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On the Reuse of Dredged Marine Sediments: No Dumping, Reuse Please.

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Abstract— **Dredged marine sediments, conventionally considered a waste material for disposal, are either in designated offshore locations or inland containment facilities. Either of these measures incur additional costs, time and labor, not to mention the obvious lack of sustainable values. In addition, there is always the risk of transferring undesirable contaminants in the dredged materials to the disposal sites or along the transportation routes. It is however, possible to reuse this otherwise waste, with suitable and adequate pre-treatment. The material is essentially soil-based, primarily consisting sand, silt and clay with some coarse marine debris. To minimize processing time and costs, it is therefore considered most apt to harness the material's inherent properties as a 'soil' and reuse it as a geomaterial in various civil engineering applications. These include reusing the sediments as a backfill material, for creating new land bases or restoring eroded ones in near-shore areas. In summary, this paper puts the recycling and reuse of dredged marine sediments into practical engineering context, by highlighting the improved properties with solidification. Some key findings from on-going research work are included to substantiate the potential of the material reuse.**

***Keywords*— dredging, sediments, solidification, resuse, geomaterials, susainable, soil**

I. Introduction

In 2013 alone Malaysia has dislodged nearly 4 million m^3 of sediments for maintenance dredging of ports and jetties [1]. The dredged sediments were routinely disposed offshore in designated dumping sites 10 nautical miles (1 nautical mile = 1.852 km) from the shoreline. These dumping sites are required to be of at least 20 m deep to minimize disruption to the surrounding waters. The cost incurred for the dumping process could be as high as 20 % of the total dredging cost. Financial implications apart, the damaging consequences of the dredge-and-dump process on the marine environment are of greater concern, as the damages are irreversible with far-reaching impact, e.g. [2] and [3]. It is therefore imperative to explore the possibilities of giving a second life to these dredged sediments, to avoid the negative dumping effects and to introduce alternative, green products for construction purposes. Essentially soils of poor quality, the dredged materials can be potentially improved to function as usable geomaterials.

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II. Properties of Dredged Marine Sediments

The dredged marine sediments examined in this paper were collected from dredged sites located at Lumut (Perak), Marina Melaka (Melaka) and Tok Bali (Kelantan). The Perak and Melaka sampling locations were on the west coast of Peninsular Malaysia while the Kelantan one was on the east coast. All 3 sites were unique from the environmental conditions' point of view:

- Lumut, Perak: Offshore, 8-12 m depth, 120 000 m^3
- Marina Melaka, Melaka: Nearshore and within the marina area, 4 m depth, 120 000 m^3
- Tok Bali, Kelantan: Near river mouth, 3-5 m depth, 140 000 m^3

The sampling locations are illustrated in Figure 1. The relevant physical, chemical and biological properties of the dredged samples, as influenced and shaped by the environmental conditions, are discussed in the following sub-sections.

Figure 1. Sampling locations of dredged marine sediments.

A. *Physical Properties*

The physical properties of all the dredged samples are given in TABLE I. The standard test procedures for making the measurements are as prescribed in [4].

TABLE I. PHYSICAL PROPERTIES

Properties	Samples		
	Lumut (L)	**Marina Melaka (M)**	**Tok Bali (T)**
Particle size distribution:			
▪ Gravel (%)	3	3	5
▪ Sand (%)	15	9	20
▪ Silt (%)	4	20	15
▪ Clay (%)	78	68	60
Natural water content (%)	166.16	145.77	92.23
Atterberg limits:			
▪ Liquid limit (%)	95.80	58.50	36.80
▪ Plastic limit (%)	34.50	38.39	25.83
▪ Plasticity Index	61.30	20.11	10.97
Specific gravity, G_s	2.60	2.63	2.38
pH	8.30	8.32	8.51
Soil classification (USCS)	CH (high plasticity clay)	MH (high plasticity silt)	ML (low plasticity silt)

Texture-wise, it is apparent from the particle size distribution data that the dredged samples 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, as reported by [5], [6] and [7]. Nonetheless this has transformed the sediments into a soft, fluid mass inadequate for any load-bearing purposes, a key feature which renders the material useless for construction applications, e.g. backfill material. Based on the physical properties obtained and by referring to the Unified Soil Classification System (USCS), the samples were found to be of clay and silt mainly. Note that the comparatively high Plasticity Index of the Lumut sample is an indicator of the predominant presence of clay in a soil mass. As such, the amount of fines, i.e. silt and clay particles, diminishes as the Plasticity Index approaches zero, where the soil loses its elasticity and becomes crumbly.

