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GENERALIZED STRENGTH DEVELOPMENT MODEL OF SOLIDIFIED DREDGED MARINE SOILS WITH GRANULAR FILLER ADDITION

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ABSTRACT: Dredged marine soils (DMS) are the sediment and debris removed in the dredging process. Large amount of DMS is generated from the dredging operations yearly, especially from the maintenance of existing shipping channels and the development of various coastal infrastructures. In practice, DMS are generally disposed of at designated offshore dump sites. Inadvertently, these discarded DMS would in time be deposited back near shore due to tidal dynamics, necessitating dredging works again. Considering that DMS are essentially soils with poor engineering properties, particularly low shear strength, there could be potential for the materials' reuse as acceptable or good geomaterials if the original conditions can be improved. Pre-treatment for enhancement of the soil's strength, such as solidification, is a feasible option. In the present study, the solidification of 3 DMS samples was examined with the admixing of cement and/or bottom ash, where cement acts as a binder while the bottom ash functions a filler material to lend structure to the weak soil. The strength improvement of the solidified DMS was monitored with the unconfined compression tests. The key factors that influence strength development in solidified soils were investigated, i.e. curing period, water-binder ratio and binder-filler mix ratio. The curing period was prefixed at 3, 7, 14, 28 and 56 days, while the water-binder ratio examined were 1, 3 and 5. The test results indicated that strength increased with curing time and higher water-binder ratio. The optimal binder-filler mix ratio determined was 75 % cement to 25 % bottom ash. The bottom ash was found to contribute to strength gain too, albeit in a minor way compared to the highly reactive cement. For the generalized strength development plots, the unconfined compressive strength of a particular day (q) was divided with the strength on day 28 (q_{28}). The resulting q/q_{28} vs. curing period plots were linear with varying gradients dependent on the water-binder ratio, though it was apparent that the gradient of the plot decreased with increased water-binder ratio. In summary, solidification with cement-bottom ash is expedient in improving the original low strength of the DMS, and the generalized strength development model is useful for modeling, design and prediction on site.

Keywords: dredged marine soils; solidification; water-binder ratio, cement, bottom ash, strength development

1. INTRODUCTION

Dredging is defined as underwater excavation of soils and rock that generates large volume of dredged marine soils [1]. Dredged marine soils (DMS) are the sediments and debris were removed during the dredging process [2]. Every year, hundreds of million cubic meters of DMS are generated from the dredging operations. For instance, the volume of DMS removed in the maintenance dredging works at Kuala Perlis alone was reported to be 300,000 m^3 within 2-3 years [3].

In Malaysia, DMS are considered a geowaste and are therefore not being considered for recycling or reuse. In general, the DMS are disposed off in open waters at designated locations [4]. Unfortunately, after a certain time, these DMS would be re-deposited near shore with the wave dynamics and tidal effects, and dredging would be required again.

The disposal of DMS is mainly due to economic, logistical, legislative and environmental constraints, as well as a lack of understanding of the materials' reuse potential. DMS can be a valuable resource and a reusable material for construction purposes, unless the dredged material is found to be excessively affected by industrial contaminants. For example, if the dredged material consists of coarse particles, it can be reused in backfills, while the finer particles can be used for landscaping or improving agricultural land [1]. Indeed, the reuse of DMS can make major contribution towards sustainable development, simultaneously reducing the quantities of primary resources needed for construction and habitat creation activities [5].

The fine-grained DMS is usually grey in colour with high plasticity, and contains predominantly clay and silt fractions. The plastic limit and plasticity index were often found to be significantly high and that the optimum moisture content upon compaction was generally below the plastic limit [6 & 7]. These inherent physical properties indicate the poor engineering properties of the material, especially in terms of load resistance. For reuse, DMS need to undergo some form of pre-treatment to enhance the strength. An alternative is to admix binding additives like cement with the DMS to both reduce the initially high moisture content and to subsequently improve the engineering properties via cementation [1].

