Small-strain shear modulus of soft clay treated with Saccharomyces cerevisiae and cement

Module de cisaillement à petites contraintes d'argile molle traité avec Saccharomyces cerevisiae et ciment

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ABSTRACT: Soil stabilisation by means of microorganisms is an emerging and novel technique in geotechnical engineering. On the other hand, cementation, as one of the conventional ground improvement techniques, has been proved to be an effective method to enhance the engineering properties of soils. Hence, it is believed that the combination of these two approaches can be extremely valuable and offer a novel, cost effective, environmentally friendly and practical engineering solution. In this study, the Saccharomyces cerevisiae, a species of yeast, has been selected owing to abundance and production cost to conduct the experiment in order to investigate its influence on the shear wave velocity and the small-strain shear modulus of cement stabilised clays using bender element test. It is observed that an appropriate amount of Saccharomyces cerevisiae can adequately improve the stiffness of soft clays treated with cement and microorganisms in long term.

RÉSUMÉ: La stabilisation du sol par microorganisme est une application prometteuse et attrayante en génie géotechnique. D'autre part, la cémentation, comme l'une des techniques conventionnelles d'amélioration du sol, s'est révélée être une méthode efficace pour améliorer les propriétés d'ingénierie des sols argileux. Par conséquent, on pense que la combinaison de ces deux approches peut être extrêmement précieuse à la lumière de leurs avantages potentiels, y compris le rendement élevé, économique, respectueux de l'environnement et ainsi de suite. Il en résulte que Saccharomyces cerevisiae a été choisie en raison de ses grandes supériorités pour conduire l'expérience afin d'étudier ses influences sur la vitesse d'onde de cisaillement et le module de cisaillement à petite déformation de l'argile stabilisée au ciment en utilisant l'essai d'élément de pliage. On observe que la quantité appropriée de Saccharomyces cerevisiae peut améliorer de manière adéquate la vitesse de l'onde de cisaillement et la raideur supplémentaire de petites déformations des argiles de kaolinite traitées avec du ciment.

KEYWORDS: Ground improvement, small-strain shear modulus, shear wave velocity, bender element test, microorganisms

1 INTRODUCTION

With the recent advancement in geo-biological engineering, bio-clogging, bio-cementation and bioengineering techniques, are gaining their increasing popularities and employed by many researchers in the ground improvement field. Biological additives such as microbes, have demonstrated their contribution in influencing soil engineering properties such as shear strength, stiffness, and permeability (DeJong et al 2010; Mitchell and Santamarina 2005). Hence, they have the potential to be adopted as an effective ground improvement technique to deliver new solutions considering both economic and environmental aspects. As mentioned by Ivanov and Chu (2008), in both bio-clogging and bio-cementation processes, altering the strength and permeability is mainly achieved due to the microbial induced calcite precipitation, which is a process of the microbial reaction of producing carbon compounds then initiating the formation of calcium carbonate that can fill the pores and bind soil particles. This concept can be traced back to the late 1990s, when researchers at Geo-Delft were inspired to stimulate bacteria underground to breakdown contaminants, and then discovered that the bacterial reaction can lead to local clogging of pores. In addition, later in 2005, along with the development of a technique known as Bio-Sealing (or bio-clogging), researchers successfully sealed the leaks in clay as well as peat layers (Paassen and Molendijk 2009). Moreover, according to Stabnikov et al. (2011), generated binding products through microbial activity reduce the permeability of urease producing bacteria treated sand from 10^{-4} m/s to 1.6×10^{-7} m/s. The aforementioned literature has demonstrated that it is feasible to use bacteria as an effective additive in improving the engineering properties of soils.

Although some research has been conducted to explore the mechanical properties of different types of soils treated with bacteria or microorganisms, there is a lack of studies on the effect of bacteria on the small-strain properties of cemented clays. As observed by Trhlikova et al. (2012), small-strain shear modulus of kaolinite clay can be significantly enhanced by cementation. In addition, the authors believe that solely relying on the effects of microorganisms may not be sufficient to attain the desired soil properties. Instead, bio-stabilisation methods can be adopted to complement the cementation process.

Saccharomyces cerevisiae (commonly known as yeast) has been considered in this study because: (a) it can live in both aerobic and anaerobic conditions, and (b) it can adapt to alkaline environment and sunlight would not be required so that it will be still alive in the environment including lime, and more importantly (c) it is readily available, which makes the application economical. In this study, the effects of Saccharomyces cerevisiae on the shear wave velocity and small-strain shear modulus of cement treated kaolinite are investigated using the bender element test conducted on 45 different samples.