B. *Chemical Properties*

The chemical components of the samples were determined using the X-ray fluorescence (XRF) elemental analysis technique (TABLE II). Silicon (Si) appears to constitute the largest portion of element in the dredged samples, i.e. 56-63 %, followed by aluminium (Al) at 17-21 %. The large amount of Si is attributed to the presence of quartz in dredged soil. Si is the most common mineral in earth, and a significant mineral for all igneous, sedimentary and metamorphic rocks, which constitute the parent material of most soils. According to [8], silicone mainly derives from sand and silt while the source for aluminium is primarily the clay fraction. Overall the chemical composition of the samples is comparable to those previously reported, e.g. [9]. 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.

TABLE II. CHEMICAL PROPERTIES

Element oxides (%)	Samples		
	Lumut (L)	**Marina Melaka (M)**	**Tok Bali (T)**
Aluminium oxide (Al_2O_3)	17.10	20.73	21.10
Calcium oxide (CaO)	3.25	2.58	4.19
Iron oxide (Fe_2O_3)	4.60	6.50	7.50
Potassium oxide (K_2O)	2.24	2.81	2.75
Magnesium oxide (MgO)	2.44	2.30	2.20
Silicon dioxide (SiO_2)	63.40	55.67	55.67
Sulfur trioxide (SO_3)	1.66	1.53	1.84
Titanium dioxide (TiO_2)	0.68	0.96	0.91
Sodium oxide (Na_2O)	1.67	2.49	1.57

C. *Biological Properties*

Enumeration of the E. coli and Total Coliform was conducted in accordance with the procedures given in [10]. TABLE III summarises the results.

TABLE III. BIOLOGICAL PROPERTIES

Biological Properties	Samples		
	Lumut (L)	**Marina Melaka (M)**	**Tok Bali (T)**
E. coli	n.d	1.0×10^2	2.0×10^2
Total Coliform	3.1×10^2	2×10^2	n.d
Microbes	*Serratia plymuthica* *Vibrio alginolyticus* *Corynebacterium genitalium*	*Serratia marcescens* *Vibrio vulnificus* *Edwardsiella tarda* *Bacillus cereus* *Escherichia coli*	*Escherichia coli*

All the dredged samples had E. coli below EPA's recommendation safe level of = 2.35×10^2 cfu/ml, though the record for the Tok Bali sample is admittedly high. This is attributed to the human dwellings and anthropological activities upstream to the sampling point near the rivermouth. The microbes identified are also shown in TABLE III. A major concern of microbial presence in dredged materials is the potential health risks involved, especially if the material is to be reused for the creation of new landforms for human's usage. Dredged sediments are particularly rich with microbes as they provide an abundant source of nutrients for these microorganisms [11] and [12]. The sedimentation bed also serves as a protection blanket from sunlight inactivation [13] and protozoan grazing [14] of the microbial consortium. Besides, many of these microbes are capable of metabolizing chemical contaminants, such as those derived from oil spills, to inert or less toxic substances.

III. Reuse of the Dredged Marine Sediments: Solidification

A. Binders and Fillers

It is important to note that dredge sediments of the coarse-grained nature, i.e. sand and gravels, can be readily reused as ordinary geomaterials in various construction areas, so long as the probability and consequences of contamination as well as health hazards are ascertained and mitigated. The applications include reclamation, beach rehabilitation and recharge schemes [15].

For fine-grained dredged sediments as described in the present study, the applications are less straightforward. In order to put the otherwise geowastes into useful second lives, certain pre-treatment is necessary to improve the poor quality of the dredged sediments. The approach adopted as discussed in the paper is solidification, where hydraulic binders are admixed with the sediments of high water content to effectively reduce the moisture, increase the strength and minimize the compressibility upon loading. Solidification itself is not new, as known by other names including soil mixing, chemical stabilization and modification.

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 from the combustion in a coal power plant, and slag produced in steel-making, were collected to form part of the binders (Figure 2). 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.

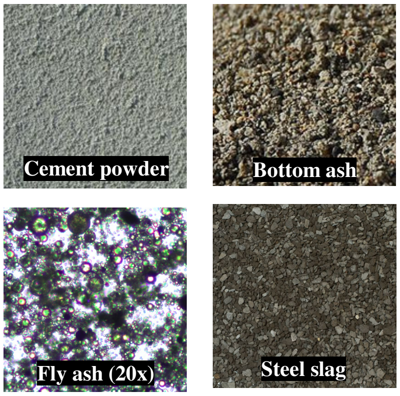

Figure 2. Binders and fillers.

Cement is arguably the most popular binder's choice, and a small quantity can be sufficient to produce meaningful performance improvement of the soils. As pointed out by [16], many soils can be successfully treated with considerably lower cement contents, as corroborated by the findings of [17] and [18].

