The Thixotropic Hardening Behaviour of a Low Plasticity Dredged Marine Silt

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Abstract: An alternative to solve the problem of disposing dredged marine sediments (DMS) in open sea, which could lead to undesirable contamination and destruction of the marine ecosystem, is to reuse the material in reclamation works. For such applications, it is important to determine the time required for strength gain of the relocated DMS. A lab-based study was conducted to simulate and examine the post-consolidation hardening of DMS when placed as a backfill with relation to time. A separate series of tests were also carried out on the DMS being lightly solidified with cement, with the purpose of identifying potential shortening of the waiting period. The DMS sample was prepared at different water contents based on the soil's liquid limit (LL = 54.5 %), i.e. 0.90, 1.25 and 1.81LL. The undrained shear strength was measured using the laboratory vane shear (VS) test. Complementary fall cone (FC) tests were conducted for additional information on the improved remoulded strength and stiffness of the DMS. The results showed that the strength and stiffness (cone penetration resistance) of the relocated DMS could effectively improve with time, though the rest period required is shorter for a sample with lower initial water content. On the other and, light cementation shortened the rest period, and significantly improved the strength and stiffness at dosages as low as 5 % (as per dry weight of the soil). Overall the study gave an overview of the reusability of DMS as a backfill material in reclamation works, whether with or without lightly induced solidification, depending mainly on the limitations of rest period available.

Keywords: Thixotropic hardening, vane shear, fall cone, stiffness, strength, light solidification.

1. INTRODUCTION

The dredging of waterway basin is necessary to sustain the ideal depth of ferry or shipping path in jetties and harbours worldwide [1]. Dredged marine sediments (DMS) are produced from these dredging activities. It is commonly disposed of in open sea, potentially harming the marine ecosystem. In order to address this problem, one potential alternative is to recycle the otherwise waste material, i.e. reuse of DMS as a backfill material in reclamation works, especially in nearshore rehabilitation projects or small island creation.

In order to deploy DMS for such purposes, one needs to first identify the rest period required after relocating the material, particularly post-consolidation under its own weight. The time-dependent regain of hardness under constant water content or volume condition after the soil undergoes sedimentation and self-weight consolidation is termed 'thixotropic hardening' [2]. It was further claimed to occur due to energy imbalances caused by remoulding or compaction. The process essentially allows the soil to return to a harder state without change in either water content or volume after loss of its original structure upon dislodging from the seabed and the subsequent replacement on the reclaimed site. The stiffness or strength recovery could be fully or partially, depending on the material's inherent properties and characteristics. Besides, the process is reversible upon remoulding and resting, and vice versa [3].

As it is time-dependent, thixotropic hardening is also known as a kinetics process involving the time effect on the soil's structural destruction / formation mechanisms [4]. In other words, the continuous viscosity decrease with time when flow is applied to a previously at-rest sample, flips to subsequent recovery of viscosity with time when the flow is discontinued [5]. In similar past works, Seng and Tanaka [2] reported that the effect of thixotropy increases when the soil is within the range of the liquid and plastic limits. Beyond the liquid limit, thixotropic behaviour was found to diminish as the water content rises. This is consistent with observations by Skempton and Northey (1952) [6], though Seed and Chan (1957) [7] did find that thixotropic effect can be low or negligible at or close to the soil's plastic limit.

Solidification with cement is widely researched, especially in the attempt to improve the mechanical properties of soft, fine-grained soils like clay and silt. The hydration of cement with water and the subsequent pozzolanic reactions contribute to strength and stiffness gain within a hastened period. Nonetheless the strength and stiffness gain is very much dependent on the soil type, binder used, water/binder ratio, curing period, mixing quality and other related factors, as can be found in [8-10].

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Table 1: Physical Properties of Soil Sample

Moisture content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Specific Gravity	pH
98.66	54.51	24.44	30.07	2.35	8.9

*The above parameters were obtained using conventional geotechnical test methods as per the procedures outlined in BS1377 (1990) [12].

