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GEO-CHARACTERISATION OF DREDGED MARINE SOILS FROM MALAYSIAN WATERS FOR POTENTIAL REUSE ASSESSMENT

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ABSTRACT

Dredging is routinely carried out for the maintenance of shipping channels, ensuring safe trafficability of vessels within the designated depths and breadths. The process involves removal of large quantities of sediments from the seabed for disposal. The disposal, whether onland or offshore, could incur additional costs as well as contamination risks along the transportation path and at the disposal site. Dredged materials are primarily soils, albeit much of the fine-grained type, i.e. clay and silt. Nonetheless the reuse potential of the material should be explored, as this can lead to less dumping and lowered associated risk levels. As these soil types are generally of poor engineering properties and with high probability of contamination, they cannot be reused without thorough characterisation. Accordingly, it is important to determine the material's inherent geo-characteristics as the first step in ascertaining its physical reusability. This paper describes the tests and measurements of key geotechnical properties for 4 dredged marine soil samples retrieved from Malaysian waters. The parameters examined include particle size distribution, water content, Atterberg limits, specific gravity and organic content. The results obtained were also compared with those of related soil samples collected from land. Overall it was found that the dredged marine soils do not differ significantly from ordinary fine-grained soils, and could be potentially reused as a sound geomaterial, though certain pre-treatment and processes may be necessary depending on the intended applications. Thorough geo-characterisation of the dredged marine soils provides the basis for further determination of the material's reusability.

Keywords: dredged marine soils, geotechnical tests, reuse, landfill, reclamation, sustainable development.

INTRODUCTION

The maintenance of waterways requires dredging on a regular basis to prevent flooding, facilitate navigation and allow for use of a given water system (Bert *et al.*, 2012). Maintenance dredging works are primarily the periodic removal of accumulated bottom sediments from waterways (Pebbles and Thorp, 2001). Indeed, dredging can be categorized according to the purpose, i.e. (1) maintenance of waterways for shipping and water discharge, (2) capital dredging for reforming shorelines and marine infrastructure development, and (3) remediation of contaminated sites (Bortone and Palumbo, 2007). As described by International Association Dredging Companies (2005), all major ports periodically require new dredging works to enlarge and deepen access channels, provide turning basins and achieve appropriate water depths along waterside facilities, i.e. capital dredging. Dredging is also undertaken to create underwater foundations, facilitate the emplacement of pipelines or immersed tunnel elements and to construct flood control such as dams. Subsequently, these channels would require maintenance dredging to remove sediments which have accumulated at the bottom of the channels. This ensures the depth and breadth of the channels are kept at the designed dimensions for optimal shipping operations, as well as to improve the discharge capacity of watercourses and create storage capacity in water supply reservoirs. In environmental dredging, the main aim of the operation is to remove contaminated sediments, thus improving water quality and restoring the health of aquatic ecosystem. This is often carried out in waterways, lakes, ports and harbours situated near industrialized or urbanized areas, where contaminants are inadvertently discharged and accumulate in the sediments. The removed materials may be treated and reused or disposed under strict environmental controls though. For instance, dredged material dumping in existing water bodies should be carried out in accordance with strict environmental standards to avoid long term, irreversible environmental problems (DredgingToday.com, 2015) Procedure on appropriate assessment methods can be found in guidelines, such as the ones by IMO (2015). Nonetheless the dredged soils are predominantly clean and usable products, and are categorized into five sediment types: rock, gravel and sand, consolidated clay, silt or soft clay and a mixture of rock, sand silt and soft clay. Table-1 gives some common definitions of dredged marine soils.

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Table-1. International definitions of dredged marine soils (Owens, 2008).

International organization	Definition
Oslo-Paris Convention (OSPAR)	Sediments or rocks with associated water, organic matter etc., removed from areas that are normally or regularly covered by water, using dredging or other excavation equipment.
International Standard Organization (ISO)	Materials excavated during maintenance, construction, reconstruction and extension measures from waters.
London Convention	Material dredged that is by nature similar to undisturbed sediments in inland and coastal waters.