Captured in electrostatic precipitators, fly ash particles contained in the flue gas from coal combustion are spherical and non-uniform in size (see Figure 2). There are 2 major classes of fly ashes based on their chemical compositions resulting from the type of coal burned, namely Class F and Class C ashes [19]. Class F ash (as used in the present study) is derives from the burning of anthracite or bituminous coal, while Class C ash is the residue from burning sub-bituminous coal and lignite. The latter usually has cementitious properties in addition to pozzolanic properties due to its free lime content, unlike the former which is rarely cementitious when mixed with water alone [20]. Class C fly ash is self-cementing even when mixed with water without activators, due to the presence of 20-35 % calcium compounds (CaO). Hence it can be used on its own to solidify moderately plastic soils [21] with no addition of activators like lime and Portland cement. As reported by the same author, fly ash treatment can also reduce the swell potential for fat clays and increase the strength of pavement subgrades. In coarser aggregates, fly ash functions both as a pozzolan and/or filler to reduce the void spaces among the aggregate particles.

The cementitious properties of steel slag can be attributed to the presence of C_3S, C_2S, C_4AF and C_2F [22].It was also reported that the reactivity of steel slag increases with its basicity. However due to the much lower C_3S content in steel slag is compared to in Portland cement, steel slag can be regarded as a weak Portland cement clinker. [23] further established that the presence of NaOH in a steel slag – water reaction can accelerate the hydration process of the steel slag. In their work with Osaka clay solidified with non-activated steel slag, [7] concluded that higher fine slag portion in the dredged material induces greater strength improvement, due to the larger surface of the finer particles and the greater solidification potency of the unreacted inner surfaces of ground slag.

B. Changes in Inherent Properties

The following discussions are based on data collected from measurements of the Lumut dredged sediments admixed with cement and fly ash. The dosage was fixed at 10 % (per dry weight of the soil), with various combinations of cement to fly ash ratios, i.e. 10 % cement + 0 % fly ash (10C), 30 % cement + 70 % fly ash (3C7FA), etc. In admixing fly ash to the Lumut dredged sample, the loss on ignition (LOI) parameter for the sample was found to be 6.33 %, suggesting the presence of a small amount of organic matter in the dredged soil. Soil with organic content greater than 20 % is considered as organic soil in geotechnical engineering, beyond which the mechanical characteristics of soil will no longer apply [24]. According to [25], ordinary Portland cement should have an LOI value of less than 3 %. The LOI value for Class C and Class F fly ash should be less than 6 %, but the LOI value of Class F fly ash can be as high as 12 % [10]. The rather wide range provided is attributed to the variation in sources and properties of fly ashes.

In Figure 3, the LOI value for all the solidified specimens decreasedn throughout the curing period up to a month, except for 3C7FA which shows a slight rise towards the end. As the constituents of the solidified specimens are relatively complex, i.e. soil, cement and fly ash and cementitious products from the chemical reactions, the LOI values barely represent the actual amount of organic matter present. In addition, it is highly likely that the cementitous products coated and entrapped the organic matter contained in the respective raw materials, resulting in the weight loss recorded in the LOI test with the lapse of time. Longer curing periods allow more hydration and pozzolanic reactions to take place, hence the less organic matter available or 'exposed' for combustion in the furnace.

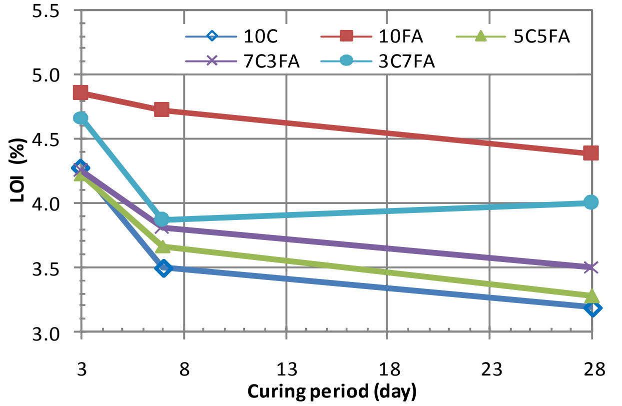

Figure 3. Loss on ignition – curing period of solidified dredged samples- Lumut.

