# Pseudo-solidification of Dredged Marine Soils with Cement - Fly Ash for Reuse in Coastal Development

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*Abstract: - The dislodged and removed sediments from the seabed, termed dredged marine soils, are generally classified as a waste material requiring special disposal procedures. This is due to the potential contamination risks of transporting and disposing the dredged soils, and the fact that the material is of poor engineering quality, unsuitable for usage as a conventional good soil in construction. Also, taking into account the incurred costs and risk exposure in transferring the material to the dump site, whether on land or offshore, it is intuitive to examine the possibilities of reusing the dredged soils, especially in coastal development where the transportation route would be of shorter distance between the dredged site and the construction location. Pseudo-solidification of soils is not a novel idea though, where hydraulic binders are injected and mixed with soils to improve the inherent engineering properties for better load bearing capacity. It is commonly used on land in areas with vast and deep deposits of soft, weak soils. However, to implement the technique on the displaced then replaced dredged soil would require careful study, as the material is far more poorly than their land counterparts, and that the deployment of equipment and workforce in a coastal environment is understandably more challenging. The paper illustrates the laboratory investigation of the improved engineering performance of dredged marine soil sample with cement and fly ash blend. Some key findings include optimum dosage of cement and fly ash mix to produce up to 30 times of small strain stiffness improvement, pre-yield settlement reduction of the treated soil unaffected by prolonged curing period, and damage of the cementitious bonds formed by the rather small dosage of admixtures in the soil post-yield. In short, the test results show a promising reuse potential of the otherwise discarded dredged marine soils.*

*Key-Words: - dredged soil, solidification, strength, stiffness, reuse*

## 1 Introduction

Dredging is a necessary measure to create and maintain shipping channels for the safe navigation of vessels. Considering the robust growth of the shipping and maritime sector, with 90 % of world trade sustained by the industry, dredging is inevitable and expected to expand with time. Most dredging is carried out to maintain or deepen water depths for safe and efficient navigation of vessels. Dredging location has a strong influence on the mineralogy, morphology and composition of dredged marine soils. Being heterogeneous, the material can be characterized by grain size distribution, density, water and organic matter contents [1].

The dislodged and removed sediments from the seabed are generally classified as a waste material requiring special disposal procedures [2]. This is due to the potential contamination risks of transporting and disposing the dredged soils, and the fact that the material is of poor engineering quality, unsuitable for usage as a conventional good soil in construction. Also, taking into account the incurred costs and risk exposure in transferring the material to the dump site, whether on land or offshore, it is intuitive to examine the possibilities of reusing the dredged soils, especially in coastal development where the transportation route would be of shorter distance between the dredged site and the construction location. The economic sense is further enhanced by the exponentially growing population inhabiting coastal regions, which inadvertently transforms the coastline naturally and artificially, with occurrence of erosion, scouring and sedimentation recorded at unprecedented pace.

It was with this background that the project was conceived, that is to explore the feasibilities of reusing the dredged soils, albeit with some form of pre-treatment, i.e. pseudo-solidification. Solidification of soils is not a novel idea, where hydraulic binders are injected and mixed with soils to improve the inherent engineering properties for better load bearing capacity. It is commonly used on land in areas with vast and deep deposits of soft, weak soils. Salvaging the otherwise geo-waste destined for disposal makes the method uniquely sustainable as an engineered solution, as reported by Chan [3] and Lee and Chan [4]. In addition, based on the studies of Lindmark *et al.* [5], the stabilized soils can be used as filling material in ports as the replacement for conventional filling material. Kamali *et al.* [6] found the treated material to be usable in the road engineering as sub-base and base course materials. Besides, the dredged marine soils have been successfully implemented in natural habitat restoration and development, beach nourishment, park and recreation, aquaculture, surface mine reclamation and other construction or industrial development [7]. However, to implement the technique on the displaced then replaced dredged soil would require careful study, as the material is far more poorly than their land counterparts, and that the deployment of equipment and workforce in a coastal environment is understandably more challenging.

