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Solidification of dredged marine clay under varied mix conditions: A laboratory study

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ABSTRACT: Dredged marine clay, treated with binders like cement, can be reused in various geotechnical applications as sound geomaterial. By adding and mixing binders with the clay, the soft material can be transformed into stronger and stiffer stratum for load bearing. Admittedly advancement in machinery and computerized operations have significantly improved the mixing process, but individual factors contributing to the mixing condition still leave room for further refinement of the effectiveness. This paper describes a series of laboratory tests, mainly unconfined compressive strength tests complemented with X-ray CT (Computer Tomography) scans, conducted on cement-stabilised dredged clay specimens of varied uniformity. The variation in uniformity was introduced via different Water/Cement (W/C) ratios, number of cement layers in the initial state as well as the number of mixing cycles adopted. The wide spectrum of specimens tested allowed a comprehensive cross-comparison of the results, which showed that while mixing effort is crucial, the initial conditions of clay's consistency and binder's distribution do affect the solidification mechanism to certain extents.

1 INTRODUCTION

The Japan Port and Harbour Association reported back in 1999 that the country produces 10–15 millions m^3 of dredged soils from maintenance of water channel and construction of marine structures. The number can only be expected to rise with increased maritime traffic and international trade via sea ports. As uncontrolled offshore dumping of dredged material is known to cause severe degradation of natural coastal or marine ecosystems (Kapsimalis et al. 2010), the waste has been traditionally stored in custom-built bulkheads to prevent contamination. Moreover, offshore disposal of dredged materials can cause irreversible and severe disruption to the sensitive marine food chain (Harvey et al. 1998), not to mention the potential rise of heavy metals and hydrocarbon in the waters to critical levels (Simonini et al. 2005). Leotsinidis & Sazakli (2008) aptly cautioned that release of these contaminants could lead to long term damaging pollution.

Instead of storing the dredged clay as waste, it can be re-introduced into the production cycle of secondary raw materials as an environmentally-friendly and viable solution (Kan 2009). Mainly a very soft geomaterial with high water content, limited strength and excessive compressibility, the reuse of dredged clay obviously requires certain pre-treatment, such as solidification with chemical admixing. This ground improvement technique combines an engineered approach with 'green' appeal, for the material is being recycled and reused (Chan 2009 and Lee & Chan 2008). For instance, Sun et al. (2010) solidified dredged Nagoya Port clay with cement and gypsum to slow down the rate of structural decay, while Okumura et al. (2000) introduced air bubbles and expanded polystyrene beads into dredged soils to form a lightweight treated soil for backfilling retaining structures. These innovations successfully contain the potential harm of dredged material, simultaneously giving a second life to the otherwise waste.

As far as the Authors are aware of, there has yet to be a study specifically on the mix uniformity aspect of induced solidification. Some of the more recent related work is included here though. Åhnberg & Holm (2009) reported anomalies in the measured strengths, attributable to the effect of time lapse between mixing and compaction of the mixture. This 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). Besides, Marzano et al. (2009) found that the initial water content of a mixture is inversely related to the unconfined compressive strength and secant Young's modulus (E_{50}). From the data compilation of an international collaborative study of lab-mixed specimens, Kitazume et al. (2009) concluded that extended mixing time is marginally beneficial to the resulting solidified strength.

Focus of the present study was on the effect of different mixing conditions on the solidification of cement-treated dredged clay. Considering in situ mass stabilisation of shallow depths (≤ 5 m), where backhoes are commonly used to mix the materials, the mixing condition is understandably subjected to variations. This is due to the limitations of the scooping motion of a backhoe, as well as initial conditions of the materials, i.e. water-cement (W/C) ratio, mixing water content and distribution of cement powder. These factors were examined in the present study.

2 EXPERIMENTAL WORK

2.1 *Materials*

The soil used in the present study was dredged from the shipping channels of Kawasaki Port in Japan. The clay was next wet-sieved to remove any remaining foreign or coarse particles, where only the fine-grain material was collected for use. Properties of the soil are summarized in Table 1. Mixing water content used in preparing the specimens was based on multiples of the liquid limit, LL = 55.2%. Ordinary Portland cement ($G_s = 3.15$) was added to the clay as binder to induce solidification.