MATERIALS AND METHODS

Sample collection

The disturbed dredged marine soils were collected from Lumut (Perak), Marina Melaka (Melaka), Tok Bali (Kelantan) and PasirGudang (Johor). The samples were dredged by a trailing suction hopper dredger (TSHD) at a depth of 8-12 m from sea level for Lumut site, and recovered using a backhoe dredger (BHD) at a depth of 3.5-6.5 m and 3.5-5.0 m respectively from sea level at Marina Melaka and Tok Bali (Figure-1). Only samples from the PasirGudang site were manually retrieved during low tide from 0 - 10 cm of the sediment surface. The samples were put in sealed plastic bags to prevent moisture loss during transportation and storage. Small quantities were chilled upon retrieval from site to preserve the microorganisms for biological assessment (not reported in this paper).

Figure-1. Sampling locations in Peninsular Malaysia and the dredgers used.

GEO-CHARACTERISATION TESTS

Note that all the tests described below were performed in accordance with prescriptions by BS1377 (1990) unless otherwise specified.

Particle size distribution

Wet sieve was conducted to determine the particle size distribution of the samples. This test is necessary for soils which contain mainly of silt, clay or both. Briefly, the experiment commenced with mixing the sample with a solution of sodium carbonate and sodium hexamethaphosphate. The solution was used to separate discrete particles of the samples. Next, the soil was soaked with just enough water to keep it wet, before being put through the sieving procedure. Referring to BS 1377 (1990), the sieves used in the present study were 5 mm, 3.35 mm, 2 mm, 1.18 mm, 600 µm, 425 µm, 300 µm, 212 µm, 150 µm, 63 µm. Water was supplied continuously to the soil to isolate the soil sample according to the respective particle sizes as the sample was washed through the stacked sieves. Fines retained in the pan was further quantified using the hydrometer test, which caters for particles in the range of silt (2-63 µm) and clay (<2µm).

Natural moisture content

This method is used to determine the moisture content of a soil specimen as a percentage of its dry mass. Small quantities of samples were oven dried at 105 - 110 ˚C for 24 hours. The recorded mass loss gives the amount of water in the soil, while the remaining solids give the soil's dry mass. The moisture content of a soil is then expressed as a percentage of its dry mass.

Atterberg limits

Liquid limit is an empirically established moisture content at which a soil passes from the liquid state to the plastic state. At the liquid limit, a soil would lose its shear strength and start flowing like a liquid. The liquid limit (w_L) is the value of the water content corresponding to a cone penetration of 20 mm. The mechanics of this test is depending on the directly static shear strength of the soil. In the test, water was added in small increments to produce soil pastes of different consistencies, resulting in penetration of the cone in the range of 15 - 25 mm for the derivation of w_L at 20 mm. On the other hand, the plastic limit test is carried out to establish the lowest moisture content at which the soil is plastic, i.e. particles are just about being held together without crumbling. The plastic limit (w_P) is used together with the liquid limit to determine the plasticity index of the soil sample. 20 g of homogeneous soil paste is generally used for this test. The sample is rolled into threads until they appear crumbly at just over 3 mm diameter. The water content is then measured and recorded as w_P.

Specific gravity, G_s

Specific gravity (G_s) is defined as the ratio of the unit weight of a given material to the unit weight of water, and the common method adopted is the small pycnometer

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method. The density bottle and stopper were first weighed to the nearest 0.001 g (m_1). The sample used was dried at 110 ˚C and ground to pass a sieve of 2 mm aperture. 8 g of the sample was transferred to the density bottle. The bottle, contents and the stopper were then weighed to the nearest 0.001 g (m_2). Covered with liquid, the bottle and contents were placed in a desiccator without the stopper. Considering that the sample was retrieved from the sea, kerosene was used in this study. The desiccator was evacuated for at least 1 hour until no further loss of air was apparent. Kerosene was then added to half the bottle before further placement in desiccator for an hour. After that, with the liquid added to fill the bottle, it was transferred to a temperature-controlled bath for the final cooling down process.

