Use of elevated curing temperature for accelerated testing of cement stabilized dredged Singapore marine clay

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ABSTRACT
Cement stabilized Singapore marine clay is the material associated with the Stabilized Dredged Fill (SDF) technology practiced in Singapore. A novel accelerated curing/testing procedure is proposed in this study making use of a constant temperature hot water bath. The accelerated testing technique enables the later-age strength (7-day strength in this study) of the SDF material to be forecasted at a very early curing age (~30 hrs).

Laboratory samples are prepared by mixing Singapore upper marine clay at high water content with Portland blast furnace cement. The mixes are designed to reflect the actual constituent proportions on the site. Samples are cured in a hot water bath at 60 ºC for 24 hrs followed by 6 hrs of cooling. Unconfined compression tests and bender element tests are conducted on specimens cured under both accelerated condition (30 hrs) and normal room temperature condition (7 days). Test results show that both the unconfined compressive strength (UCS) and the small-strain shear stiffness (G_{max}) are controlled by the water/cement ratio in either curing condition. Accelerated UCS after 30 hrs of curing can be used to predict 7-day UCS, although it may over-predict by 20%. In addition to the strength-to-strength correlation, stiffness-to-stiffness and strength-to-stiffness correlations are also established between the two conditions. As effective quality control requires early determination of the material later-age strength, these correlations may be used to improve the current SDF quality control.

RÉSUMÉ
L'argile marine de Singapour stabilisé par ciment est un matériau associé à la technologie de remblai de dragage stabilisé («SDF»), qui est pratiqué à Singapour. Une novelle procédure accélérée d'essai et durcissement est proposé dans cette étude avec l'aide du bain d'eau chaude. Le technique d'essai accélérée permet la résistance du matériau de SDF être prévue à un âge très précoce de durcissement (~30 heures).

Les échantillons de laboratoire sont préparées par mélanger de l'argile marine de Singapour avec du ciment de haut fourneau. Les mélanges sont conçus pour refléter les proportions des constituants réels sur le site. Les échantillons sont remédiés dans le bain d'eau chaude à 60 ºC pendant 24 heures suivie par 6 heures de refroidissement. Essais de compression simple et des essais de languettes piézocéramiques sont effectués sur des échantillons durcis sous la condition accélérée (30 heures) et la condition normale de température ambiante (7 jours). Les résultats des essais indiqués que la résistance en compression simple («UCS») et le module de cisaillement à faible déformation («G_{max}») sont contrôlés par le rapport d'eau/ciment dans les deux conditions de durcissement. UCS accélérée après 30 heures de traitement peut être utilisé pour prédire l'UCS de 7 jours, même s'il peut surestimer de 20%. En plus des corrélations de résistance-à-résistance, les corrélations de rigidité-à-rigidité et résistance-à-rigidité sont établies entre les deux conditions de durcissement. Comme contrôle de la qualité efficace exige une détermination rapide de la résistance de mélange d'âge tard, ces corrélations peuvent être utilisées pour améliorer le contrôle de la qualité de SDF.

1 INTRODUCTION

Huge amounts of dredged material are generated from dredging to maintain harbours and channels (Dermatas et al., 2003; Kitazume and Satoh, 2003; Rekik and Boutouil, 2009). Dredged materials are usually clayey soils of high water contents, and are traditionally managed by dumping the soils in disposal sites (Dermatas et al., 2003; Kim et al., 2010). However dumping of these materials in landfill is economically unviable in Singapore. Stabilized Dredged Fill (SDF) technology, which reuses the dredged soils as reclamation filling material, resolves not only the problem of unwanted soil disposal, but also the shortage of reclamation fill (Tan et al., 2010).

Stabilized Dredged Fill (SDF) technology involves mixing the dredged soil at high water content with small amount of stabilizing agent, usually cement. The workable mixture in mayonnaise-like form is then placed after being pumped through a transfer pipeline. SDF technology has become more popular in recent years, notable projects include the Ishinomaki reclamation project (Porbaha et al., 1999; Sakamoto, 1998), Central Japan International Airport man-made island project (Kitazume and Satoh, 2003), and more recently, some parts of the reclamation work for the extension of Haneda Airport (Morohoshi et al., 2010).

