Optimising Cement Dosage in Ground Improvement and Early Quality Control Schemes

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ABSTRACT: Judicious dosage of cement in soft clayey soils is key in reducing waste, time and cost in this growingly environmental conscious modern society. Despite being a well-established technique in ground improvement, studies on the prediction of strength development of cement stabilised soils are often limited to a couple of clay types or site specific. This paper presents an extensive suite of unconfined compressive strength tests of cement-mixed clayey soils over a wide range of mix ratios, curing ages and sand impurities. A strength predictive model encompassing the above variables was developed and validated with several types of clay and cement from different sources. This enables the optimisation of cement dosage to achieve a desirable unconfined compressive strength to satisfy the ground improvement criteria with ease. Quality control schemes using early age strength and portable bender element were also discussed in this paper.

KEYWORDS: Soft clays, Cement stabilisation, Unconfined compression test, Mixing ratio, Curing age, Quality control

1. INTRODUCTION

Many coastal urban cities such as Bangkok, Singapore, Tokyo and Shanghai are underlain with soft marine clays which require ground improvement to support high-rise buildings and critical infrastructures. Cement stabilisation is where cement is added into soil to increase its shear strength. The performance of cement stabilized clay has been widely studied in the past few decade (Nagaraj et al., 1996; Uddin et al., 1997; Wu et al., 1998; Chen et al., 2001; Horipibulsuk et al., 2003; Verastegui Flores et al., 2010; Kitazume and Terashi, 2013). Most studies were limited to their own database and involved relatively pure clay without granular impurities. With development of underground space to address land scarcity, there are incentives to consider the effects of sand impurities in clays during such cement stabilisation works.

In many cases, ground improvement contracts specify minimum performance of the cement stabilised soils, particularly based on unconfined compressive strength. As such, contractors resort to applying high cement dosage to ensure the final strength is sufficient to satisfy the required performance stipulated in the contract. In addition, contractors often apply a constant dosage of cement across non-uniform soil profile out of convenience, thereby leading to large variation in improved strength. The outcome is a site with pockets of overly stiff soil which can cause problems during excavation and driving of piles. Overuse of cement also increase carbon footprint and cost wastage which are undesirable. There is hence enormous incentives to optimise cement dosage in cement stabilisation of soft clayey soils so as to achieve a more consistent improved strength profile while lowering cost, time and environmental impact.

2. FACTORS AFFECTING STRENGTH OF CEMENT STABILSED SOILS

The strength development of cement treated soils is dependent on the properties of the reactants, reaction conditions and sample preparation (Terashi and Kitazume 1999). In this study, different type of soil, cement, mix proportions and curing time are investigated so as to produce a broad guide on the optimisation of cement to achieve a target strength.

The type of cement was investigated by Verástegui Flores et al. (2010) who observed that the strength development of Kaolin clay with Portland blast furnace cement is slower in the early stage than that those of ordinary Portland cement due to presence of slag which retards the hydration process. However, the long-term strength of Portland blast furnace cement can be significantly higher, which is in line with findings of concrete researchers (Roy et al. 1982; Escalante et al. 2001).

Taki and Yang (1991) carried out unconfined compressive strength test of cement treated gravel, sand, silt and clay. Their results showed that coarse grained soils produce higher strength than finer grain soil specimens with similar cement content. This is supported by Bell (1993) who found that treated soils with higher content of clay require more quantity of stabilising agent to attain a similar strength.

Miura et al. (2001) and Horpibulsuk et al. (2003) identified the water:cement (w/c) ratio as the main parameter governing the strength behaviour of cement treated Bangkok clay. Higher w/c ratio leads to a reduction in unconfined compressive strength. In the case of soil:cement (s/c) ratio, at least three zones of strength improvement were identified with cement content (Bergado et al. 1996; Uddin et al. 1997; Zhang et al. 2013). When the cement dosage is very low, the cement is unable to bind the soil together, hence the strength improvement is marginal, as identified as the “inactive zone”. With higher cement dosage, the strength increases significantly and undergoes an “active zone” with large quantity of binding cementitious products generated from hydration and pozzolanic reactions. However, when the cement dosage becomes excessive such that the available amount of water in the mix is insufficient to support the hydration process, strength development may be hindered (“inert zone”).

Similar to concrete, longer curation time would permit more complete hydration and pozzolanic reactions to take place. Hence, the strength of the mix is expected to increase with more extensive and hardened cementitious matrix. A linear relationship of normalised unconfined compressive strength with the logarithm of curing time have been widely reported (Nagaraj et al. 1996; Horpibulsuk et al. 2003; Chian et al. 2015a).

3. EXPERIMENTAL SETUP

3.1 Materials

The soil used in this study is the Singapore upper marine and Kaolin clays. The Singapore upper marine clay was collected near Pulau Tekong, an offshore island northeast of Singapore. The Kaolin clay was procured from Kaolin (Malaysia) Sdn Bhd. The minerals in Singapore marine clay is predominantly kaolinite with moderate contents of illite and smectite. Kaolin clay is primarily kaolinite. According to the Unified Soil Classification System (USCS), they are classified as high plasticity clay (CH). Table 1 summarises the basic physical properties of the two clays, indicating a higher plasticity index of Singapore marine clay as compared to Kaolin clay.