2.2 *Preparation of test specimens*

The clay was remoulded in a conventional kitchen mixer a day prior to mixing. Distilled water was added to the clay to achieve the consistency of 1.5 LL, 2.0 LL, 2.5 LL or 3.0 LL respectively. Cement was added to the clay in dosages of 8–41% (C), corresponding to water/cement ratios (W/C) ranging from 4 to 15. Disposable plastic moulds of 50 mm diameter and 135 mm high were used to form the specimens, where they were trimmed to 100 mm height upon demoulding. Mixing in the mould 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 levels of agitation to the soil-cement mixture. When mixing was completed, the mould was gently 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. All specimens were cured in an airtight container at controlled room temperature of 20°C and relative humidity of 70%.

Table 1. Properties of dredged clay.

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%

Table 2. List of specimens.

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

Table 2 lists the specimens prepared for the tests. For example, specimen 1.5 LL-8 C-50 S represents mixing water content of 1.5 times the clay's liquid limit (1.5 LL), with 8% cement addition (8 C), subjected to 50-cycle mixing (50), with the cement powder placed in a single (S), double (D) or triple (T) layers, at equal distances within the specimen before mixing. Note that the 5-cycle specimens are not included as test was made impossible because they remained too soft and unsolidified for demoulding.

2.3 *Test methods*

Unconfined compressive strength test was conducted on the specimens at the age of 28 days, following the standard procedure prescribed by JIS A 1216–1993. Load was applied at 1% per minute. The test was considered appropriate for assessing the effect of uniformity as it measures the overall or representative strength of a specimen, which is a measurement of the average compression resistance. Ends of the specimens were carefully trimmed flat to avoid bedding errors. Complementary observations of the specimens' uniformity were also carried out using X-ray CT scans. The Shimidzu scanner employed for the purpose had a cone-shape X-ray irradiation angle of 60°, with a micro-focus function (minimum focus size 4 μm) for capturing high resolution images of very small parts in a specimen.

3 RESULTS AND DISCUSSIONS

3.1 *Unconfined compressive strength* (q_u)

Taking the specimens with the same cement content (C), i.e. 11 C, a graph of unconfined compressive strength (q_u) versus mixing water content (w_{mix}) was plotted (Figure 1). 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 cycles of mixing. It is apparent 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. Besides, 50 cycles mixing at lower w_{mix} was clearly detrimental to uniformity of the specimens, as shown by the low q_u recorded.

In Figure 2, the data presented were those of specimens mixed at W/C = 4 and 10 respectively. For both cases, strength (q_u) dropped with increased cement content (C) and mixing water content (w_{mix}), though the 10 WC specimens showed distinct clustering of the data points with q_u not exceeding 900 kPa. The cement content in the 10 WC specimens were clearly much lower, which could account for the low strengths 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.

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 paramaters that govern the solidification effectiveness. However this is not novel, as pointed out by Horpibulsuk et al. (2005) & 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 2 arguments which the Authors would like to put forth referring to the work of the aforementioned researchers. Firstly, well-mixed solidified soils with the same W/C do not necessarily display the same strength, suggesting that W/C is not an exclusive signature for estimating the strength. Secondly, due to the diversed mineralogy and chemical composition of the base soils, a universal predictive model that suits all soils when subjected to chemical stabilisation is highly debatable. These are further highlighted in the following analysis and discussions of the present work.

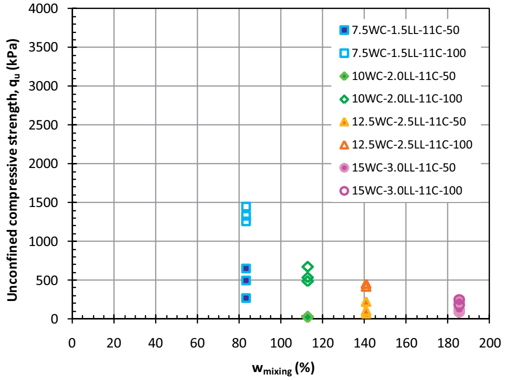

Figure 1. Unconfined compressive strength versus mixing water content (w_{mixing}).