The pH of the natural dredged soil sample was 8.22, indicating that it was moderately alkaline, with possibly low organic content in the soil [24]. Figure 4 shows the pH values of the solidified specimens over the 1-month curing period. It appears that cement dosage of 3 % is the minimum before the pH trend starts to decline with time. Generally, the hydration of cement leads to pH increment of the pore water, caused by the dissociation of the hydrated cement [26]. The addition of fly ash led to a reduction in the pH of the mixture, as demonstrated by the dip in specimen 10FA. According to [27], the lower the pH is, the higher the degree of reaction in fly ash is in the mixture. This could explain the pH trend observed when fly ash content increased while the cement dosage decreased, where pozzolanic reaction of the fly ash caused the simultaneous occurrence of two mechanisms: (1) decline of the alkality of the pore water solution, and (2) consumption of calcium hydroxide (CH) from the hydration of cement. The exception of 5C5FA and 7C3FA may be due to non-uniform mixing of the materials, leading to formation of sporadic and localized pockets of incomplete fly ash reaction within the specimens.

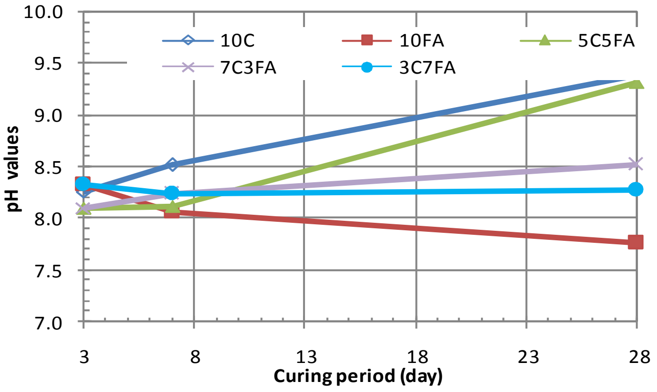

Figure 4. Change of pH values with time- Lumut.

The post-solidification XRF analysis showed some interesting changes in the chemical composition of the dredged sediments. For specimen 10C, a marked increase in the CaO content of the solidified specimen was recorded in comparison with the original soil (CaO = 3.33 %). On the other hand, the addition of fly ash alone (i.e. specimen 10FA) did not result in much change of the CaO content. This is understandable as the Class F fly ash itself contains negligible amount of CaO. Overall, other elements in the mixture remained largely unchanged, regardless of the variations in the cement : fly ash ratio and curing period. This is suggestive of the limited solidification efficacy of small dosages of binder in these soft dredged soils, and that prolonged curing could not overcome the unsatisfactory solidification outcome of low binder dosages. Figure 5 shows the relationship between CaO content and fly ash dosage in the solidified specimens. Note the almost linear declining trend of the plot, irrespective of the curing period, highlighting the nominal effect of Class F fly ash in the solidification of the dredged soil.

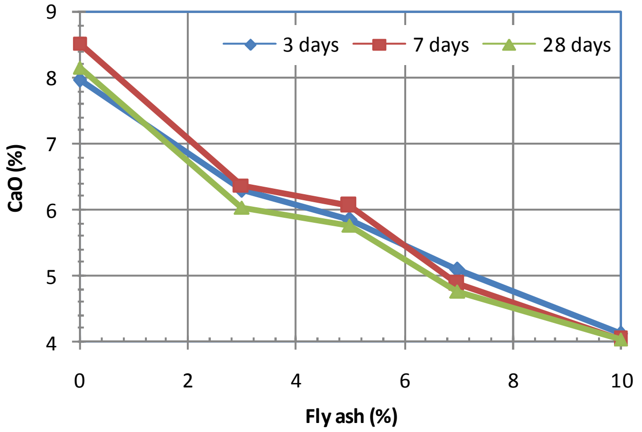

Figure 5. Relationship between CaO and fly ash content- Lumut.

C. *Strength*

Figure 6 shows the vertical stress (strength) – curing period plots for the cement - fly ash solidified Lumut specimens. The strength attained may not be very significant, but they are within the range acceptable for reuse as sound geomaterials, such as stipulated in the requirements by [28]. With the exception of 10FA which showed negligible strength improvement with time, the strength does appear to increase with higher fly ash content (Figure 6). Large fly ash content has been reported to have an adverse effect on solidification due to presence of fine particles and unburned carbon in the fly ash [29]. The results obtained in the present study seem to suggest otherwise.

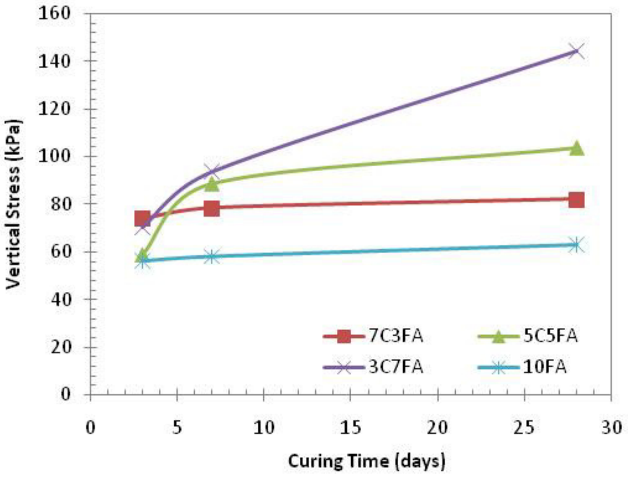

Figure 6. Strength increment with time- Lumut.