The components of solidification include soils and binders. As mentioned above, the binders used are normally cementitious materials [8]. Coarse particles can also be admixed with the soil as filler materials to lend structure for the bonding process, i.e. enhance the resulting strength improvement. 3 DMS samples were used in the present study, with cement used as the binder and bottom ash added as a filler material respectively.

2. MATERIALS AND METHODS

2.1 Test materials

Three types of fine-grained dredged marine soils (DMS) were used in this study, and they were all sourced from the Malaysian waters. The first DMS sample was retrieved from Marina Melaka, Melaka (sample MM). According to the Unified Soil Classification System (USCS) [9], the sample was classified as a high plasticity clay (CH). The second and third samples were collected from Tok Bali, Kelantan, samples TBA and TBB. These samples were classified as high plasticity (MH) and low plasticity silt (ML) respectively. The binder used in this study was ordinary Portland cement (C) while the filler added was bottom ash (BA). The bottom ash was collected from Tanjung Bin coal power plant in the locality. The properties of the DMS, OPC and BA are shown in Table 1, while Table 2 summarizes the chemical compositions of the DMS, cement (C) and filler, i.e. bottom ash (BA).

2.2 Specimen Preparation and Test Methods

The DMS were mixed with the additives based on predetermined water-binder (w/b) ratio as well as C:BA portions. Calculations for the amount of cement and bottom ash for each mixture was made based on dry mass and moisture content of the soil. The w/b ratios were fixed at 1, 3 and 5. Elaborations on the mix ratio derivation can be referred to in Azhar *et al.* [10]. The mixing procedure began with remoulding of the DMS which was left standing overnight to ensure uniform pore water distribution in the soil mass. The measured dry cement and bottom ash were then added to the remoulded soil.

Table 1 Properties of dredged marine soil samples

Properties	DMS samples			C	BA
	MM	TBA	TBB		
Moisture content (%)	142.97	137.60	92.23	-	-
Liquid limit (%)	65.00	51.80	36.90	-	-
Plastic limit (%)	50.46	35.30	25.83	-	-
Plasticity index (%)	14.54	16.50	11.07	-	-
Specific gravity	2.56	2.43	2.41	3.10	2.30
Loss on ignition (%)	9.49	1.38	4.78	-	-
pH	8.32	8.53	8.51	12.35	9.17
Soil classification	CH	MH	ML	-	-

Table 2 Chemical compositions of DMS, C and BA (%)

Chemical composition	DMS samples (soil type)			C	BA
	CH	ML	MH		
Al_2O_3	21.60	21.10	24.40	9.52	26.60
CaO	1.93	4.04	4.04	54.10	8.73
Fe_2O_3	7.33	7.05	7.87	5.32	8.51
K_2O	2.97	2.64	2.66	0.88	1.05
MgO	2.18	2.24	1.91	1.20	1.76
SiO_2	57.00	57.00	54.40	24.50	48.80
TiO_2	1.03	0.85	0.87	0.69	1.95
Others	5.96	3.67	4.95	3.79	2.6

The mixture was initially hand-mixed with a spatula prior to more vigorous mixing with a kitchen mixer. The mechanical mixing process was paused every 3 minutes, so that materials adhering to the sides of the mixing bowl and mixing paddle can be scraped off and returned to the bowl. The steps were repeated 2-3 times till all cement and bottom ashes were thoroughly mixed with DMS.

The mixture was next transferred to a cylindrical split mould to form specimens of 38 mm in diameter and 76 mm in height. In 3 equal layers, the mixture was flattened and lightly compressed and kneaded using a miniature compaction tool. Upon removal of the mould' collar, the excess mixture was trimmed off and the cylindrical specimen was slid out of the mould.

Wrapped in cling film and stored on raised platforms in a tight-lid bucket with mild bleach solution to prevent fungal growth, the specimens were left to cure for 3, 7, 14, 28 and 56 days prior to the unconfined compression tests.

