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Properties of Singapore Marine Clays Improved by Cement Mixing

ABSTRACT: Stabilization of soft ground by the deep cement mixing (DCM) method has become an increasingly popular method to improve stability in an excavation in soft clay and to limit movement in adjacent sub-structures. The desired increase in strength and stiffness to fulfil the intended functions can be achieved provided that the right mix proportion is adopted. To proceed with this kind of soil improvement, prediction of the strength and stiffness of the improved soil is necessary. Due to a short history of the DCM method in Singapore, there is limited data on the improved properties of local clays. This study is conducted to bridge that gap and also extends its usefulness to clays elsewhere. In the paper, the influences of three main constituents of the mixture, namely clay, water, and cement on the strength development of Singapore marine clays improved by cement mixing are investigated. Based on the experimental results, it is shown that a convenient normalization can produce a consistent pattern for evaluation of improved strength of clays from different parts of Singapore. This normalization is also shown to work for one Japanese clay. Correlations between strength and stiffness of the improved clay are also obtained. Lastly, it is shown that for a cement mixed clay there is a continual increase in strength and stiffness with time. This will help to reduce ground movement, and it will also increase the bending moment in the retaining wall. Both aspects must be considered in a design.

KEYWORDS: soil stabilization, deep cement mixing (DCM) method, strength, stiffness, Singapore marine clays

To control movement in an excavation in soft ground, soil improvement technique is often needed to rapidly improve the strength of the treated ground. In-situ soil stabilization technique by feeding cementing agents into soft ground is one such approach and has become increasingly popular. In this technique, chemical reactions among the stabilizing agent, clay minerals, and water are allowed to take place deep below the ground to produce a high-strength product quickly which will continue to strengthen with time. Several such techniques are presently used in Singapore, including jet grouting, deep cement mixing, and lime column methods.

The deep mixing method (DMM), a mechanical mixing method, is nowadays considered as an alternative to jet grouting, which is still the more popular choice in Singapore. In DMM, a blade is pushed into the ground and mixes the soil while cement grout or dry cement is injected into the mix, whereas in jet grouting air and water are first used to cut the soil and mix it while grout is injected, and all these are carried out under fairly high pressure. As a result, DMM causes little expansion to the surrounding soil during installation and thus minimizes uncontrolled movement in adjacent ground. Furthermore, as it mixes the soil at the in-situ water content, it does not produce any slime. In contrast, the jet grouting method produces a large amount of slime, which is an industrial waste and must be properly disposed. From the perspective of improved property, the principal difference between a jet-grouted soil and deep mixed soil is the range of water content of the soil being mixed; this is usually much higher in a jet-grouted soil. In the early stage, lime is the hardening agent, but, later, ordinary portland cement (OPC) was introduced in DMM due to problems encountered in storing unslaked lime in a hot and humid country like Singapore (Broms 1984). The method is now known as the deep cement mixing (DCM) method.

Research and development of this method was initiated in Japan in the late 1960s (Okumura and Terashi 1975). Stimulated by the successful applications of this technology in Japan in the 1970s, many related studies on the engineering properties of improved soils have been carried out (Terashi et al. 1979; Kawasaki et al. 1984). The first major application of DMM in Singapore was in the 1980s when it was used to improve the bearing capacity of a reclaimed land located on the southeast of the island (Kado et al. 1987). This method was used again in subsequent years to improve the foundations of various mass rapid transit stations (Kado et al. 1987, which were founded in soft clay. In a recent project in Singapore, this method was adopted to stabilize a deep excavation located next to a mass rapid transit's station in the eastern part of Singapore. The consultants in that project were concerned about the strength and stiffness of local improved clays and also the effect of continual increase in stiffness of the improved soil on the design of the diaphragm wall. Thus far, only limited data, mainly from contractors' records, are available on such improved properties in Singapore.

As the clay mineralogy and climatic conditions in various countries are different, often there is concern about using correlations from elsewhere for local usage. This study is carried out to establish the characteristics of improved Singapore marine clays, but, more importantly, also to investigate the possibility of using a normalized approach to ensure greater applicability of results. In the paper, the interaction among various constituents and their impact on improvement with time will be evaluated. Measurements with local strain transducer were used and indicate significantly higher stiffness measured compared to the conventional approach, though this point is well understood in the testing of solid material, but not

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in the testing of soil. As an improved soil is very much like stiff clay, most studies continue to use the conventional soil testing approach.

Properties of Clays and Cement Used

The majority of marine clays found on the island of Singapore are composed of a sedimentary deposit known locally as the Kallang Formation. This deposit is widely distributed and covers nearly 25% of the total land surface of the island (Chang 1991). This formation usually consists of an upper marine clay and a lower marine clay separated by a stiffer dessicated intermediate layer (Chong et al. 1998). Common properties of Singapore marine clay around the Singapore Island have been extensively reported (Chong et al. 1998; Tan 1983). This clay is highly plastic with the liquid and plastic limits typically ranging from 65 to 85 and 38 to 55, respectively. The average bulk unit weight is 15.2 ± 0.6 kN/m^3, and the natural moisture content is about 50 to 69%. The upper marine clay is highly plastic with the liquid and plastic limits typically ranging from 76 to 101 and 45 to 69, respectively. The average bulk unit weight is 16.3 ± 0.5 kN/m^3, and the natural moisture content is about 60 to 92%. Typically, the organic content for both clay members is around 3%, with moderate contents of kaolinite, illite, chloride, and smectite.

In this study, three clays from the Kallang formation were used. Clays collected from Eunos and City Hall sites are from the upper marine clay, while the clay from the Singapore Art Centre (SAC) site is from the lower marine clay. Prior to cement treatment, the initial physical and chemical properties of these marine clays and their pore fluids were determined and the results are summarized in Table 1. The cement used in the test was ordinary portland cement. To ensure that the cement used throughout the study had consistent physical properties and chemical compositions, cement from the same batch of production was used. Table 2 shows the physical properties and chemical compositions of the cement used.

TABLE 1—*Properties of the Eunos, City Hall, and Singapore Art Centre marine clays.*

Properties	Eunos	City Hall	Singapore Art Centre SAC
Specific gravity	2.61	2.61	2.62
Natural water content	66.23	61.52	57.62
Liquid limit	71.89	65.12	72.63
Plastic limit	31.89	30.03	30.82
Organic content	2.09	1.66	1.37
Chloride content	0.38	0.30	1.10
Sulphate content	1.70	1.60	0.92
pH	7.4	7.4	6.5

TABLE 2—*Physical properties and chemical compositions of portland cement.*

Physical Properties	Value
Density	3140 ± 3 kg/m^3
Fineness	327 ± 2 m^2/kg
Chemical Composition	**Unit (% w/w)**
Silica, SiO_2	21.3 ± 0.2
Alumina, Al_2O_3	4.7 ± 0.2
Ferric Oxide, Fe_2O_3	3.1 ± 0.1
Calcium Oxide, CaO	64.4 ± 0.3
Magnesia, MgO	2.3 ± 0.1
Sulphur as SO_3	2.3 ± 0.1
Sodium as Na_2O	0.47 ± 0.1
Potassium as K_2O	0.63 ± 0.1
Loss at Ignition	0.7 ± 0.1
Insoluble Residue	0.1 ± 0.1

Sample Preparation and Testing

Besides the three main constituents of mixture (clay, water, and cement), other factors such as the mixing time, kind of blades, rotational speed of blades, curing temperature, and humidity also have an effect on the properties of the cement-treated clay (Babasaki et al. 1997). Thus, to investigate only the effect of the constituent materials on the strength of improved clay, it is necessary to adopt a standard procedure for preparing the sample.