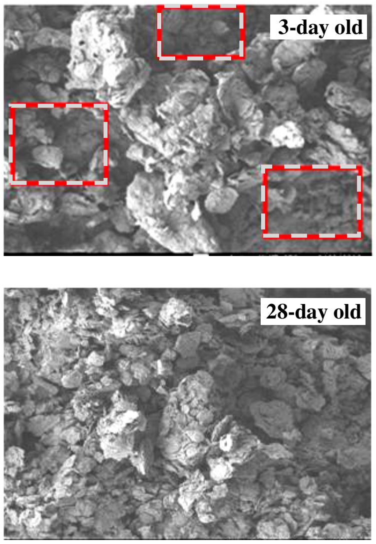

Figure 7. FESEM images (5000x) of specimen 5C5FA at 3 and 38 days- Lumut.

The strength increment is attributed to the formation of gelatinous cementing compounds, which occupies the voids within the soil spaces and binds the soil particles together [30]. Cement treatment typically leads to flocculation of the fractions in soils, consequently increasing the particle size and modifying the plasticity of the original soil [31]. This expedient effect of solidification can be clearly observed in Figure 7, where the images of specimen 5C5FA were captured using field emission scanning electron microscopy or FESEM. At 5000x magnification factor, the large voids at early stage of solidification (3-day) were apparently filled up by the cementing compounds derived from cement-fly ash (28-day). The large voids are distinguished in the 3-day micrograph of Figure 7 (boxed), which are no longer visible in the same specimen a little over 3 weeks later. Also, it can be seen that the soil's microstructure changed significantly with prolonged curing time, with the 28-day specimen showing larger adjoined lumps of solids. While it remains unclear if the fly ash contributed to the gelatinous filler, it is almost certain that they at least helped to form the solid mass to strengthen and stiffen the originally weak soil structure, i.e. the 'filler' effect.

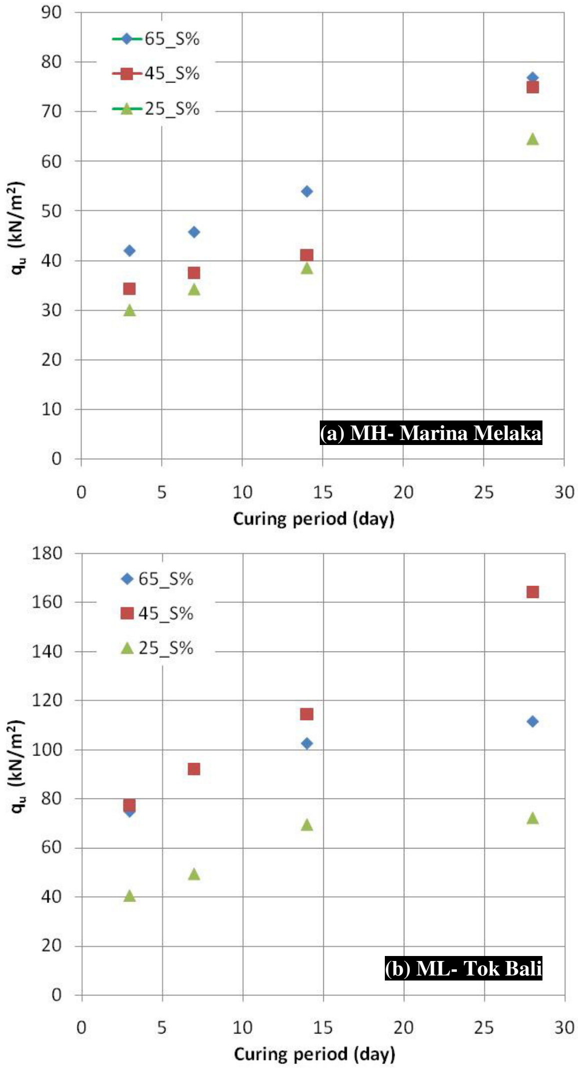

Figure 8. Strength increment with time: (a) Marina Melaka and (b) Tok Bali.