The unconfined compression tests were conducted according to BS 1377:1990, Part 7 [11]. Load was applied at a rate of 1.5 mm per minute and the data were recorded in a stress-strain plot for determination of the maximum stress, i.e. unconfined compressive strength, q. Duplicate samples were tested to verify reliability of the measurements.

Table 3 Mix portions of cement and bottom ash

Specimen	Portion of cement, C (%)	Portion of bottom ash, BA (%)
100C	100	0
75C25BA	75	25
50C50BA	50	50
25C75BA	25	75

3. RESULTS AND DISCUSSIONS

3.1 Granular Addition Effect

The mixing percentage of granular admixture also affects strength improvement of the samples. As the percentage of cement increased and the percentage of the granular admixture decreased, the strength of solidified samples also increased. In this study, bottom ashes were used as granular admixture. The usage of bottom ash in solidification helps to reduce the amount of cement needed to solidify the DMS. Horpibulsuk *et al.*, [17] state that, in order to increase the samples strength, economic value and environmental impact, ashes can be used to substitute cement. The proportion of ashes content is determined in percent with respect to the dry weight of clay.

From Fig. 1, it can be seen that the strength of the solidified samples increases with BA content and reached maximum at BA=25 %. The strength of solidified samples decreased gradually after BA contents exceeded 25 %. From the plots, it can be seen that the highest strength for each samples were at 25 % of granular admixture content. Thus, the optimal granular admixture content for the solidified samples is 25 %. This corroborates with findings by Horpibulsuk *et al.* [17], that the strength of solidified DMS would increase till the optimum granular admixture content. It was further postulated by the authors that the optimal percentage of granular admixture that can be used in mixing is 25 %.

If the ashes content exceeds 25 %, the ashes have the possibility to coat the cement grains and prevent further reaction between the cement grains and water. Thus, it can be concluded that the cementitious products will decrease after BA exceeds 25 %. The comparison between the amount of granular admixture for solidified DMS and Bangkok clay can be seen in Fig. 1. It is apparent that the optimal percentage of ashes uses in admixture of Bangkok clay was also 25 %. Hence it can be said that the optimal BA content is 25 % regardless of the cement content.

It is unnecessary to admix too much of cement or BA in achieving the target strength, such as for laying road sub-base course or foundation layer, as this could lead to cost-saving in the solidification process. As shown in the present study, the strength of solidified DMS would increase until it reaches the optimum granular admixture content. Also, the bottom ash can be used as a partial substitute material for cement in DMS solidification. The usage of bottom ash can reduce the amount of cement used in the sample mixing. This will help to reduce the environmental impact and also being more economical. The disposal of the bottom ash in landfill may harm the environment. So if the bottom ash is reused it could help to reduce the environmental effects.

3.2 Binder Content Effect

In this study, cement was used as the binder. Fig. 2 shows the relationship between unconfined compressive strength with cement content. Based on the plots, the optimum cement content in the soil admixture is 75 %. The optimum granular admixture is 25 % as discussed earlier. The combination of 75 % of OPC with 25 % of granular admixture would give the optimal in strength gained. Comparison was made with data on the Bangkok clay (Fig. 2). The plots in Fig. 2 show that the finding by Horpibulsuk *et al.*, [17] were similar to this study. The optimum binder (OPC) content for Bangkok clay also 75 %. Thus, it can be concluded that the optimal binder (cement) content to solidify DMS samples is 75 % regardless of the water-binder ratio.

3.3 q-w/b Relationship

As mentioned earlier, without any solidification process or treatment, the natural dredged soil has limited undrained shear strength for load-bearing. The undrained shear strength of natural DMS is often no more than 50 kPa [12]. Therefore the solidification process was aimed at improving the strength of the naturally weak material for possible reuse as good soils. Results from the unconfined compression tests are compiled and discussed below.