### 1.1 Disposal of dredged marine soils (DMS)

The traditional handling of dredged materials is either discharge into a confined disposal facility (CDF) or designated open waters, with or without pre-excavated pits (Fig. 1). Unfortunately offshore dumping could inadvertently lead to negative physical, chemical and biological impacts to the marine environment. While designated sea disposal site is usually located at an adequate distance from fisheries and areas of human dwelling, such disposal method would still create disturbance to the aquatic ecosystem [8].

Various long term adverse environmental impact of offshore dumping has been reported. For instance, Bogers and Gardner [9] found that light attenuation by suspended sediments can affect the amount of light available to seagrass plants, coral reefs and other marine organisms, while soft bottom macrobenthic assemblages may respond quickly to the disturbance associated with the dumping of dredged materials and affect the overall marine ecosystem [10]. More worrying is the fact that dredged materials potentially contain toxic chemicals accrued from upstream waste disposal. High concentrations of toxic chemicals can decrease or exterminate the activity of the marine microorganisms crucial to the balance of ecosystem [11]. When dislodged and disposed of at the dump site, these contaminated materials could leave permanent damage to the marine environment at the disposal area and surrounding waters.

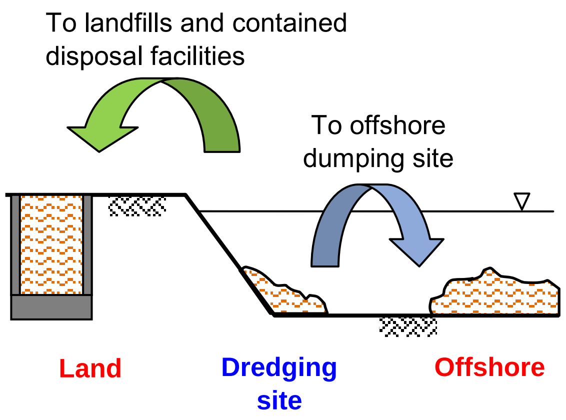


Fig. 1: On-land and offshore disposal of dredged marine soils

### 1.2 Pseudo-solidification: How it works

The key problem for reuse with the dredged soils is the poor engineering quality, i.e. low strength and high compressibility, making the materials unsuitable for load-bearing when used as backfills. In order for the poorly soils to be usable as a sound geo-material like any other engineering soils, the properties need to be improved with some pre-treatment measures. An effective way for strengthening and stiffening the dredged materials is via pseudo-solidification (Fig. 2). The process involves mixing the soil with a hydraulic binder and/or filler to transform it to a more manageable mass with higher strengths and reduced subsidence. The solidified soil can be formed in columnar or block forms, as shown in Fig. 2.

The term ‘pseudo’ indicates transformation of the originally soft, weak material to a semi-solid soil-binder matrix, and not a rock-hard mass. The semi-solidified soil would interact with the surrounding untreated soil to function as an efficient load-bearing system. The mechanism of load transfer depends on the configuration of the treated soil, as illustrated in Fig. 3. The system could consist of individual slender columns of soil-binder extended to certain depths, mobilising frictional resistance between the columns and surrounding soil for load-bearing (Fig. 3a). For economical reasons for a relatively small building footprint, large-diameter or adjoined columns can be installed too (Fig. 3b). In cases where greater loads are to be borne by the soft ground, the solidified columns could be made to reach hard stratum to provide sufficient end-bearing resistance (Fig. 3b&3c). A shallow depth up to 5 m can also be mass-treated to form working platforms in a soft soil layer, on condition the load applied is not too significant (Fig. 3e).

