Small strain shear modulus of high cement-admixed marine clay with fibers

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ABSTRACT: This paper presents a laboratory study, using bender element testing and unconfined compression test, on the small strain shear modulus (G_{max}) of high cement-admixed Singapore marine clay with fibers. The cylindrical specimens tested contain 50% to 100% cement, 100% to 133% water by mass, 0% to 3.04% fibers by volume, and 7 to 28 days of curing. Two different fibers with 6 mm cut lengths, i.e., polypropylene (PP6) and polyvinyl alcohol (PVA6), were adopted. The results showed that the G_{max} of cement-admixed clay increases after adding fiber. It was found that G_{max} increases with increasing cement content and curing period and decreasing water content. However, the G_{max} variation with fiber content seems to be minor when fiber content is not lower than 2.28%. The results indicate that fiber reinforcement has more effect on G_{max} in specimens with higher cement content (75%-100%) and longer curing period (28 days). Fiber reinforcement has slightly more effect on G_{max} of specimens reinforced with PVA6. Furthermore, it was observed that G_{max} can be linearly related to the unconfined compressive strength q_u. However, the fiber introduction will reduce the ratio of G_{max} to q_u by about 10%, compared to cement-admixed clay without fibers.

RÉSUMÉ : Dans cet exposé, une étude de laboratoire à travers des éssaies de bender éléments et de compression non-confinées est présentée sur le module de cisaillement maximal de l'argile marine de Singapour traitée en haute teneur de ciment et renforcée avec fibres. Les échantillons cylindriques sont composés de 50% à 100% de ciment, 100% à 133% d'eau par poids, 0% à 3.04% de fibres par volume, et le temps de durcissement varie de 7 à 28 jours. Deux différents types de fibres de longueur 6 mm sont utilisés, notamment le polypropylène (PP6) et alcool de polyvinyle (PVA6). Les résultats ont démontré que le Gmax de l'argile traité au ciment s'accroit avec l'ajout de fibres. Il a été constaté que le Gmax s'accroit avec la teneur en ciment et le temps de durcissement, de même qu'une réduction en teneur d'eau. Cependant, le changement de Gmax avec la teneur en fibres semble mineur à une teneur de pas moins de 2.28%. Les résultats sont démontrés que l'effet des fibres sur Gmax est plus conséquent sur les échantillons en haute teneur de ciment (75%-100%) et avec une plus longue période de durcissement (28 jours). Les fibres de PVA6 ont plus d'influence sur Gmax. De plus, on remarque une relation linéaire entre Gmax et la contrainte de compression non-confinée qu. Cependant, l'addition de fibres va réduire la proportion de Gmax à qu par environ 10%, en comparaison avec l'absence de fibres.

KEYWORDS: small strain shear modulus, fiber, cement-admixed clay, bender element, unconfined compressive strength.

1 INTRODUCTION.

Cement stabilization is used widely in many areas such as deep excavation and underground construction works, in which the cement content is typically at least 20% or higher (e.g. Gallavresi 1992, Uddin et al. 1997, Lambert et al. 2012, Melentijevic et al. 2013). However, the cement stabilized soil may fail suddenly under loading due to its brittle nature, leading to the adoption of high safety factor during design, or it may be rendered unacceptable for use at high cement content. To overcome this limitation, fibers are added into the cement soil mix to improve the ductility as well as maintain the strength of the treated soil (e.g. Maher and Ho 1993, Consoli et al. 2003, Tang et al. 2007, Ud-din et al. 2011, Xiao et al. 2013, 2014, 215). For improved soil systems designed to be far from failure, such as those supporting urban excavations, the mobilized strains in the ground are typically small. A good knowledge of the improved soil stiffness at small strain is essential for realistic predictions of the ground movements that may affect adjacent buildings or underlying infrastructure.

The use of bender element for soil testing was first introduced by Shirley & Hampton (1977). It is a simple technique to obtain the very small strain, elastic shear modulus G_{max} of a soil by measuring the propagation velocity of a shear wave through a specimen. There have been many discussions on the selection of the travel length and travel time for shear wave velocity determinations with bender elements. For the travel length, the tip-to-tip distance is usually adopted, which is supported by data from other studies (e.g., Dyvik and Madshus 1985, Viggiani and Atkinson 1995). Cross-correlation was first introduced by Viggiani and Atkinson (1995) in laboratory bender element testing and shown to be efficient to reduce the uncertainty in identifying the arrival time if the transmitted shear wave retains its wave shape or frequency, even after it passed through the soil. Much research have been conducted on both untreated soil (e.g., Viggiani and Atkinson 1995, Lee and Santamarina 2005, Fonseca et al. 2008, Yamashita et al. 2009) and cement-treated soil (e.g., Bahador and Pak 2012, Flores et al. 2010, Fatahi et al. 2013) with bender element testing, most of which involve either sand or Kaolin clay. For cement-treated soils, the cement content is usually less than 10%.