After the water content of each batch of clay was determined, water was added to fix the water content at 90, 120, and 150%. Subsequently, a specified weight of dry cement powder was added to fix the cement content at 10, 20, and 30%, which is defined as the ratio of mass of cement, *C*, to the mass of dry soil, *S*. The water and cement contents considered in the study are within the practical ranges encountered in deep cement mixing. The sequence of mixing was also standardized; first the soil is mixed with water and then with cement, as the sequence will also influence the strength of the cement clay mix (Fam and Santamarina 1996). The hydrated clay and cement powder was mixed thoroughly by a “Hobart” mixer for exactly 10 min with a rotational speed of 48 rpm.

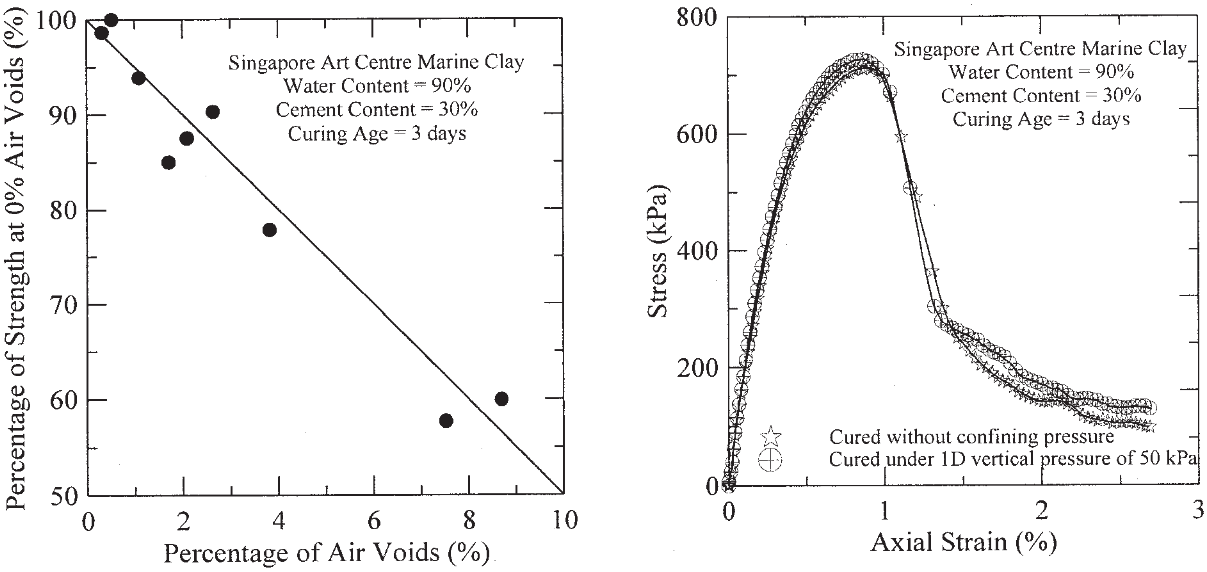
After mixing, the cement clay paste was placed into a cylindrical mold with an inside diameter of 70 mm and length of 140 mm. To reduce the trapping of air bubbles, the paste was compacted in three layers by slowly tamping the mold on the ground. Compaction by vibrating and ramming were tried, but this was unable to provide sufficient densification due to the high viscosity and low workability of the cement clay paste. Hence, all the samples were compacted by the tamping method to a percentage of air voids below 1.5 %. This is important in order to produce samples with almost identical compaction effort.

The presence of air voids has an adverse effect on strength development of the cement-treated clay. To illustrate this, several samples were compacted using different amount of tamping effort and consequently have different percentage of air voids in them. These samples were then cured for three days, and, after that, the strength of each sample was determined. Figure 1*a* shows that the strength reduces linearly with an increase in air voids; the reduction is about 5% for every 1% increase in air voids for the range evaluated in this study. It is therefore important to control the amount of air voids in the sample, and, for the study, the percentage of air voids is kept within 1.5%, allowing the strength to vary only within a very small range.

After compaction, samples were left overnight and demolded on the following day. Each sample was then sealed inside a polyethylene bag and covered with wet textile to preserve the humidity during curing at a controlled temperature of 26°C. In field applications of DCM method, the improved soil is cured under confining pressure provided by the soil above. To evaluate this effect, two samples were prepared. One sample is cured without confinement, while the other sample is subjected to 1-D consolidation with a vertical pressure of 50 kN/m^2. Figure 1*b* shows that the stress strain curves for these two samples are almost identical after three days of curing. Thus, the effect of confining pressure is not significant, as the strength improvement comes mainly from hydration products of the cement and water.

Unconfined compression tests were performed on the cement-mixed samples to evaluate its strength and elastic modulus. The test was conducted in accordance with BS 1377: Part 7: 1990. All the tests conducted in this study are summarized in Table 3. Two methods were used to measure the axial displacement of the specimen. The first method, a conventional approach, measures the external displacement between the two end platens using a set of LVDTs. This method of measurement does not have to be corrected for apparatus compliance as the LVDTs are directly placed between the platens. The second method uses a Hall's effect strain transducer placed at the center part of a sample to measure the displacement (Clayton et al. 1989).

For testing of solid materials such as concrete and steel, the issue of bedding errors is well understood, and measuring displacement between end plates is rarely done. Usually, strain gages are attached directly to the specimen to measure the deformation. However, in soil testing, this issue has been recognized only recently. As the clay-cement mix is more like very stiff clay, engi-



(a) Effect of air voids (b) Effect of curing conditions

FIG. 1—*Effect of air voids and curing conditions on the strength of cement-treated clay.*

TABLE 3—*Overall test plan for this study.*

Type of clays	Cement content, A_w (%)	Water content, w (%)	Curing (days)									
			1	3	7	14	28	70	77	140	154	161
Eunos	10	90	●	●	●	●	●	●		●	●	
	20	90	●	●	●	●	●	●			●	
	30	90	●	●	●	●	●	●			●	
	10	120			●	●	●					●
	20	120			●	●	● ⇨		**Eunos (20.120.28)**			●
	30	120			●	●	●					●
	10	150			●	●	●				●	
	20	150			●	●	●				●	
	30	150			●	●	●				●	
City Hall	10	90	●	●	●	●	●		●	●		
	20	90	●	●	●	●	●	●				
	30	90	●	●	●	●	●	●				
SAC	10	90	●		●	●	●			●		
	20	90	●		●	●	●					
	30	90	●		●	●	●					
	30	120	●		●	●	●					
	30	150	●		●	●	●					

neers have continued to use conventional soil testing apparatus for such measurement. A second relevant issue is that for materials like concrete and steel, it is generally accepted that the behavior is linearly elastic at small strain. However, for soil, at a strain level between 0.001 and 0.1%, the behavior is now generally recognized to be nonlinear elastic. It is therefore important to establish whether this also holds true for the clay-cement mix. To date, only Tatsuoka et al. (1996) have specifically investigated this aspect.