Table 1 Basic properties of Singapore Upper Marine Clay and Kaolin Clay

Properties	Singapore Marine Clay	Kaolin Clay
Liquid Limit (%)	70 – 90	60.5
Plastic Limit (%)	36 – 56	42.5
Specific Gravity	2.62 – 2.69	2.60

In order to better represent field conditions where sand impurities are present, fine grained sand is added to study the influence of coarse grain particles in clay. The admixed sand has a specific gravity of 2.63 and bulk density of 1500 kg/m^3 with particle size shown in Figure 1. The mean effective diameter (D_{50}) is 0.25mm. The uniformity coefficient (C_u) and curvature coefficient (C_c) are 1.43 and 1.07 respectively.

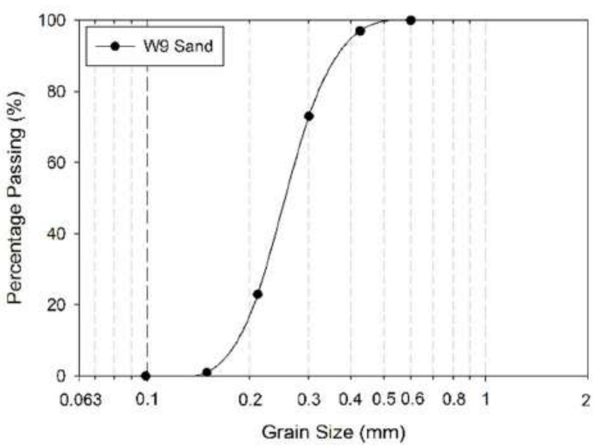


Figure 1 Particle size distribution of admixed sand

Portland blast furnace cement (PBFC) with 85% of slag content, supplied by Engro Corporation Ltd Singapore, was used as the stabilising agent in this study. Its lower early strength gain is beneficial for early quality control. The basic properties of PBFC are presented in Table 2.

Table 2 Basic properties of Portland Blast Furnace Cement (PBFC)

Physical Properties	Value
Density	2900 kg/m^3
Fineness	429 m^2/kg
Initial Setting Time	125 mins
Final Setting Time	225 mins
Soundness	< 0.5 mm
Consistency	29.6%
Compressive Strength (28-day)	40 MPa

3.2 Preparation and testing

The raw Singapore Marine Clay was sieved for removal of stones and shell pieces. The sand fraction was less than 5% and hence, its influence is deemed negligible. For mixes involving the study of sand impurities, the desired sand content was calculated based on the total dry weight of soil. The amount of PBFC and water to be added were computed based on the total soil weight (clay plus sand, if any).

The Japanese standard JGS 0821 (Japanese Geotechnical Society, 2000) was adhered with the mixing process maintained at 10 minutes in total, of which 1 minute was allocated for manual mixing and scraping of materials attached to the sidewall and bottom of the mixing bowl. After mixing, the mixture was transferred to cylindrical split moulds of 50mm in diameter and 100mm in height. The specimen was compacted in three layers by manual tamping to minimise entrapped air voids. Next, the specimens were fully immersed in water and stored under constant temperature for curing (23±2^{O}C) until the desired curing age (3, 7, 14, 28, or 91 days) is achieved. Prior to testing, the top and bottom of the specimen were trimmed flat to 100±5mm to maintain a length to diameter ratio of about 2.

During mixing, it was observed that higher percentage of sand content leads to a more slurry mixture. This is expected as sand does not retain water as significantly as clay. Liquid limit (w_L) of the soil mixtures was therefore determined using the cone penetration test to assess their water holding capacity. Skempton (1953), Seed et al. (1964), Pandian and Nagaraj (1990) indicated that the composite effects of soil constituents and their interactions with pore fluid are largely reflected in their liquid limit (w_L). In addition, liquid limit is essentially a measure of lower strength limit of shearing resistance, representing the water content at which soil approaches liquid state. Figure 2 shows the liquid limits of the clays with percentages of sand impurities.

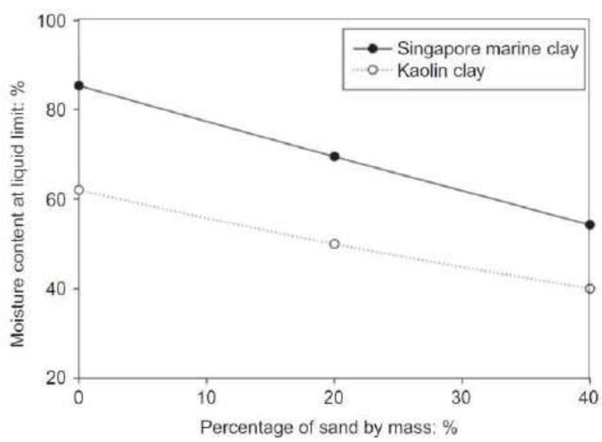


Figure 2 Liquid limit of Singapore marine clay

Unconfined compressive and bender element tests were carried out in this study to obtain estimates of the unconfined compressive strength and small-strain shear modulus of the cement treated specimens.