The current SDF design criteria focus on the overall stability of the reclamation bund, which is controlled by the strength of the SDF material after curing. 7-day and 28-day unconfined compressive tests are therefore taken as the main parameters of the SDF quality control (QC) scheme in Pulau Tekong land reclamation. Similar QC scheme has been reported by Kitazume and Satoh (2005). However, it would be too late for inexpensive remedial measures to be implemented if defective materials were detected after 28 days of curing. Even 7-day tests are considered late especially when the cement dosage is excessive. There are practical benefits if the expected later-age strength can be predicted at a much earlier curing age, as the young defective material can be much more easily removed as compared to hardened material after prolonged curing.

Higher curing temperature has been found to increase significantly the early strengths of cementitious materials. Though there is limited research on the subject of accelerated testing of cement treated soils using elevated curing temperature, there is much wider recognition of accelerated testing technique on concrete materials (e.g., ACI, 1978; Das Gupta and Tam, 1989; Ozkul, 2001; Tokyay, 1999). Such testing technique has been included in international standards (e.g., ASTM, 2003; BSI, 1983). Accelerated testing technique has been employed as a part of the field quality control of concrete construction from as early as 1930s (Patch, 1933), and has since been reported world-wide (e.g., Bickley, 1978; Ferrer, 1978;Resheidat and Madanat, 1992).

In this study, an accelerated testing procedure is proposed based on a hot water bath to cure SDF material under elevated temperatures. Unconfined compression (UC) tests and bender element (BE) tests are conducted on SDF mixtures under both the accelerated and normal conditions. Later-age (7-day in this study) strength and small-strain stiffness under normal condition are found to be closely correlated to the accelerated strength and small-strain stiffness tests results obtained after only 30 hrs upon mixing.

2 MATERIALS

2.1 Singapore Upper Marine Clay

Soil sample used in this study is Singapore Upper Marine Clay (UMC) dredged from the Pulau Tekong land reclamation site. Soil lumps are broken down using mechanical pan mixer first, after which impurities such as shells and stones are carefully removed. The basic properties of UMC have been reported in various studies (Chin, 2006; Tan et al., 2002). Basic properties of the UMC used in this study are summarized in Table 1.

Table 1 Basic properties of the UMC used in this study

Liquid Limit	Plastic Limit	Specific Gravity
85	36	2.66

2.2 Portland Blast Furnace Cement

Portland Blast Furnace Cement (PBFC) with 65% of slag content is used as the stabilizing agent of the SDF mixtures in Pulau Tekong land reclamation project. The same type of cement is hence adopted in this study. The basic properties and chemical compositions of PBFC are given in Table 2.

Table 2 Basic chemical compositions and physical properties of PBFC used in this study

Chemical Composition	Unit (% w/w)
Silica, SiO_2	39.41
Alumina, Al_2O_3	11.63
Ferric Oxide, Fe_2O_3	3.35
Calcium Oxide, CaO	36.56
Magnesium Oxide, MgO	5.52
Sodium Oxide, Na_2O	0.32
Potasium Oxide, K_2O	1.21
Sulfur Oxide, SO_3	-
Physical Properties	**Value**
Density	3000 kg/m^3
Fineness	404 m^2/kg
Initial Setting Time	~189 mins
Final Setting Time	~225 mins
Soundness	<1mm
Consisency	30%

3 METHODS

3.1 Sample mixture preparation

Samples are pretreated and water contents are determined one day before mixing with cement. Pretreatment is essentially a mixing process in which the sample is homogenized using the Hobart mixer. A small quantity of seawater is introduced into the sample to facilitate pretreatment mixing.

Prior to mixing the soil sample with PBFC, the required additional seawater to achieve a target water/cement ratio is calculated based on the total weight and the water content of the pretreated sample. Desired amount of PBFC is then carefully poured into the mixing bowl. The mixing process takes 10 mins in total, in which one minute is allowed for scraping the materials attached to the side wall and bottom of the mixer bowl using spatula so as to avoid any "dead corners" of the machine mixing. The Hobart mixer operates at a constant rate of 180 rpm. The total unit weight and the water content of the mixture are taken upon completion of mixing to monitor the consistency of the mixture.

3.2 Test specimen preparation

The mixture is placed into plastic molds of 50 mm in diameter and 100 mm in height immediately after mixing. To minimize the air voids trapped inside the specimen, the mixture is compacted following a standardized working procedure: the mixture is placed into the mold in three layers (40% full, 80% full and 100% full, respectively), and the mixture is compacted after each layer has been placed. The manual compaction is performed by slowly tamping the mold along with the mixture on the ground by fixed number of blows (60 blows per layer). Similar specimen making procedure has been reported by Tan et al. (2002).