Typical Stress Strain Curves

For each mix proportion, two samples were tested to ensure reliability of the result; a third sample would be used if the first two did not show good agreement. Figure 2 shows a set of typical stress strain curves for two samples of cement-mixed clay with the same cement content (20%) and water content (90%) tested after three days of curing. The stress strain curves for the two samples using the Hall's effect transducer for strain measurement are virtually identical, indicating that the results are consistent and repeatable. However, for external measurements, the strain measured is considerably larger, and there is significant difference between the two samples tested. Closer examination indicates that the initial movement measured by the LVDT for Sample 2 is unusually large, clearly showing that bedding error due to imperfect end-restraints in this case is more substantial than in Sample 1. This set of results reinforces the reliability of using local strain transducers.

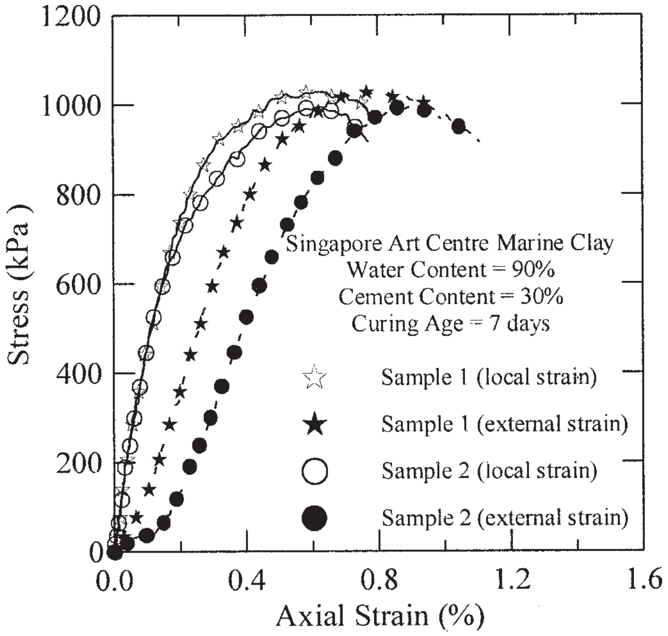


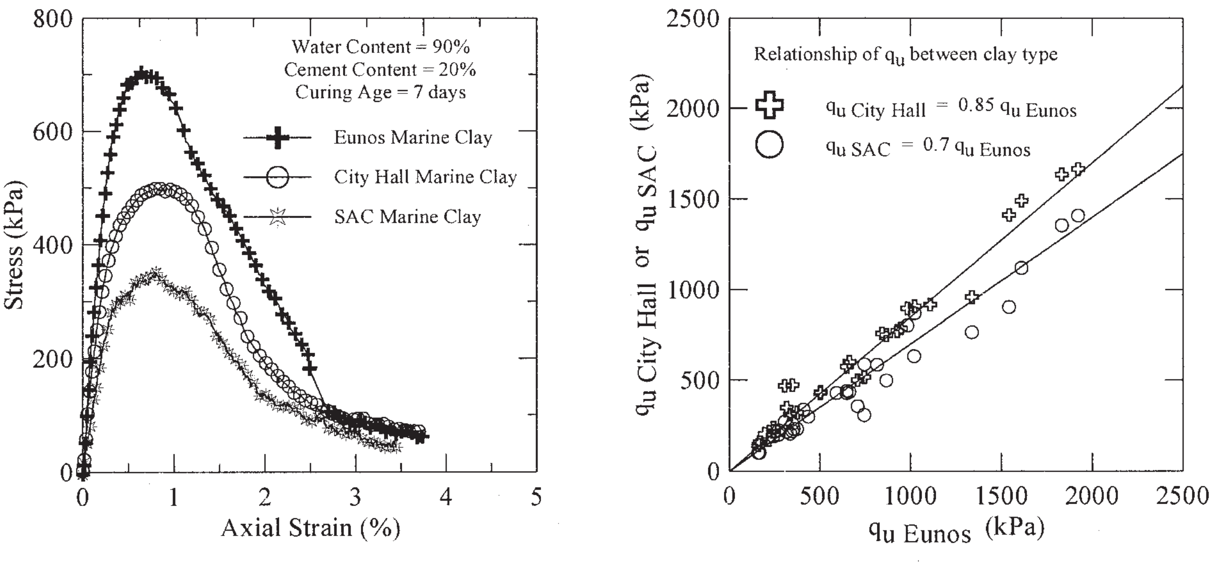
FIG. 2—*A typical stress-strain curve of unconfined compression test, using local and external strain measurement methods.*

Strength of Improved Clays

The unconfined compression test is frequently used to evaluate the degree of improvement of treated soil. Many factors affect the unconfined compressive strength, q_u, of a cement-mixed clay, but the more important factors are the type of clay, cement content, water content, and curing time. Therefore, an investigation was carried out on how each of these factors would influence the strength of the improved clays.