The present study was carried out to examine the thixotropic hardening behaviour of a low plasticity dredged marine silt, symbolized by ML according to USCS classification system [11]. The DMS sample was retrieved from the east coast of Peninsular Malaysia, and conditioned to water contents in multiples of the soil's liquid limit, LL = 54.5 %. A separate series of test specimens were lightly solidified with cement dosages of 1-5 %, to examine the possibilities of shortening the rest period required. Measurements were performed to gauge the strength and stiffness gain with time over 7 days, using the Vane shear (VS) and fall cone (FC) test apparatus.

2. MATERIALS AND METHODS

2.1. Preparation of DMS Sample

Table **1** summarises the DMS properties. Prior to remoulding, the sample had to be slowly semi-dried over a gas stove, as it was overly liquefied with the natural water content almost twice the liquid limit (see Table **1**). Next the semi-dried sample was batched and remoulded with water addition to form mixtures of water contents in multiples of the liquid limit (LL), i.e. 0.90, 1.25 and 1.81LL. The soil-water mixtures were thoroughly remixed with a kitchen mixer, then stored overnight to allow for uniform redistribution of the pore water. The mixture was then transferred to a plastic mould of 330 mm x 180 mm x 135 mm (Figure **1**). For the lightly solidified samples, cement (C) was added in 1, 3 and 5 % (based on dry weight of the soil) to the soil at 1.25LL only.

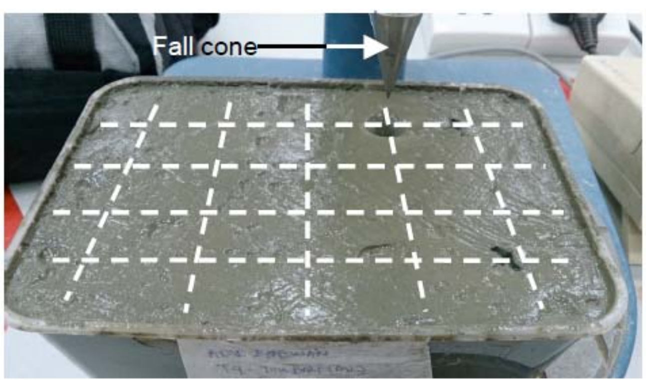

Figure 1: The soil bed.

The mixture was placed in 4 layers, where for every layer, the mould was lightly tapped on the bench to remove any entrapped air from the partially liquefied material. The soil bed was kept at 60 mm thick, with each layer measuring approximately 15 mm. The layer thickness was used as guide in maintaining the volume of the soil bed in each sample prepared. To ensure a smooth and flat surface of the soil bed, a simple in-house designed scraper was used to smoothen the surface with repeated sweeping action along the top of the mould (Figure **2**). With the soil bed ready, measurements commenced immediately to account for the time 'zero' reading. For longer time lapse, the soil bed was carefully covered with cling film over the top and stored at room temperature of approximately 20^{o}C. Intervals of measurements fixed at 0, 0.5, 1, 2, 4, 8, 24, 48, 96 and 168 hours.

Figure 2: Smoothening of the bed's surface.

2.2. Fall Cone (FC) Test

The FC test was carried out in the present study as a complementary measurement to the VS monitoring. Essentially the 80 g cone of 30^{o} was dropped on the soil bed and the resulting penetration was recorded over the same time lapse as the VS measurement (Figure **3a**). Some slight modifications of the test procedure given in BS1377 [12] for using the FC test in gauging liquid limit were adopted. With the penetration cone locked in the raised position, the supporting assembly was gradually lowered to rest the tip of the cone on the soil's surface. Next the cone was released to penetrate the soil and the resulting penetration depth was obtained by reading the dial display to the nearest 0.1mm.