Figure 8 shows the strength (q_u = unconfined compressive strength) increment with curing period for the Marina Melaka and Tok Bali dredged samples admixed with steel slag. The dosages were 25, 45 and 65 % of slag to the dry weight of the soil. The low plasticity silt from Tok Bali apparently reacted better with the steel slag compared to the high plasticity silt from Marina Melaka, resulting in greater strength enhancement. However the strength increment was continuous for all mixes in the latter (MH), while the former (ML) showed plateaus after 14 days for the specimens with 25 and 65 % of slag addition. Irrespective of the strength increment rate, both soils demonstrated effective solidification using steel slag, a promising results for full or partial substitution of cement with this alternative binding agent.

D. 1-dimensional Compressibility

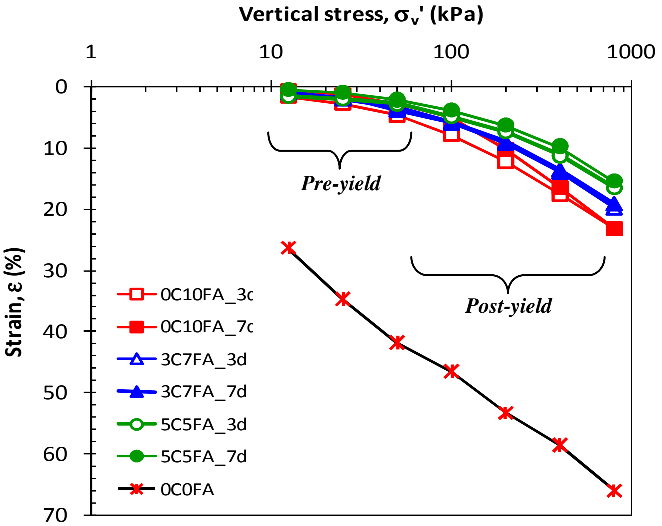

Figure 9. Compression curves- Lumut.

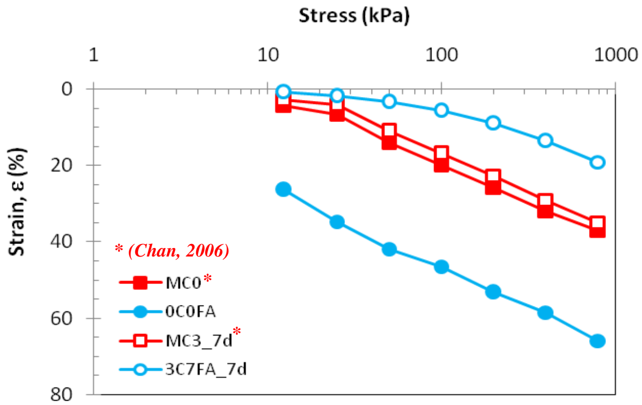

Figure 10. Compression curves- Lumut.

Figure 9 shows the settlement curves for the Lumut specimens, as recorded in the oedometer tests. Referring to the low-lying plot for the original soil (0C0FA), the treated specimens recorded an average of approximately 68 % settlement reduction. 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. 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 10 illustrates an example of the possible function of fly ash in a cement-fly ash blend. Incorporated in the same figure is the data from [31] on the cement-treated soft marine clay (MC: water content = 74 %, G_S = 2.66), cured for 7 days, as well as the data from the present study with the same cement content, i.e. 3C7FA. With a much higher mixing water content, 3 % cement produced marginal reduction to MC's compressibility. On the other hand, a 3C7FA blend reduced settlement of the present dredged soil by almost 70 %, besides giving structure to the initially weak mass. As such, it can be concluded that with low cement dosages, prolonged curing cannot ensure meaningful stiffness gain in solidified soils, and that the mixing water content plays an important role too for effective solidification.

E. Small Strain Stiffness

The small strain stiffness can be indirectly derived using the bender element measurement system, where P-wave velocity is obtained by dividing the travel distance with the travel time between the transmitting and receiving bender elements. It gives a quick and non-destructive monitoring of improved stiffness of the solidified soils.

Figure 11 summarises the P-wave velocity (v_p) against curing period for the Lumut dredged sediments treated with cement – fly ash. It can be observed from Figure 11 that the v_p pattern is generally not dissimilar to those of the strength's (q_u) evolvement with time (Figure 6). Specimen 10FA registered the lowest velocities, followed by 5C5FA, 7C3FA and 3C7FA. Note that specimen 5C5FA initially had a lower v_P than 10FA, but eventually overtook it at around 18 days. As the 7C3FA specimen lies above that of 5C5FA, it does not correspond with the relationship between strength increase and flyash content in the specimens. Nonetheless the specimen with the least cement content (3C7FA) attained the highest v_P. Considering that v_P is an indicator of stiffness, albeit at small strain levels (i.e. strain not exceeding 0.001 %), the strength and stiffness values do match up to a certain extent. The discrepancies mentioned earlier may be implausible at the moment, but they are very likely due to masking of the actual arrival time commonly encountered in less than satisfactory waveforms received. This could be caused by loose contact between the bender element and specimen, uneven end surfaces of the specimen leading to poor interface, and interference of the received signals by external factors. The mismatch notwithstanding, it can be noted that prolonged curing did not result in marked increase in the v_P, as observed in the q_u plots, especially in specimen 3C7FA.