4. STRENGTH DEVELOPMENT OF CEMENT STABILISED CLAYS

Figure 3 illustrates the influence of water:cement and soil:cement ratios on the unconfined compressive strength of Singapore marine clay at different curing time. Results showed that lower water:cement ratio produces a higher strength of the specimen. This is analogous to concrete technology. In the case of cement treated soils, the soil:cement ratio is often significant and its effect on the strength development should be investigated.

It can also be inferred from Figure 3 that higher soil:cement ratio leads to a reduction in unconfined compressive strength of the specimen. This is logical since a higher soil:cement ratio would imply a relatively lower amount of cement to soil. Hence, more cement is available to bind the soil particles together, thereby producing a stiffer material.

The curing time also has a significant effect on the strength of cement treated specimens. With longer curing time, more thorough hydration reaction and pozzolanic reactions can be achieved, thereby achieving a stronger specimen.

In order to compare the strength of cement treated clay with respect to the conventional 28-day strength requirement, a normalised strength versus curing time is depicted in Figure 4. In the figure, the points fall along a rather linear relationship in the semi-log scale, indicating a convenient regression for the strength development with time. It is also noted that the trend persists for specimens with different *w/c* and *s/c*, implying comparable development characteristics despite differing mix proportions.

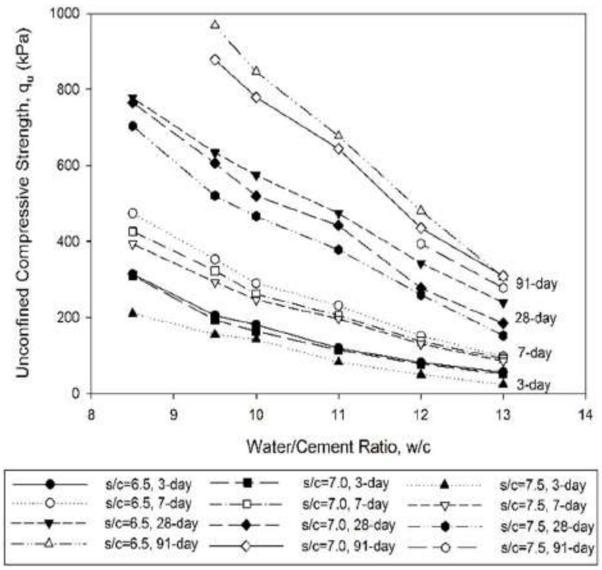


Figure 3 Effect of mixing proportions on unconfined compressive strength of Singapore marine clay

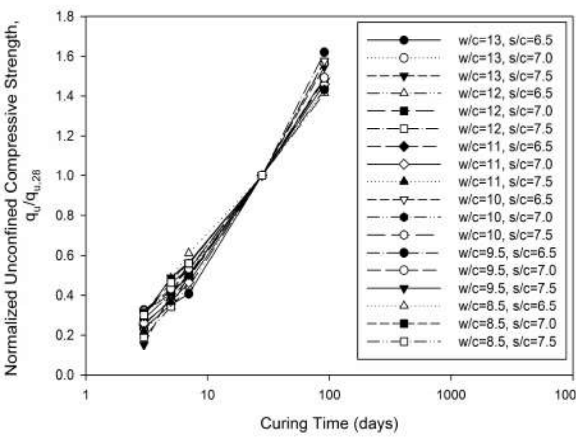


Figure 4 Effect of curing time on normalized unconfined compressive strength

5. PROPOSED STRENGTH PREDICTIVE EMPIRICAL MODEL FOR CEMENT STABILISED CLAYS

Empirical relationships based on experimental studies have been suggested to describe the effects of w/c to the strength of cement stabilised soil. Horpibulsuk et al. (2003) proposed strength development models expressed by an exponential function similar to the Abrams' Law commonly used for predicting strength of cementitious materials (e.g. concrete) as shown in Eq. (1):

$$q_u = \frac{A}{B^{w/c}} \tag{1}$$

where *A* and *B* are experimentally fitted coefficients. Values of *A* depend on soil types and other soil-related factors, while value of *B* is usually taken as 1.24.

Having identified Abrams' law as a possible expression to depict strength development of cement treated clay, the next step is to incorporate curing time and soil:cement ratio effects to cement treated clay. The effect of curing time (t) on the strength development of cement treated clay can be described with a linear semi-log relationship with time (Mitchell et al., 1972). This is valid for this present study as shown in Figure 4. A natural logarithmic term is proposed to be added to the Abrams' equation:

$$q_u = \frac{X}{Y^{w/c}} \ln(t) \tag{2}$$

where X and Y are fitting constants. It is noted that the effect of curing time should consists of a y-intercept constant in the natural logarithmic form. However, the objective of this paper is to produce a simplified model with minimal fitting parameters. Since this constant is of a small value, it is neglected while accepting some slight inaccuracies.

