STRENGTH IMPROVEMENT CHARACTERISTIC OF CEMENT-SOLIDIFIED DREDGED MARINE CLAY WITH RELATION TO WATER-CEMENT RATIO

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ABSTRACT: Dredged marine sediments were retrieved from a maintenance dredge site for examination on the solidification efficacy. The high plasticity clay (CH) sample had low shear strength and high compressibility, making it unacceptable as a geomaterial for construction purposes. Due to its poor engineering properties, the material was destined for disposal offshore: incurring cost, time as well as contamination risks along the transportation route. With solidification, the soil could be improved for potential reuse in reclamation works, for instance. The laboratory investigation involved admixing ordinary Portland cement with the soil at different water-cement (WC) ratios, ranging from 1.5 to 3.5. Left to mature in a confined, damp environment for periods up to 56 days, the solidified specimens were subjected to the unconfined compression test. The measurements were conducted at predetermined intervals of 3, 7, 14, 28 and 56 days. Duplicate specimens were tested using the unconfined compression apparatus in accordance with BS1377 (1990). The unconfined compressive strength (q_u) and Young's modulus (E_P) were derived from the stress-strain plots. Both the strength and stiffness were found to increase with lower WC ratio and prolonged maturing, where the solidified soil transformed from a soft, weak material to that of a hard, strong one. The strength improvement was as high as 2.5 times that of the 3-day old specimens, while the stiffness increased by 4 times for the large strain range, as derived from the compression tests. Expediency of solidifying the soil with cement was further examined by correlating the strength, stiffness and deformation with WC as well as rest period.

Keywords: dredged marine clay, solidification, water-cement ratio, unconfined compressive strength, Young's modulus

1. INTRODUCTION

Dredging is a necessary measure for maintaining the breadth and depth of shipping channels, erecting new maritime infrastructure and removing contaminated sediments from sea beds. Dredging is also performed as a maintenance exercise on a regular basis to prevent flooding, facilitate navigation and allow for use of a given water system [1]. Dredged marine sediments can be classified according to the contamination level of the materials [2]. Clean materials allowable for placement in any type of open water disposal site, e.g. open placement on the seabed are categorized as Class 1. A slightly contaminated sediment would be allowed for placement in certain open water disposal sites with care, such as in a pre-dug pit or depression on the seabed (Class 2). Class 3 materials include sediments of contaminated kind unsuitable for disposal in open water, which are consigned to confined or capped disposal facilities to avoid propagation of the contaminants.

Dredging and the disposal of dredgedmarine sediments in the open sea can result in contamination and destruction of the marine ecosystem. Considering the proximity of dredge sites with estuaries and human dwellings along the coast, contamination of the waters and sediments is barely unexpected. Transportation and disposal of the material offshore could pose serious, long term threat towards marine lives and ecosystems, especially in the absence of adequate monitoring and control systems. This was noted by [3] as far back as the 70's. The realization of such irreversible destruction has led to a shift in emphasis from disposal to the beneficial reuse of dredged marine soils for environmental gain, such as the purpose for protection or creation of salt marshes and mud flats which would in turn serve as flood and coastal defences. Ironically, most of the sediments dredged from harbours, estuaries and at sea are dumped offshore, with a very small amount of the material being beneficially revived [4].

The dredged material is essentially a soil, albeit with poor engineering properties to make it useful in its natural form. Characterisation studies based on the physico-chemical properties of dredged marine soils have been conducted by [5], for instance. The dredged sediments can, however, be potentially reused with some pre-treatment. An option is solidification, which can effectively enhance the soil's originally poor strength and stiffness [6]. The binders used arenormally

cementitious materials [7], like cement and lime or other industrial by-products like slag and ashes. The treated soil can then be reused as a backfill material for reclamation works, including the creation of artificial islands, restoration and rehabilitation of eroded shorelines. The concept of solidification is similar to that of soil mixing, where the binder admixed with a wet soil reacts with the pore water to form cementitious bonds that lend structure to the poorly soil, as reported by [8],[9]and [10]. Comparative studies were also conducted to examine the time-dependent self-hardening and artificially induced cementation of dredged marine soils, with potential for shortening work time on site in reclamation projects [11, 12 & 13].