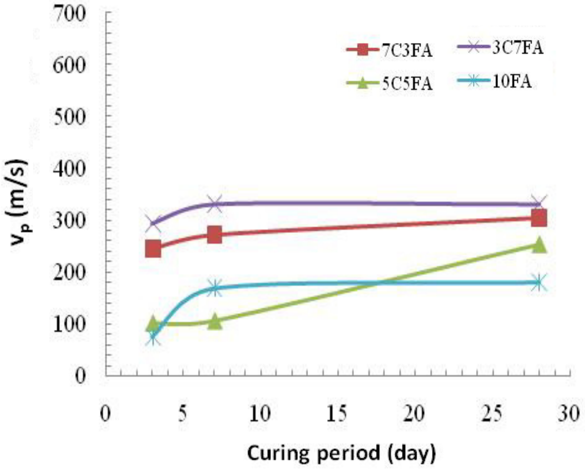

Figure 11. P-wave velocity plot with time- Lumut.

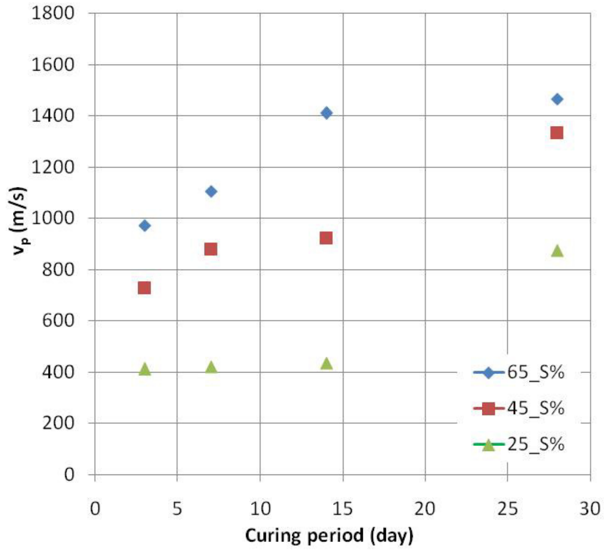

Figure 12. P-wave velocity plot with time- Marina Melaka.

Figure 12 shows the v_p plot over time for the Marina Melaka sample (MH) solidified with steel slag. The stiffness improvement is more significant with increased slag content. Overall the solidification effectiveness of steel slag is found to be approximately twice that of the cement – fly ash blend. This is attributed not solely to the hydration and chemical bonding effect, but the 'filler' effect of the particulate steel slag too. The original steel slag received had a particle size range of 20-60 mm, but it was ground and reduced to finer particles of <2 mm for better blending with the dredged soil. Taking into account that the dredged sediments were predominantly silt and clay (particle size < 63 µm), the steel slag particles would have contributed to the enhanced stiffness by providing a more rigid structure to the original soil mass. The combined effect of cementation and structure stiffening is illustrated in Figure 13.

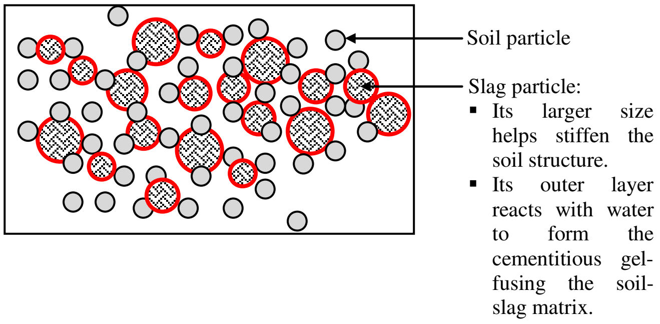

Figure 13. The combined effect of cementation and structure stiffening by steel slag particles in dredged soil mass.