In order to study the effect of soil:cement ratio (*s/c*), a back-fitting analysis was carried out to identify the range of parameters *X* and *Y* in Eq. (2) for different *s/c* values. From the analysis, it was found that parameter *X* has a linear relationship with *s/c* as shown in Figure 5. Water was ample for complete hydration and pozzolanic reactions due to the high water content. Parameter *Y* at the denominator of Eq. (2) was found to be unaffected by *s/c*. The full equation can therefore be written as:

$$q_u = \frac{X}{Y^{w/c}} \ln(t) = \frac{a + b(s/c)}{Y^{w/c}} \ln(t) \tag{3}$$

where *a* and *b* are the y-axis intercept and slope of parameter *X* versus *s/c* respectively. The proposed model requires 3 constants (*a*, *b*, *Y*) to be calibrated from experimental data. Figure 6 shows Eq. (3) fitting the full range of tests in the present study. The *a, b* and *Y* constants used are 3700, -75 and 1.35 respectively.

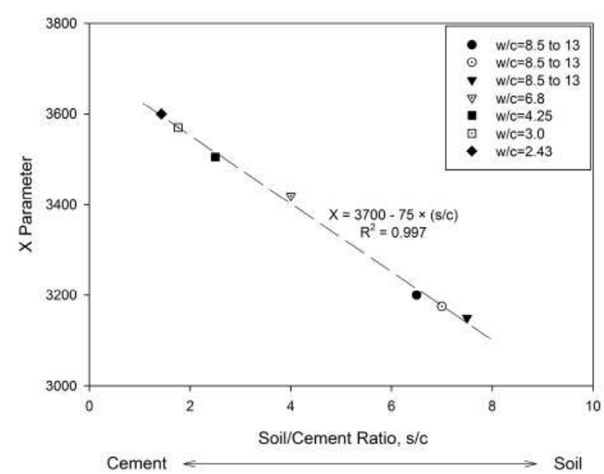


Figure 5 Linear relationship between *X* parameter and soil:cement ratio

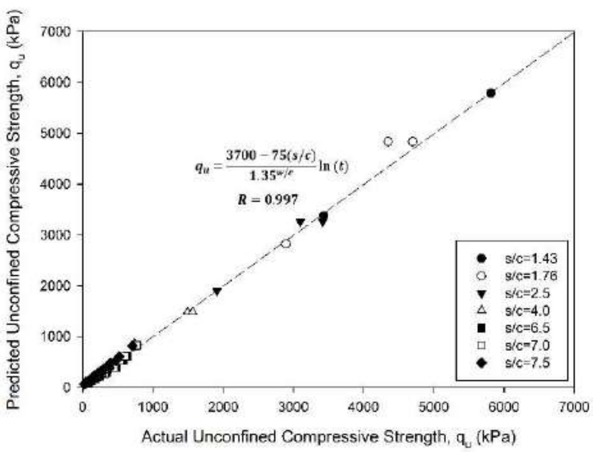


Figure 6 Predicted versus actual unconfined compressive strength with Eq. (3)

6. APPLICABILITY OF PROPOSED MODEL TO OTHER CLAY AND CEMENT TYPES

Different clay and cement types were assessed in order to validate the applicability of the proposed equation for wider use. Back fitting analysis based on Eq. (3), similar to the Singapore marine clay were carried out for some published cement treated clays to obtain their X and Y parameters. Figure 7 demonstrates the improvement of predicted compressive strength using Eq. (3) as compared to the conventional Abrams' equation. In the figure, results show that the prediction using the proposed equation, Eq. (3) is well fitted to the published measured values over their complete range of *w/c*, *s/c*, and *t*, with correlation coefficients exceeding 0.95. In addition, narrower scatters were observed with Eq. (3) as compared to the Abrams' predictions. It is also observed that the *Y* values obtained from these analysis fall within a narrow range of 1.22 to 1.86, suggesting the effect of *w/c* over these wide range of clay types including the Singapore marine clay are quite similar. This forms a reference for estimating the *Y* value for new mixes of clay and cement types. In the case of the *X* parameter in Eq. (3), the value is dependent on the nature of cement and clay type, method of preparation and temperature of curing. More extensive tests are necessary to clarify the differences in the *X* values.

Chian et al. (2015a) postulated that the value of *X* has to do with the difference in liquid limit of the clay. Higher liquid limit takes up more water to form slurry, hence the cement has lesser available moisture or "apparent *w/c*" for hydration. According to classic strength development of cement mortars, lower *w/c* mixes produce higher strength of cement and hence a larger y-axis intercept value (i.e. *a* constant) of the *X* parameter in Eq. (3). Chian et al. (2015a) showed that the *a* constant appears to increase with liquid limit of the clay. Some relationship was also suggested between the *a* and *b* constants of *X*. Their findings also showed a linear trend between *Y* parameter and liquid limit, thereby allowing engineers to obtain a quick initial estimate of the *Y* parameter value to work with for different clay types.