The proportion of cement and water, i.e. water-cement (WC) ratio, is an important factor for determining the ultimate strength and stiffness gain of the soil. Indeed, the WC ratio affects the hydration kinetics, with higher WC ratio leading to higher hydration rate post mid-period of the hydration process, though WC ratio has a small effect on the hydration rate in the early stage of hydration [14]. It was also reported that the mean improved compressive strength of solidified soils decreases with higher WC ratios, accompanied by a decline in the quality of the consolidated mass under the unfavourable, wet mixing conditions [15]. Chan [16], explored the mix uniformity effect of cement-treated Kawasaki dredged clay and found that the efficiency of mixing can be categorized into two conditions, i.e., 'too wet' and 'too dry', where the 'wet' condition results in lumpy, non-uniform mixtures, while the 'dry' one causes segregation of materials and bleeding, both detrimental to the overall quality of the solidified soil.

The present study examined the WC ratio effect on the solidification of a high plasticity clay (CH) dredged from the east coast of Peninsular Malaysia. Ordinary Portland cement was used as the binder, where it was admixed with the soil at WC ranging from 1.5 to 3.5. The specimens were left to mature for up to 56 days. At the age of 3, 7, 14, 28 and 56 days, the unconfined compression test was performed on the specimens to monitor the strength and improvement characteristics.

2. MATERIALS AND METHODS

2.1 Test materials

The soil used in the present study was dredged from the waters of Tok Bali on the east coast of Peninsular Malaysia. As the dredged clay was observed to be relatively 'clean' without the presence of pebbles, shell or drift wood fragments,

it was used as retrieved without further sieving. Fundamental physical properties of the soil can be found in Table 1. Mixing water content used in preparing the specimens was based in multiples of the liquid limit, LL = 56.50 %. As the natural water content (w = 52.79 %) was close to the LL, the clay was in liquefied form even prior to mixing. Ordinary Portland cement (G_s = 3.15) was added to the clay as binder, in water-cement (WC) ratios as summarized in the specimen list (Table 2). Note that the cement powder was oven-dried at 105°C overnight to remove any entrapped moisture prior to admixing with the soil.

Table 1   Physical properties of dredged marine soil sample

Soil type	High plasticity clay, CH
Water content, w (%)	52.79
Specific gravity, G_s	2.45
Liquid limit, LL (%)	56.50
Plastic limit, PL (%)	16.92
Plasticity index, PI (%)	39.58

2.2 Preparation of test specimens

The clay was remoulded in a conventional kitchen mixer a day prior to mixing. This was mainly to ensure uniformity of the remoulded soil used for solidification, and to identify the actual water content of the clay for formulating the accurate amounts of water and cement required. With the mixer running at low speed, distilled water was added to the clay to achieve the consistency of 1.5LL, 2.0LL, 2.5LL, 3.0LL and 3.5LL respectively. Cement was next added to the clay at predetermined dosages corresponding to the WC shown in Table 2. The mixture was then transferred to a split mould to form specimens of 38 mm diameter and 76 mm height. Wrapped tightly in cling film, the specimens were left to mature in an airtight container at the room temperature of 20°C and relative humidity of 70 % for 3, 7, 14, 28 and 56 days before measurements were made.

2.3 Unconfined compression test

The unconfined compression test is by far the most popular method of soil shear testing because it is one of the fastest and cheapest methods of measuring shear strength. The unconfined compressive strength (q_u) of the specimen was measured at a strain rate of 2 % or 1.5 mm per minute. The test procedure was as prescribed in

Part 7 of BS 1377 (1990). Care was taken to ensure that both ends of the sample were as flat as possible to minimize bedding error. The test produced vertical stress (σ_v) – vertical strain (ε_v) curves for each specimen, where q_u was derived from the peak vertical stress attained by the specimen tested. Duplicate specimens were tested for each mix and age to account for reliability of the measurements made.

Table 2 Specimen list and mix ratios

W/C	Natural Water Content	Mix Proportions (in mass)			
		Wet Soil	Dry Soil	Water, W	Cement, C
	(%)	(g)	(g)	(g)	(g)
1.5					230.9
2.0					173.2
2.5	52.79	1000.0	653.6	346.4	138.6
3.0					115.5
3.5					99.0

3. RESULT ANALYSIS AND DISCUSSIONS

3.1 Stress-strain plots

The vertical stress (σ_v) – vertical strain (ε_v) of the specimens aged 3 and 56 days old are shown in Fig. 1. Note that only plots from the minimum and maximum maturing period were shown here to illustrate the effect of time lapse on the strength improvement of the solidified soil. Clearly lower WC ratios resulted in higher strengths in the specimens, despite the rest period allowed, as illustrated by the consistency of ascending peak strength attained with decreasing WC ratio. Within 8 weeks, the solidified soil showed remarkable strength improvement well over twice the 3-day strength in most cases, though the increment was more pronounced with lower WC ratios. Rise in strength of the 3-day old specimens were found to be less dramatic (Fig. 1a), accompanied by a less distinct attainment of the peak strength as shown by the gentler climb in the plots as well as the blunt peaks.