2.3. Vane Shear (VS) Test

The test was performed in accordance with the procedure in BS1377 [12]. Figure **3b** shows the test in progress. The VS apparatus consists of four blades on the end of a rod, where the vane measures 12.7 mm high and 12.7 mm in diameter. The vane was gently pushed into the soil (to mid-depth of the soil bed) without disturbing the soil appreciably. Torque was then applied at the top of the road to rotate the vanes at a standard rate of 0.1^o/ sec. This rotation engaged the soil surrounding the vane, leading to failure in a cylindrical shape around the vane. Figure **3c** shows the soil bed after a series of VS test. The maximum torque (T) applied to cause failure was then used to calculate the undrained shear strength (S_u), as shown in Eq. 1.

$$Su = \frac{2T}{\pi D^2 \left[H + \frac{D}{3} \right]} \tag{1}$$

4. RESULTS AND DISCUSSIONS

Figure **4** summarises the cone penetration depth (H) as recorded for each sample over the 7-day period. In Figure **4a**, it is apparent that greater water content in the soil resulted in less resistance against the cone penetration, where the 1.81LL sample showed almost no improvement over the 1-week period. A closer look at the plots for 0.90LL and 1.25LL shows that the improvement rate of resistance against cone penetration was higher in the former. Besides, 0.90LL showed a relative plateau compared to 1.25LL, indicating a slight continuous penetration of the cone even after 7 days of placement in the mould. The cone penetration depth is indeed a representation of the resistance provided by the soil with time. In other words, the soil gained stiffness when allowed to rest over a certain period of time.

Figure **4b** shows the 1.25LL samples admixed with 1, 3 or 5 % cement. Note the markedly reduced H with increased cement dosage in the soil. The close proximity of the plots for 1.25LL+3%C and 1.25LL+5%C suggests that for more significant stiffness improvement, the cement dosage would have to be increased beyond 5 %. However the time required for the plots to undergo gradient transition, i.e. stabilizing of the stiffness gained by the soil, does appear to shorten with increased cement dosage. In comparison with Figure **4a**, it can be inferred that admixing the DMS with small dosages of cement can effectively accelerate the stiffness gain, notwithstanding the initial high water content. For instance, although the slightly solidified samples had a higher initial water content (1.25LL), the cone resistance stabilized at about the same time and at about the same H values as sample 0.90LL (see dashed line in both plots at about H = 7 mm). Bearing in mind that the natural water content of DMS is generally way above the liquid limit, to attain water contents below that limit would necessitate preloading or dewatering on site. This incurs additional costs, which could become a hindrance factor in the mass reuse of DMS in reclamation works.