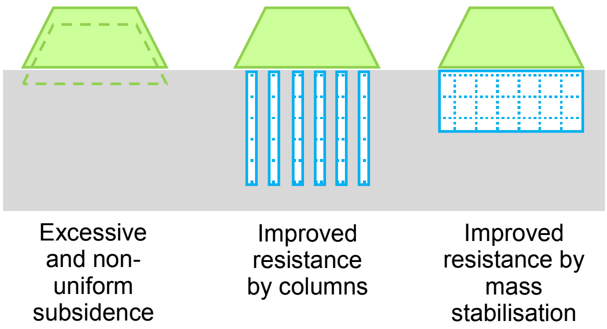


Fig. 2: Improved grounds with pseudo-solidification

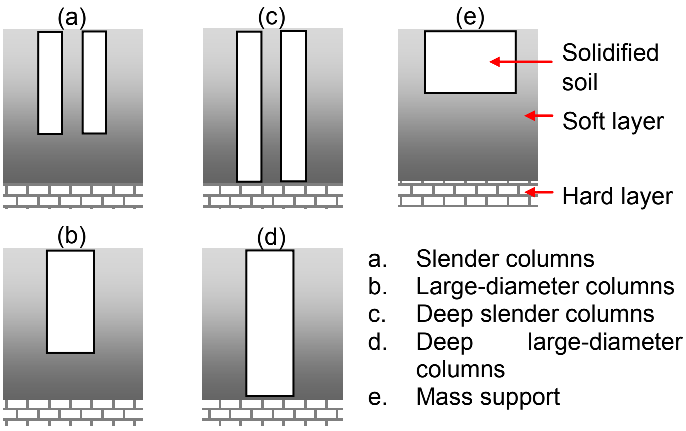


Fig. 3: Configurations of pseudo-solidification on site

The versatility of the pseudo-solidified method is further enhanced by the potential availability of non-commercial binders which derive from industrial wastes, for example. Slag from steel-making plants, bottom and fly ashes from coal power plants are some common substitutions for cement and lime used in soil mixing. Note that some non-reactive materials are added to the mixture to act as a fillers and not binder, such as steel slag and bottom ash. The sand-like coarser material lends structure to the soft soil matrix by bonding with the finer soil particles when admixed with the binder [12].

## 1.3 Usable land creation with treated DMS

Fig. 4 illustrates a conceptual design of reclaimed land or rehabilitated shoreline. It essentially consists of 4 primary layers of soil, namely the original firm layer, eroded or exposed layer, reclaimed layer (made from reused dredged marine soils, DMS) and capping layer. The original firm layer is usually at great depths, making installation of deep-stemmed seawall or foundations impractical. It also serves as a foundation layer for newly constructed land over it. The overlying eroded / exposed layer is the original visible grounds and marks the existing ground level too. It provides the base for the backfilled material, and may require certain improvement measures prior to backfilling (e.g. separator geosynthetics). Once covered with backfill, the layer will be protected from further erosion and mass loss. The backfilled layer makes up the reclaimed layer, which plays the role of replacing and rehabilitating the eroded soil mass. The backfill of DMS restores the lost soil mass, and could also help to increase ground elevation from rising sea level. It creates new grounds for development, but the short and long term stability, particularly subsidence, must be carefully estimated and controlled. The capping layer functions to protect the backfilled material, and to serve as a working and construction platform. It could also act as a surcharge over the reclaimed layer for accelerated consolidation to avoid excessive subsidence in future. Further protective measures could be provided by a retaining sea wall along the rebuilt shoreline. Of course other designs with slightly different configurations are possible to suit the site conditions as well as resources availability. For instance, proximity of the reusable DMS from nearby dredge sites makes the solution particularly attractive and feasible in terms of logistics and cost-savings.