3.3 Proposed accelerated curing procedure

Immediately following the specimen-making, the specimens to be cured under accelerated curing condition are fully immersed in seawater in the constant temperature water bath. The seawater temperature is maintained at 60 ºC from the point of immersion, and the constant temperature is maintained throughout the entire curing period (24 hrs) as well.

Besides the limited research on the effect of higher curing temperature on the strength of stabilized soil, little attention has been directed to the specimen cooling regime prior to testing, which is inevitably associated with the high temperature curing. Cooling regime is generally not documented (e.g., Clare and Pollard, 1954; Marzano et al., 2008; Noble and Plaster, 1970), or at best specimens are cooled by subjecting them to a sudden drop in ambient temperature from 60 ºC to ~22 ºC (e.g., Biswas, 1972; Chitambira et al., 2007). Baghadi (1982) reported specimen disintegration when the cooling period is less than 30 mins though there was also no in-depth investigation on the causes of such damage. Kim et al. (1998) suggested gradual cooling regime should be applied to avoid any damage to the specimen, but the subject of the study by Kim et al. (1998) was concrete .

To avoid "thermal shock", i.e. a sudden drop in temperature that may cause damage to the specimen, a cooling regime is hence proposed in this study. After the 24-hr curing period in the 60 ºC water bath, the specimens are immediately transferred into a plastic box (L 25cm by W 18cm by H 14cm) containing seawater preheated to 60 ºC as well. The box with specimens immersed in seawater inside with the cover closed is then allowed to cool down naturally in air. The seawater time-temperature history is observed to vary little from test to test. Figure 1 shows the time-temperature history of the cooling regime from five independent measurements. Based on these results, it is judged that specimens cooled for 6 hrs in the cooling box prior to testing would not be subjected to significant thermal shock.

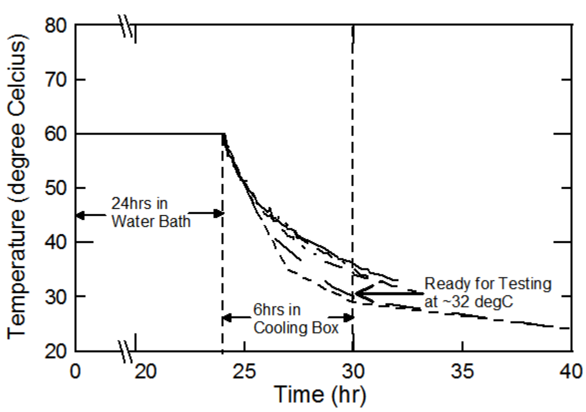

Figure 1. Temperature-time history of the accelerated curing stages with cooling regimes obtained from five independent measurements

3.4 Testing programme

Both bender element (BE) tests and unconfined compression (UC) tests are conducted. Because BE tests are non-destructive, the BE test precedes the UC test on each specimen. Specimens of varied sample constituents proportions under both the normal room temperature curing condition (room temperature = 22±2 ºC) and accelerated curing condition (24 hrs at 60 ºC followed by 6 hrs of cooling, refer to section 3.3) are tested. The specimens are tested in triplicate for both the UC and BE tests at specified curing time under each curing condition. The detailed testing plan is summarized in Table 3. The mixes are designed based on the practical range of the SDF constituent proportions in Pulau Tekong land reclamation project.

UC tests are conducted following British Standard (BSI, 1990). The details of the BE test are elaborated in section 3.5.

Table 3. Summary of testing programme of this study

w/s ratio	w/c ratio	s/c ratio	UC test		BE test	
			30-hr	7-day	30-hr	7-day
150	7.50	5.0	•	•	•	•
180	9.00	5.0	•	•	•	•
135	7.43	5.5	•	•		
165	9.08	5.5	•	•		
185	10.18	5.5	•	•		
142	8.50	6.0	•	•	•	•
175	10.50	6.0	•	•	•	•
135	9.45	7.0	•	•		
165	11.55	7.0	•	•	•	•
185	12.95	7.0	•	•		
140	11.20	8.0	•	•	•	•
155	12.40	8.0	•	•	•	•
170	13.60	8.0	•	•	•	•
135	11.48	8.5	•	•		
155	13.18	8.5	•	•		
150	13.50	9.0	•	•	•	•
139	12.50	9.0	•	•	•	•
135	13.50	10.0	•	•		
140	14.00	10.0	•	•		

Note: (1) 30-hr refers to the accelerated curing condition and 7-day refers to the normal curing condition. (2) w = mass of water, s = mass of soil solid and c = mass of cement

3.5 Bender element test

Shear-wave velocity (v_s) is measured from the bender element (BE) test and the small-strain stiffness of the specimen can be obtained from the relationship

$$G_{max} = \rho \cdot v_s^2 \quad [1]$$

where ρ is total density of the specimen.

