WC of 10, it is imperative from the economic point of view to identify the most practical combination of w_{mix} and C. The unique signature WC value serves well as a reference and target in both the design as well as quality control stages of work on site. Also, with higher w_{mix}, the decline in q_u can be observed to be less dramatic and that the mixture's identity waned with increased liquefied condition of the mixture.

Solidification effect is known to be enhanced with decreasing WC. However, Miura et al. (2001) reported that specimens with identical WC demonstrate the same stress–strain behavior as well as strength characteristics in unconfined compressive strength tests. It was further elaborated that WC up to 10 is considered in the low range, where the fabric of the clay–cement mixtures plays a negligible role in the shearing resistance or load-bearing. At higher water contents, the plot's gradient takes a gentler turn, indicating lesser dependency of WC ratio on the cement dosage. With increased water content, the effect of fabric diminishes, particularly if the cement percentage added is comparatively low.

Mixing efficiency ratio (q_{u100}/q_{u50})

The mixing efficiency ratio is defined as q_u of a specimen of the same mix ratio subjected to 100-cycle mixing over that of 50-cycle mixing, i.e., q_{u100}/q_{u50}. Note that q_u at

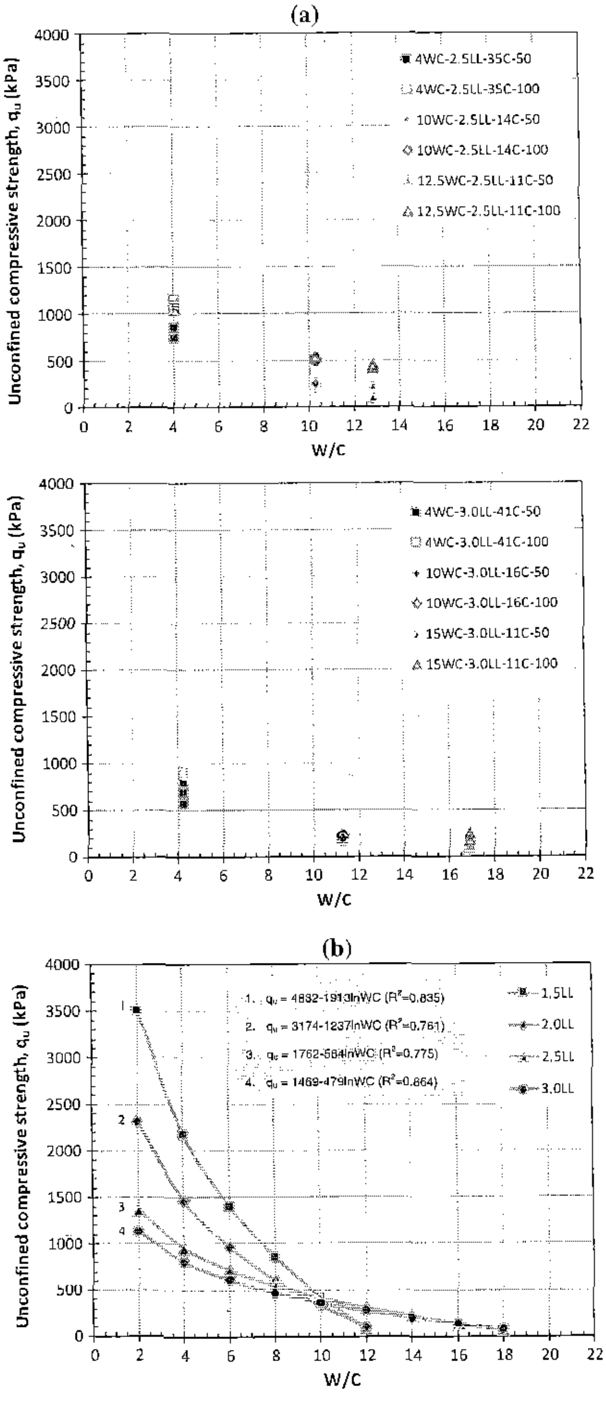


Fig. 4 **a** Unconfined compressive strength (q_u) against water/cement ratio (*W/C*) plots. **b** Combined plots of q_u–WC