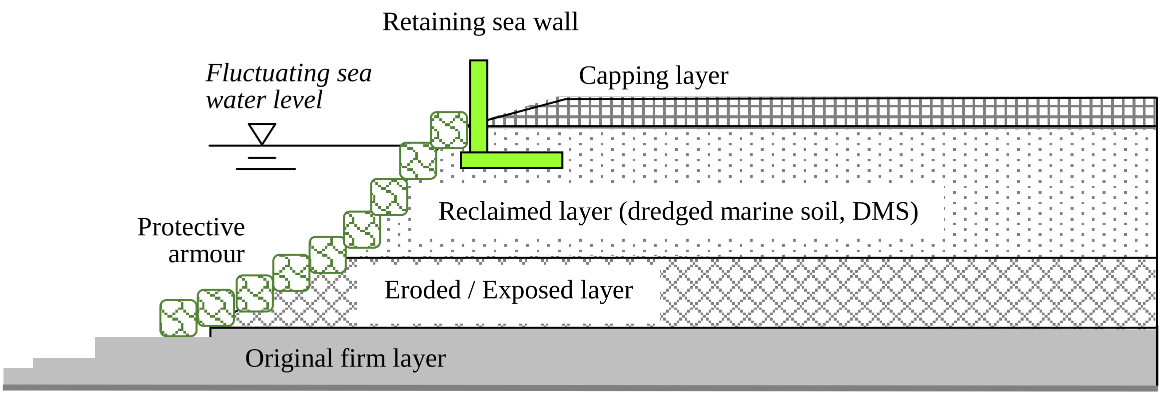


Fig. 4: Example of DMS reused for eroded beach restoration

## 2 Laboratory explorations

In collaboration with the Marine Department of Malaysia, a number of dredged marine soil (DMS) samples were retrieved from waters surrounding Peninsular Malaysia. The samples were generally fine-grained soils predominated by silt or clay fractions with small amounts of course particles and debris. The laboratory measurements included the bench tests, i.e. undrained shear strength and bender element tests, and the oedometer test for gauging the 1-dimensional compressibility under constant load over a period of time. The strength test was conducted using the standard unconfined compressive strength apparatus, while the non-destructive bender elements test was used to obtain P-wave velocity, a parameter which is related to the small strain stiffness of the material tested. The oedometer test, on the other hand, involves placing the soil sample in a confining ring (constrained lateral expansion, hence 1-dimensional displacement is measured) under constant loading for 24 hours, to obtain the compression curve plotted against time with information on the immediate, primary and secondary settlement of the soil. All tests were performed in accordance with BS1377 (1990) [13], except for the bender element test which followed the procedure prescribed by the manufacturer for an automated test setup [14].

Note that to demonstrate the reusability of the improved material, the test data discussed in the following sections are for a typical DMS sample. It was collected in a slurry state from the dredge site and was greyish in colour with an unpleasant smell (due to microbial activities). The initial water content was 166 %, based on dry mass of the soil, with a composition of 22 % sand, 78 % of silt and clay. The specific gravity of the sample was 2.60. With liquid and plastic limits of 95.8 % and 34.4 % respectively, referring to the Unified Soil Classification System (USCS), the soil was classified as a high plasticity clay, CH. The admixtures consisted of cement (C) and fly ash (FA) from a coal power plant, added to the soil at various combination ratios but always kept at 10 % (per dry mass of the soil). The rather small dosage of admixtures adopted was to avoid over-treating the soil, hence defeating the purpose of pseudo-solidification, i.e. creating an improved material which derives its strength and stiffness from interaction with the surrounding untreated soil. The mixing water content was fixed at 42 %, which was found to produce the best workability for the DMS-cement-fly ash mixture.

## 3 Bench Tests: Mixing, Strength and Stiffness

Fig. 5a shows the DMS-C-FA mixtures prepared at different water contents (w) between 20-50 %. It is apparent that the mixing water content has a significant effect on the resulting mixtures and specimens prepared. Considering that the specimens were prepared by kneading and pressing of the mixtures into a cylindrical split mould by 4 layers of equal mass, the layering effect observed on the outer surface is expected. Nonetheless both bisection of the specimens and subsequent mechanical tests did not reveal any signs of poor contact or fusion between the layers. Indeed, as the top surface of each compacted layer was carefully scarified before laying the next layer, the specimens were found to be sufficiently ‘homogeneous’ with blurring of the boundaries.

While water is necessary to facilitate good mixing of the material, excessive addition of it can cause segregation of the soil and admixture particles, where the solids appear to be suspended in flocculation with limited strength. On the other hand, too little water would produce brittle and semi-dry mixtures which crumble when compacted. This is due to the lack of lubrication among the solid particles, causing them to slide and roll over one another in aggregates or individual particles. This often leads to non-uniformity in the treated soil mass with sporadic weak pockets as well as localised over-solidified zones, causing uneven load-bearing capacity which is detrimental to the overall design [15].

Also, the mixing water content is a crucial factor in pseudo-solidification, with an optimum water content necessary to enable thorough mixing of the materials and effective hydration of the binders added. Soils with low water content may theoretically require less binder for improvement (hence cost-saving) but the mixing process could be too laborious and ineffective to produce the desired mix uniformity. Vice versa, high water content in the soil may help enhance the mixing efficiency but compromise on the cost and time, necessitating a greater demand on the binder and longer mature period to achieve the design strength (Fig. 5b).