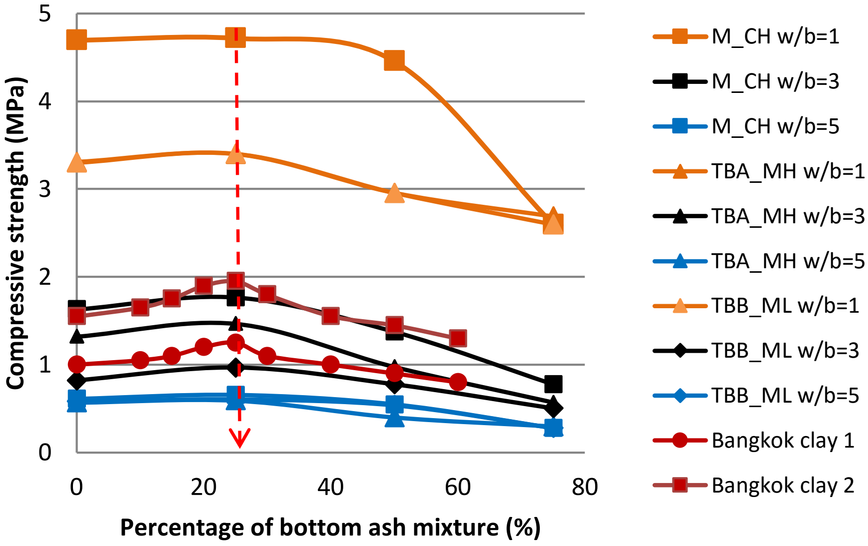

Fig. 1: Filler content effect on q

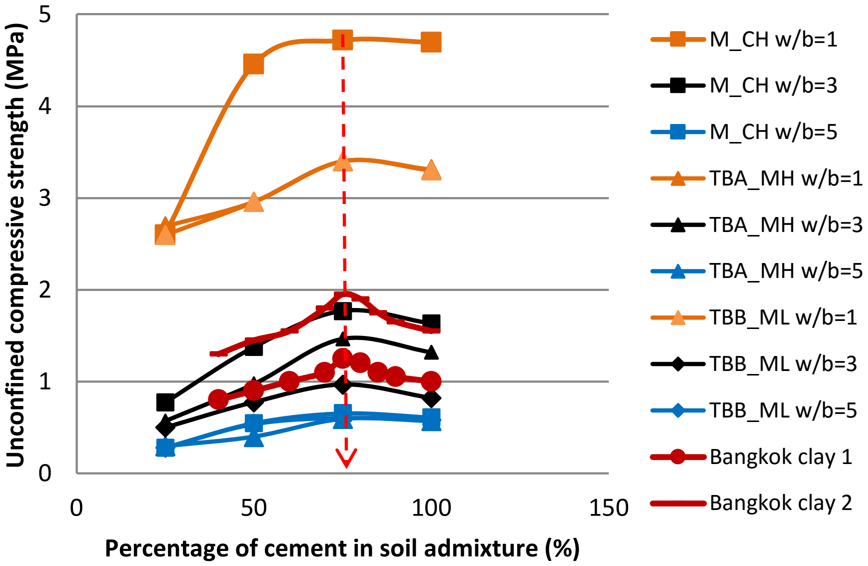

Fig. 2: Binder (Cement) content effect on q

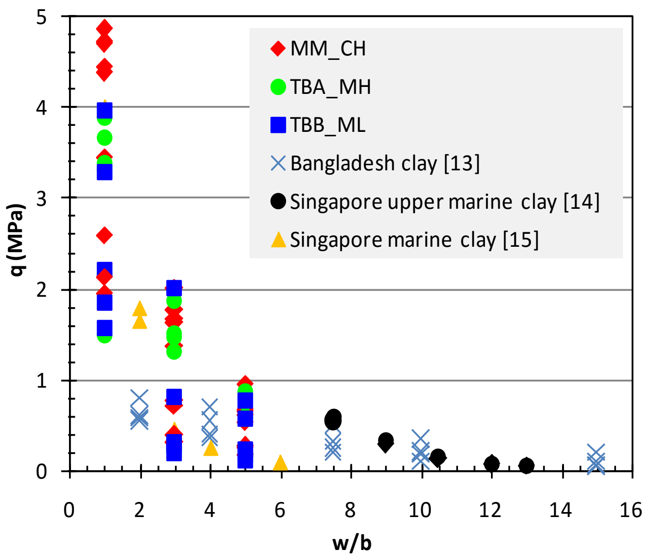

Fig. 3: q - w/b plot

Figure 3 shows the unconfined compressive strength (q) of the solidified CH, MH and ML samples plotted against the water-binder ratio (w/b). It is immediately apparent that higher w/b resulted in lower strength gain, irrespective of the soil type. Compiled with data from past studies of similarly treated fine-grained marine soils from Bangladesh and Singapore [13, 14 & 15], the trend was found to be similar as that of the present study. Note that all 3 samples were not admixed with binders at w/b less than 2, with resulting strengths of no more than 2 MPa. While the data points at w/b greater than 5 appears to confirm the expected diminishing trend of the q-w/b plot, the strengths recorded in the present study do seem to be higher in the w/b range of 3 to 5. Some factors that can account for the discrepancies are the type of binders used, curing time and pore water chemistry.

The increased strength with lower w/b can be attributed to the amount of cement and bottom ash used in the solidification. Inversely related, lower w/b corresponds with higher cement dosages at the same water content. Hence as w/b decreased, the amount of cement in the DMS increased, producing more effective solidification and strength gain. At approximately w/b=3, the q-w/b relationship appeared to level off, as depicted by the rather drastic change in gradient of the plot in Fig. 3 to a plateau. It is indicative that beyond a certain w/b, i.e. 10 in this case, strength improvement was no longer significant with almost unchanged q with higher w/b.

When too much water is present in the soil-additive mixture, flocculation tends to occur with the cemented aggregates of soil-BA dispersed in a porous matrix [16]. Without good contact between the cemented aggregates, load resistance would be limited as the voids are filled with semi-solidified fine particles. Also, the amount of cement available for reaction with the excess water was disproportionate, causing the mixture to harden but not strengthened. This can be observed in the greater deformation recorded of the weaker specimens in the unconfined compression test. Radial deformation accompanied by vertical displacement resulted in apparent bulging of these specimens prior to failure.

3.4 Curing Effect on q

Fig. 4 illustrates the strength (q) recorded for all specimens at different curing time (D). Immediately noticeable is the remarkable strength improvement charted by CH compared to MH and ML, particularly at w/b=1.

