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Induced Cementation of Dredged Marine Soils for Civil Engineering Reuse

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ABSTRACT

Ports and harbour facilities require regular dredging to maintain trafficability and safety of the vessels. The material removed from the seabed, i.e. dredged marine soils, is generally considered a waste material for disposal, either in designated offshore locations or inland containment facilities. Either measure incurs costs, time and labour, not to mention the obvious lack of sustainable values. Besides, there is always the risk of transferring undesirable contaminants in the dredged materials to the disposal sites, as well as along the transportation routes. It is however, possible to reuse this otherwise waste, with suitable and adequate pre-treatment. Considering that the material is essentially soil-based, primarily consisting sand, silt and clay with some larger marine debris, it is perhaps most apt to harness its inherent properties as a ‘soil’ and reuse it as a geomaterial. In civil engineering and construction terms, this would mean reusing the soils as a backfill material, for creating new land bases or restoring eroded ones in near-shore areas. However the inherent poor physico-mechanical properties of dredged soils, such as high saturation with water, low strength and high compressibility, make the material unsuitable to be reused as it is. An expedient approach is induced cementation, where additives are mixed with the soil to improve the necessary properties prior to reuse. This paper examines the induced cementation of some dredged marine soil samples from the Malaysian waters with cement and/or other binders. The common factors, such as binder dosage, curing period and water/binder ratios, were monitored to ascertain the mechanisms involved to enhance the material’s performance.

Keywords: dredged marine soils, reuse, induced cementation, strength, stiffness

1. INTRODUCTION

Historically traced as far back as the Roman times, dredging has been used to remove materials from the bottom of lakes, rivers, harbours and other water bodies, for the purpose of maintaining or deepening water depths necessary for safe and efficient navigation of vessels [1]. Dredging essentially involves loosening and dislodging the sediment materials, and disposing it at designated sites either offshore or on land [2]. However offshore dumping especially, could inadvertently lead to negative physical, chemical and biological impact on the marine environment. Such disposal method could create damaging disturbances to the aquatic ecosystem [3]. For instance, light attenuation by suspended sediments [4] and the effects on sensitive soft bottom macro-benthic assemblages [5].

Increased awareness for nature conservation and sustainable development has led to dredged materials being considered as potential ‘good’ soil for reuse, in place of the traditional “dredged and disposed” approach. Some areas of applications include habitat creation or restoration, landscaping, road construction and land reclamation [6]. The mud-like material requires some pre-treatment though, to improve the poor engineering properties prior to application, such as enhanced soil’s strength and reduced vulnerability to water. One pre-treatment option is induced cementation, where hydraulic binders are admixed with the soil to enable partial solidification to take place. This paper describes finding from some exploratory work conducted with dredged marine soils retrieved from the Malaysian waters subjected to induced cementation. The improved properties suggest that the otherwise waste material can be effectively transformed to usable forms just like any other soils of similar characteristics.

2. DESCRIPTION OF MATERIALS

Dredged marine soils In general, the 3 dredged samples examined were essentially fine-grained soils with small quantities of sand. All samples contained ≥75 % of silt and clay fractions, resulting in the dominant role of the fine particles in the geo-mechanical behaviour of the soils. The natural water content for all samples exceeded the liquid limit, which is not unusual given the submerged nature of the sediments prior to removal from the seabed [7-9]. This results in the material's soft and fluid form unsuitable for load-bearing purposes, a key feature which renders the material useless for civil engineering applications.

X-ray fluorescence (XRF) elemental analysis showed that Silicon (Si) constitutes the largest portion of element in the dredged samples, i.e. 56-63 %, followed by aluminium (Al) at 17-21 %. Si mainly derives from sand and silt while the source for Al is primarily the clay fraction [10]. Illite, an aluminium silicate, was found to be the main clay mineral in the samples. This could account for the presence of Al detected in the XRF spectrometry results.

Biological properties wise, the dredged samples had E. coli below EPA's recommendation safe level of = 2.35 x 10^2 cfu/ml. The source is understandably human dwellings and anthropological activities upstream to the sampling points. It is reported that dredged sediments are particularly rich with microbes serving as a source of nutrients for the microorganisms [11&12]. The sedimentation bed also serves as a protection blanket from sunlight inactivation [13] and protozoan grazing of the microbial consortium [14]. A major concern of microbial presence in dredged marine soils is the potential health risks involved, especially if the material is to be reused for the creation of new landforms for human's usage.