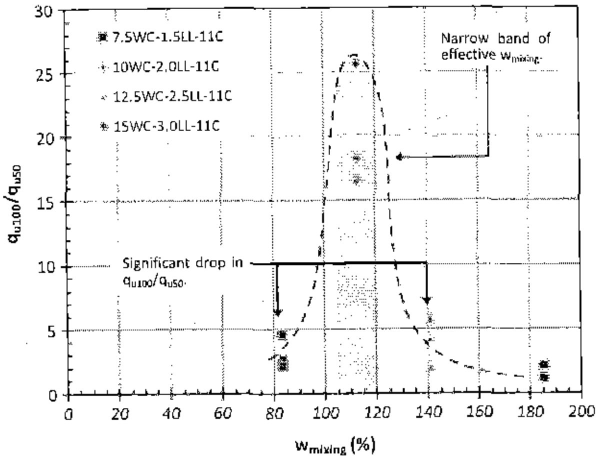


Fig. 5 q_{u100}/q_{u50} against mixing water content (w_{mixing}) plots

5-cycle mixing was not used as the reference value as most of the specimens were too weak for extraction from the mold, let alone tested. Effect of cement content on the mixing efficiency ratio is illustrated in the q_{u100}/q_{u50}–w_{mixing} plot in Fig. 5. While all specimens were prepared at the same cement content of 11 %, the varying mixing water content resulted in a range of WC between 7.5 and 15. The vertically stacked data points of each mix consisted of specimens with initial single, double, or triple cement layers. As expected, the triple-layer specimens consistently gave the highest strength increment, due mainly to the more effective dispersion of the binder. Interestingly though, WC = 10 emerged the optimum mix for 11 % cement addition. The plots further revealed a significant drop in strength increase on both sides of the optimal peak, indicating a narrow band of w_{mixing} permissible for effective solidification to take place. The severe drop of the mixing efficiency ratio in either 'too dry' or 'too wet' conditions can be explained as follows:

1. On the 'dry' side: Mixing was hampered by the stiff clay-cement mass, where the repeated scooping motions *failed to agitate the materials into a uniform* mix. This formed a random matrix of partially solidified clay, unreacted cement lumps coated by clay, large voids as well as unbound clay.
2. On the 'wet' side: The ease of mixing was obvious but ineffective, as there was simply insufficient cement to react with the excessive water present. This caused the specimens to be *bottom heavy: the partially solidified* clay settled at the bottom of the mold and was overlain by the gradual sedimentation of unbound clay particles. Bleeding was also severe.

Figure 6 shows the mixing efficiency ratio plotted against the cement content (*C*), for the 4- and 10WC specimens. A uniform mix clearly resulted in significant strength enhancement, giving an increment ratio between approximately 5 and 25 at cement dosages of 8 and 11 %, respectively. However, initial water content of 2.0LL produced greater workability and increased mix uniformity, as evidenced by the mixing efficiency ratio which

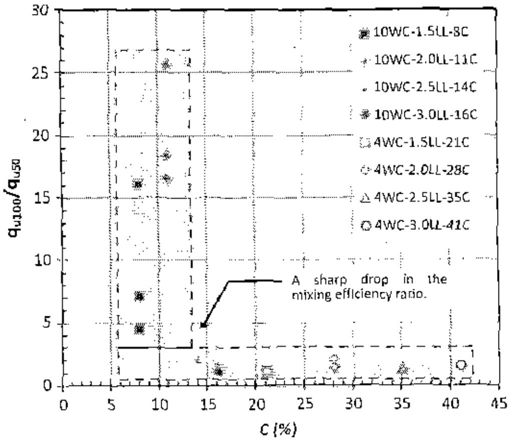


Fig. 6 q_{u100}/q_{u50} against cement content (C) plots

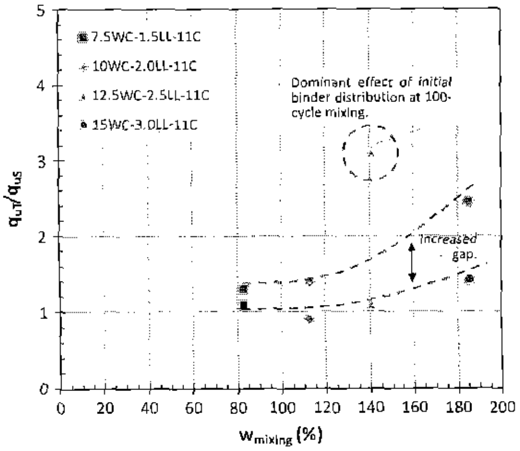


Fig. 7 q_{uT}/q_{uS} against mixing water content (w_{mixing}) plots

falls within the higher range of 15–25. Increased mixing water content does not necessarily impede cementation of the clay, albeit at the same WC ratio, i.e., WC = 10. This is in accordance with observations made earlier referring to Fig. 5, with the optimum mixing water content playing a crucial role in achieving maximum strength improvement when the same cement dosage was adopted.