This paper presents a laboratory study, using bender element testing (BET) and unconfined compression testing (UCT), on the small strain shear modulus (G_{max}) response of high cement content admixed Singapore marine clay with fiber reinforcement. The cylinder specimens contain 50% to 100% cement, 100% to 133% water by mass, 0% to 3.04% fibers by volume and 7 to 28 days of curing period. Two types of fibers with 6 mm cut length will be investigated. The factors affecting the G_{max} values of fiber-reinforced cement-admixed clay will be discussed. The empirical relationship between G_{max} and unconfined compressive strength q_u will also be discussed.

2 TESTING PROGRAM

2 .1 *Testing materials*

The materials used in this study are Singapore upper marine clay, type I Ordinary Portland Cement (OPC) and fibers. The constituents of the clay are 24.13% colloid, 21.77% clay, 47.71% silt and 6.39% very fine to medium sand. The plastic and liquid limit of the clay is 31% and 74% respectively. Two different fibers were used, namely polypropylene (PP) and polyvinyl alcohol (PVA) fibers. The properties of the fibers are given in Table 1. A naphthalene-based superplasticizer (Rheobuilder 1000) was used in some mixtures for workability purpose.

2.2 *Specimen preparation*

The cement soil mix ratio will be expressed in the form of S:C:W wherein S is mass of soil solids, C the mass of cement and W the mass of water at the point of mixing. The cement content Aw is defined as the ratio of mass of cement to the mass of soil solids. The water content Cw is defined as the ratio of mass of water to the total mass of soil solids and cement. In this study, following Xiao et al. (2013), the fiber content is defined as the ratio of volume of fiber to the total volume of the mixture at the point of mixing, and ranges from 0 to 3.04%. The mix ratios used in this study are listed in Table 2.

Table 1 Physical and mechanical properties of fibers

Fiber type	L (mm)	D (μm)	Aspect ratio	σ_t (MPa)	E (GPa)	ρ (kg/m^3)
PP6	6	26	231	540	7	910
PVA6	6	26	231	1600	40	1300

Table 2. Mix ratio used in this study.

Mix proportion S:C:W	Fibre content (%)	Aw (%)	Cw (%)	Curing period (days)
2:1:3	0-3.04	50	100	7, 28
4:3:7	0-3.04	75	100	7, 28
1:1:2	0-3.04	100	100	7, 28
2:1:4	0-3.04	50	133	7, 28

The remoulded marine clay was mixed with the cement slurry with the water-cement ratio needed to achieve the desired mix ratio in a Hobart Mixer at a rotational speed of 125rpm for around 5 minutes. The fiber was added to the cement soil mix and mixed for another 10 minutes. For mixtures with water content of 100%, the superplasticizer was used to improve their workability. The dosage of the superplasticizer was 1.13-2.27l/100kg soil+cement solids. The mixture was then carefully placed into 50mm (diameter) by 100mm (height) cylindrical polyvinyl chloride (PVC) split-moulds. No compaction was applied during placement. The cylindrical specimens were then submerged in distilled water for curing.

2.3 *Bender element test*

The small-strain shear modulus, G_{max}, is related to the velocity of shear wave as follows:

$$G_{max} = v_s^2 r \tag{1}$$

where G_{max} is small-strain shear modulus; v_s is shear wave velocity at small strains; and ρ is mass density of soil specimen. The measurement of shear wave velocity using the bender element technique allows estimation of small-strain shear modulus through Eq.1.