The BE test has become increasingly popular over the past decade or so. The popularity received by the BE test may be attributed to its simplicity and non-destructive nature, which features make the BE test a promising Quality Control (QC) tool in SDF works. Basic testing and interpretation procedures can be found in Yamashita et al. (2009). In this study, the GDS bender element system is used for the shear wave velocity measurements. Signals are interpreted using the cross-correlation method proposed by Viggiani and Atkinson (1995). The associated code is written in MATLAB for signal interpretation purpose.

The shear wave velocity measurements are performed in quadruplicate on each specimen. Very consistent velocity measurements are obtained, showing error margin <±1% and therefore the average values are used for analyses. BE test results presented in this paper are based on transmitted signal frequency of 5 kHz at 500k/s sampling rate. Sinusoidal waveform is adopted in this study.

4 RESULTS AND DISCUSSIONS

4.1 Effect of water/cement ratio on unconfined compressive strength

7-day unconfined compressive strength (UCS) is plotted against water/cement ratio in Figure 2. As can be seen in Figure 2, the 7-day UCS is a function of the mixture water/cement ratio regardless of its corresponding soil/cement ratio. This observation is in line with those studies conducted on similar materials, i.e. cement treated soft marine sediments at very high water contents (Boutouil and Levacher, 2005; Horpibulsuk et al., 2003; Liu et al., 2008; Miura et al., 2001; Rahman and Taiyab, 2008).

On the other hand, accelerated UCS is plotted against water/cement ratio in Figure 3. Similar to UCS under normal curing condition, the accelerated UCS is also controlled by the mixture water/cement ratio regardless of the corresponding soil/cement ratio.

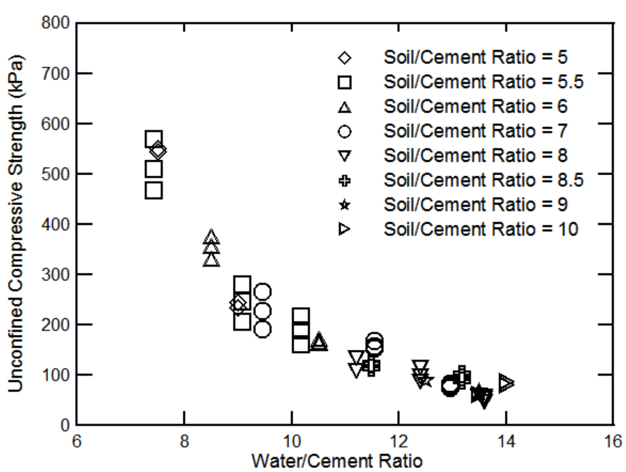

Figure 2. 7-day UCS versus water/cement ratio

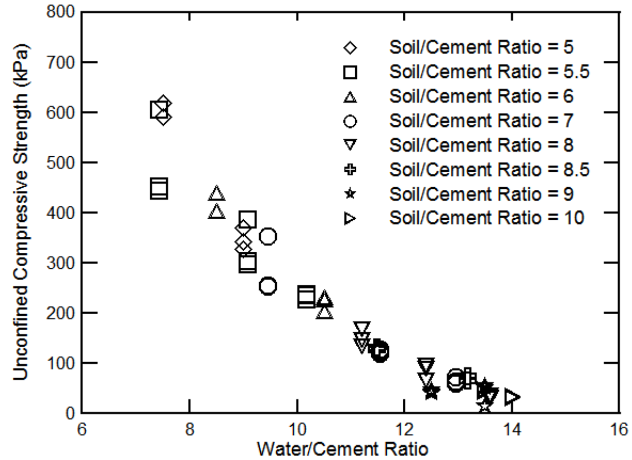

Figure 3. Accelerated UCS versus water/cement ratio

4.2 Small-strain stiffness

Small-strain shear moduli (G_{max}) are plotted against the corresponding UCS in Figure 4. It appears that the mixtures cured under normal condition show higher G_{max} than those of the same strengths cured under accelerated condition.