F. *Strength-Stiffness Correlations*

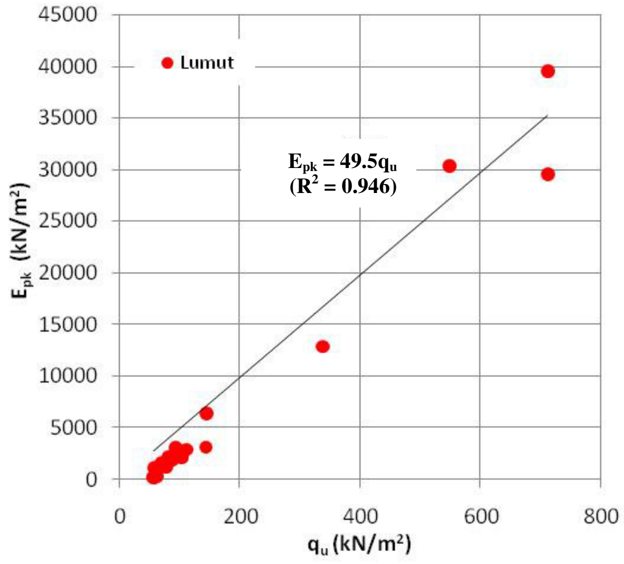

Figure 14. E_{pk} vs. q_u plot- Lumut.

The Young's modulus can be derived from the stress-strain curve of the unconfined compression test, simply by taking the gradient of the line connecting the origin and the peak stress (i.e. q_u). The modulus, E_{pk}, can then be plotted against q_u, as shown in Figure 14. The linear relationship identifies E_{pk} to be about 50 times that of q_u, with a strong correlation coefficient (R^2=value) of over 90 %.

Figures 15 illustrates the relationship between q_u and v_p for the Lumut specimens. Note that the seemingly outlying high strength data points correspond with the cement-added only specimens. A correlation chart like this is useful for estimation of the strength of a solidified soil without excessive sampling and measurements as the it is a non-destructive test. Moreover the same specimen can be repeatedly tested at different time intervals, simulataneously omitting the errors due to differences in specimens as well as the compression test. Nonetheless it should be cautioned that the strength-stiffness correlation is unique for a specific soil solidified with a certain binders. Attempts are currently being made to identify the possibility of a unified model for the correlation irrespective of the soil and binder types.

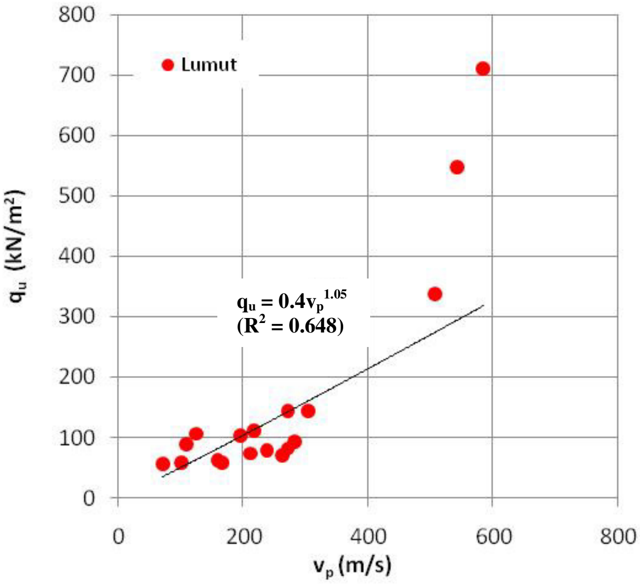

Figure 15. $q_u - v_p$ (Lumut).

IV. Conclusions

This paper gives an overview of the current research efforts to reduce the dumping and to promote the reuse of Malaysian dredged marine sediments. While the outcome is not ready for filed implementation, the test results thus far are encouraging and there certainly is potential in the reutilization of the otherwise waste material. Following is a summary of the key findings to date:

- The dredged sediments are mainly silt and clay, with small quantities of gravel and sand, resulting in the predominantly fine-grained soil's geo-mechanical behaviour.
- While the chemical and microbial presence in the material is not found to be at an alarming rate, a more robust monitoring programme with scheduled sampling and measurements is necessary to identify seasonal fluctuations and the long term impact.
- 2 industrial wastes, namely coal ashes and steel slag, show good bonding mechanism with the dredged sediments. This highlights the possibility of cost reduction with the partial or full substitution of manufactured cement.
- The reduction of organic content in the dredged material is attributed to entrapment by the cementitious products from the chemical reactions of the binders.
- Fly ash addition to the dredged sediments results in pH reduction and the consumption of CH from the hydration of cement.
- Higher dosages of fly ash substitution for cement are found to be beneficial for strength enhancement of the dredged sediments.
- Prolonged time lapse allows for better bonding of the soil-binder, to form a stronger and stiffer structure for load-bearing.
- The steel slag functions both as a binder and filler, simultaneously bonding the soil and slag particles, while stiffening the structure of the mixture by its own larger particle size and denser form.
- The strength-stiffness correlations can be used for making quick estimations of the strength, especially in the design mix stage of a dredged sediments solidification exercise.

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