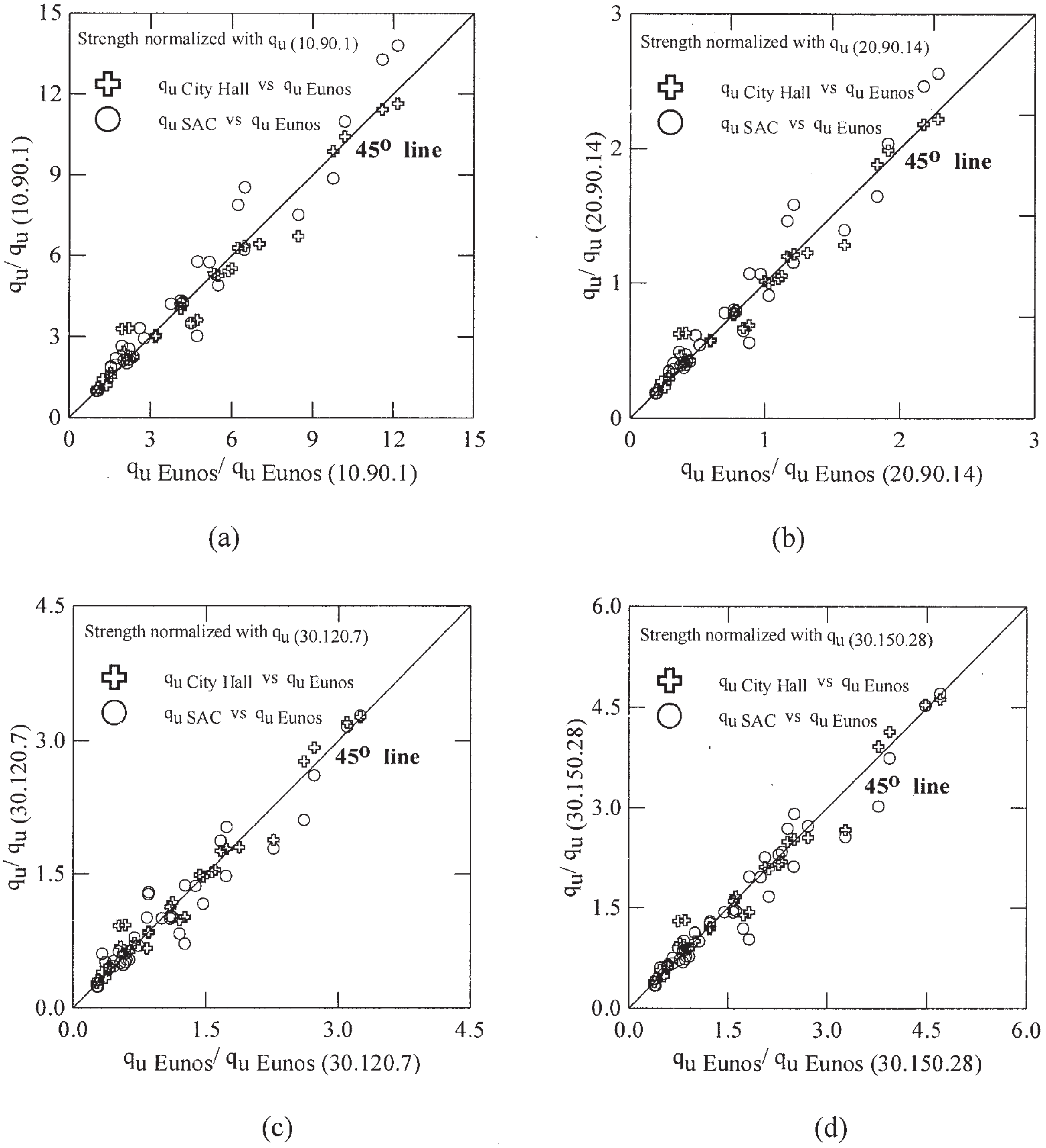
Effect of Clay Type

Figure 3*a* shows the stress strain curves of the clay-cement mix of the three clays after seven days of curing and where the cement content is 20% and the water content is 90%. This shows that the unconfined compressive strength, q_u, varies considerably according to the type of clay even though these clays come from the same sedimentary deposit. Figure 3*b* shows the correlation of the unconfined compressive strength of improved City Hall clay and SAC clay versus that of Eunos marine clay under identical conditions. This shows that the improved Eunos clay attains the highest strength, followed by City Hall clay, which achieves only 85% of that for Eunos clay and the SAC marine clays, which achieve only 70% of that for Eunos clay. A more pertinent and interesting observation from Fig. 4*b* is the fact that the shear strengths of the dif-



(a) (b)

FIG. 3—*Effect of different types of Singapore marine clay improved by cement mixing.*



(a)

(b)

(c)

(d)

FIG. 4—*Relationship between normalized strength of Eunos, City Hall, and SAC marine clay mixed with cement, normalized with: (a)* $q_u(10.90.1)$*; (b)* $q_u(20.90.14)$*; (c)* $q_u(30.120.7)$*; (d)* $q_u(30.150.28)$*.*

ferent improved clays show nearly linear correlation with each other. This observation provides the motivation for a normalized approach to be discussed next.

Every clay has its own mineralogy with different physical and chemical properties, and each of these properties may affect the strength improvement (Gotoh 1986). To derive a strength relation that incorporates all relevant factors, especially at a fundamental level, is ideal and desirable, but is extremely complicated. However, if the improved strengths of different clays under the same conditions show a consistent pattern, an effective alternative is to explore if a normalized strength shows the same consistent pattern. This is motivated by the linear correlations observed in Fig. 4*b* for the three clays studied.

In this paper, it is proposed that the strength of any improved soil, q_u, is normalized against a reference unconfined compressive strength of the same clay improved at a specified cement content (A_w), water content (w), and curing age (t), $q_u\,(A_w \cdot w \cdot t)$ as follows:

$$\text{Normalized strength of improved soil} = \frac{q_u}{q_u(A_w \cdot w \cdot t)} \qquad (1)$$

First, it is important to establish whether this approach works only for a special case where the strength has to be normalized against a specific reference value determined through trial and error, in which case the usefulness is limited. However, if the reference value is general and the normalized behavior shows consistent pattern, this is a powerful approach. To evaluate this, the normalized strengths for improved City Hall clay and SAC clay, following the definition in Eq 1, are plotted against that for improved Eunos clay, as shown in Figs. 4*a* to 4*d* for four different widely differing reference values.

As an example, Fig. 4*a* shows the normalized strength of improved City Hall and SAC marine clays compared against those from Eunos marine clay, where the reference strength for normalization is the unconfined compressive strength for a clay improved with cement content, A_w, of 10%, water content, w, of 90% and curing age, t, of 1 day, q_u(10.90.1). This figure indicates that a very good correlation between the normalized strengths of the improved clays. Figures 4*b*, 4*c*, and 4*d* show the results when the reference unconfined compressive strengths are set for conditions of (20.90.14), (30.120.7), and (30.150.28), respectively, and again very good correlations are obtained. This is an important result and leads to the conclusion that, though different clays were used, the normalized strengths for these clays are consistent with each other. Based on this observation, a generalized relationship between the normalized strength of improved soil for the three different marine clays studied can be proposed as follows:

$$\frac{q_{u\,Eunos}}{q_{u\,Eunos}(A_w \cdot w \cdot t)} = \frac{q_{u\,CityHall}}{q_{u\,CityHall}(A_w \cdot w \cdot t)} = \frac{q_{u\,SAC}}{q_{u\,SAC}(A_w \cdot w \cdot t)} \qquad (2)$$

However, if this relation is applicable only to the three clays studied here, again the usefulness is limited. Thus, this idea is extended to the normalized improved strength of two Japanese clays, namely Tokyo-4 and Kanagawa-2, inferred from the results presented by Kawasaki et al. (1984). These Japanese clays have water content of approximately 90%. In this case, the reference unconfined compressive strength used is that for clays improved with cement content of 30%, water content of 90%, and cured for 28 days. Earlier, Fig. 4 has shown that the actual reference mix proportion used is not critical as long as it is from the same clay. The results of Fig. 4 also mean that the choice for cross-referencing is not critical; any clay could have been chosen. Figure 5 shows the normalized results using the strength of Eunos clay for cross-referencing, and again a very good correlation is obtained though very different clays are now used. This suggests that Eq 2 is quite universal and can be used for a wide range of clays. This is an important point of this paper as this approach means that cross-referencing of results from literature on different clays can now be done. To use this with confidence, a detailed statistical study is needed, but is beyond the scope of the present study.

Effect of Water Content (w) and Cement Content (A_w)

In the field, using the DCM technique, the only parameter that can be controlled is the cement content. However, the cement content to be added is influenced very much by the in-situ water content of the clay. In this section, these two factors will be investigated. First, the influence of water content on the strength of improved soils is studied. For this it is necessary to fix the cement content and the curing age of the sample. Three water contents were used in the study, namely 90, 120, and 150%. All three clays were tested and their results normalized with the respective q_u (30.90.28). As pointed out in the previous section, the precise choice of this particular set of reference parameters is not a critical issue.

Figure 6*a* shows the effect of water content on the normalized strength for the three local clays, tested after 28 days of curing. Though different clays were used, the normalized results show a