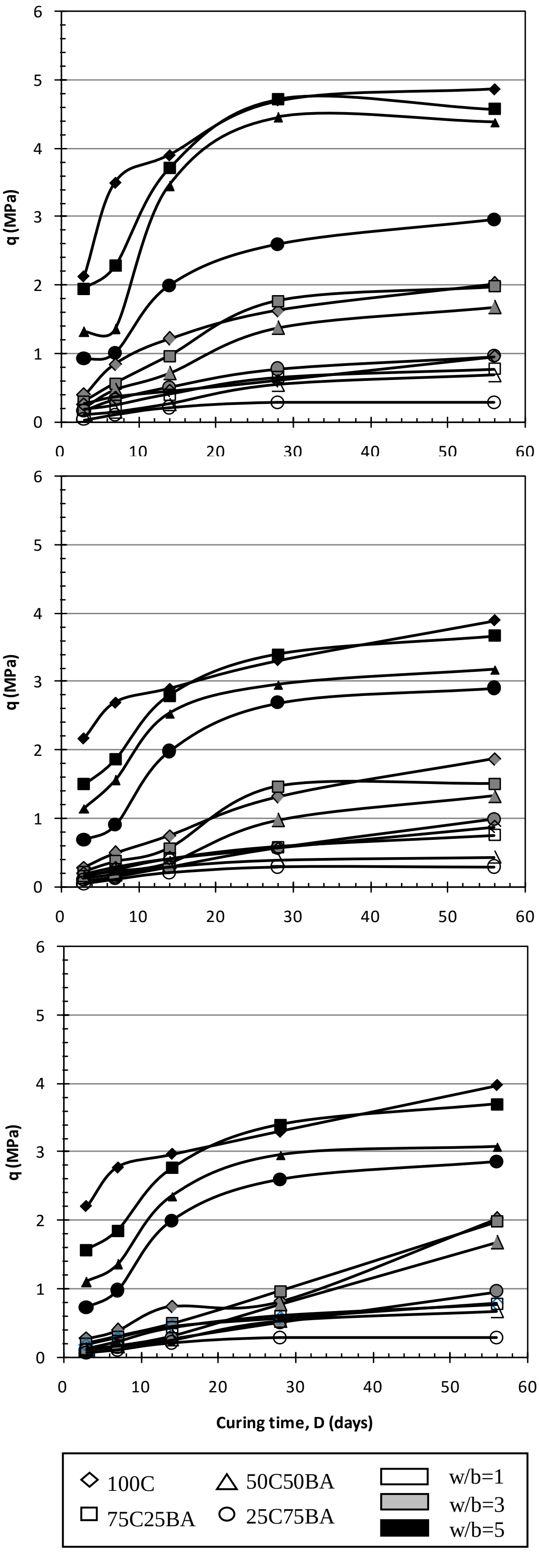

Fig. 4: q – curing time plots

This could be explained by the greater specific area of the finer grained CH soil available for reaction with the cement and eventual soil-BA bonding. Note that clay particles are smaller than 2 µm, whereas silt particles range between 2 and 75 µm [9]. Comparing the q-D plots at w/b=3 for MH and ML, there appeared to be a continuous rise in strength for ML while MH demonstrated a decline in strength gain rate beyond 28 days of curing. Nonetheless at the final measurement age, i.e. 56 days old, both MH and ML showed very similar q attained for all C-BA mix ratios.

It is also apparent that the unconfined compressive strength attained by the solidified soil is very much dependent on the w/b ratio, with increased w/b resulting in lower strengths. This is in line with earlier discussions referring to Fig. 3, where q declined with increased w/b. The seeming banding of the q-D plots according to w/b for all soil samples also suggests the dominant influence of w/b on the resulting strength of the solidified soil. In general, the steep rise in q with time was sustained up to 14 days of curing, after which the gradual turn in the plots of Fig. 4 indicates less remarkable strength gain even with prolonged curing. The initial high water content apparently impeded further strength improvement of the soil.

To examine the influence of curing on the solidified strength, q/q28 is plotted against curing time (D) in Fig. 5. For w/b=1, the rate of strength improvement from day 3 to day 28 is higher compared to the subsequent days. This indicates that the cementation process which includes hydration and pozzolanic reactions were most active in the first 4 weeks. There was almost no increment at all in strength after day 28 as shown in the w/b=1 plots in Fig. 5. For w/b=3 and w/b=5, the strength increased steadily from day 3 till day 56, though the strength increment rate in w/b=3 was clearly higher. This could be due to the less excessive water present in the soil-additives mixtures. However, in both cases of w/b=3 and w/b=5, the strength is expected to keep rising with prolonged curing.

3.5 q/q_{28}-D correlation

In the same plots in Fig. 5, comparison was made with results of treated Bangkok clay as derived by Horpibulsuk *et al.* [17], which is similar to the materials used in the present study (w/b = 3, 5 and 10). Gradient of the q/q_{28}-D plot can be seen to reduce with prolonged curing, pointing to the reduced strength gain as well as diminishing influence of w/b on the