On contrary, the steep climb of the stress-strain plots in the 56-day specimens in Fig. 1b suggests a hardened solidified soil matrix which demonstrated the failure pattern of materials of stiff and brittle nature. The abrupt and sharp decline in the plots, notably in the stronger 56-day old specimens, further justifies this point. Interestingly, post yield, all plots seemed to undergo severe decline to reach a similar strength level, regardless of the WC ratio and age of the specimens. This indicates the collapse of the

cemented structure with excessive loading, which apparently caused the soil to revert to its original structure with poor load resistance capacity. Note that the original soil underwent negligible strength gain over time without solidification.

3.2 Strength gain with time
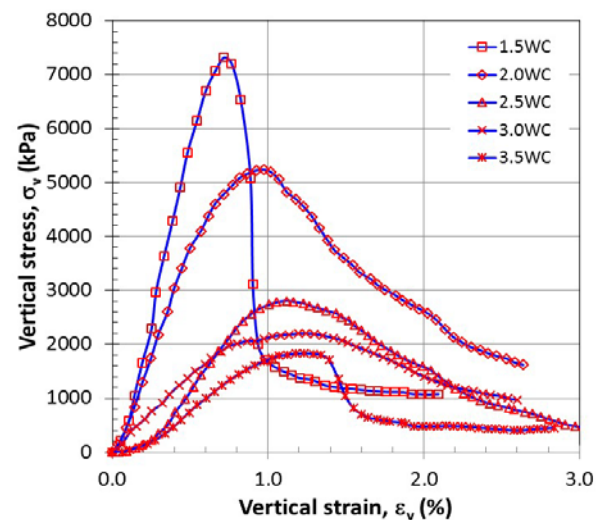
(a) 3-day old
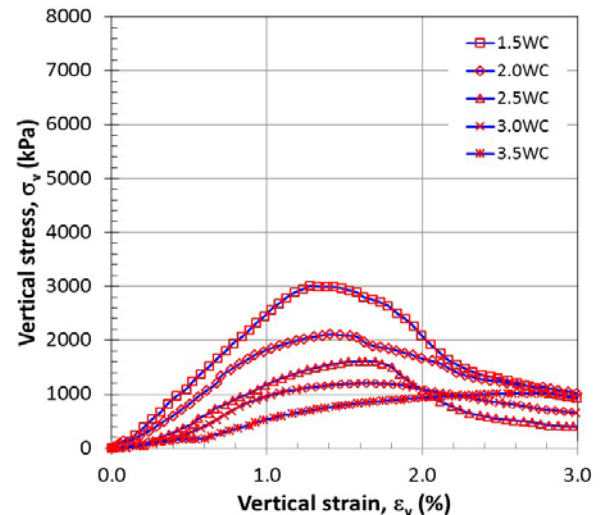
(b) 56-day old

Fig. 1 Stress-strain plots for specimens aged for 3 and 56 days.

Fig. 2 summarises the strength gain over time for all specimens. Fig. 2a shows the q_u-D plots, from which can be seen the efficacy of cementation to the originally weak material. The ultimate q_u recorded was obviously influenced by both the WC ratio and curing period, D. It is interesting to note the almost unchanged q_u for all specimens other than 1.5WC for the first 2 weeks. In fact specimens 3.0WC and 3.5WC underwent