7. INFLUENCE OF SAND CONTENT

The influence of sand content on the strength of cement treated clay can be observed from Figure 8. The figure shows that the unconfined compressive strength is lower with increasing sand content in the clay. This appears to differ from findings by Taki & Yang (1991) who postulated higher strength development for coarser grained soils. The reason for the lower strength obtained in this study is attributed to the presence of more free-flowing water in the mix. Although the micro-roughness of soil increases with sand fraction, direct contact between sand grains is impeded by clay particles and pore water. The soil is in a more porous and slurry state. Soil clusters easily slide over one other when shearing, hence exhibiting a lower strength (Chian et al. 2017). This suggests that the strength development of cement treated soil is influenced by both microfabric characteristics and induced pore spaces. This is in line with the observation by Consoli et al. (2007) on the reduction in strength with increase in porosity in the mix. However as the *w/c* decreases, the strength increment of cement-treated soil is steeper with increasing amount of sand. This is caused by a lower amount of water-filled voids within the soil matrix and higher frictional resistance of the sand can now be mobilised as the sand grains are packed more closely together, although this effect is marginal in some cases depending on the initial arrangement of grains.

8. INTRODUCTION OF FREE-WATER: CEMENT RATIO

In order to incorporate the effect of sand content, the 'liquid limit ratio (w/w_L)' is proposed to describe the state of soil microfabric and amount of free water involved. w/w_L is defined as the soil water content divided by the water content at the liquid limit (Chian et al. 2017). This free water concept can be associated with earlier studies by Wroth (1979), who postulated that fine-grained soils tend to equilibrate from the same high initial water content to their respective liquid limit water content at an effective stress state. Other studies (Nagaraj et al., 1991; Mitchell, 1993) also suggested that the microfabric of different soils would be similar at their liquid limit state, reflecting the same order of pores distribution.

The 'free water to cement ratio $(w/w_L)/c$', is thus proposed to offer a more comprehensive relationship between the three constituents: water, cement and sand (Chian et al. 2017). Figure 9 presents the *qu* plotted against $(w/w_L)/c$ of cement-treated clayey specimens. The curves of the 20% and 40% sand specimens previously presented in Figure 8 are now shifted to the right relative to the 0% sand specimen curves, thereby producing a more consistent and uniform trend among these specimens.

In addition to the role of the microfabric characteristic as described earlier, this notion can be explained by the chemical mechanism of the soil-water-cement reaction. In concrete technology, the aggregates and sand are both non-interacting particles which do not participate in pozzolanic reaction. However, in the case of a clay and sand mixture, the inclusion of sand leads to a less cohesive soil specimen as the sand grains form weak discontinuities within the clay matrix. These discontinuities can be more susceptible to fracture than a cemented clay matrix under uniaxial compression loading. Furthermore, clay participates in pozzolanic reaction and forms hardened soil bodies that enhance strength development, but sand does not. In view of the above reasons, higher sand content leads to lower gain in strength (Chian et al. 2017).

On the other hand, sand grains can aid in breaking up large clay-cement lumps and increase surface contact with cement to react. This is especially the case where the water content relative to the soil's liquid limit is low. Over time, more hydrated lime dissociates and leads to a rise in pH value. These conditions encourage hydration and pozzolanic reactions, and a more rapid gain in strength of the specimen may be produced (Chian et al. 2017). At higher $(w/w_L)/c$, cement content is too low to provide significant strength gain and therefore the effect of sand impurities at high $(w/w_L)/c$ is minimal as observed in Figure 8.

Referring to Figure 9, the *qu* plotted against $(w/w_L)/c$ curves follow a trend similar to the conventional *qu* against *w/c* plots in Figure 3. This opens up the opportunity to apply similar strength development models of cement-treated clay with some slight modifications. As the *w/c* ratio is unable to incorporate the effects of sand content as discussed earlier, the parameter is replaced with the $(w/w_L)/c$ ratio, while other terms remain the same.