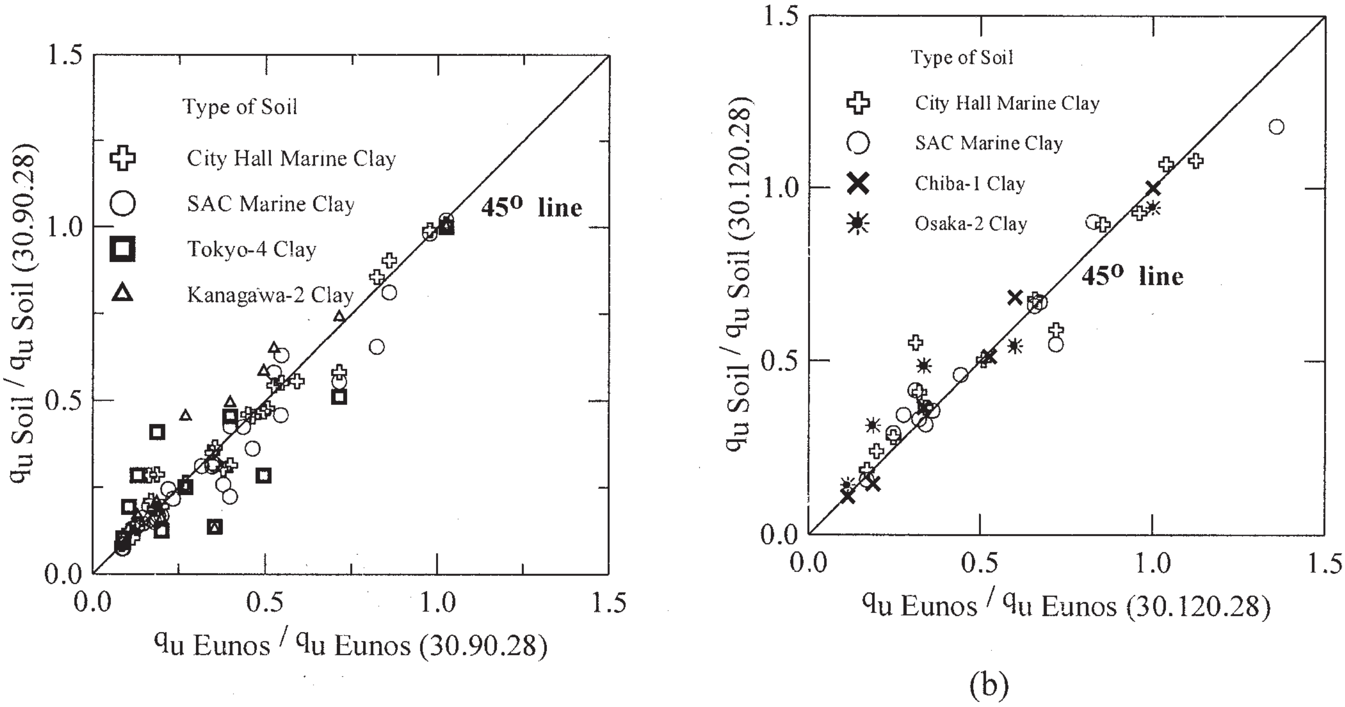
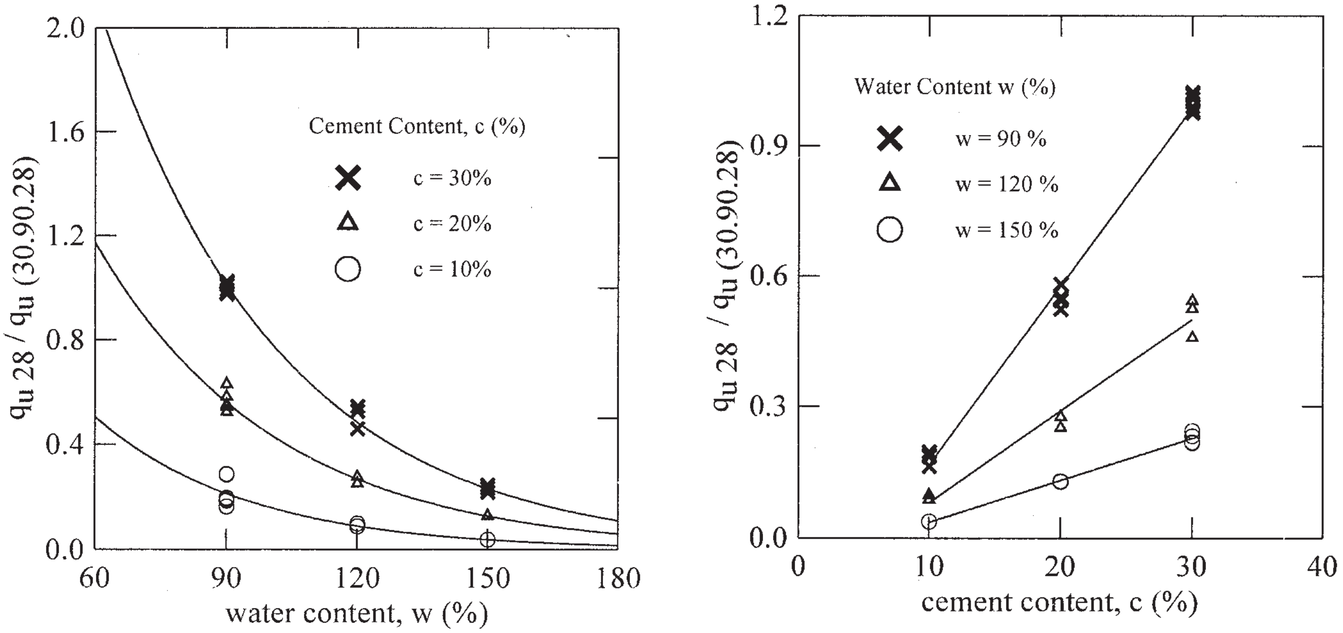
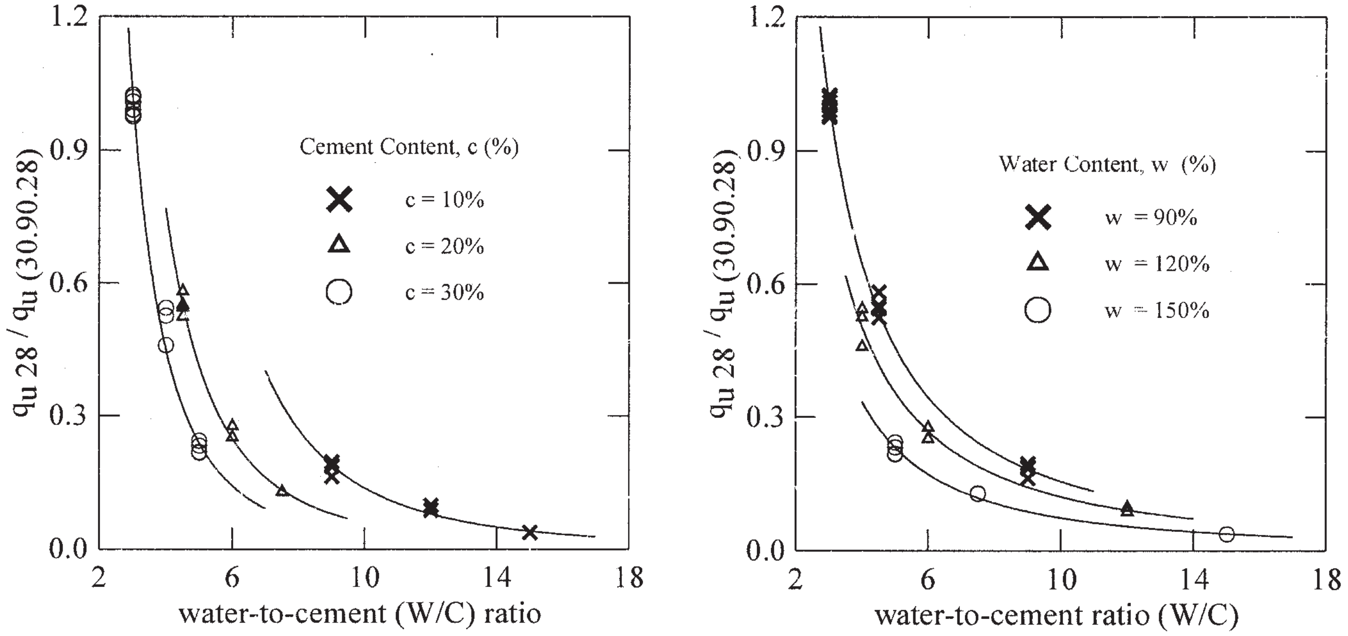


FIG. 5—*Relationship between normalized strength of Singapore and Japanese improved clays normalized with: (a) q_u(30.90.28); (b) q_u(30.120.28).*



(a) Effect of water content

(b) Effect of cement content



(c) Effect of water-cement-ratio, differentiated by cement content

(d) Effect of water-cement-ratio, differentiated by water content

FIG. 6—*Effect of water and cement contents on the normalized strength of Singapore improved clays.*

consistent trend confirming the usefulness of this approach. As expected, the lower the water content of the clay, the greater is the strength improvement; this inverse relationship was also reported elsewhere (Kawasaki et al. 1987; Babasaki et al. 1997. Because of this, to boost the improved strength, a dryer mix proportion is often desired. This is one reason why dry cement powder has been introduced and has proved to be successful in the Dry Jet Mixing Method. However, mixing the clay in a dryer condition creates problems of homogeneity and workability that affect the degree and efficiency of mixing and therefore the improvement.