almost the same strength improvement, as can be seen in the overlapping data points in Fig. 2a.
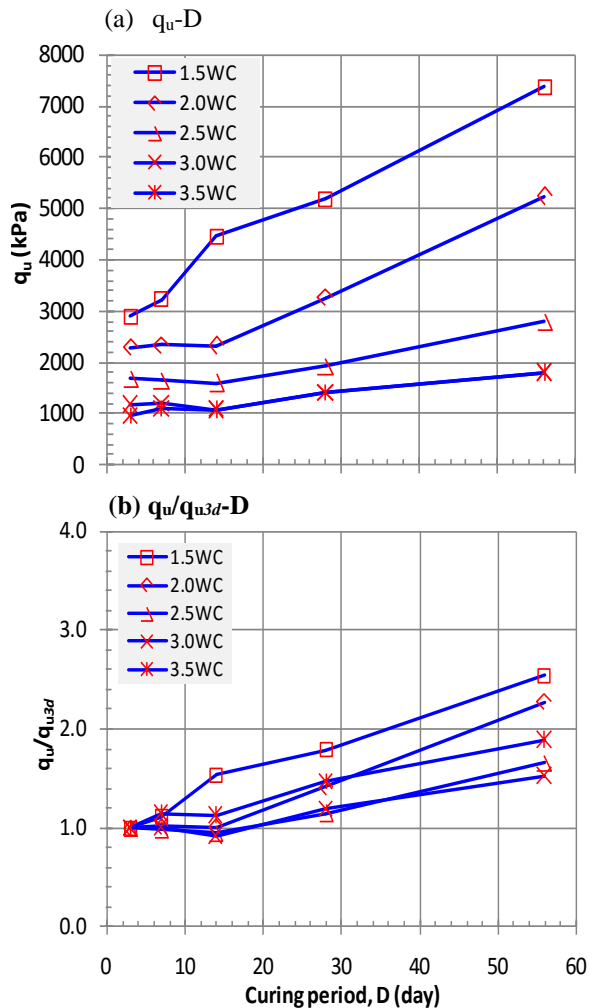

Fig. 2 Plots of strength gain with time.

These observations indicate that extended time is required to induce cementation of the soil at WC ≥ 2.0, a phenomenon unfavourable for speedy field implementation. All plots suggest continuous strength gain beyond 56 days, except for 3.0WC and 3.5WC, which show a slight decline in the q_u-D relationship from day 28 to 56.

In Fig. 2b, the unconfined compressive strength (q_u) was normalized against that of day 3 (q_{u3d}) to better illustrate the improvement ratio with time. In general the normalized q_u/q_{u3d} shows strength increment ratio of the solidified specimens at all WC ratios. Nonetheless the rise in q_u for the first 2 weeks was insignificant, except for the 1.5WC specimens. The lower mixing water content and higher cement dosage apparently induced accelerated strength improvement of the dredged marine soil. Third week onwards, the q_u increment ratio was found to be relatively similar for specimens 1.5WC and 2.0WC, as denoted by

the top two lying parallel plots. The strength gain ratio for specimens 3.5WC was found to be more encouraging than those of 2.5WC and 3.0WC, though the plots appeared to be rather parallel to one another too, i.e. similar strength gain rate. It follows that the solidified soil at different WC could have the same strength gain rate but not the same strength gain ratio, i.e. ultimate q_u resulting from solidification.

3.3 Relationship between strength and Water-Cement ratio (WC)

Relationship between WC and the strength of the solidified soil specimens are shown in Fig. 3. The general decline of q_u with increased WC is captured in Fig. 3a, where prolonged curing was shown to result in greater strength gain, noticeable in the ascending stacking order of the plots. The declining rate of q_u with WC is also found to decrease with higher WC ratios, irrespective of the rest period allowed for the solidified specimens. The change in q_u reduction rate seemed to occur around 2.5WC in all cases. On the other hand, the overlapping plots for specimens aged 14 days and below suggest solidification to be effective only after the specimens were being left to mature over a fortnight. The seemingly outlying data for specimen 14-day old at 1.5WC points to the necessity of a sufficiently low WC for the cement-admixed soil to produce better strength improvement within 2 weeks of curing. This corroborates with earlier discussions referring to Fig. 2b. Ensuing the gradual decline of the solidified strength with increased WC appeared to be a plateau regardless of the curing period, though the initial upper hand gained by older specimens is locked in, as illustrated by the final stacking order of the plots at 3.5WC.