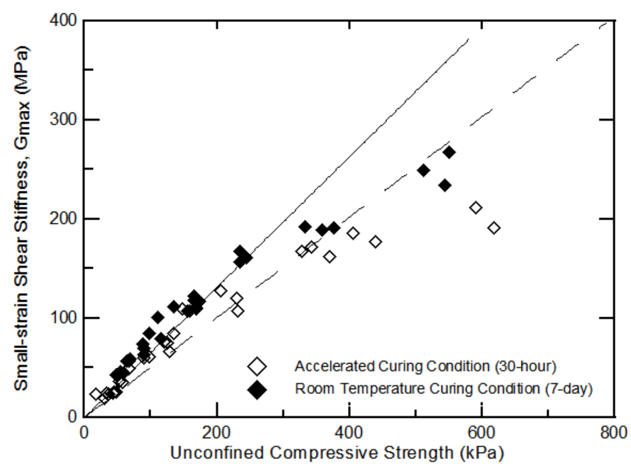

Figure 4. Relationship between G_{max} and UCS

Figure 5 and Figure 6 show G_{max} versus water/cement ratio under normal and accelerated curing conditions, respectively. Under either curing condition, G_{max} follows a function of water/cement ratio. To the authors' knowledge, no study has been conducted on the relation between G_{max} and water/cement ratio. It is interesting to observe in this study that G_{max} is also governed primarily by the water/cement ratio. This trend is similar to that discussed for UCS.

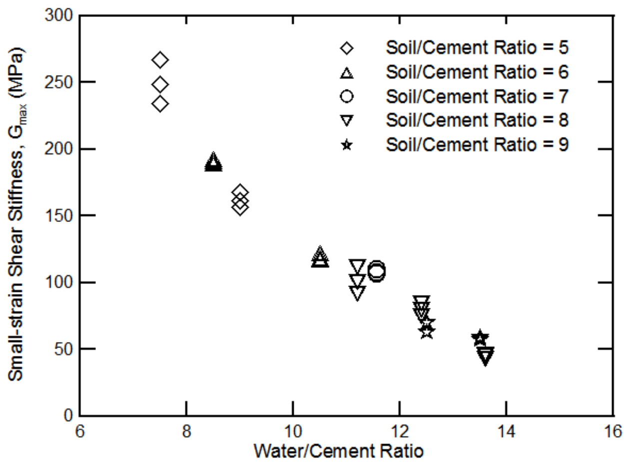

Figure 5. 7-day G_{max} vs. water/cement ratio

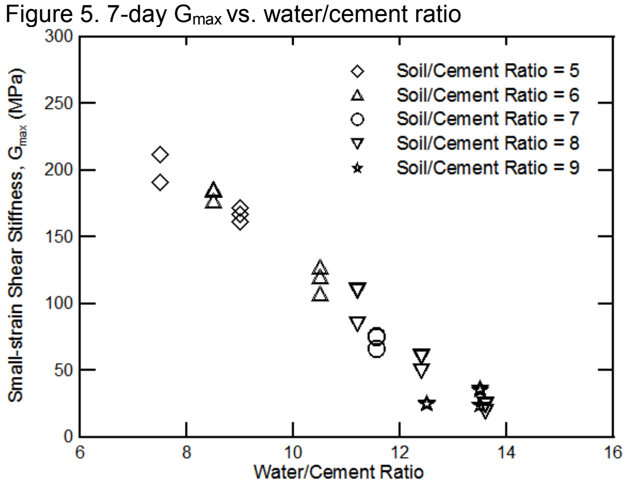

Figure 6. Accelerated G_{max} vs. water/cement ratio

4.3 Rigidity index

Given the similar trends shown above for UCS versus water/cement ratio (Figure 2 and Figure 3) and G_{max} versus water/cement ratio (Figure 5 and Figure 6), it is worthy to explore the effect of water/cement ratio on the rigidity index, $I_r = G_{max}/(0.5UCS)$, as shown in Figure 7 and Figure 8. The Cam-Clay framework predicts that the rigidity index decreases with OCR and undrained shear strength increases with OCR, i.e. the rigidity index decreases with strength. Since strength decreases with the water/cement ratio as shown in Figure 2 and Figure 3, the observed trends shown in Figure 7 and Figure 8 are in agreement with the Cam-Clay framework.