To evaluate the effect of the cement content, Fig. 6*b* shows the variation of normalized strength with cement content for samples at three different water contents and cured for 28 days. The normalized strength for different clays at a fixed water content is seen to increase nearly linearly with the cement content. Though the increase is expected, the nearly linear increase is not and has important practical implications. But, due to the limited number of tests used in this study, it is not possible to explore this further. Another point to note is that the rate of increase of strength with increasing cement content also increases with a reduced water content of samples. As many factors influence the strength improvement, it is equally important to look at the relative proportion of the constituents in the mix.

Effect of Water-to-Cement (W/C) Ratio

To illustrate the influence of water-to-cement (W/C) ratio on the strength, the normalized soil strength at 28 days is plotted against W/C ratio for different cement content (Fig. 6*c*) and different water content (Fig. 6*d*). As shown in these two figures, the greater the W/C ratio, the lower the strength. This inverse relationship of strength with W/C ratio has also been reported in the studies of concrete (Neville 1996) and is referred to as Abrams' rule.

However, Fig. 6*c* also shows an intuitively not obvious trend. When the W/C ratio is kept constant (say, $W/C = 6$), the improved strength at 20% cement content is higher than at 30% cement content, suggesting that a decrease in cement content will result in an increase in the strength, an apparently counter-intuitive observation. To make sense of this requires an evaluation of the interactions among the parameters. Table 4 provides a summary of these interactions and shows that an increase in q_u under Condition 1 and Condition 2 is intuitively expected but not for Condition 3. In Condition 1, if the amount of water (W) and soil (S) are kept constant and the amount of cement (C) is increased, the W/C ratio will reduce while the C/S ratio will increase, and both will cause an increase in q_u. In Condition 2, if C and S are kept constant and W is reduced, W/S and W/C ratios will reduce, and both will cause an increase in q_u. In Condition 3, if W and C are kept constant and the amount of soil treated, S, is increased, the W/S and C/S ratios will both decrease, but a reduction in W/S will cause an increase in q_u, whereas a reduction in C/S will cause a reduction in q_u. Therefore, the trend of q_u depends on whether the effect of decreasing the W/S ratio or C/S ratio is more dominant for a particular mix proportion.

In the range of water and cement content used in this study, decreasing the water content seems to be more effective than reducing the cement content, which results in an increase in the compressive strength even though the C/S ratio has reduced, as the results of Fig. 6*c* suggest. This understanding is important for the field application of DCM stabilization whereby the W/C ratio is often kept constant (Yoshizawa et al. 1997) while determining the proportion of mix design. Hence, the accurate determination of water content, including the natural water content of clay, is important before a decision to fix the W/C ratio can be made.

Stiffness of Improved Clays

Most of the previously reported results were on the strength of improved clays, which is important in stability design. However, if ground movement is the key design consideration, then the stress-strain relation is more important. For soils, it is now recognized that even at very small strain the stress-strain behavior is highly nonlinear, but thus far only Tatsuoka et al.'s study (1996) has specifically focused on this for an improved soil. The variation of stiffness with strain is vital as it can affect the design of the improved clays considerably.

Accurate determination of stiffness is never easy. Tatsuoka et al. (1996) had pointed out that measurement of deformation between end-platens, frequently used for soils and also improved soils, usually underestimated the stiffness considerably. Clearly, the way strain is measured has an important bearing on the correlation of stiffness with the unconfined compressive strength, q_u. Published literatures yield an extremely wide range of values; these relationships, based on different studies undertaken by others, are summarized in Table 5.

TABLE 5—*Relationships between E and q_u from different studies.*

Reference	Relationship
Kawasaki et al. (1984)	$E_{sec50} \sim 350$ to $1000\ q_u$
Tatsuoka et al. (1996)	$E_{max} \sim 1000\ q_u$
Futaki et al. (1996)	$E_{sec50} \sim 100$ to $250\ q_u$
Asano et al. (1996)	$E_{sec50} \sim 140$ to $500\ q_u$
Present study	$E_{sec50} \sim 350$ to $800\ q_u$

E_{sec50} = secant Young's modulus at 50% of ultimate strength.
E_{max} = young's modulus at strain below 0.001%.

TABLE 4—*Influence of the three main constituents of mixture.*

	Condition		W/S (Water Content)	W/C (Water to Cement)	C/S (Cement Content)		q_u	Comments
(1)	S constant W constant	C↑	•	↓	↑	⇨	↑	Apparent
(2)	S constant C constant	W↓	↓	↓	•	⇨	↑	Apparent
(3)	W constant C constant	S↑	↓	•	↓	⇨	↑	Not apparent

• denotes value that is constant.

Stiffness at small strain

The variation of stiffness with strain for SAC clay is shown in Fig. 7 by plotting the results in term of E_{sec}/q_u versus log ε, where the strain (ε) was measured using the Hall's effect strain transducer. E_{sec} is the secant Young's modulus, while q_u is the unconfined compressive strength. The behavior of the cement-treated clay is clearly non-linear, with E_{sec}/q_u decreasing from about 1400 at 0.005% strain to less than 100 at 1% strain for improved clay with 30% of cement. The same behavior is also observed for samples with lower cement content. It is therefore important to consider such non-linearity for the improved clays as in practical excavation; the strain induced in this layer is expected to be very small. However, it must be noted that the behavior is more brittle and will fail at a smaller strain.