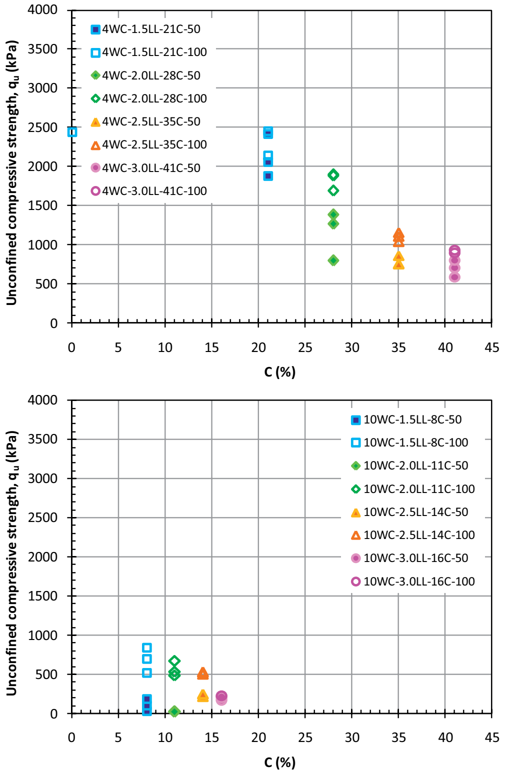

Figure 2. Unconfined compressive strength versus cement content (C).

Figure 3 compiles q_u of the specimens plotted against W/C, where each plot represents specimens prepared with the same mixing water content (w_{mix}), i.e. 1.5, 2.0, 2.5 and 3.0 LL. Within the range of up to WC = 10, it is apparent that gradient of the q_u-W/C curves reduced with higher w_{mix}. Although

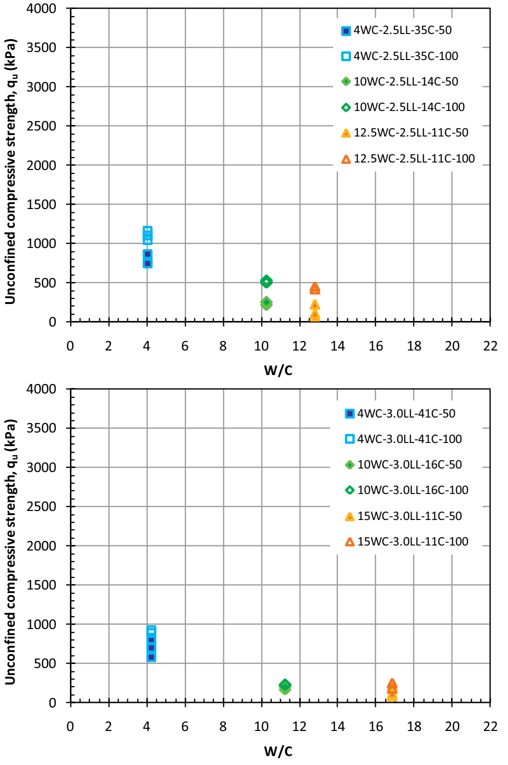

Figure 3. Unconfined compressive strength versus Water/Cement ratio (W/C).

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 registered. 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}. As such, 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 cycles of 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 vigour employed.

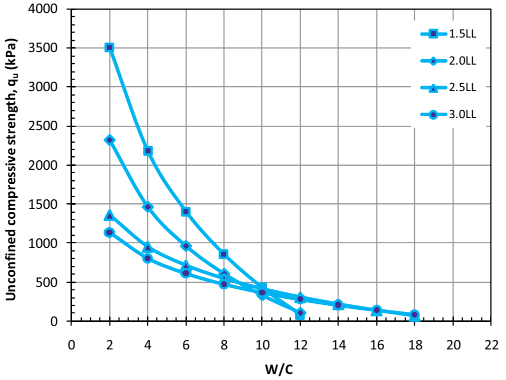

Figure 4. Combined plots of q_u–W/C.

Figure 4 shows the combined plots of all the specimens, as derived by using natural log-based regression on the data sets in Figure 3. In spite of the scatter of data, especially in the 1.5 and 2.0 LL data sets, the figure reveals a unique mixture identity at W/C = 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 W/C is kept at 10. However as a more liquefied soil needs a higher cement dosage to attain the optimal W/C 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 W/C 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.