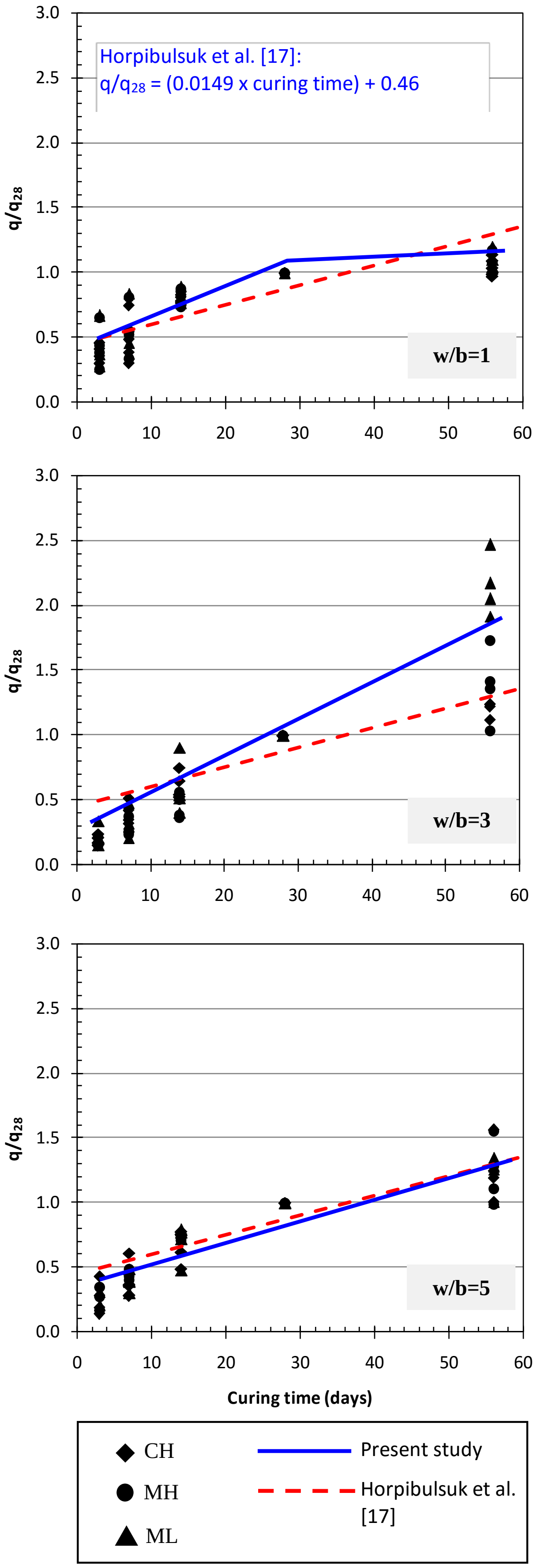

Fig. 5: q/q_{28} – curing time plots

solidified strength of different C-BA mix ratios. Nevertheless the best sustained strength improvement ratio is observed in specimens with w/b=3, with q/q_{28} at 56 days clustered according to the soil type, i.e. CH, MH and ML in ascending order. This is an indicator of soil type dependency of strength gain with solidification, though at a certain w/b ratio. More detailed work is required to validate this postulation though. In addition, the best fit line for Bangkok clay [17] was found to line up best with that of w/b=5. This is suggestive of a common q/q_{28}-D correlation for solidified soils pre-dominated by the w/b ratio.

4. CONCLUSIONS

The granular addition of bottom ash as a filler material was found to complement solidified strength of the dredged marine soil at 25 %, with the corresponding binder (cement) dosage of 75 %, irrespective of the w/b ratio. Also, the strength development of solidified DMS is influenced by w/b and curing period. It was observed that as w/b decreases, the strength (q) would increase regardless of the soil type. The q-w/b plot shows significant drop of strength with increased w/b up to approximately w/b=5, beyond which q appeared to be rather insensitive towards the change in cement dosage with excessive water in the mixture. On the other hand, the normalized strength of the solidified DMS (q/q_{28}) – curing time relationship at w/b=5 was found to be compatible with reports by Horpibulsuk *et al.* [17]. This suggests a universal correlation of q-D irrespective of the origin of the fine-grained soils. It is however uncertain if the agreement between different soils types would persist at w/b ratio more than 5. Further work could be directed at identifying the extent of the compatibility with increased w/b.

5. ACKNOWLEDGEMENT

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