Fig. 5a: Mixing water content effect on homogeneity of specimens

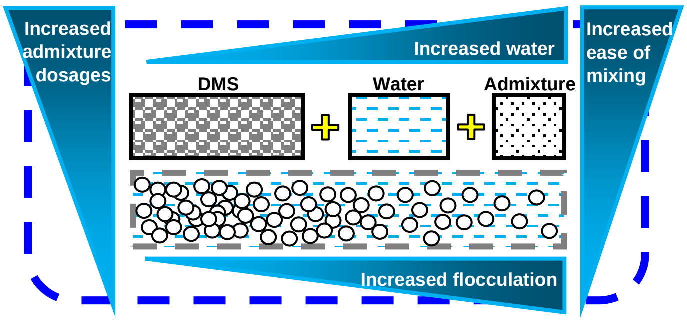


Fig. 5b: Optimum mixing water content in pseudo-solidification for effective mixing and improved properties

Mixing the DMS with admixtures of binder and filler materials involves transformation of the soil physically and chemically. It follows that some loss in the initial water content is to be expected, where water is necessary to lubricate the solid particles for mixing and compaction, and for the chemical reactions of binder hydration to take place. Fig. 6 shows the normalised water content (water content of a particular age divided by that of day 0, i.e. initial water content, $w_O$) plotted against the curing time, D. Note the increased demand for water with greater dosages of cement in the mix. The sudden drop in $w_D/w_O$ for all mixes with cement added suggests the water consumed for hydration to form the cementatious gel which eventually binds the soil into a stronger and stiffer matrix. When no cement was used in the admixture, the change in water content was almost linear. This indicates proportionate water loss with increased FA in the soil, which can be attributed to the increased specific surface as FA is about as fine as the clay particles of the DMS (<63 μm).

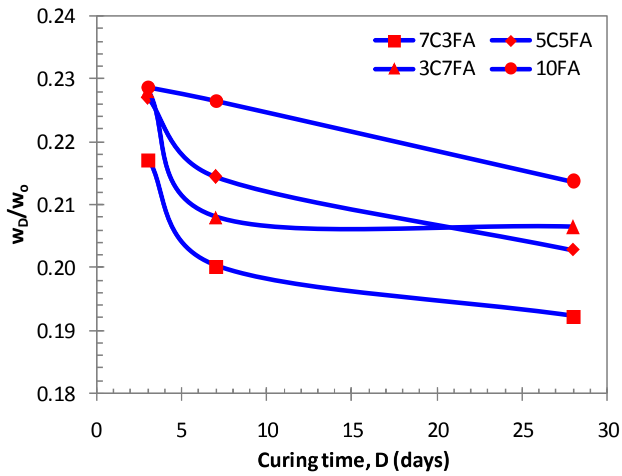


Fig. 6: Change of water content ($w_D/w_O$) with curing time, D

Corroborating with the water content changes, as a partial substitute of cement, FA's addition to the DMS had significant effect on the resulting strength ($q_D$) and P-wave velocity ($v_D$), measured with the unconfined compression and bender test apparatus. The measured strength and stiffness are grouped according to the curing period, D = 3, 7 and 28 days, and plotted against FA content in Fig. 7 and 8. Generally, longer curing period (D) allowed for greater strength and stiffness gains. This was however, not as distinct in the $v_D$ results, as the plots for 3D and 7D mostly overlapped except at FA = 7 % (i.e. specimens 3C7FA). This suggests that the $v_D$ measurement was less sensitive to the inherent properties changes, though the distinction was captured at the optimum FA content of 7 % in both $q_D$ and $v_D$ plots. Regardless of the curing period, $q_D$ and $v_D$ were both highest at 7 % FA, with prolonged curing producing the not unexpected more significant improvement. Again, the strength gain was more pronounced than the stiffness improvement, indicative of the solidified soil mass of good load-bearing capacity but not necessarily adequate subsidence control for long term stability (see Fig. 2).