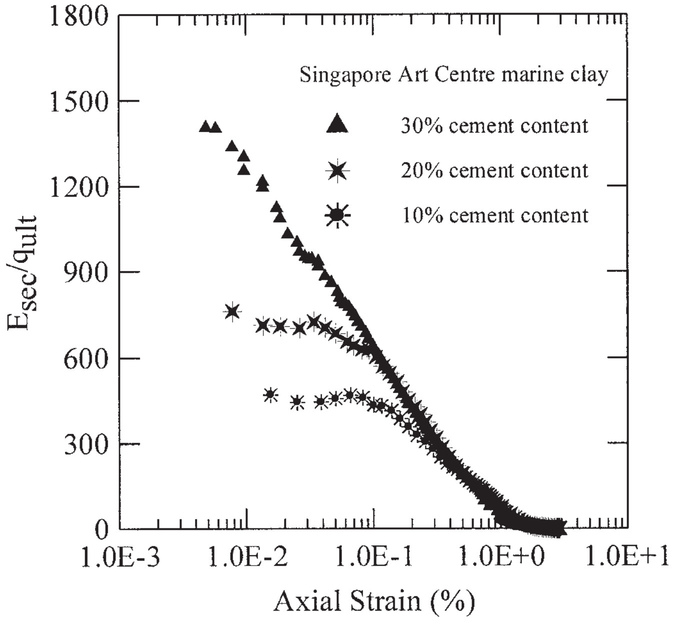


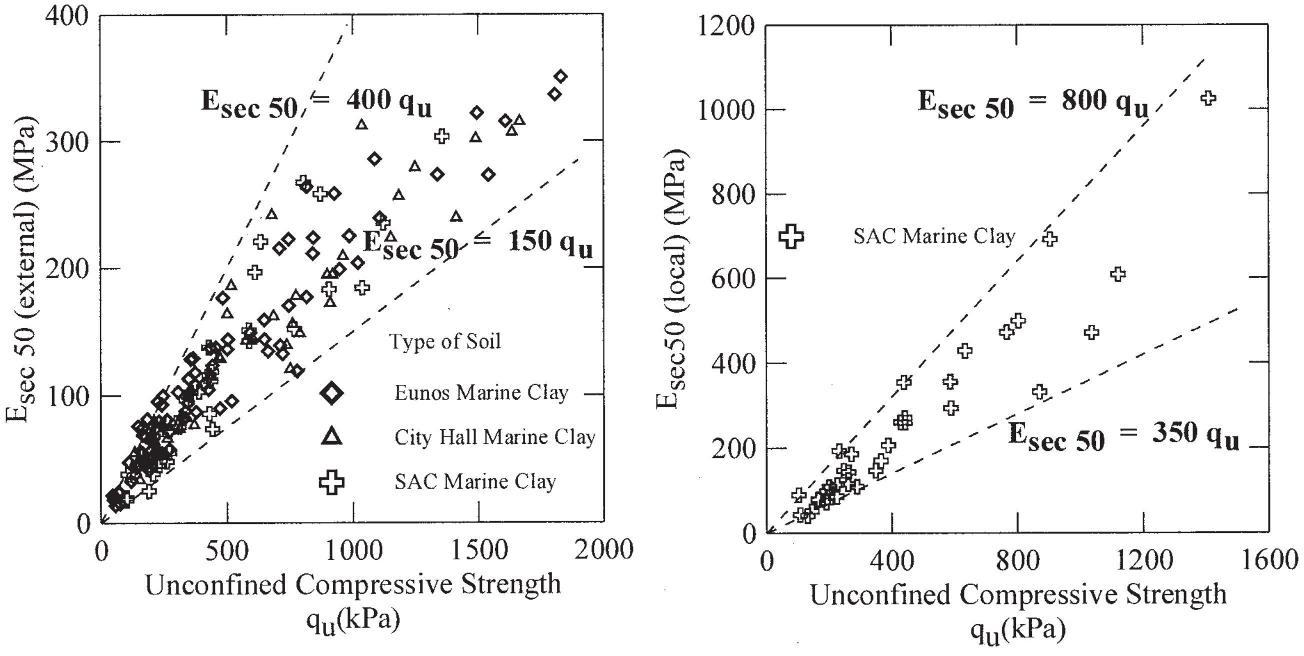
FIG. 7—*Variation of stiffness with strain.*

Relationship between E_{sec50} and q_u

It is common practice to relate the Young's modulus (E) with the unconfined compression strength (q_u) so as to establish a correlation between the two parameters. The relation between E_{sec50} and q_u, based on the conventional method of strain measurement, for the three improved Singapore marine clays is shown in Fig. 8*a*, where E_{sec50} is the secant Young's modulus at 50% of the ultimate strength. This shows that the data all fall within the range of $E_{sec50} = 150$ to $400\ q_u$, similar to those reported by Asano et al. (1996) and Futaki et al. (996). Figure 8*b* shows the relation between E_{sec50} and q_u, using local strain measurement by a Hall's effect transducer. The results now fall within the range of $E_{sec50} = 350$ to $800\ q_u$, much higher than that from using the external strain measurements and more in line with that observed by Tatsuoka et al. 1996, who used a similar method of measurement.

Effect of Time (t)

Like concrete, cement-mixed soil will continue to improve with time. Thus, a primary concern in characterization study of improved soil is to estimate this expected increase in improvement, usually based on properties after 1 day or 7 days of curing. This will give an early indication of whether a particular mix proportion can achieve the design strength at 28 days, the usual benchmark for determination of strength. Another important reason, which to the authors' knowledge has not been discussed before, is the effect this increase in improvement has on the bending moment of the retaining wall, an issue of concern to structural engineers.



(a) (b)

FIG. 8—*Correlation between E_{sec50} and q_u, derived using: (a) external strain measurement method; (b) local strain measurement method.*

Figure 9 shows the relation between the normalized strength at 28 days with the normalized strengths at other time intervals. Generally, the relationships are linear and the following empirical linear relations can be surmized. The normalized strength at 28 days is 2.9 times the strength after 1 day of curing, 2.1 times that after 3 days, 1.6 times that after 7 days of curing, and 1.2 times that after 14 days. Figure 10 shows the increase in normalized strength and stiffness with time. The greatest rate of strength gain occurs within the first 28 days, but the improved clays continue to improve significantly after 28 days. As improved soil is introduced mainly to control movement and improved stability, in many practical situations the strength and stiffness after 28 days of curing are used in design. Often, a smaller value is used in design and is considered conservative as increasing stiffness and strength will mean smaller movement, a valid design assumption provided the only consideration is movement.

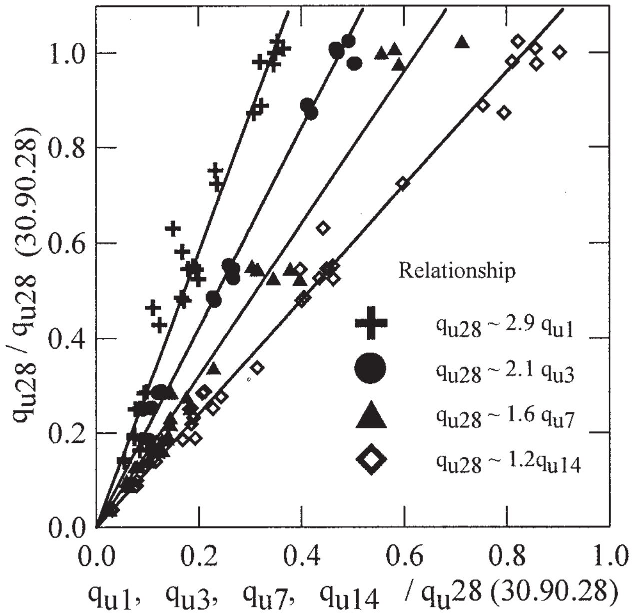


FIG. 9—*Relationship between q_{u1}, q_{u3}, q_{u7}, q_{u14}, and q_{u28} of Singapore improved clays.*

However, with a stiffer improved soil layer, the bending moment will increase. An example from centrifuge tests is now described. Two different plane strain excavation tests with an unstrutted retaining wall were conducted in the centrifuge at 100 *g*, where a specially developed in-flight excavator was used to remove the soil (Loh 1998). In each test, the soil model was first subjected to a small surcharge consolidation at 1 *g* before consolidated in-flight under its own self-weight to produce a thin over-consolidated clay at the top followed by a normally consolidated layer. The retaining wall, an aluminium plate equivalent to a prototype concrete wall of 600-mm thickness, was then inserted at 1 *g* while the soil on the excavation side was removed down to 8 m to place a 2-m-thick cement-mixed soil layer (dimensions in prototype scale). The removed soil was trimmed and placed back on top of the cement-mixed soil and the entire setup was consolidated again until nearly full consolidation.