For this particular clay, the mixing efficiency ratio was reduced to a mere average of 2 at WC = 4, and when the mixing water content went beyond 2.0LL (Fig. 6). This was despite the much higher cement dosages in the specimens. Note that the actual q_u values were higher for the WC = 4 specimens (see Fig. 3), but the mixing efficiency ratio reveals inefficiency of the mixing process when the maximum workability has been exceeded. This is clearly denoted by the sharp kink in the plot of Fig. 6. Considering that the mixing efficiency ratio is an index of the effect of mixing cycles or level of agitation, the plateau in the plot suggests the redundancy of mixing energy expended in mixtures of high workability. In practice, with greater ease of mixing provided by a more workable mixture (i.e., higher mixing water content), mixing efficiency can be markedly improved by reducing the mixing duration, for instance. This, however, should not be confused with achieving the ultimate target strength, where cement dosage remains the dominant factor.

Initial binder distribution factor (q_{uT}/q_{uS})

The initial binder distribution factor (q_{uT}/q_{uS}) is simply a measure of the effect of the number of cement layers placed in the specimen in terms of unconfined compressive strength. In Fig. 7, the factor is plotted against the mixing water content for specimens with the same cement dosage, i.e., 11C. Generally, benefits of the initial cement distribution increased with higher mixing water content, as represented by the enlarging vertical gap between the data points. The data points lying along the upper line are those of specimens subjected to 100-cycle mixing. This suggests the importance of adequate mixing in order to optimize the distributed binder. The effect of clay's consistency is also apparent, as seen in the gradual rise of the plots.

Note the dominant effect of the initial cement distribution (circled in plot) at w_{mixing} = 2.5LL or approximately 140 %. This seemingly anomalous data point could indeed be indicating an optimal consistency of clay to take full advantage of the initial cement distribution. In comparison with the mixing efficiency ratio effect (Fig. 5), a less liquefied clay was found to be more conducive for effective agitation of the mixture, i.e., w_{mixing} = 2.5LL. As such, while the two factors may not always be compatible with each other, increased mixing energy seems to be the more dominant factor in the solidification of clay soils. In other words, a vigorous mixing mechanism could compensate for the initial poor distribution of binder in the soil, provided the clay has the right mixing water content.

On the other hand, cement content did not appear to have much influence on the q_{uT}/q_{uS}, as can be seen in the horizontal spread of data points in Fig. 8. There is no apparent pattern of change on the strength increment induced by the cement content. This is in contrast with earlier discussion on the influence of w_{mixing} on the strength increment of the specimens (Fig. 7). It is indicative that as long as the base clay contains sufficient water to facilitate effective mixing, the amount of cement added and the number of cement layers initially introduced (i.e., initial distribution) have negligible impact on the mix uniformity, which is translated as the strength of the specimens prepared. Nevertheless, the adequacy of mixing effort or prolonged mixing duration plays a vital role in ensuring subsequent distribution of the dry binder within the soil mass to achieve a uniform mix.