2 EXPERIMENTAL PROCEDURE

To examine the capability of bacterial combined with different cement contents for soft clay improvement, cement contents of 10%, 15% and 20% by weight of dry clay were adopted in this study (Fatahi et al. 2012 and 2013; Nguyen and Fatahi 2016). Yeast contents of 0.5%, 1%, 2% and 5% by weight of dry clay were adopted to modify the cement treated clay, which is then compared with the control samples without yeast. In total 45 samples were prepared for bender element test. Table 1 presents the mixes used in this study. The detailed experimental procedure is described below:

- Kaolinite and yeast were initially mixed thoroughly in the form of powder; then water content of 75% was added to achieve an adequate workability.
- Cement slurry with a water-to-cement ratio of 1:1 was then added to clay slurry prepared in the previous step.
- Alternate hand and vibration mixing were introduced to ensure the mixtures were homogeneous and the presence of air entrapped was minimised.
- To achieve an adequate compaction effort, the mixture was placed in the mould of 50mm in diameter and 100 mm in height by palette knives in four layers.
- The final specimens were wrapped with plastic wrap to minimise the moisture loss.
- All the specimens were kept in the mould with plastic sheets wrapped under room temperature and constant humidity to cure for 48 hrs.
- After gaining sufficient strength and stiffness, the samples were demolded and placed in a standard curing bath with 2% of quicklime, and remained in the curing bath during the testing period.

Table 1. Mixes used in the experimental program

Test type	Soil type	Cement content (%)	Yeast content (%)
Bender element (shear wave velocity)	Kaolinite	10	0 0.5 1 2 5
		15	0 0.5 1 2 5
		20	0 0.5 1 2 5

The bender element test is a non-destructive test extensively employed to determine the shear modulus at small strains. The bender element (Figure 1) consists of a pair of ceramic plates and two pieces of piezoelectric ceramic bimorphs, which can turn voltage applied at two ends into electric signals, and detect the signals from the receiver and store the wave travelling time. The system is connected to a master control box, attached to a PC running bender element control software.

To conduct the bender element test, the soil specimen removed from the mould (which was stiff enough to stand without a need for mould) was placed between the ceramic plates, while inserting the bender elements a small distance into the soil specimens. Then a shear excitation was sent from the transmitter side and received on the receiver side to obtain the time that required for wave traveling through the specimen. The time intervals between the 1st sent and received peaks in the shear waves, were used to measure the shear wave velocity.The shear waves used in this study were sine waves with an amplitude of 10 V and frequency of 20 Hz. The bender element tests were repeated on all 45 samples at different curing time through the testing period, lasting 62 days.

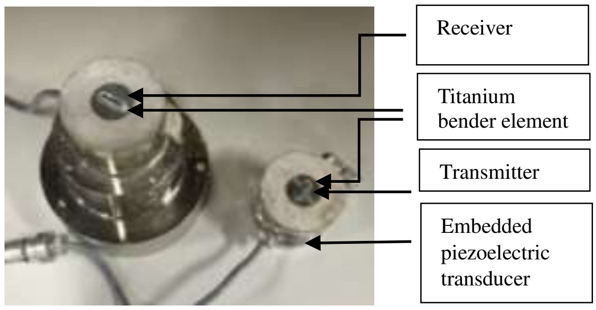

Figure 1. Bender element major features

3 RESULTS AND DISCUSSION

Yeast (Saccharomyces Cerevisiae) are single-celled microorganisms, classified as members of the fungus kingdom. This species of yeast is very strong and capable of fermentation. The fermentation process produces carbon dioxide (gas) and ethyl alcohol. These end products are released by the yeast cells into the surrounding voids. Generally, yeast size is slightly greater than clay particles, typically measuring 3–4 µm in diameter, although some yeasts can grow up to 40 µm in size. The doubling time for yeast (the time required for a cell to duplicate and divide itself) is about 90 minutes. When using a notable dosage of yeast in the soil mix (e.g. greater than 2%), the soil may inflate as a result of gas generation, and its shear modulus possibly decreases.

Figure 2 shows the results of shear wave velocity during 62 days of curing for clays treated with various cement and Saccharomyces cerevisiae contents. It is observed that the shear wave velocity generally increases with the cement content and curing time. Besides, the addition of certain amount of Saccharomyces cerevisiae can, to some extent, increase the shear wave velocity. Taking 10% cement content mixture for example (Figure 1a), induced an increase of 9% and 7% in shear wave velocity, and compared to the case with no yeast added, at 62 day of curing, respectively. However, an excessive amount of Saccharomyces cerevisiae (e.g. 2% and 5%) can lead to a considerable reduction in shear wave velocity for all samples irrespective of the cement content. Additionally, it can be observed that the contribution of such bacteria becomes insignificant in soil improvement when higher cement contents are adopted (e.g. 20% cement content). Furthermore, as Figure 2 illustrates, although samples with 0% yeast indicate the largest shear wave velocity at the initial stages of curing, as time progresses and samples cure further, addition of 0.5% and 1% Saccharomyces cerevisiae contributes to the increase in the shear wave velocity.