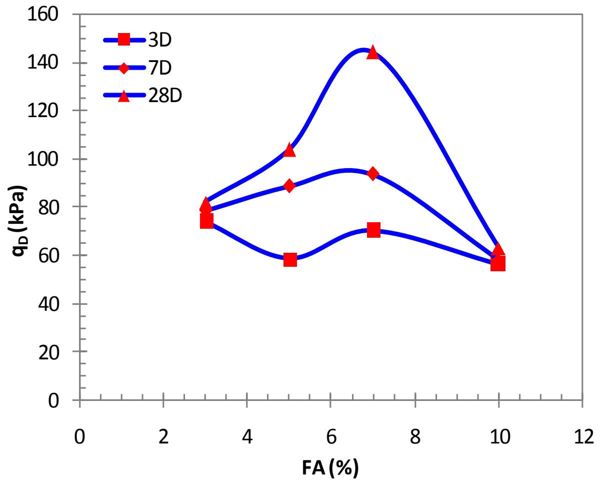


Fig. 7: Effect of fly ash content (FA) on $q_D$

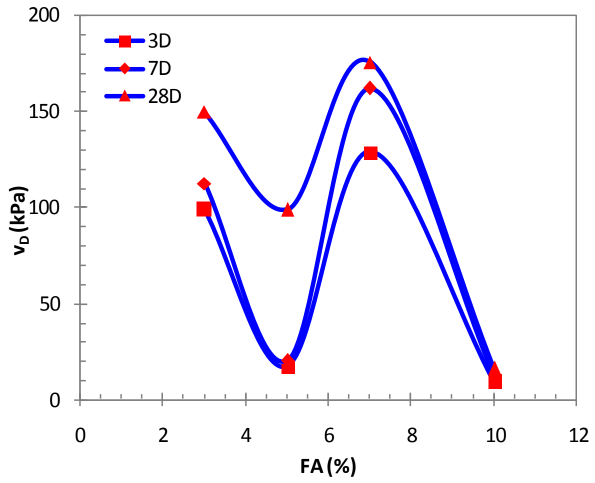


Fig. 8: Effect of fly ash content (FA) on $v_D$

It is interesting to note the severe drop in stiffness (not as distinct in the $q_D$ plots) at 5 and 10 % FA (Fig. 7 & 8). While an optimum blend of 3C7FA produced the best solidification effect for the DMS, a slight change in the cement:FA ratio on both ends of the spectrum produced similar $q_D$ and $v_D$. A plausible explanation is that at 5 % FA, the combined reaction of the cement itself and with the FA produced less cementitious gel for bonding compared to 3C7FA, where there was probably enough FA to react with the activator cement for combined expediency in solidification of the soil. In other words, the 3C + 7FA blend was more potent than the 5C + 5FA mix for the DMS at the specific mixing water content, i.e. 42 %. It follows that there may be a signature blend for each water content of the soil, necessitating trial-and-error with the DMS sample prior to reaching a suitable, effective mix ratio. Nonetheless, at 10 % FA, the large quantity of FA simply remained unreacted and functioned mainly as fillers in the DMS-FA mixture, without much cementation due to FA's rather inert nature in the absence of an activator like cement.

Fig. 9 and 10 illustrate the time factor on the improved mechanical properties of the DMS by referring to the strength and stiffness gain ratios, i.e. $q_D/q_O$ and $v_D/v_O$ respectively (subscript 'D' represents the specimen age and 'O' indicates the initial value as per the original soil). It is immediately apparent that $q_D$ underwent far less significant change than $v_D$, though the general trend was that the improvement was time-dependent, i.e. higher strength and stiffness were recorded at prolonged curing period. It is also observed that the improvement rate was rather mild and uniform, except for the marked rise in $q_D/q_o$ for specimens with ≥5 % FA (Fig. 9), but a similar steep climb is not observed in $v_D/v_o$ (Fig. 10). It is also worth noting that $q_D/q_O$ for specimen 5C5FA was greater than that of 7C3FA, but it was the other way round for $v_D/v_O$. This again points to the possibility of mismatch between load-bearing and compressibility of the solidified soil under load, which is an area of concern for overall long term stability of the made ground. The plots also corresponded with earlier discussions on the optimum blend of cement-FA for a specific water content. A higher FA content does not necessarily produce the best solidification effect, where the ideal blend of 3C7FA gave the most satisfactory strength and stiffness gain.