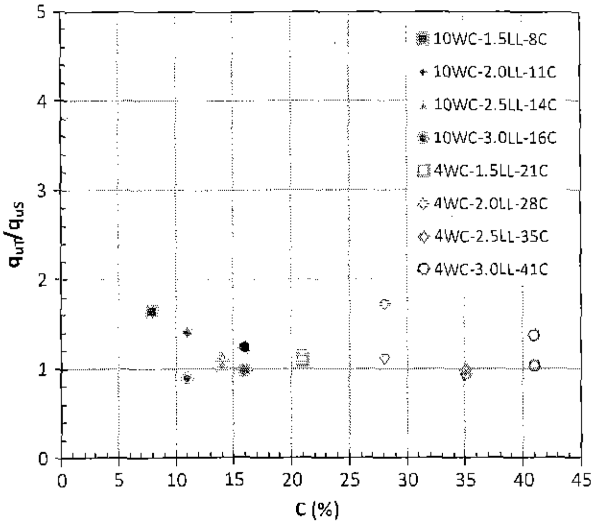


Fig. 8 q_{uT}/q_{uS} against cement content (C) plots

Discussion on overall UCS test results

Difference in laboratory measured and field monitored strengths of solidified soils has been known to be caused by several factors, namely the degree of mixing, separation of stabilizer in the water, execution method, and curing environment (Coastal Development Institute of Technology (CDIT), Japan 2003). The aforementioned findings of the present study apparently echoed these factors, particularly the former two. These two factors are not mutually exclusive indeed, as can be noted from the earlier discussions. The degree of mixing is very much influenced by the initial water content, where an excessively liquefied state of the mixture cannot be compensated by efficient mixing. Marzano et al. (2009) indicated the same, reporting of the generally unchanged unconfined compressive strength of solidified specimens prepared at elevated water contents despite the different molding techniques adopted, i.e., static and dynamic compaction. Interestingly, Åhnberg and Holm (2009) found that higher mixing water content could result in higher strengths, a phenomenon explained by the retarded structural transformation of the cementation process, allowing time for the damaged structure to repair itself. Low mixing water content, on the other hand, can lead to lower degrees of saturation, which in turn affects the stiffness of the solidified soil. Shear modulus, for instance, was reportedly lower in solidified specimens of the 'dry' side (Åhnberg and Holmén 2009; Clariá and Rinaldi 2008). The risk of premature dehydration is also imminent for specimens prepared at low water content, where the reduced fluidity of the soil–cement mixture could hinder effective removal of entrapped air during mixing and result in less than satisfactory strength gain (Kitazume and Nishimura 2009).

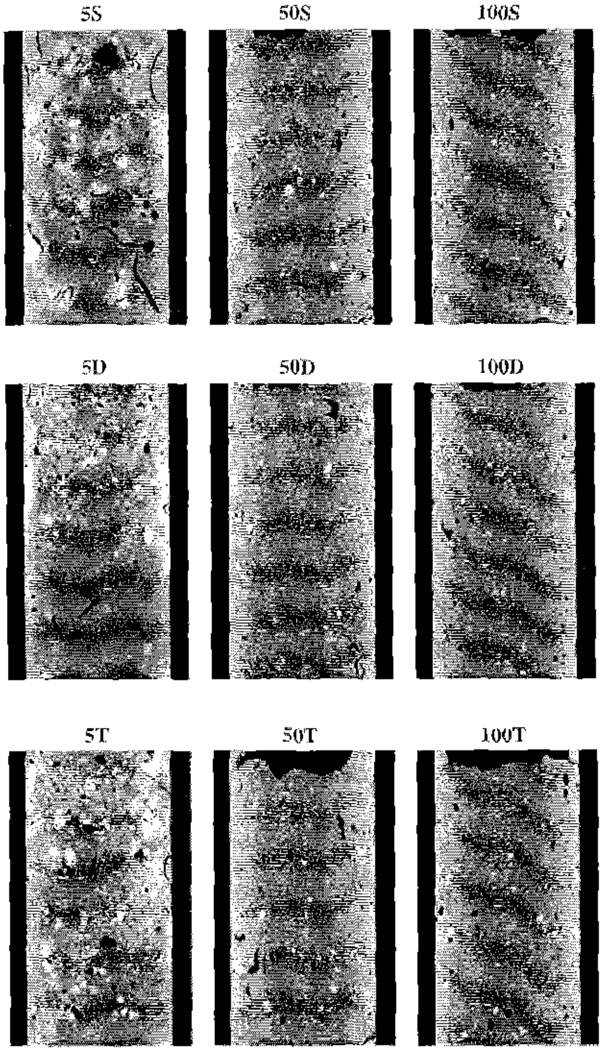


Fig. 9 X-ray CT images of specimens 4WC–1.5LL

X-ray computer tomography (CT) images

Figures 9, 10 and 11 shows the X-ray CT images captured of the specimens at 28 days curing prior to the UCS tests. A quick glance is sufficient to reveal that vigorous mixing (i.e., 100-cycle mixing) effectively dispersed the cement powder to blend with the soil, regardless of initial conditions of clay's consistency and cement distribution. Inadequate mixing, on the other hand (i.e., 5-cycle mixing), was most detrimental to the mixture's uniformity in all cases. In the 'dry' mix (Fig. 9), the cement formed clods and lumps throughout the specimens, though admittedly the increased number of cement layer did seem to result in smaller and more dispersed cement aggregates. Severe cracks and large voids were found in the 5S specimen, a consequence of poor mixing and compaction as well as potential localized cement hydration that caused shrinkage. In the 'wet' mix