The compilation of q_u/q_{u3d} - WC plots in Fig. 3b exemplifies the effect of WC ratio on strength gain ratio of the solidified soil. Understandably longer curing period (D) produced greater strength gain ratio, as depicted by the q_u/q_{u3d}. Besides, it is again shown that rest period up to 14 days was insufficient to produce remarkable strength improvement in the solidified soil at all WC. This corresponds with earlier discourse and observations in Fig. 2b that strength gain ratio markedly improved after the first 2 weeks. In addition, while significant strength improvement was observed in specimens aged 28 and 56 days old, the decreasing q_u/q_{u3d} with increased WC ratio and the eventual climb between 2.5WC and 3.5WC suggest possible benefits of prolonged maturing time or rest period for soil-cement mixtures with high WC ratio. In actual field implementation, high WC may be preferable to facilitate ease of mixing and to save on cement

usage, though at the price of longer wait-out period. It is cautioned however that this is applicable to the strength gain ratio and not the actual strength attained. This correlation chart could be used as a quick reference in trial mixes of known WC ratio to estimate the projected strength after a certain rest period.
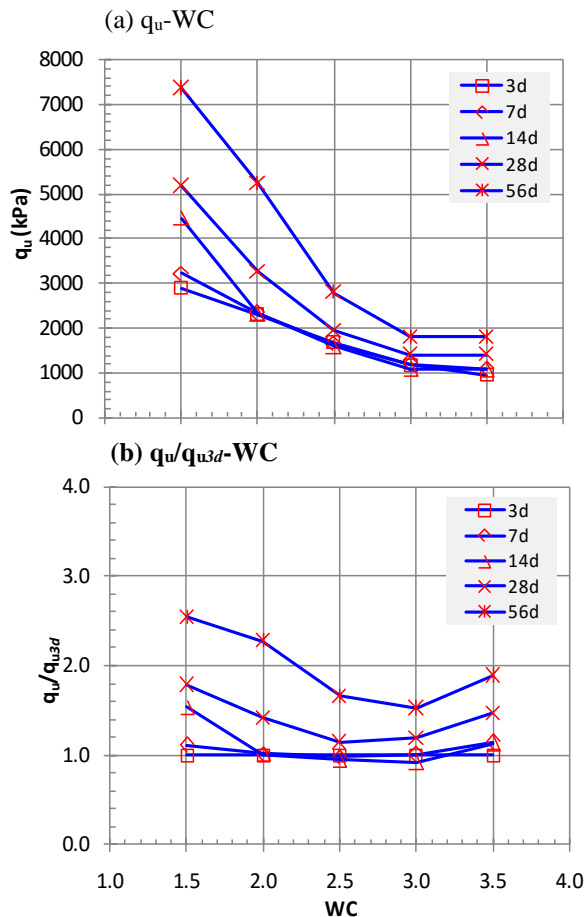

(a) q_u-WC

(b) q_u/q_{u3d}-WC

Fig. 3 Relationship between strength and WC.

cases of very soft and weak specimens, the peak may not be easily discernible at all, where the material shows strain-hardening effect with a seemingly continuous gentle rise in the stress-strain plot. Compiled in Fig. 4, it is therefore apparent that high q_u is accompanied by low ε_f, and vice versa. Specimens with higher WC and shorter rest period tend to yield at higher ε_f, as can be seen cluttering at the bottom right of the plot in Fig. 4. At approximately $\varepsilon_f = 1.3$ % (equivalent to about 1 mm from the 76 mm height of the test specimen), the q_u-ε_f plot undergoes a transition indicating the onset of a narrower range of low q_u with a wider range of relatively high ε_f. This implies larger deformation of the material at low strength levels, with possibilities of the aforementioned strain-hardening occurrence, obscuring the advent of a well defined, distinct peak in the stress-strain plot. Notwithstanding this postulation, as the present test specimens were mainly well solidified, especially with prolonged curing, note that the maximum ε_f recorded was actually 2.5 %, equivalent to about 2 mm in the specimen's height.
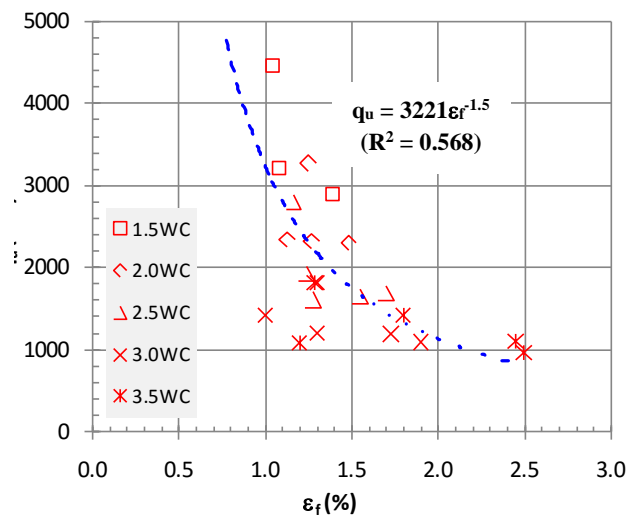

$$q_u = 3221\varepsilon_f^{-1.5}$$
$$(R^2 = 0.568)$$

Fig. 4 q_u-ε_f plot.