Hydraulic binders The hydraulic binders are shown in Figure 1. Ordinary Portland cement was used as the primary binder, but the use of some industrial wastes is also highlighted to enhance the 'green' value of the revived dredged materials. Ashes, i.e. bottom and fly ashes, by-products of the combustion in a coal power plant, and slag produced in steel-making, were collected to form part of the binders. The coarser fractions of the bottom ash and steel slag, even with limited binding capacity, are expected to contribute to the performance of the solidified dredged sediments via the 'filler' functions. The Class F ash used in the present study was derived from the burning of bituminous coal, and is rarely cementitious when mixed with water alone, where alkali-activation is preferred to produce cementation effects. Steel slag, on the other hand, is often regarded as a weak cement clinker with increased activity under alkaline conditions. Higher fine slag portion is known to enable greater strength improvement due to the larger reaction surface of the finer particles and the greater solidification potency of the unreacted inner surfaces [9].

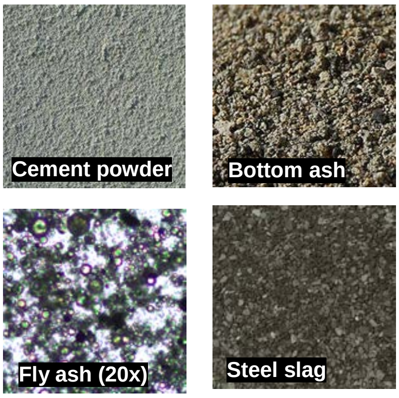

Figure 1. Hydraulic binders for induced cementation of dredged marine soils.

3. INDUCED CEMENTATION: SOME FINDINGS

Thixotropy vs. cementation (cement addition) Left on its own, the saturated dredged soil would eventually regain strength and hardness under constant volume and water content by thixotropic hardening due to rearrangement of the soil particles to a more stable state. The recovery could be fully or partially, depending on the material's inherent properties and characteristics. Soil beds prepared from remoulded dredged silt (5-100 μm) and clay (<5 μm) samples, with and without light cementation (<10 % cement addition) for shortened rest period, were monitored using the cone penetration and laboratory vane shear tests (Figure 2). The cone penetration resistance and strength improvement rates follow the ascending order of 0.75LL > 1.00LL > 1.25LL, indicating the setbacks of high initial water contents on the rest period. The fall cone method seemed less sensitive to the rather small improved structure of the soil with time, which could be attributed to a weakened upper layer of the soil bed due to bleeding. The cone penetration resistance also indicates stiffness gain of the material over time (Figure 3), 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. Besides, small cement dosages were sufficient to shorten the rest period of the DMS. In fact, it was found to contribute to prolonged improvement of the soil too. For the silt, approximately 20-day rest period could transform the DMS to a sound geomaterial of undrained shear strength, S_u = 300 kPa. These findings are useful for estimating the rest period required for sufficient strength and stiffness gain when constructing backfills.

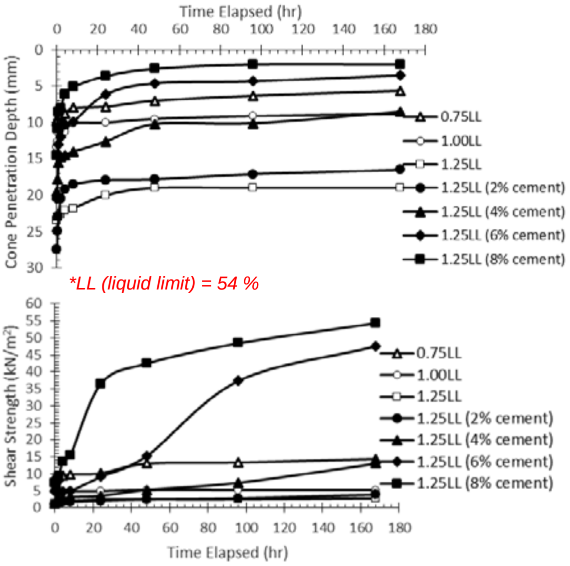

Figure 2. Dredged marine clay with and without light cement addition.

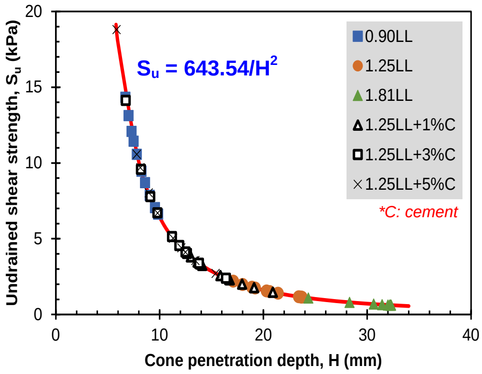

Figure 3. Dredged marine silt- enhanced strength and stiffness correlation.