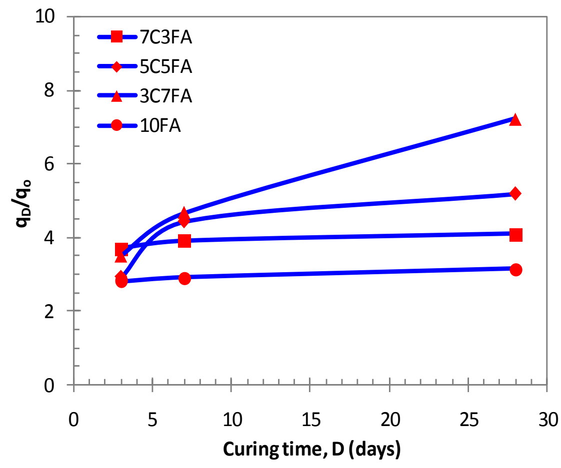


Fig. 9: Strength gain ($q_D/q_O$) with curing time, D

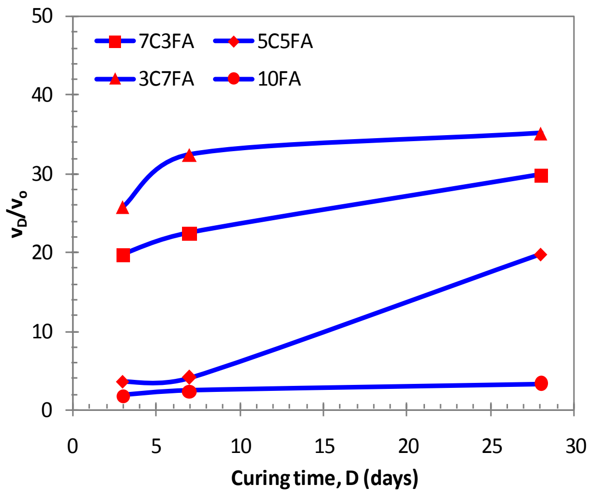


Fig. 10: Stiffness gain ($v_D/v_O$) with curing time, D

### 3.1 1-dimensional Oedometer Test: Subsidence

The settlement or compression curves derived from the oedometer tests are plotted in Fig. 11 and 12. The oedometer test essentially works on the principle of gradual pore water dissipation under constant load. The amount of water expelled is equivalent to the volume change experienced by the soil disc. As such, in a confined 1-dimensional test condition, the vertical displacement or settlement is directly proportionate to the volume of water discharged, i.e. volume change of the soil specimen. Note that the specimens were tested at age 3 and 7 days only as beyond 2 weeks, the solidified soil was too firm to be subjected to the test, which involved a small disc specimen of 75 mm diameter and 20 mm thick. Moreover it would have defeated the purpose of the test, which measures settlement due to expulsion of excess pore water when the soil is under loading. Looking at Fig. 9 and 10, the justification for testing specimens no older than 7 days can be found in the relatively gentle rise of both $q_D$ and $v_D$ after the first week. It is suggestive that the settlement would have remained largely unchanged over the period, as the stiffness stabilizes after 7 days. The curve for the original DMS was not included as it lies far below the plots with a linear stress-settlement relationship of about 22 % vertical displacement for every 1 kPa applied, corresponding with settlement of 26 % at 12.5 kPa and 66 % at 800 kPa.

Referring to Fig. 11 and 12, vertical stresses were applied to the specimen incrementally from 12.5 kPa to 800 kPa, followed by the stepped unloading stage. The plastic strain due to unloading shows permanent deformation of the soil under prolonged, constant loading, and is undesirable in actual field implementation for safety concerns. The settlement reduction was apparently dominated by the cement content, where the curves show settlements at different stresses in the ascending order of 5C5FA > 3C7FA > 10FA. Exception can be observed in the 7-day compression curves (Fig. 12), where all curves folded into one up to 100 kPa, with the recorded settlement not exceeding 5 %. Compared to the 3-day curves, the settlement was generally more pronounced. This is indicative of the expediency of solidification for pre-yield (i.e. the part of settlement curve before curvature to a steeper gradient leading to linearity), where the subsidence was relatively negligible. Post-yield, the compression curves seemed to revert back to those of the younger specimens (3-day old, Fig. 11) with substantial settlement. The breakdown of the cementation bonds is thought to account for the reversion as they could not have been very extensive or resilient due to the low binder dosage used, i.e. 3-5 %.