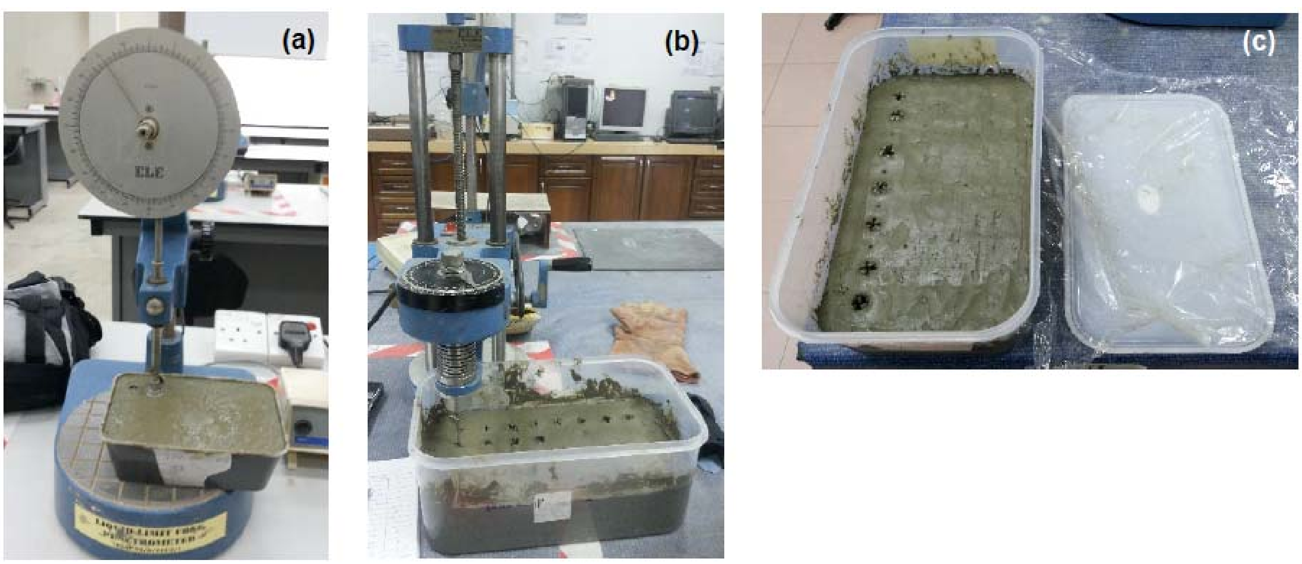

Figure 3: (**a**) Fall cone (FC) test. (**b**) Vane shear (VS) test. (**c**) Soil bed after the VS measurements.

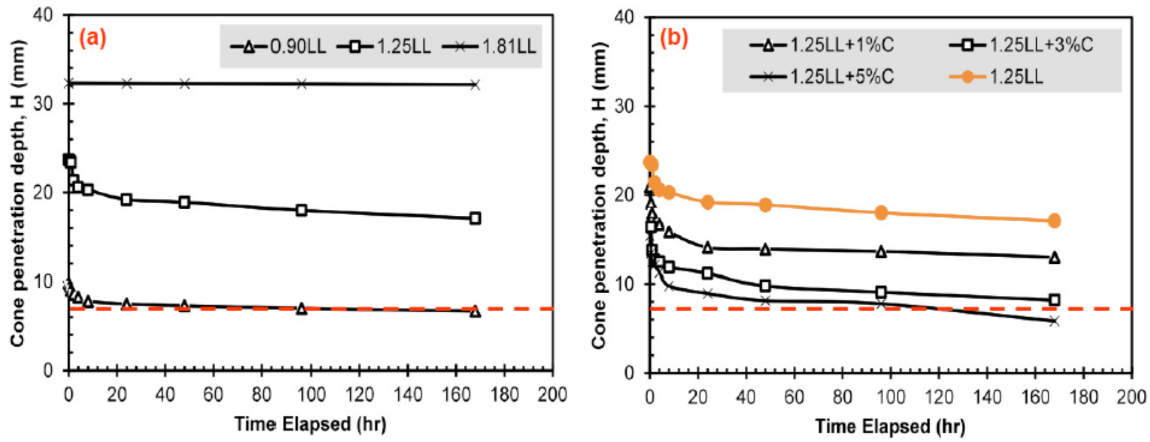

Figure 4: Cone penetration (H) – time plots.

In Figure **5**, the undrained shear strength derived from the VS tests are compiled for all the samples. Note sample 1.81LL was not measurable with the VS test as the soil bed was excessively wet and soft (Figure **5a**). The estimated S_u for such a viscous soil mass would most probably be no more than 0.5 kPa. Note that trend lines for 1.25LL and 1.25LL+1%C are very closely plotted (Figure **5b**), highlighting the small strength improvement resulting from the small cement dosage solidification. With cement addition of 3 %, S_u can be seen to rise to a plateau of approximately 7 kPa within the 7-day rest period. This is about the same S_u recorded for sample 0.90LL in Figure **5a**, as denoted by the dashed line in the plots. In fact, after 48hours, the non-cemented 0.90LL sample continued to rise in strength. This is in line with earlier discourse on the cone penetration resistance, further emphasizing the existence of a threshold cement dosage to produce meaningful increase in strength of a wetter DMS.

With 5 % cement addition, S_u showed marked departure from the strength range recorded of the other samples, with or without solidification. The rising gradient if the 1.25LL+5%C plot clearly point to the efficacy of small dosages of cement addition in both enhancing the strength as well as the strength gain rate. The strength gain rate for the 1.25LL+5%C sample was calculated and indicate in Figure **5b**, i.e. ≈1.50 kPa/day. As such, if the DMS admixed with 5 % cement is backfilled in a reclaimed site, it would take about 10 days to achieve 150 kPa. If left for a further 10 days, the S_u reached would be 300 kPa, which is the minimum strength expected of a Type IV geomaterial acceptable for civil engineering applications [13], for instance. This example demonstrates the applicability of light solidification in enhancing the performance of DMS placed as a backfill, in terms of rest period shortening and strength improvement.