3.2 *X-ray CT images*

Figures 5 and 6 shows the X-ray CT images captured of the specimens at 28 days curing prior to the UCS tests. Grey level of the images decreases with increased density, i.e. black spots indicate voids, and white spots suggest high density. Clearly, 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 4 WC specimens (Figure 5), the cement formed clots 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

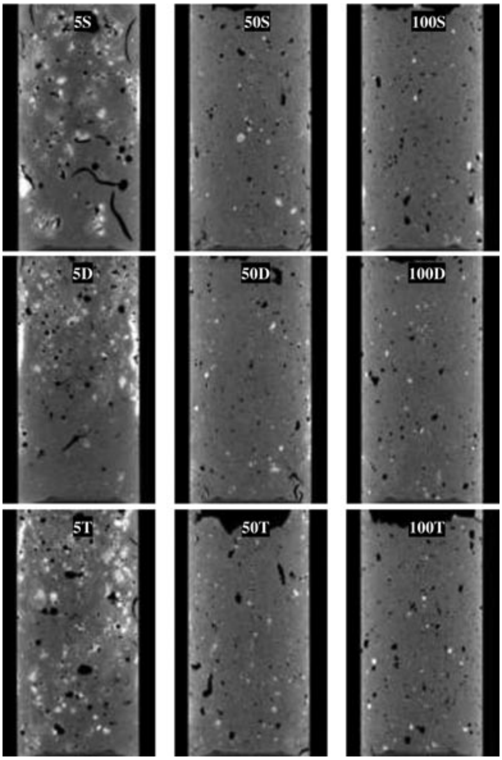

Figure 5. X-ray CT images of specimens 4 WC-1.5 LL (28-day).

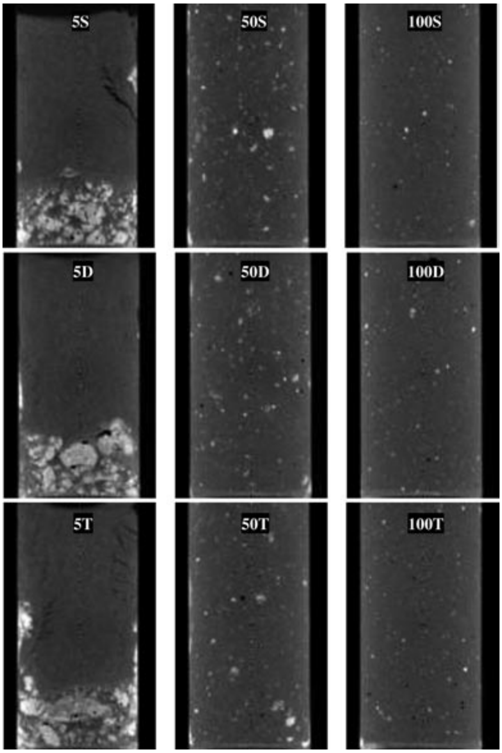

Figure 6. X-ray CT images of specimens 10 WC-3.0 LL (28-day).

were found in the 5 S specimen, a consequence of poor mixing and compaction as well as potential localized cement hydration that caused shrinkage. Interestingly, 50-cycle mixing did not make a significant difference to the uniformity compared to 100-cycle mixing in the 'dry' specimen. The specimens appeared similar with well distributed small cement aggregates and voids. With increased workability of the mixture, i.e. with lower cement dosage or increased water content, 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 prevailed, with the images showing a generally singular grey tone throughout the specimens. In the 10 WC specimens (Figure 6), 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.

In short, the CT images lend further visual evidence to the observations and analysis discussed earlier, where mixing vigour remains the dominant factor in ensuring 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 stabilised 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.

4 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:

- The mixing water content remains the primary factor in producing a uniform mix, on condition a compatible mixing effort is adopted.
- Initial poor distribution of cement in the soil mass can be adequately reconciled with vigorous agitation of the mixture, if the clay provides sufficient water for improved workability.

- The mixing efficiency is a more dominant factor producing mix uniformity in solidified clay, as compared to the initial distribution of binder.

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