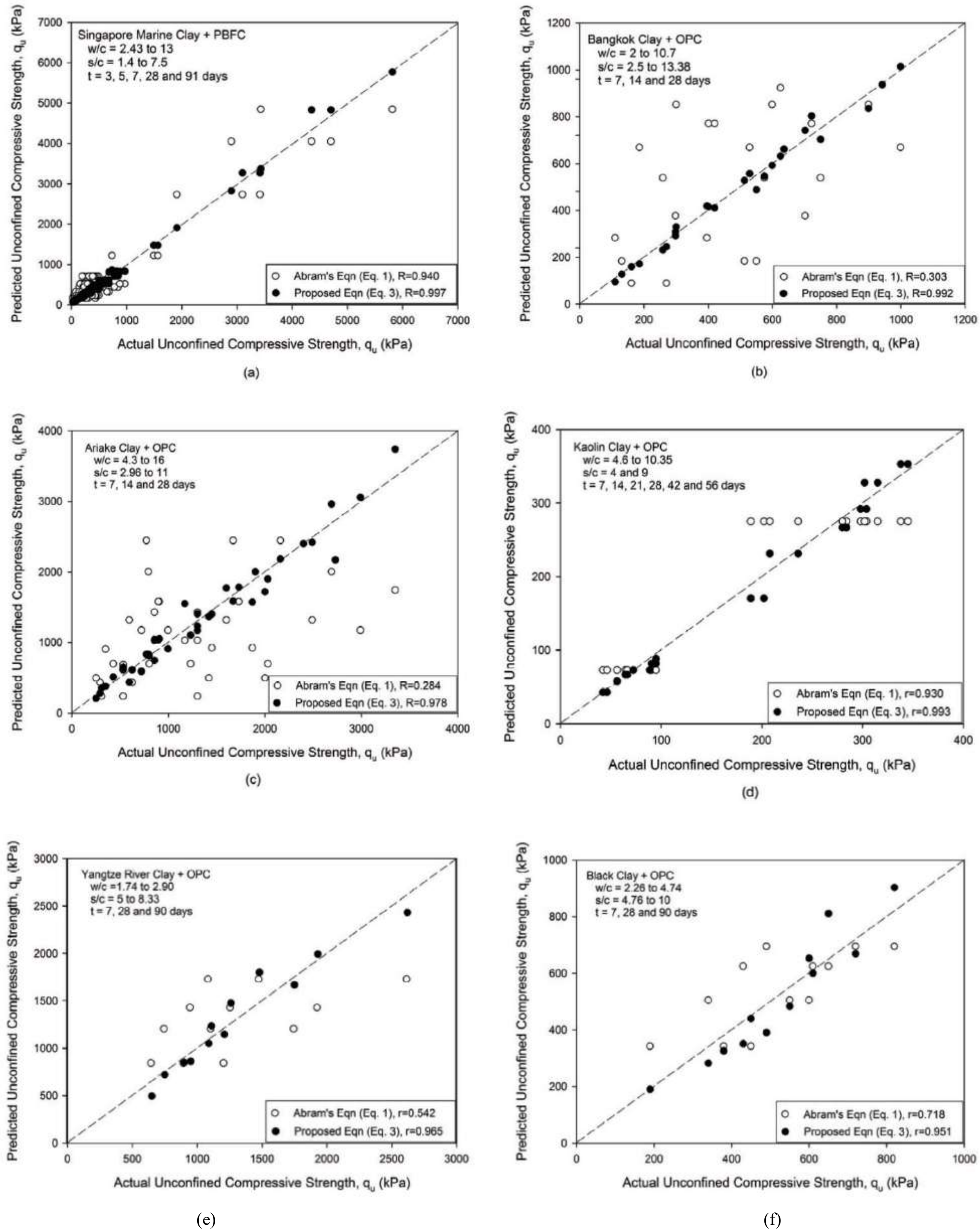
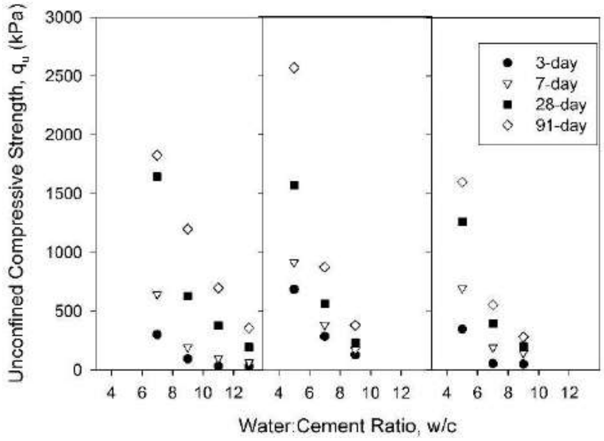
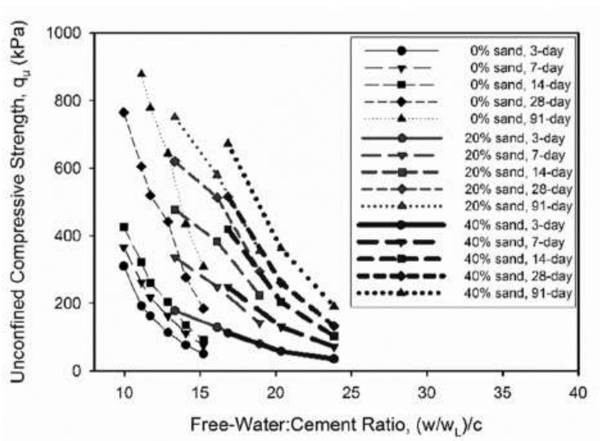


Figure 7 Strength prediction of various clay and cement types at different water:cement, soil:cement ratios, and curing time; (a) Singapore marine clay (Chian et al. 2015a) (b) Bangkok clay (data from Horpibulsuk et al. 2003) (c) Ariake clay (data from Horpibulsuk et al. 2003) (d) Kaolin clay (data from Verástegui Flores et al. 2010) (e) Yangtze river clay (data from Wu et al. 1998) (f) Black clay (data from Chen et al. 2001)