Loss on ignition (LOI)

Loss on ignition (LOI) refers to the mass loss of a combustion residue whenever it is heated in an air or oxygen atmosphere to high temperatures. The mass lost from a soil on ignition is related to the organic matter of the soil sample. High temperature would break down certain minerals in clay and carbonates, and remove water of crystallization. However, in some soils, the mass loss can be due to the loss of moisture, carbon, sulphur and from the decomposition or combustion of the residue. A dried sample at 50 ˚C was heated to 440 ˚C for no less than 3 hours or till a constant mass is achieved.

pH value

The pH value of the sample was determined by using a pH meter. The sample was first mixed with distilled water and allowed to stand for at least 8 hours. Then the electrode of the pH meter was immersed in the sample suspension. The pH reading was taken 3 times to obtain the average pH value. A solution with an exact balance of H^+ and OH^- ions is neutral and has a pH value of 7.0, where an excess of H^+ and OH^- would cause pH value to decrease and increase respectively.

RESULTS AND DISCUSSIONS

Tables 2-4 summarize the properties of the dredged marine soil samples examined in the present study.

Particle size distribution

Soils are generally termed gravel, sand, silt and clay depending on the predominant size of particles within the soil. Based on American Association of State Highway and Transportation Officials, AASHTO (2004), gravel grain size is 76.2 mm to 2 mm, sand grain size is 2 mm to 0.075 mm, silt grain size is 0.075 mm to 0.002 mm, and grain size less than 0.002 mm is considered clay. Referring to Table 3, the particle size distribution indicated that clay is the dominant constituent of all samples in this study, except for the PasirGudang sample. The results also showed that three quarters of the samples are fine particles. The Lumut sample contained the highest clay content, i.e. 78 %, followed by Melaka 68 % and Tok Bali 60 %. The PasirGudang sample contained the least clay content of 26 %. Sand portion for the Lumut and Tok Bali samples was higher than the silt portion. This was different with the Melaka and PasirGudang samples, where there was more silt than sand in the compositions. Besides the silt portion of the PasirGudang sample was also greater than its clay portion.

As can be seen in Table 4 in comparison with other similar soil samples, most dredged marine soils contain high fine particles (silt and clay) than gravel and sand. Some differences can be noted though. For instance, as reported by Wan Salim *et al.* (2012), the Kuala Perlis dredged sample contained greater sand portion than fines. The economic activities near the dredge site and sampling area could contribute significantly to the particle size composition of the dredged sample. Besides the sampling location is an important factor to consider when analysing the particle size distribution of a dredged sample. The lower percentage of silt and sand particles for the Lumut sample to those of Melaka and Tok Bali could be attributed to the distance of the sampling location, for example. The Lumut sample was sampled offshore while the Melaka and PasirGudang samples' collection points were nearshore. The Tok Bali sample was retrieved near the river mouth. The high contents of silt and sand particles in Tok Bali sample could be traced to the mining activities at nearby Sungai Semerak.

Moisture content

The moisture contents of the dredged samples are summarized in Table-2, i.e. Lumut sample 166.16 %, Melaka sample 145.77 %, PasirGudang sample 122.29 %, and Tok Bali sample 92.23 %. Higher moisture contents have been reported by others, including Meegoda and Perera (2001) and Miraoui *et al*. (2012), both of which had very wet soils of moisture contents exceeding 170 %. Indeed, the moisture content was found to increase with greater quantities of fine particles (silt and clay) and the moisture content of the soils. Winfield and Lee (1999) noted that the moisture content is influenced by soil particles composition, where the presence of large quantities of fines helps entrap moisture in the soil. This explains the rather low moisture content for the Kuala Perlis sample (66.13 %), which contained less fine particles compared to the others.

Atterberg limits

The liquid limit (w_L) of the Lumut, Melaka, Tok Bali and PasirGudang samples were 95.80 %, 54.20 %, 36.80 % and 46.10 % respectively (Table-3). A soil is categorized as high plasticity (H) when its $w_L$is more than 50 % and low plasticity (L) if w_L is less than 50 %. The plastic limit (w_P) of the Lumut, Melaka, Tok Bali and PasirGudang samples were 34.50 %,30.72 %, 25.83 % and 35.60 % respectively. Plasticity Index (I_P) of the Lumut sample was highest among the four samples (61.30 %), followed by the Melaka sample at IP = 23.48 %.

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Table-2. Key properties of dredged marine soils.