The FC and VS results were compiled and plotted against each other in Figure **6**, where S_u was established to be inversely related to the square of H, i.e. $S_u = 643.54/H^2$. It is interesting to mention that

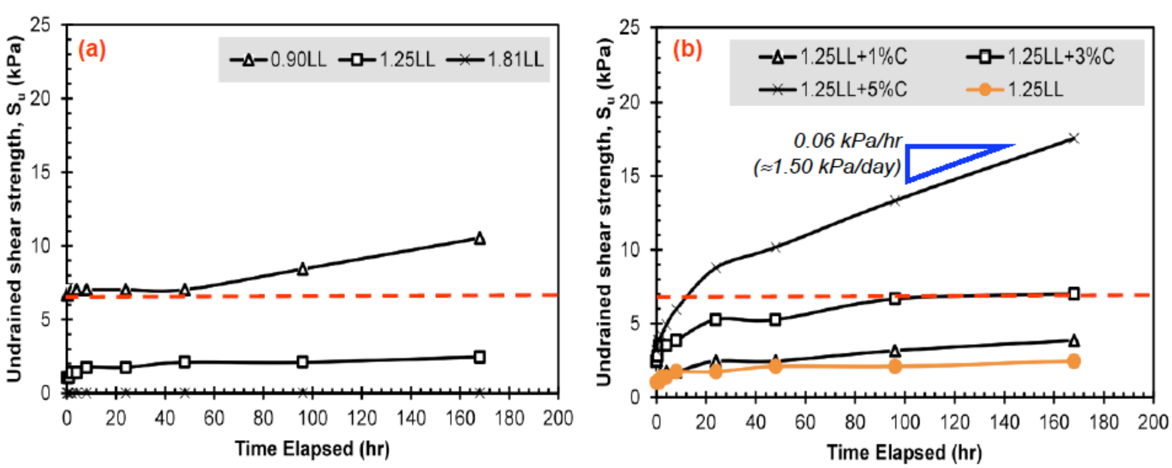

Figure 5: Undrained shear strength (S_u) – time plots.

regardless of whether or not cement was admixed with the soil, the correlation stands true to both the non-solidified and solidified samples. This is suggestive of the negligible effect the small cement dosages had on the soil's inherent properties, besides contributing in the dehydration (hence drying up of the soil's water content) and chemically but lightly bonding the soil particles into a stronger and stiffer matrix. The good correlation also indicates reliability and repeatability of both the FC and VS tests for measurements of the at times very small strength and stiffness changes in the soil bed. In addition, the soil bed preparation method is also shown to be relatively free from errors, in condition care is taken in the preparatory steps. The plot can easily serve as a quick guide in S_u estimation of the DMS, with or without cement addition. This is notwithstanding the observation reported earlier of the better sensitivity of the VS test in gauging the performance improvement of the DMS with time, especially in cases with induced light solidification.

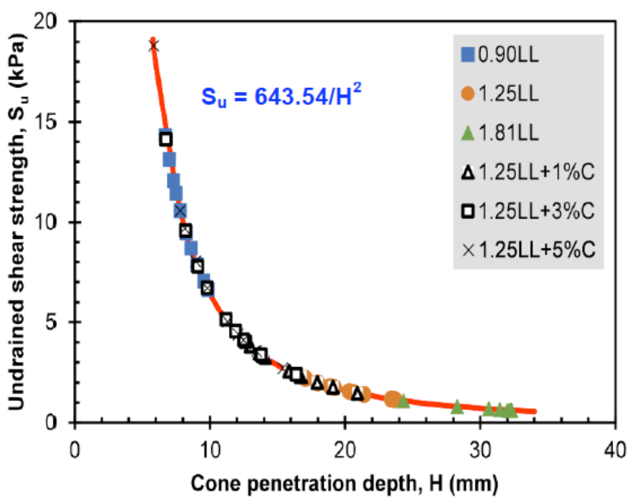

Figure 6: S_u-H correlation.