In Case 1, the cement mixed soil layer was cured for 7 days, while for Case 2, the cement mixed soil was cured for 28 days. Bending moment along the retaining wall was measured using strain gages installed on the plate and is shown in Fig. 11. It is clear that a noticeable difference between the two bending moment profiles can be observed. Clearly, a stiffer improved soil layer induced a much larger bending moment in the retaining wall. It is also clear that this problem will become more severe with time as the cement-mixed soil continues to improve as shown in Fig. 10.

Thus, it is recommended that in the design of the retaining wall the maximum expected stiffness in the improved soil is used for analysis, and the combined maximum bending moment envelope is used. The estimate of the maximum stiffness should preferably include small strain effect. But, in estimating the ground movement

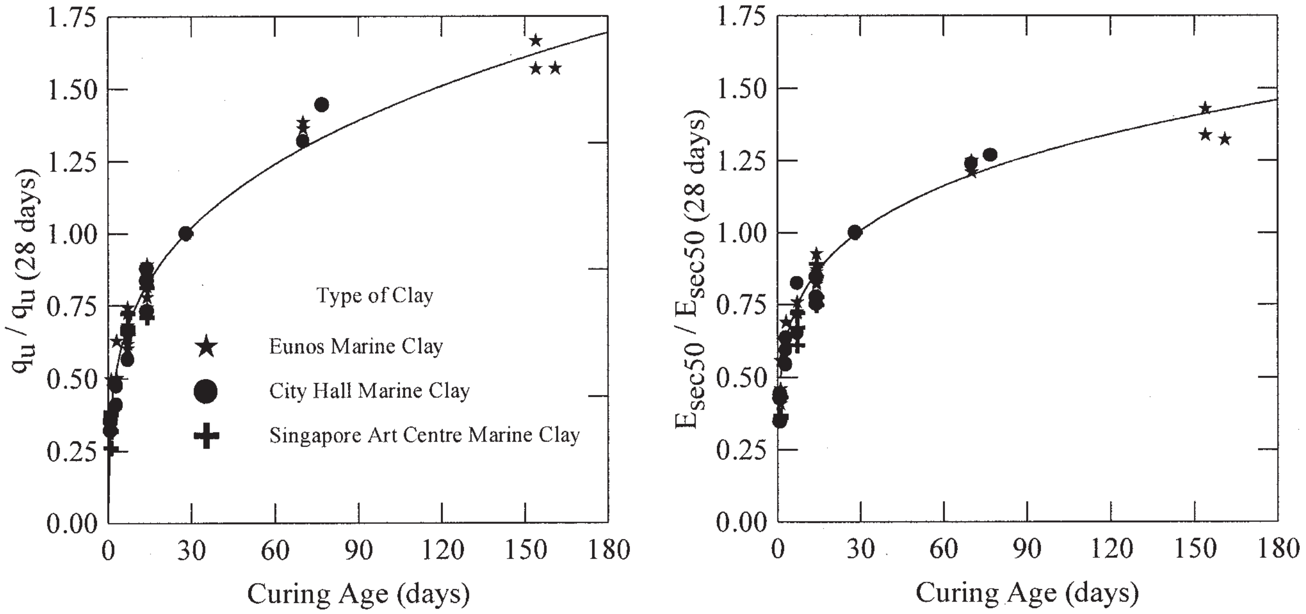


FIG. 10—*Strength and stiffness development of Singapore cement-treated clays.*

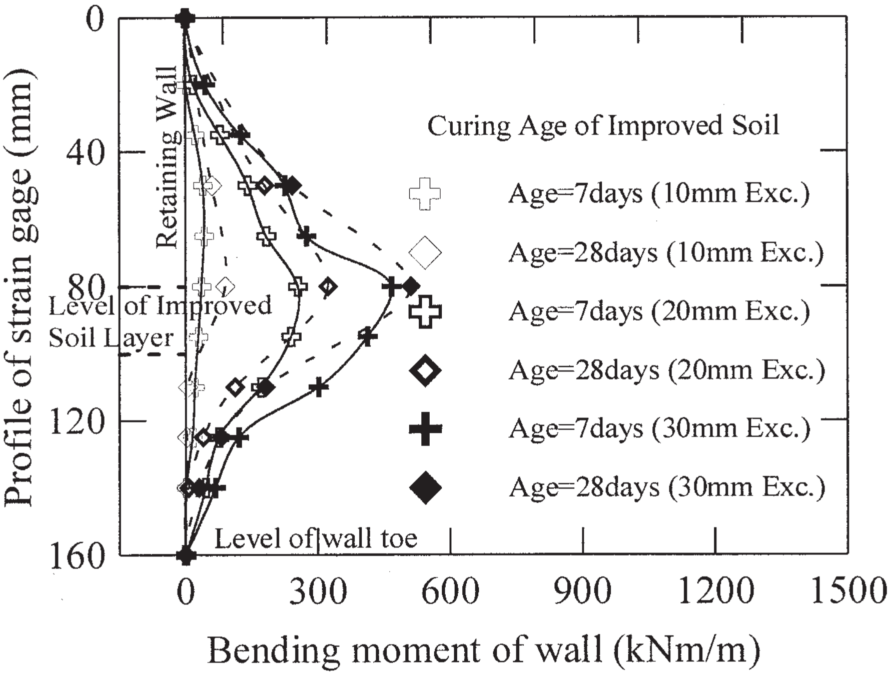


FIG. 11—*Bending moment of retaining wall with improved soil layer, cured at 7 and 28 days.*

or stability due to the excavation, the strength and stiffness at 28 days can still be used as per present practice. This is an important consideration that needs to be enforced to ensure a safer design. This was the approach adopted in an excavation project in Singapore recently.

Conclusion

This study is to establish the properties of cement mixed clays for a range of mixed proportion commonly associated with the Deep Cement Mixing Method. Based on the experimental results, the following conclusions can be drawn:

1. When different marine clays are improved using cement mixing, the degree of improvement for each clay is different. Many physical and chemical factors contribute to this, and it is difficult to isolate the effect of each factor. However, the results of this study show that using a normalization approach, as given in Eq 2, is able to ensure that the behavior of these different improved clays gives a unified behavior.
2. There are three key constituents in cement-mixed soils, namely water, cement, and soil. It is important to recognize that the interactions among these constituents do not always produce an obvious trend about the way the soil will improve. For example, when the water-to-cement ratio is fixed, decreasing the cement content gives rise to an increase in strength, an observation that is not intuitively obvious. The interactions among these constituents and their impact on strength improvement are summarized in Table
3. The cement-mixed clays are seen to behave non-linearly at very small strain, just like most soils. Thus, it is important to ensure correct strain measurement. Due to bedding errors, the external strain measurement method (LVDT) generally shows a softer behavior as compared to the local strain measurement method (Hall's effect transducer). This is known in testing of solid, but less so in soil testing, including stiff soil.
4. Hardening of a cement-mixed clay is a time-dependent process. Some empirical relationships have been proposed to relate the strength at 28 days with that at 1, 7, and 14 days. More importantly, bending moment results from a set of centrifuge tests indicate that this increase in stiffness with time is an important design consideration. It is recommended that the highest expected stiffness should be used in the design of the retaining wall.

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