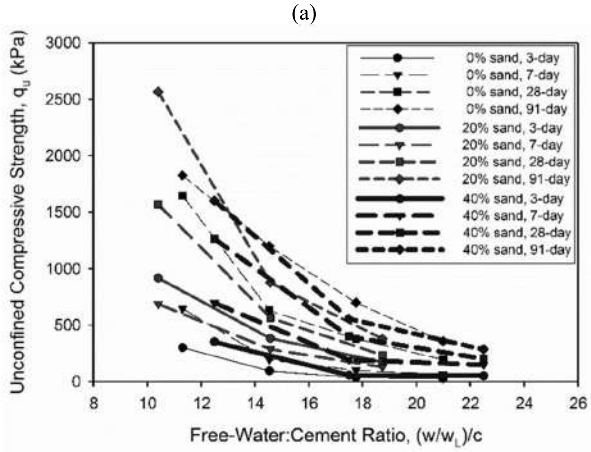


(a) (b) (c)

Figure 8 Influence of water to cement ratio on unconfined compressive strength of cement-treated kaolin clay with soil to cement ratio of 7; (a) 0% sand content (b) 20% sand content (c) 40% sand content



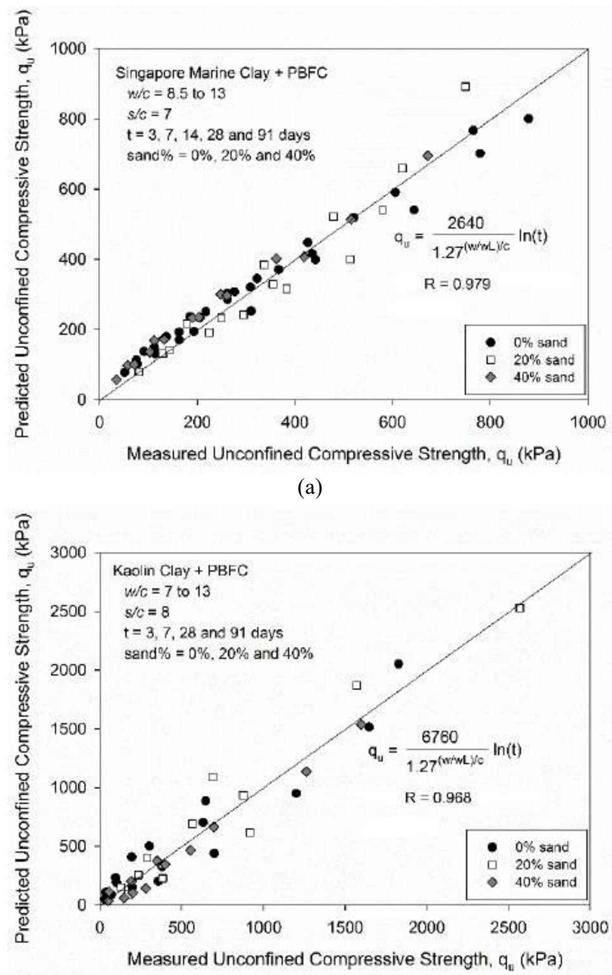
(a)



(b)

Figure 9 Influence of free water to cement ratio on unconfined compressive strength for cement-treated clay with different sand content and curing duration; (a) Singapore marine clay, (b) Kaolin clay

Figure 10 shows the comparison between the predicted and measured strengths of cement-treated Singapore marine clay and Kaolin clay specimens over the range of mixing ratios, curing time and sand content considered in this study. In accordance with Chian et al. (2015a), a single constant is only required in the numerator of Eq. (3) (i.e. parameter X) for each s/c ratio. This is in agreement with the findings in this study, as shown in Figure 10. The matching strength predictions against the measured values for both Singapore marine and Kaolin clays confirm the applicability of the existing model for strength prediction, with merely a change of the *w/c* term to *(w/wL)/c*, as shown in Figure 10.



(a)

(b)

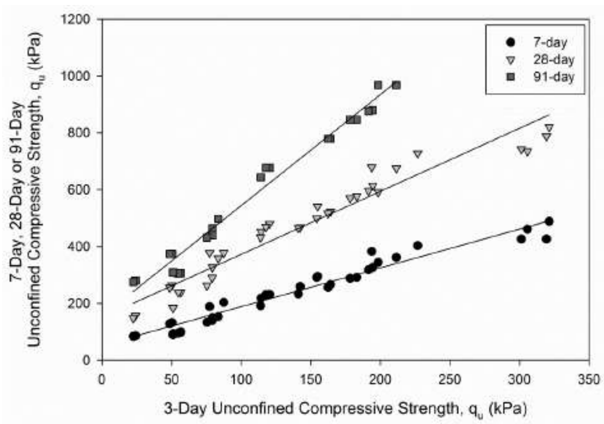
Figure 10 Comparison between predicted and measured unconfined compressive strength of cement-treated clay; (a) Singapore marine clay, (b) Kaolin clay

It is hence confirmed that the effect of sand content in the existing cement-treated clay strength model can be considered using the soil's liquid limit, which accounts for the change in water affinity of the sandy-clay, based on the proposed 'free-water:cement ratio'. These findings can have significant implications with respect to current cement stabilisation practice, where the dosage of cement in ground improvement may have to be altered when encountering sandy clays in the field to achieve a consistent spatial strength performance.