4.4 Correlation between strengths under normal and accelerated curing conditions

Since strengths under both curing conditions are functions of water/cement ratio, a distinct correlation must exist between the strengths attained under the two curing conditions. Figure 9 shows 7-day UCS under normal condition plotted versus accelerated UCS. Symbols in Figure 9 represent the average values of the test results obtained in triplicate and the corresponding error bars are included

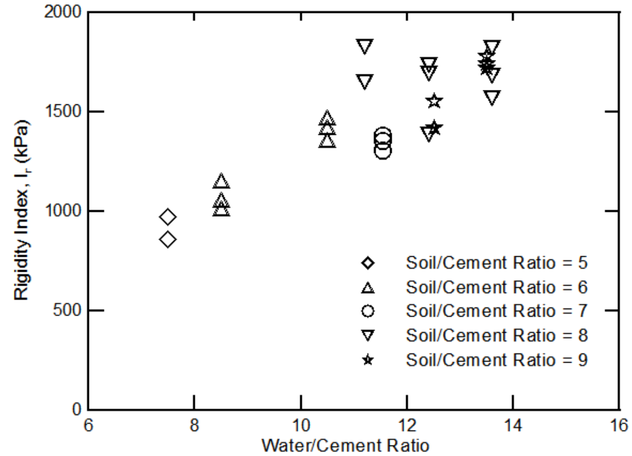

Figure 7. 7-day rigidity index I_r, vs. water/cement ratio

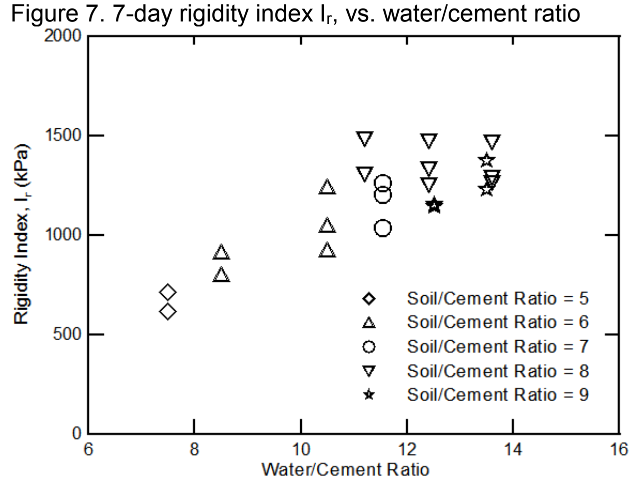

Figure 8. Accelerated rigidity index, I_r vs. water/cement ratio

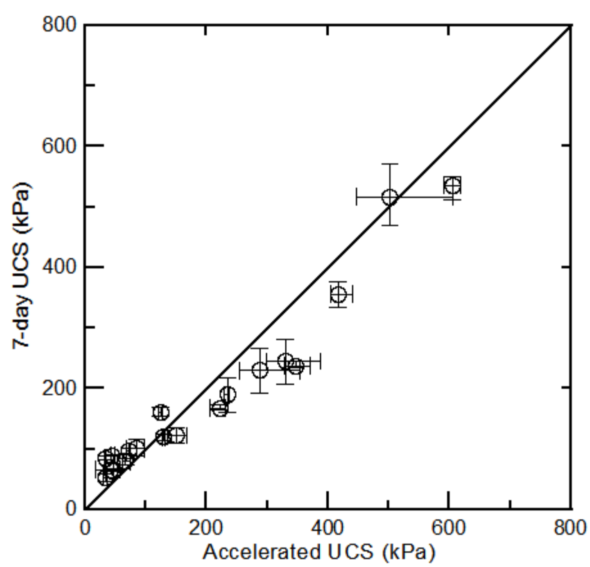

Figure 9. 7-day UCS versus accelerated UCS

The correlation shown in Figure 9 suggests that accelerated UCS after 30-hour curing can be used to predict 7-day UCS, although it may over-predict by 20%.