1-dimensional compressibility (fly ash addition) Figure 4 shows the compression curves derived from oedometer tests on dredged marine clay admixed with a cement-flayash (FA) blend. The treated soil recorded an average of 68 % settlement reduction compared to the original soil (0C0FA). This suggests stiffening of the soil mass, either by cementation alone or with the filler effect. The solidification process also transformed the soft soil into a structured mass, as demonstrated by the curvature of the treated specimens' plots. The initial part of the curve with a gentler slope shows the pre-yield state, while the second part with a steeper plot represents the yield state. The intersection of the two parts gives the yield stress (σ_y'), a parameter commonly used in the study of solidified soils to indicate the maximum vertical stress bearable by the soil before failure, i.e. onset of excessive compressibility. Also, it is apparent that the extended curing period of 7 days did not contribute significantly to the improved compressibility, where the compression curves for all the pairs of 3d and 7d treated specimens did not differ much. Nonetheless the longer curing time did result in slightly lower compressibility, i.e. the 7d curve lies above that of 3d.

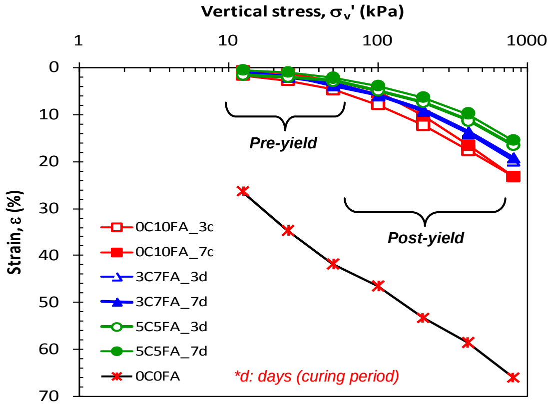

Figure 4. Dredged marine clay- reduced compressibility with small amount if cement addition [15].

Strength – Stiffness (slag addition) The dredged marine silt was admixed with 4 mol NaOH-activated steel slag and monitored over a period of 28 days. Bender element test was conducted in parallel with the unconfined compression test. In Figure 5, the P-wave velocity (v_p) for specimens 5:5 rose dramatically from about 970 m/s to 1300 m/s in a month. Anomalies in the other specimens could have caused the 5:5 specimens to have the highest v_p despite not admixed with the highest dosage of slag. The discrepancy can be explained by the ability of the bender element test in detecting (and be affected by) anomalies within the specimen, such as localized weak zones or voids. These inherent weaknesses could be caused by improper mixing and preparation of the specimens. They were invisible and not discernible in the unconfined compressive strength test, because of the large strain loading mode and measurements adopted. It can therefore be said that the bender element test, being an indirect small strain stiffness monitoring tool, has high sensitivity in identifying non-uniformity is soil specimens. Indeed, the 3:7 specimens showed a slight dip on day 7 before rising in the following intervals of 14 and 28 days. The overall bender element test results (i.e. stiffness) corroborated with those from the unconfined compressive strength test, with indication of an on-going solidification process beyond 28 days. Considering that the strength and stiffness of the solidified specimens share a common rising trend with time, it follows that a correlation can be established between the 2 parameters. Figure 6 relates q_u with K, with apparent distinction of the correlation according to the slag content. This is albeit the appreciable scatter of the data point, especially for specimens 5:5.

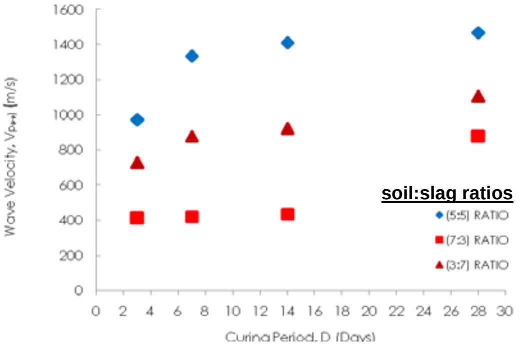

Figure 5. Slag-treated dredged marine silt- P-wave velocity change with time [16].

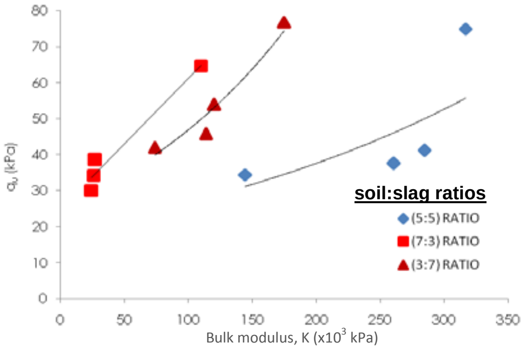

Figure 6. Correlation between strength (q_u) and bulk modulus (K) - indicator of strength and stiffness improvement [16].

4. CONCLUSIONS

Dredged marine soils, commonly classified as a geo-waste, can be effectively improved via induced cementation. The enhanced engineering properties, i.e. strength and stiffness, can be achieved using various hydraulic binders, such as cement, fly ash and steel slag. The admixing conditions, i.e. binder dosage, initial water content, mixing efficiency and curing period are key factors determining the resulting extent of improvement. In short, induced cementation could change the poor quality soil to a usable one instead of assigning it to disposal sites.

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