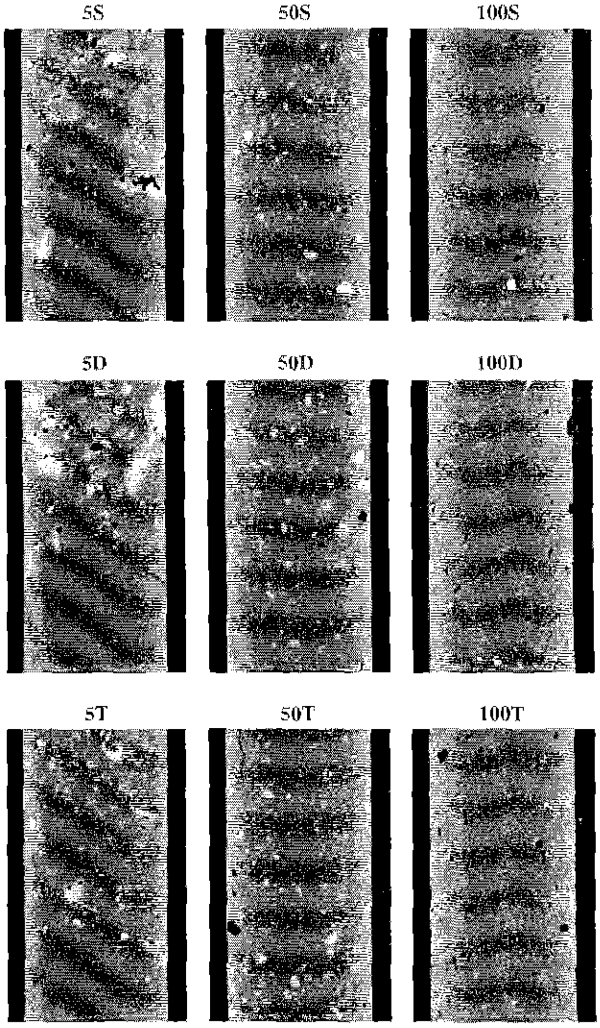


Fig. 10 X-ray CT images of specimens 10WC–1.5LL

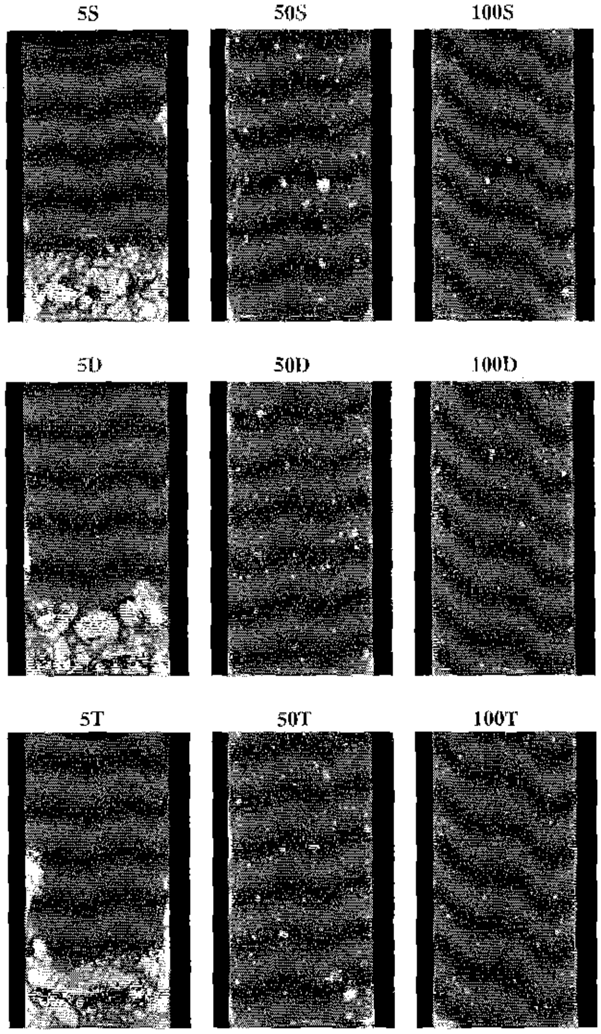


Fig. 11 X-ray CT images of specimens 10WC–3.0LL

(Fig. 11), 5-cycle mixing left almost all the cement aggregates at the bottom of the specimen. The clotted cement lumps were larger and apparently did not contribute much to the solidification of the soil.