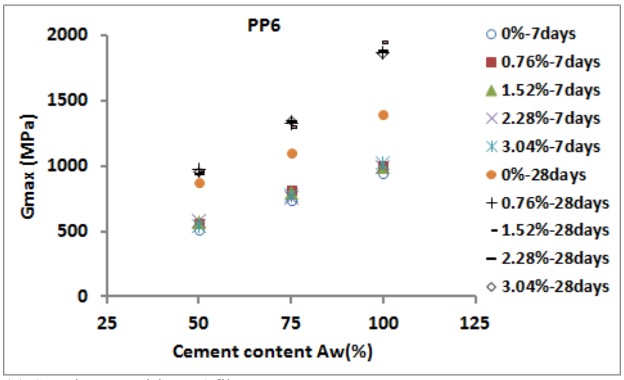
The bender elements used in this study were made by GDS Company, UK. The bender elements are 10 mm wide, 0.5 mm thick, with a protrusion distance of 1.5 mm. The weight of each soil specimen was measured, along with its diameter and length dimensions, prior to the BET test in order to determine the unit weight and mass density of the soil specimen. Both transmitter and receiver bender elements were then inserted into slots made carefully at both ends of the soil specimens. A series of bender element tests were conducted under unconfined condition by sending a sinusoidal pulse of ±14 V amplitude to the BET transmitter. The signal was triggered at regular intervals of 10 ms. A driving frequency ranging from 5 to 10 kHz was selected until the received signal showed a wave with well-defined amplitude and shape. This method was also adopted by other researchers (e.g., Bahador and Pak, 2012; Flores et al., 2010).

The UCT test procedure followed those prescribed in ISO/TS 17892 (2004). The strain rate used for the unconfined compression test was 1.32%/min.

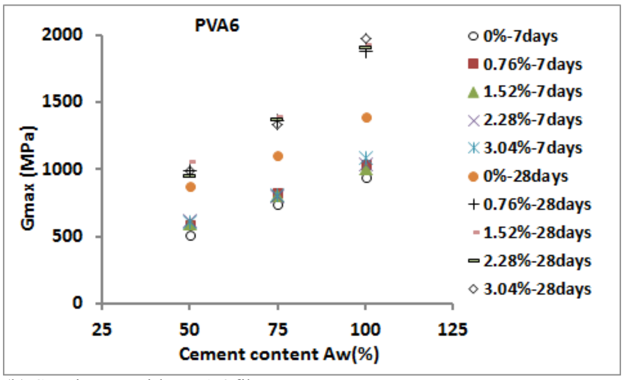
3 EXPERIMENT RESULTS AND ANALYSIS

The cross-correlation method was applied to identify the traveling time. The travel length is the tip to tip distance, which is the height of the specimen minus 3mm. Once the shear wave velocity is obtained and density is measured, the shear modulus can be estimated using Eq. 1.

Figures 1 to 2 present the relationships between the small strain shear modulus G_{max} and (i) cement content Aw and (ii) water content Cw respectively, for fiber-reinforced cement-admixed marine clay (FRCMC) specimens with different curing period and fiber content. Figure 1 shows that G_{max} of FRCMC specimens increase with the increase in cement content and curing period, while Figure 2 shows that G_{max} decreases with increasing water content. This is similar to the behavior of cement-admixed marine clay (CMC, 0% fiber) specimen. However, for specimens with longer curing period (28 days), the effect of cement content on the G_{max} of FRCMC specimens is more significant than that of CMC. Therefore, the cement content effect in FRCMC specimens is dependent on curing period. On the other hand, the water content effect on the G_{max} seems to be the same for both FRCMC and CMC specimens.



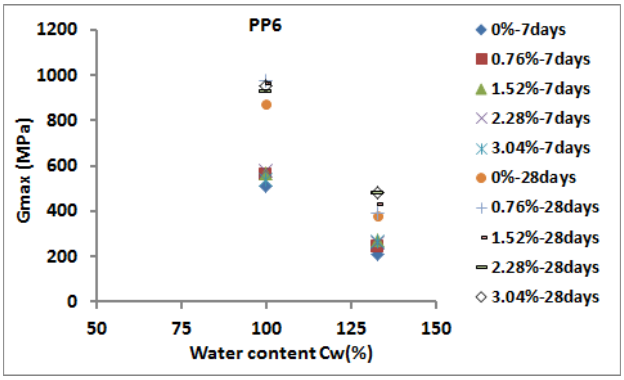
(a) Specimens with PP6 fibers.



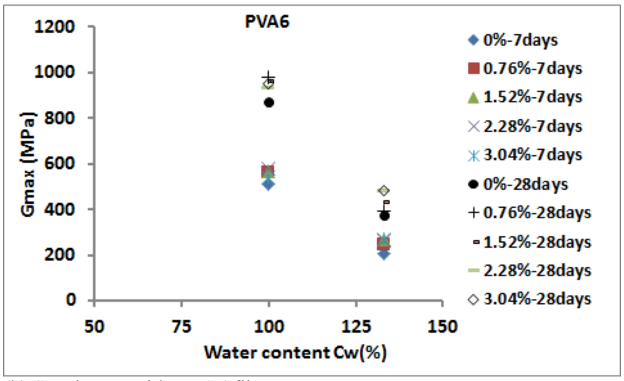
(b) Specimens with PVA6 fibers.