There are various reasons that may explain these phenomena observed from the test results, but the primary among these would likely be the effect of chemical and biological reactions taking place during the curing process. After sample demolding, all specimens were cured in the standard curing bath containing 2% quicklime for more than 60 days, so cementing agents underwent the continuous hydration and pozzolanic reactions and strengthen the soil with time.

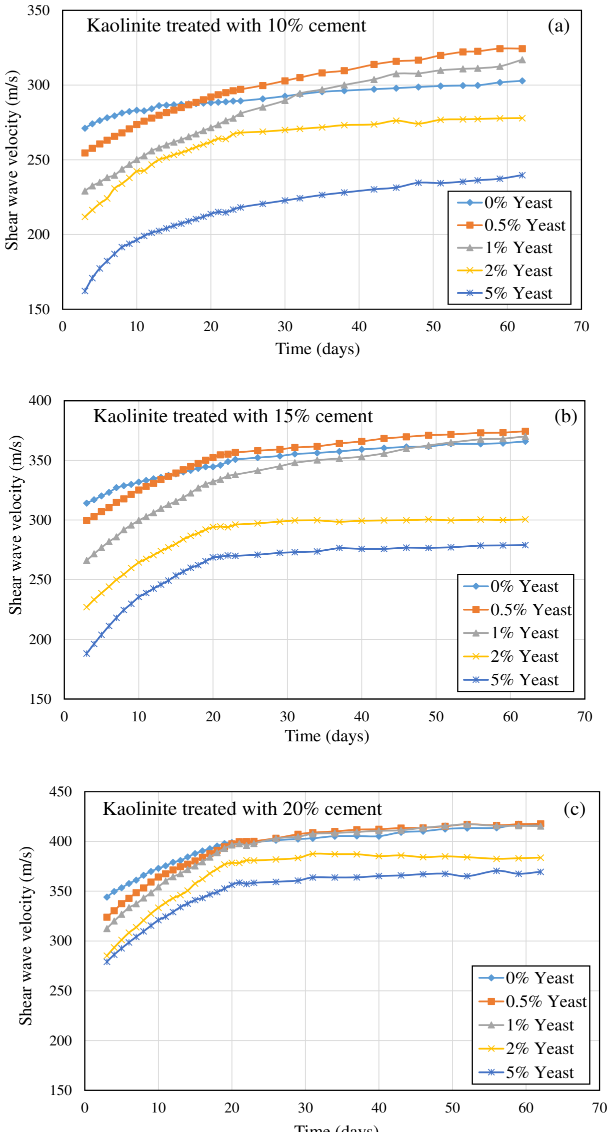

Figure 2. Shear wave velocity with curing time for Saccharomyces cerevisiae treated with: (a) 10% cement; (b) 15% cement; (c) 20% cement

Lorenzo and Bergado (2006) explained that the hydration process occurs rapidly when cement is mixed with pore water of the soil to form primary cementitious products such as hydrated calcium silicates, hydrated calcium aluminates, and hydrated lime. According to Prusinski and Bhattacharja (1999), hydrated calcium silicates and hydrated calcium aluminates play the most important role as they provide structure in the soil matrix, which consequently improves the strength of the soil. Meanwhile, the activation of yeast generates carbon dioxide. Hence, combination of carbon dioxide and calcium hydroxide solution can generate calcium carbonate ($CaCO_3$) at the contact interfaces of soil particles. Hence, it is believed that the generated precipitated calcium carbonate fills up the pores that is originally occupied by voids, and binds the particles together to form bio-clogging. Therefore, the measured shear wave velocity is increased when the sample porosity decreases. However, generating excessive amount of carbon dioxide due to excessive addition of yeast may induce superfluous gases leading to the development of internal micro cracks and voids. This will inevitably result in a notable reduction of sample stiffness as observed for samples treated with 2% and 5% of yeast.