3.4 Deformation

The corresponding failure strain (ε_f) for the peak strength (q_u) derived from the stress-strain plots are presented in Fig. 4. Typically a high strength specimen would depict a sharp rise in the stress-strain plot upon loading, followed by an abrupt fall from the peak once the peak strength is reached (see Fig. 1b). The coinciding ε_f is usually small, indicating limited vertical deformation of the solidified specimen prior to yielding. Failure of such specimens is often observed as rupture with multiple split lines weakening the load resistance. In comparison, a weak specimen would demonstrate gradual climb to a non-distinct peak in the stress strain plot, before deflecting downwards in a gentle decline (see Fig. 1a). In

3.5 Strength-Stiffness correlation

The Young's modulus (E_P) was derived from the stress-strain plot via the gradient of a straight line connecting the origin and the peak of the curve, also known as the secantial stiffness modulus. The E_P-q_u plot shown in Fig. 5 relates the parameters in a linear regression line, i.e. $E_P = 67q_u$. Considering the steep rise of the stress-strain plots for the stronger and stiffer specimens as discussed previously (see Fig. 4), higher q_u corresponds with higher E_P as expected. The lower strength specimens exhibited lower E_P as deformation was more pronounced with loading, resulting in a gradual and gentler rise to the peak

of the stress-strain plot. Referring to Fig. 1a, despite the gentler rise of σ_v with ε_v, the climb was relatively linear, not dissimilar to the stronger specimens in Fig. 1b. The E_p-q_u correlation is useful as a quick guide to the possible response of the solidified soil subjected to a known load, especially in numerical modeling endeavours.
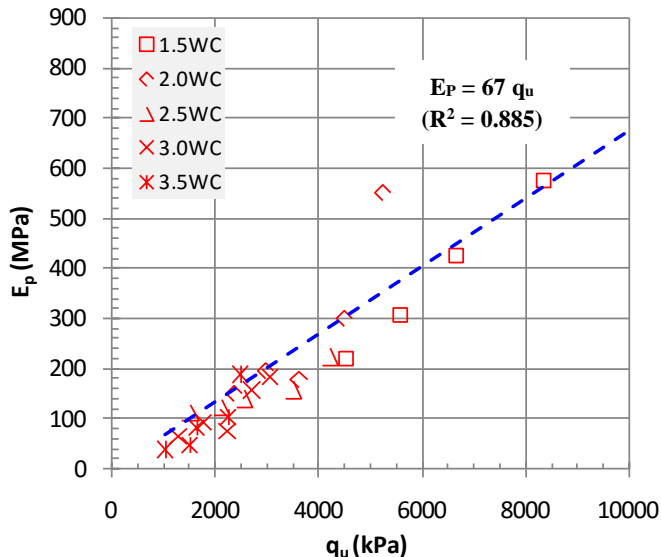

Fig. 5 Relating E_p with q_u.

4. CONCLUSION

Overall the strength of the solidified soil increased with lower WC ratios and prolonged curing. The maximum strength increment was recorded at 2.5 times between 3 and 56 days of rest period. To ensure immediate strength improvement within the first 2 weeks of solidification, WC needs to be kept no more than 1.5. Specimens with WC$\geq$2.0 were found to undergo a slow start to strength gain within the period. Besides, strength was observed to decrease with higher WC for all ages of the solidified soil specimens, and a plateau can be expected at WC greater than 3.0. In addition, higher WC mixtures can be expected to attain similar strength gain ratio as low WC mixtures, on condition of prolonged maturing period allowed for the soil-cement. Higher q_u also corresponded with lower ε_f, suggesting the solidified dredged marine clay to be effectively strengthened, i.e. high load resistance associated with small deformation and drastic post-yield loss of strength. The stiffness was found to relate with the strength in a linear relationship of $E_p = 67q_u$.

5. ACKNOWLEDGEMENTS

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