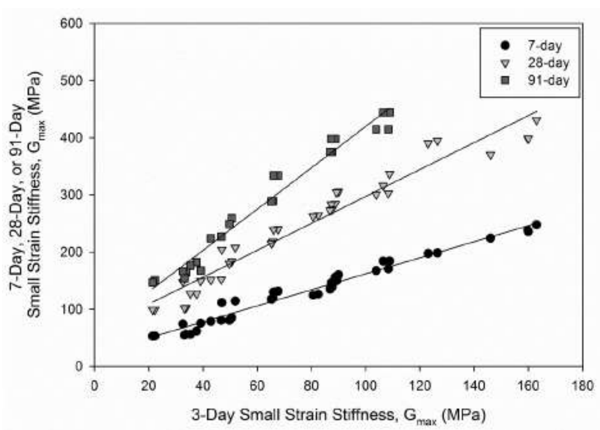
9. EARLY QUALITY CONTROL SCHEMES

9.1 Correlation between Early and Later Age Strength and Stiffness

It was observed earlier in Figure 3 that the strength development with curing time followed a similar trend for 3-day, 5-day, 7-day, 28-day and 91-day curing, suggesting the prospect of predicting later-stage (28-day) strength with the early stage (3-day) results. This is confirmed with Figure 11a, which showed linear relationships between different curing ages, regardless mixing ratios (i.e. *w/c* and *s/c* ratios). Similar observation was also noted for small-strain shear stiffness obtained from bender element tests with the same specimens. Hence, later-age stiffness may also be predicted based on the early-age stiffness based on Figure 11b. Since both correlations persist even with different mix ratios and curing age, similar relationship for other batches should concur as well.



(a)



(b)

Figure 11 Correlation between early-age (3-day) and later-age (7-day, 28-day and 91-day); (a) unconfined compressive strength, (b) small-strain shear stiffness

9.2 Correlation between Strength and Stiffness

Having observed similar strength and stiffness development in Figure 11, analysis was carried out to ascertain the presence of correlation between the two parameters. This is supported by Figure 12, where the unconfined compressive strength (q_u) and small-strain shear stiffness (G_{max}) are strongly correlated with a linear relationship. This indicates a fairly consistent Poisson's ratio (υ) for the cement treated clay samples. The linear trend persists for data obtained from published literatures (Verastegui Flores et al., 2010 and Lu et al. 2011). In addition, the correlation appears to be independent to the curing time and mixing ratios, implying the prospects of wider applications to other types of clay, cement type and curing conditions (Chian et al. 2015b).

In view of the consistent correlation of early- and later-age strength as well as strength to stiffness, they may serve as promising complementary quality control schemes in projects in the field. The portability and non-destructive nature of bender element testing also mean that the number of trial samples can be reduced significantly, along with the ease of testing onsite without the need for transportation and testing samples remotely in laboratories.

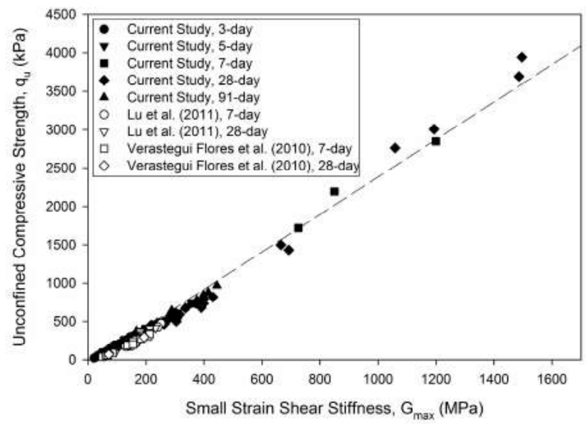


Figure 12 Correlation between unconfined compressive strength (q_u) and small-strain shear stiffness (G_{max})

10. CONCLUSION

The ability for the proposed equation to produce matching prediction of strength over these different clay and cement types, mixing ratios and curing time is encouraging and allows engineers to estimate the strength development of cement treated clays at different *w/c*, *s/c* and *t* by conducting limited mix trials based on the proposed strength model in this study. This is in contrast to many existing predictive models which do not accommodate the effect of *s/c*. In addition, given the robustness of strength estimates derived from the proposed equation at as short as 3 days of curing, the proposed model may also be used to complement existing early quality control schemes and better identify defective mixtures for timely remedial actions in the field. A complementary quality control can also be introduced with the use of portable bender element where small-strain stiffness can be correlated to strength.

The influence of sand content on unconfined compressive strength development of cement-treated clay was also investigated to better represent the field condition of sites where sand impurities are present. It was observed that the conventional *w/c* and *s/c* ratios are insufficient to present a holistic assessment of strength development of cement-treated clays with sand impurities, as the variation in microfabric characteristics and pore spaces induced by sand are not accounted for. The free-water:cement ratio, $(w/w_L)/c$ is introduced and is a more appropriate parameter in assessing strength development of cement-treated clays with sand impurities. Results demonstrate matching estimates of the strength development of such sandy-clay by merely substituting it with the free-water:cement ratio in the pure clay predictive model.

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