Interestingly, 50-cycle mixing did not make a significant difference to the uniformity compared with 100-cycle mixing in the 'dry' specimen (Fig. 9). The specimens appeared similar with well-distributed small cement aggregates and voids. With increased workability of the mixture, i.e., with lower cement dosage (Fig. 10) or increased water content (Fig. 11), the effect of inadequate mixing was more pronounced between 50- and 100-cycle mixing. Larger cement aggregates can be seen in the 50-cycle specimens, irrespective of the number of cement layers introduced. Only when 100-cycle mixing was adopted did uniformity prevail, with the images showing a generally singular gray tone throughout the specimens.

Petry and Little (2002) claimed that the degree of pulverization is a critical constructional factor in chemical solidification of soils. As pulverization is an indicator of the presence of large clods or aggregates within a soil mass, the claim appears valid for poorly solidified soils due to the formation of large cement and cement–soil aggregates observed in the present study. Large clumps of clay are found to be detrimental to the solidification process, compromising on the resulting strength and durability (Petry and Wohlegemuth 1988). These large inclusions do not only significantly reduce the available surface area of soil particles for effective cementation, but also entrap unreacted cement powder within the soil–cement lumps. This is evident in the white spots within light gray lumps of the 5-cycle specimens in Fig. 11. Naturally, being denser and heavier, these lumps sank to the bottom and remained relatively disjointed, with unsolidified clay between their gaps. In addition, prolonged curing up to 4 weeks did not contribute to solidification of the clay surrounding the lumps. This is in accordance with the postulation of Bozbey and Garaisayev (2010) that breakdown of the clods does not take place during the resting period, though the authors did suggest the probable positive effect of prolonged curing.

In short, the CT images lend further visual evidence to the observations and analysis discussed earlier, where mixing vigor remains the dominant factor in uniformity of the mixture. Nevertheless, the level of uniformity or quality of mix depends on the clay's consistency, cement dosage, and initial distribution of cement too. While an effective mixing process ensures good dispersion of the binder, the resulting strength of the stabilized soil is influenced by each factor, where an optimum combination of all the factors can only produce excellent uniformity and not necessarily the target strength.

Conclusions

The present study on a series of cement-treated dredged marine clay simulated at various levels of uniformity has led to the following conclusions:

- Greater mixing efficiency reduces bleeding and increases the mixture's uniformity, resulting in higher compressive strength of the solidified specimens. Nonetheless, the mixing water content plays the primary role in producing uniform mixtures, on condition of sufficient mixing energy being expended.
- Essentially, benefits of the initial cement distribution increase with higher mixing water content, where greater mixing vigor enables more effective dispersion of the binder. Vigorous agitation of the mixture could eliminate risks of non-uniformity due to initial poor distribution of cement in the soil mass, though this is very much dependent on the soil's workability, as determined by the mixing water content.
- Between the mixing efficiency ratio (q_{u100}/q_{u50}) and the initial binder distribution factor (q_{uT}/q_{uS}), the former emerges as a more dominant factor in the mix uniformity of solidified clay. Efficiency of the mixing process would be compromised when the maximum workability of the mixture is exceeded, suggesting energy and time wastage of prolonged mixing in highly workable mixtures.
- The efficiency of mixing is further categorized into two conditions, i.e., 'too wet' and 'too dry'. The 'wet' condition results in lumpy, non-uniform mixtures, while the 'dry' one causes segregation of materials and bleeding, both detrimental to the performance of the solidified clay.