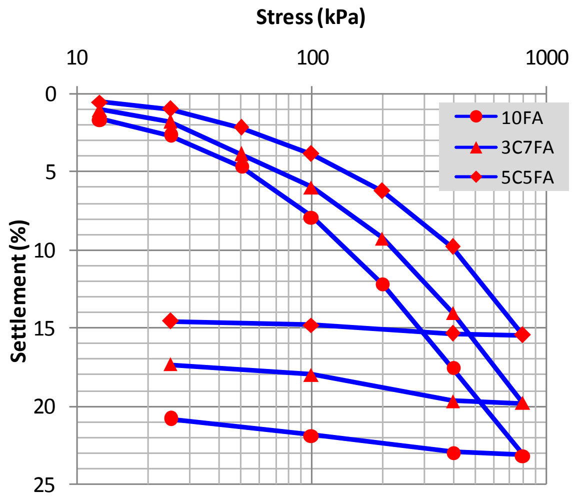


Fig. 11: Settlement curves for 3-day old specimens

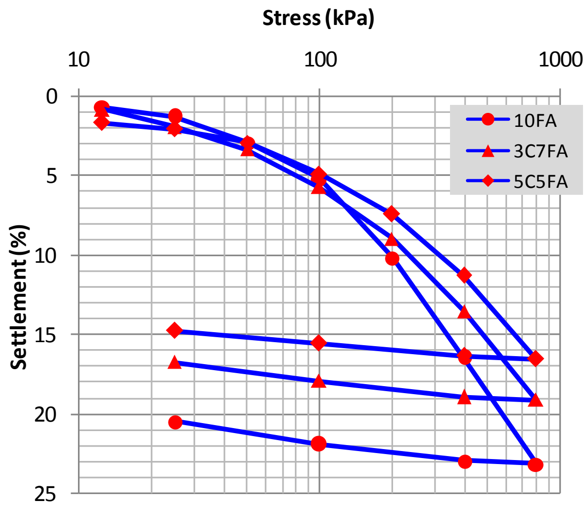


Fig. 12: Settlement curves for 7-day old specimens

# 4 Conclusions

The reuse of otherwise discarded dredged marine soils (DMS), especially of the fine-grained type, is feasible with pseudo-solidification. The admixtures could be binder or filler materials, where the former functions to react with water to bind and lend structure to the soil mass, the latter plays the role of providing a scaffolding for effective cementation. Common hydraulic binders like cement and lime are costly, hence substitution with industrial wastes, such as bottom and fly ashes, steel slag, palm oil clinkers are favaourable. Some of these materials are mildly cementitious when in contact with water, otherwise they serve well as a filler for the treated soil.

In reviewing the lab-based investigations of a DMS solidified with cement-fly ash, it was found that there is a specific recipe of the blend to attain meaningful improvement of the soil for reuse. Blending with cement is necessary as FA alone is ineffective for binding the watery soil due to its low reactivity. This was evident in the marked initial decrease in water content observed in specimens admixed with cement. The optimum dosage for the cement-FA blend was 3C7FA in the present exploratory study, recording approximately 7- and 30- fold of improvement in terms of strength and small strain stiffness respectively. It goes on to show that instead of a threshold dosage of the blend, solidification is only expedient at the 'perfect' mix ratio, as proven by the dramatic drop in $v_D$ with 5C5FA addition, accompanied by the requirement of prolonged mature period. Settlement of the solidified DMS pre-yield was clearly reduced with cement-FA addition. Prolonged curing period is unlikely to produce significant improvement of the stiffness, evidential in the stiffness gain rate obtained from the bench tests. Post-yield, the settlement curves were very similar to those of younger specimens, suggesting destructurisation of cementitious bonds formed by the rather small dosage of admixtures, i.e. 10 %.

In a nutshell, DMS can be reused in coastal development projects, particularly for reclamation and rehabilitation works where transportation of backfill material from borrow pits is scarce or unfavourable. As the fine-grained DMS are of poor engineering properties, pseudo-solidification is necessary to improve the material prior to deployment on site. The enhanced performance in terms of strength, stiffness and settlement control is certainly promising, though further work is recommended for in-depth understanding of long term behaviour and geo-environmental impact of the solidified DMS.

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