Figure 1. G_{max} versus cement content for specimens with different curing period and fiber content.

To investigate the fiber effect on G_{max}, the small strain shear modulus of FRCMC G_{max} was normalized with that of CMC, herein denoted as G_{max1}. Figure 3 shows the variation of the normalized G_{max} (G_{max}/G_{max1}) with fiber content for FRCMC specimen with 50% of cement content. As can be seen from Figure 3, for specimen with 50% of cement content and 7 days of curing, the normalized G_{max} increases about 20% to 50% and 10% to 20% for specimens with 133% and 100% water content respectively, when the fiber content increases from 0% to 2.28%. For specimens with 28 days of curing, the normalized G_{max} increases about 10% to 30% and 10% for specimens with 133% and 100% water content respectively. This indicates that, for specimen with 50% of cement content, there is more significant increase in small strain shear modulus for specimens with higher water content and shorter curing period (7 days).



(a) Specimens with PP6 fibers.

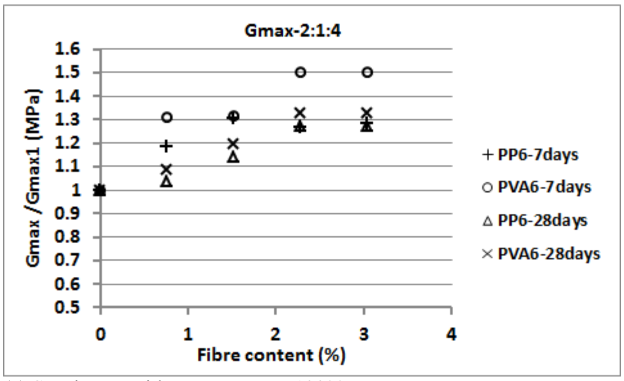


(b) Specimens with PVA6 fibers.

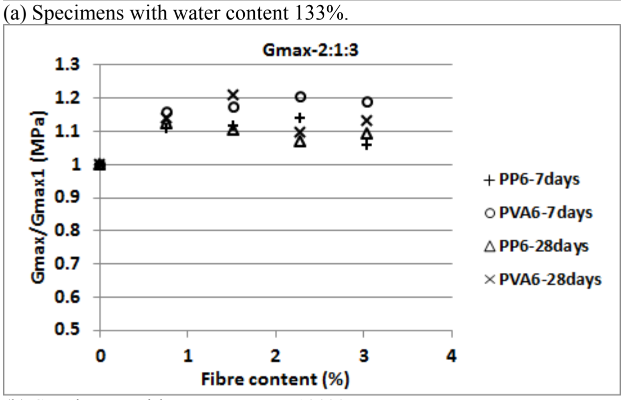
Figure 2. G_{max} versus water content for specimens with different curing period and fiber content.

Figure 3 also shows that the normalized G_{max} seems to stabilize at 25% to 50% and 10% to 20% for specimens with 133% and 100% water content respectively, when fiber content is higher than 2.28%. Therefore, the optimal fiber content may be considered as 2.28% for specimens with 50% of cement content. Figure 3 also shows that the normalized shear modulus of specimens with PVA6 seems to be slightly higher than those obtained using PP6, for the same curing period and mix ratio.

Figure 4 presents the variation of normalized G_{max} with fibre content for FRCMC specimen with 75% to 100% of cement content and 100% of water content. As Figure 4 shows, the normalized G_{max} does not change significantly with fiber content and almost stabilizes at 2.28% of fibre content. Furthermore, the normalized G_{max} increases quite significantly with curing period. For 7 days cured specimens, this stabilized value is about 1.1, whereas for 28 days cured specimens, the stabilized value is about 1.2 to 1.35. Therefore, for 28 days cured specimens with 75% to 100% of cement content, the G_{max} can be increased by about 20% to 35% after adding fibers. This indicates that the fibre effect on G_{max} is more significant for specimens with higher cement content (75% to 100%) and longer curing period (28 days), which is different from that of specimens with 50% of cement content. Figure 4 also shows that the shear modulus of specimens with PVA6 fibers is slightly higher than those with PP6 fibers.