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References

Åhnberg H, Holm G (2009) Influence of laboratory procedures on properties of stabilised soil specimens. In: Proceedings of the international symposium on deep mixing and admixture solidification, Okinawa

Åhnberg H, Holmén M (2009) Assessment of strength of stabilised soils by geophysical laboratory testing. In: Proceedings of the international symposium on deep mixing and admixture solidification, Okinawa

Bozbey I, Garaisayev S (2010) Effects of soil pulverisation quality on lime solidification of an expansive clay. Environ Earth Sci 60(6):1137–1151

Chan C-M (2009) Sustainable geotechnics via in situ soil reutilisation. Invited lecture: Evening talk session of the Geotechnical Engineering Technical Division, Kuala Lumpur, Malaysia. Institution of Engineers Malaysia (IEM), Malaysia

Clariá J, Rinaldi V (2008) Shear wave velocity of a compacted clayey silt. ASTM Geotech Test J 30(5):399–408

Coastal Development Institute of Technology (CDIT), Japan (2003) The premixing method: principle, design and construction. A.A. Balkema Publishers, The Netherlands

Hammond AA (1981) Measurement of autogenous healing in stabilised soils. In: Proceedings of the 10th international conference on soil mechanics and foundation engineering, Stockholm

Harvey M, Gauthier D, Munro J (1998) Temporal changes in the composition and abundance of macro-benthic invertebrate communities at dredged material disposal sites in the Anse a Beaufils, Baie de Chaleurs, Eastern Canada. Mar Pollut Bull 36:41–55

Horpibulsuk S, Miura N, Nagaraj TS (2005) Lay-water content ratio identity for cement admixed soft clays. ASCE J Geotech Geoenviron Eng 131(2):187–192

Japan Port and Harbour Association (1999) Technical standard for port facilities (in Japanese)

Japanese Standard Association (1993) Method for unconfined compression tests. JIS A 1216-1993, 1–11 (in Japanese)

Kan A (2009) General characteristics of waste management: a review. Energy Educ Sci Technol Part A 23:55–69

Kapsimalis V, Panagiotopoulos I, Kanellopoulus T, Hatzianestis I, Antoniou P, Anagnostou C (2010) A multi-criteria approach for the dumping of dredged material in the Thermaikos Gulf, Northen Greece. J Environ Manage 91:2455–2465

Kitazume M, Nishimura S (2009) Influence of specimen preparation and curing conditions on unconfined compression behaviour of cement-treated clay. In: Proceedings of the international symposium on deep mixing and admixture solidification, Okinawa

Kitazume M, Ohishi K, Nishimura S, Terashi M (2009) International collaborative study Task 2 report: interpretation of comparative test programme. In: Proceedings of the international symposium on deep mixing and admixture solidification, Okinawa

Lee Y-L, Chan C-M (2008) Concept and recent development in pavement design: soil subgrade solidification. In: Seminar on soil subgrade solidification (special lecture). Road Engineering Association of Malaysia, Kuala Lumpur

Lee CR, Sturgis TC (1996) Manufactured soils: a productive use of dredged material. In: Proceedings of the US/Japan experts meeting, Oakland

Leotsinidis M, Sazakli E (2008) Evaluating contamination of dredges and disposal criteria in Greek coastal areas. Chemosphere 72:811–818

Marzano IP, Al-Tabba A, Grisolia M (2009) Influence of sample preparation on the strength of cement-stabilised clays. In: Proceedings of the international symposium on deep mixing and admixture solidification, Okinawa

Miura N, Horpibulsuk S, Nagaraj TS (2001) Engineering behaviour of cement stabilised clay at high water content. Soils Found 41(5):33–45

Okumura T, Noda S, Kitazawa S, Wada K (2000) New ground material made of dredged soil for port and airport reclamation projects. In: Nakase A, Tsuchida T (eds) Coastal geotechnical engineering in practice

Petry TM, Little DN (2002) Review of solidification of clays and expansive soils in pavements and lightly loaded structures—history, practice and future. ASCE J Mater Eng 14(6):447–460

Petry TM, Wohlegemuth SK (1988) Effects of pulverisation on the strength and durability of highly active clay soils stabilised with lime and Portland cement. Transportation Research Record 1190, Artificial Ground Freezing and Soil Solidification. Transportation Research Board, Washington, DC, pp 38–45

Simonini R, Ansaloni I, Cavallini F, Graziosi F, Iotti M, Massamba N'Siala G, Mauri M, Montanari G, Preti M, Prevedelli D (2005) Effects of long-term dumping of harbour-dredged material on macrozoobenthos at four disposal sites along the Emilia-Romagna coast (Northern Adriatic Sea, Italy). Mar Pollut Bull 50:1595–1605

Sun K, Nakano M, Yamada E, Asaoka A (2010) Mechanical behaviour of compacted geomaterial changed from the dredged soil in Nagoya Port by mixing with some stabilisers. In: Proceedings of the geo-Shanghai international conference, Shanghai