4.5 Correlation between shear moduli under normal and accelerated curing conditions

Similar to strength, since G_{max} under both curing conditions are also functions of water/cement ratio, a distinct correlation exists between the moduli under the two curing conditions too. Figure 10 shows the average normal 7-day G_{max} versus the G_{max} under accelerated curing condition. Error bars are included in Figure 10 as well

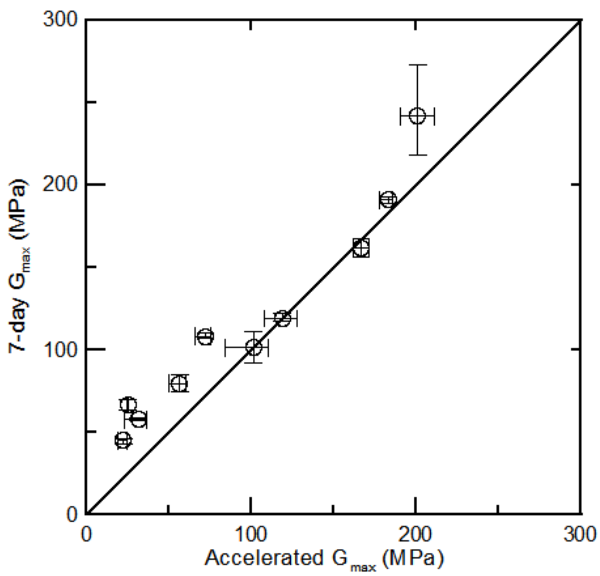

Figure 10. 7-day G_{max} versus accelerated G_{max}

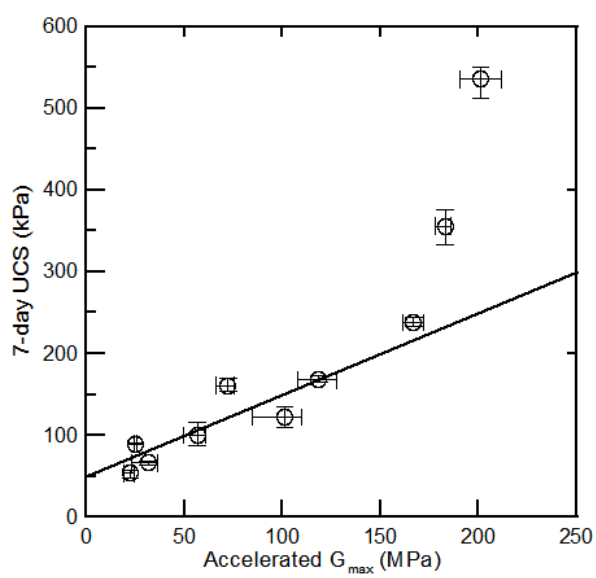

Figure 11. 7-day UCS versus accelerated G_{max}

4.6 Correlation between strengths under normal curing condition and shear moduli under accelerated curing condition

Applying the same concept elaborated in section 4.4 and 4.5, Figure 11 shows that the normal 7-day UCS is closely correlated to the corresponding G_{max} under accelerated curing condition, as both parameters are governed by the water/cement ratio. And similar to the strength-strength correlation (section 4.4), bender element test and hence the strength-stiffness correlation established between the normal and accelerated curing conditions may be used as the QC tool for SDF works as well.

5 CONCLUDING REMARKS

The applicability of the accelerated testing technique using elevated curing temperature is investigated in this study. Specimens arising from the same batch of mixture were separately cured under the two different curing conditions, namely the normal 7-day curing at room temperature (22±2 ºC) and accelerated curing using elevated temperature (60 ºC for 24 hrs). Both the strength testing (UC test) and the non-destructive small-strain stiffness testing (BE test) were included in the testing programme. Based on the experimental results, the following conclusions can be made:

(1) The mixture water/cement ratio governs the material strength under both the normal and accelerated curing conditions.
(2) The mixtures cured under elevated curing condition show lower small-strain shear stiffness than those of the same strength but cured under normal condition.
(3) Similar to strength, the small-strain shear stiffness is a function of water/cement ratio too.
(4) Accelerated UCS after 30 hrs of curing can be used to predict 7-day UCS, although it may over-predict by 20%.
(5) Accelerated testing technique, which involves the unconfined compressive strength test and bender element test, demonstrates its applicability as a quality control tool for the SDF land reclamation works. Accelerated testing results (strength and small-strain stiffness) may be used to forecast the material later-age strength (7-day strength in this study) at a much earlier age (~30 hrs upon batching), which will greatly benefit the SDF land reclamation works not only technically but also economically.

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