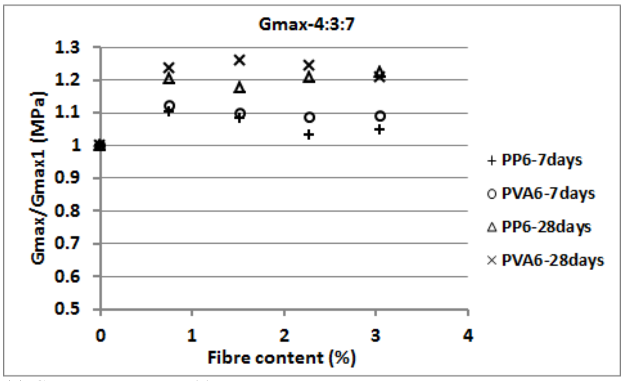


(a) Specimens with water content 133%.

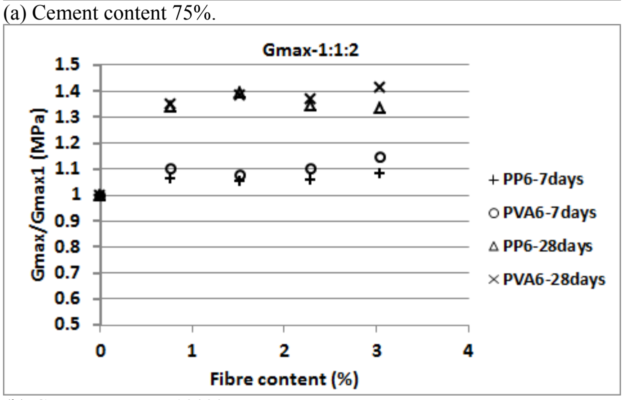


(b) Specimens with water content 100%.

Figure 3. Fiber effect on Gmax for specimens with 50% of cement content.



(a) Cement content 75%.



(b) Cement content 100%.

Figure 4. Fiber effect on G_{max} for specimens with 100% of water content.

Figure 5 shows the relationship between small strain shear modulus G_{max} and unconfined compressive strength q_u for both FRCMC and CMC specimens. As can be seen from Figure 5, there is an approximately linear relationship between G_{max} and

q_u for both FRCMC and CMC specimens, which can be expressed as follows:

$$G_{max} = 0.433 q_u \quad (2a)$$

$$G_{max} = 0.384 q_u \quad (2b)$$

These relationships provide a convenient way to estimate the small strain shear modulus by conducting UCT test, which can be done more easily in the laboratory. According to Figure 5 and Eq. 2, the fibre introduction will reduce the G_{max}/q_u ratio by about 10%, compared to CMC soil.

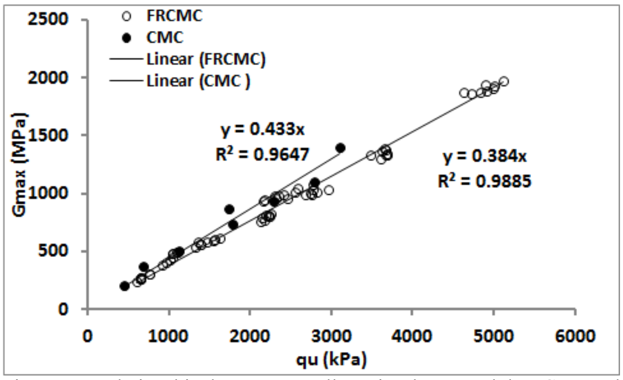


Figure 5. Relationship between small strain shear modulus G_{max} and unconfined compressive strength q_u.

4 CONCLUSION

The results from this study showed that the G_{max} of cement-admixed clay increases after adding fibers. It was found that the G_{max} increases with the increase in cement content and curing period as well as the decrease in water content, which is similar to the behavior of cement-admixed clay without fibre reinforcement. However, the G_{max} variation with fibre content seems to be quite minor when the fiber content is not lower than 2.28%. The results indicated that fibre reinforcement has more effect on G_{max} of specimens with higher cement content (75%-100%) and longer curing period (28days). The G_{max} of these specimens can be 20% to 35% higher than that of specimens without fibers. Fiber reinforcement has slightly more effect on G_{max} of specimens reinforced with PVA6. Furthermore, it was observed that the G_{max} is approximately linearly related to unconfined compressive strength q_u for both specimens with and without fibers. However, the fiber introduction will reduce the G_{max}/q_u ratio by about 10%.

5 ACKNOWLEDGEMENTS

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