Sample	Moisture content (%)	Specific gravity	Loss on ignition (%)
Lumut*	166.16	2.60	6.33
Melaka*	145.77	2.63	9.39
Tok Bali*	92.23	2.38	4.28
PasirGudang*	122.29	2.41	8.38
Meegoda and Perera (2001)	225.00	-	14.00
Grubb *et al*.(2010)	117.00	2.75	-
Chan *et al*. (2011)	124.40	2.71	-
Rao *et al*. (2011)	96.15	2.35	-
Miraoui *et al*. (2012)	181.00	-	-
Wan Salim *et al*. (2012)	66.13	2.15	11.98
Mohd Yusoff (2011)	-	2.48	-
King *et al*. (2006)	-	-	22.00
Hartley *et al*. (2011)	-	-	24.79
***In present study**			

Table-3. Physical properties of dredged marine soil samples.

Experiment	Results			
	Lumut	**Melaka**	**Tok Bali**	**Pasir Gudang**
Particle size distribution (%)				
Gravel (76.2 ≥ gravel > 2 mm)	3	3	5	2
Sand (2 ≥ sand > 0.075mm)	15	9	20	18
Silt (0.075 ≥ silt > 0.002 mm)	4	20	15	54
Clay (≤ 0.002mm)	78	68	60	26
Moisture Content (%)	166.16	145.77	92.23	122.29
Atterberg Limits				
Liquid Limit (%)	95.80	58.50	36.80	46.10
Plastic Limit (%)	34.50	38.39	25.83	35.60
Plasticity Index (%)	61.30	20.11	10.97	10.50
Soil Classification	High Plasticity Clay (CH)	High Plasticity Silt (MH)	Low Plasticity Silt (ML)	Low Plasticity Silt (ML)

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Table-4. Comparison of particle size distribution of dredged marine soils.

Location	**American Association of State Highway and Transportation Officials** (AASHTO)			
	Gravel (>2.00 mm)	**Sand** (2.00-0.075 mm)	**Silt** (0.075-0.002 mm)	**Clay** (< 0.002 mm)
Lumut*	3	15	4	78
Melaka*	3	9	20	68
Tok Bali*	5	20	15	60
P.Gudang*	2	18	54	26
Grubb *et al.* (2010)	-	13	23	64
Chan *et al.* (2011)	-	3	97 (Fine particles)	
Miraoui *et al.* (2012)	-	2.5	80	8.5
Wan Salim *et al.* (2012)	-	44.8	34.7	20.5
Zentar *et al.* (2012)	-	10.8	74.7	14.5
***In present study**				

Specific gravity (G_s)

The specific gravity (G_s) of the Lumut, Melaka, Tok Bali and PasirGudang samples were 2.60, 2.63, 2.38 and 2.41 respectively (Table-2). G_s of the Lumut and Melaka samples were in close agreement with measurement by Basack and Purkayastha (2009), i.e. within the range of 2.60 to 2.63. The Tok Bali and PasirGudang samples had lower G_s, similar to those recorded by Mohd Yusoff (2011) and Rao *et al*. (2011). According to Mulligan *et al*. (2010), dredged marine soil particles with high specific gravity would settle faster compared to those with low specific gravity. This could result in higher sedimentation rates and consequently, more frequent maintenance dredging.

Loss on ignition (LOI)

Loss on ignition (LOI) is often measured to estimate the organic matter content of soils. Soils have better quality with low value of loss on ignition (Mulligan *et al*., 2010). The Melaka sample contained the highest organic matter content (9.39 %) compared to PasirGudang (8.38 %), Lumut sample (6.33 %) and Tok Bali sample (4.28 %). All LOI values in this study were lower than those from previous studies (Table-2), suggestive of lower biological contamination risks as food source level for the microbes was low.

pH value

The pH values of the dredged marine soil samples were 8.30 (Lumut), 8.32 (Melaka), 8.51 (Tok Bali) and 8.38 (PasirGudang). This indicated that all the samples were alkaline. pH values between 7.8 and 8.2 could be indicative of large accumulations of bicarbonate ions. pH value is an important factor in soil characterization because it affects the chemical properties, including a) surface charge of organic matter, clay or mineral particles, b) solubility, mobility and toxicity of contaminants, c) relative binding of positively charged ions to the cation exchange sites, d) calcium carbonates equivalents and e) nutrient availability (Winfield and Lee, 1999). pH less than 5.5 could also indicate presence of toxic amounts of exchangeable aluminium, iron or manganese. According to Whitlow (2001), high acid contents may be found in some natural soils, especially those containing sulphides or sulphate-reducing bacteria or high alkali content in limy soils.