5. CONCLUSIONS

Following are the primary findings of the study:

- The cone penetration resistance indicates the stiffness gain of the DMS over time, where the stiffness gain was found to improve (1) with less initial water content in the soil, or (2) with light solidification *via* small dosages of cement addition.
- Cement addition of 3-5 % could lead to the same stiffness gain rate as the soil on its own, but at a much lower water content of 0.90LL, which is difficult to attain in field conditions without extra costs and time for pre-loading or dewatering.
- The undrained shear strength (S_u) gain of the samples followed similar pattern as those charted by the FC results, though the VS test was apparently more sensitive in discerning the improved performance of the DMS admixed with small dosages of cement.
- 5 % cement addition was observed to be expedient in improving the resulting strength as well as the strength gain rate of the soil at 1.25LL, where an approximately 20-day rest period could transform the DMS to a sound geomaterial of S_u = 300 kPa.
- S_u was found to be inversely related to the H^2, a correlation which could be a quick guide to strength estimation from the FC test alone. It is also indicative of minor micro-structural changes attributed to the small cement dosages added to the soil, though with appreciable strength improvement.
- In a nutshell, the thixotropic hardening of DMS could be hastened with light solidification *via* the addition of small cement dosages. The benefits encompass both rest period reduction as well greater strength improvement.

REFERENCES

[1] Wan Salim WS, Mohd Noor NA, Sadikon SF, Arshad MF, Wahid N, Mohd Salleh S. The preliminary investigation on the dredged marine sediment of Kuala Perlis as a potential brick material. Proc. 2nd Int Conf on Biotechnology and Environment Management 2012.

[2] Seng S, Tanaka H. Properties of very soft clays: A study of thixotropic hardening behaviour under low consolidation pressure. Soils and Foundations 2012; 52(2): 335-345.

[3] Braja MD. Fundamentals of Geotechnical Engineering. CENGAGE Learning, UK 2013.

[4] Malkin AY. Non-Newtonian viscosity in steady-state shear flows. J Non-Newtonian Fluid Mechanics 2013; 192: 48-65. http://dx.doi.org/10.1016/j.jnnfm.2012.09.015

[5] Lewis J, Wagner NJ. Thixotropy. Advances in Colloid and Interface Science 2009; 147-148: 214-227. http://dx.doi.org/10.1016/j.cis.2008.09.005

[6] Skempton AW, Northey RD. Sensitivity of clays. Geotechnique 1952; 3(1): 40-51.

[7] Seed HB, Chan CK. Thixotropic characteristics of compacted clays. ASCE J. Soil Mechanics and Foundation Engineering 1957; 83(SM4): 1427-1435.

[8] Horpibulsuk S, Phojan W, Suddeepong A, Chinkulkijniwat A, Liu MD. Strength development in blended cement admixed saline clay. Applied Clay Science 2012; 55: 44-52. http://dx.doi.org/10.1016/j.clay.2011.10.003

[9] Consoli NC, Festugato L, da Rocha CG, Cruz RC. Key parameters for strength control of rammed sand-cement mixtures: Influence of types of Portland cement. Construction Building Materials 2013; 49: 591-597. http://dx.doi.org/10.1016/j.conbuildmat.2013.08.062

[10] Chan C-M. Influence of mix uniformity on the induced solidification of dredged marine clay. Environmental Earth Sciences 2014; 71(3): 1061-1071. http://dx.doi.org/10.1007/s12665-013-2510-0

[11] Unified Soil Classification System (USCS), in Wagner, AA. Proc. Int Conf on SMFE, (Butterworth & Co.) 1957.

[12] British Standard Institution. British Standard BS 1377-1: Methods of test for soils for civil engineering purposes. London, UK 1990.

[13] Japan Port and Harbour Association. Technical standard for port facilities 1999; (in Japanese).

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