Morphology

Figure-2 shows the FESEM images of the dredged marine soil samples. The morphology was apparently different but not dissimilar with those of past studies, e.g. Gualtieri *et al*. (2008), Takahashi *et al*. (2013) and Shi *et al*. (1999). Dredged marine soils are microcrystalline in nature and clay minerals like chlorite, kaolinite and illite and non-clay minerals like quartz and feldspar are not uncommon in the soils (Rao *et al*., 2012). In comparison, the dominant clay mineral in the Lumut sample was most likely illite, while the Melaka sample showed presence of montmorillonite. Loosely nested with small soil particles, microorganisms of various sizes and shapes and plants, the Tok Bali sample is comparable to that examined by Shi *et al.* (1999). Dredged marine soil properties are different with space and time and are closely related to the past and present land uses in the watershed (Pebbles and Thorp, 2001; Mulligan *et al*. 2001). Dredging location could strongly affect the mineralogy, morphology and composition of the dredged marine soils too. Heterogeneity of the material can be characterized by grain size distribution, density, water and organic matter contents (Mulligan *et al*., 2001).

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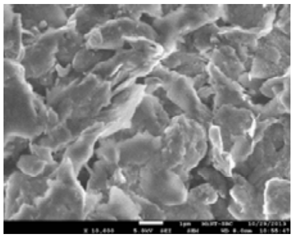
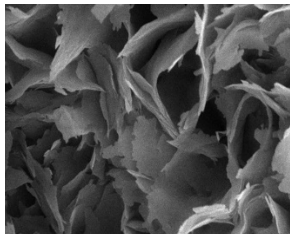
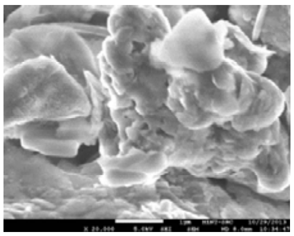


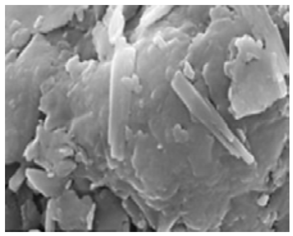
a) Lumut sample 10,000x



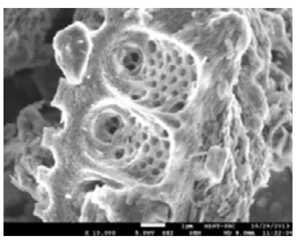
b) Illite 10,000x (Gualtieri *et al*., 2008)



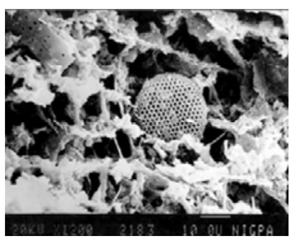
c) Melaka sample



d) Dried montmorillonite 20,000x (Takahashi *et al*., 2013)



e) Tok Bali sample



f) Marine clay 1,200x (Shi *et al*., 1999)

Figure-2. Morphology of dredged marine soils.

CONCLUSIONS

Standard geotechnical tests and measurements were successfully performed on 4 dredged marine soil samples. The results indicated that the samples were generally of the fine-grained type, i.e. clayey and silty soils in water inundated conditions. As the natural water content was exceptionally high in most cases, dredged soils are geomaterials unusable as ordinary soils in their natural conditions. The geo-characterisation study helps shed light on the properties of dredged marine soils retrieved from Malaysian waters, which could serve as the basis for further exploration on reuse potential of the material. These could include reclamation works where the dredged soils are used as backfill materials (with pre-treatment for load-bearing capacity enhancement), ceramic- and brick- making with high temperature heating, and construction of landfills where the rather impermeable soil could function as the lining and top cover materials. The second lives given to these otherwise waste materials can help alleviate environmental issues related to dumping, on land or offshore. Dredged materials reuse also contributes to sustainable development with cost and material savings. In short, further work is necessary to ascertain the reuse potential tailored for the unique features of the soil.

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