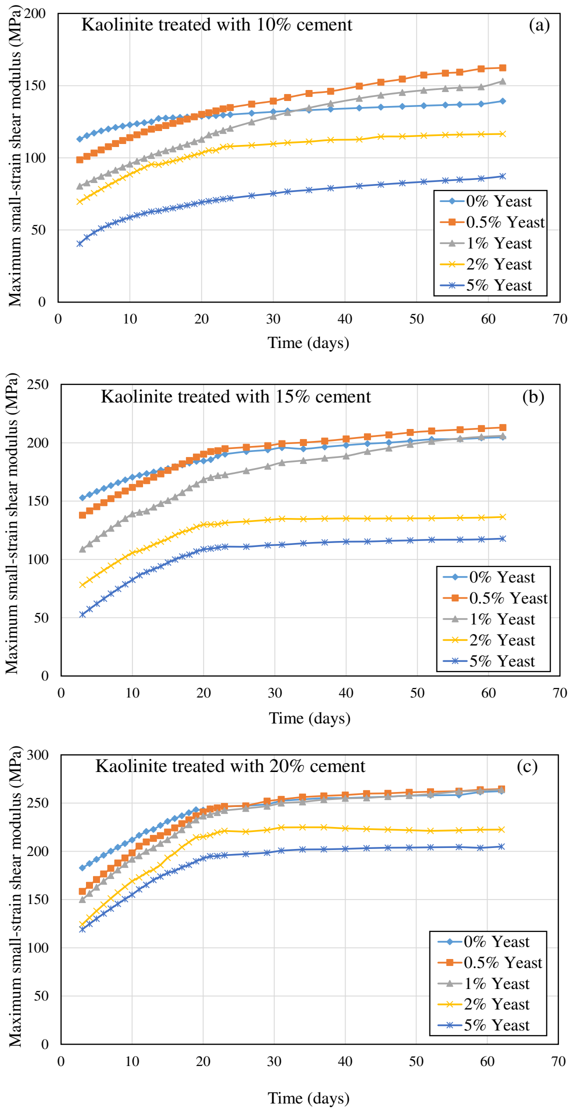

Figure 3. Variation of maximum small-strain shear modulus (Gmax) with curing time for Saccharomyces cerevisiae treated with: (a) 10% cement; (b) 15% cement; (c) 20% cement

Figure 3 summarises the calculated maximum small strain shear modulus variation with time. The maximum small strain shear modulus of samples were calculated using the following equation:

$$G_{max} = \rho \, (V_s)^2 \qquad (1)$$

where the G_{max} is the maximum small strain shear modulus, ρ is the sample density, and V_s is the shear wave velocity measured through bender element test.

It is anticipated that the maximum small strain shear modulus calculated should have a similar trend compared to the shear wave velocity, since the density of specimens would not vary notably during the curing process. Referring to Figure 3, the small strain stiffness experiences a significant increase with the cement content as well as the curing time, while the excessive addition of yeast exhibits adverse effects. For instance, in comparison to samples with no yeast, addition of 2% and 5% of Saccharomyces cerevisiae into kaolinite samples treated with 10% cement (Figure 3a) reduced the maximum small strain shear modulus by 20% and 47%, respectively. However, it is observed that a smaller quantities of yeast, for example 0.5%, can efficiently improve the maximum small strain shear modulus by 14% (from 140 to 160MPa) compared with the sample of no yeast content. As explained before, this can be attributed to the produced calcium carbonate filling the voids.

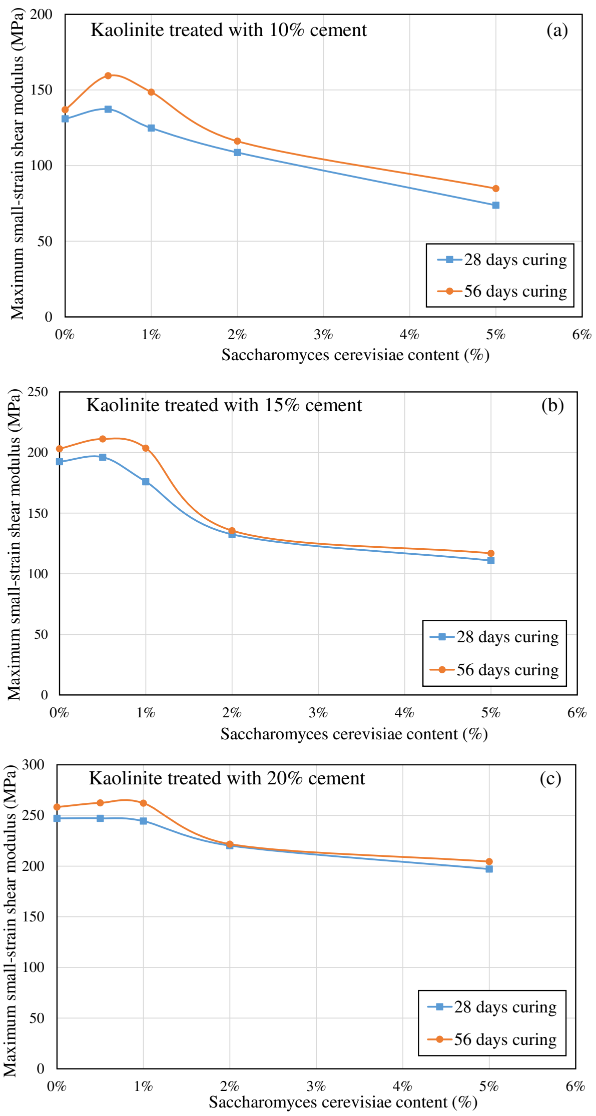

Figure 4. Variation of maximum small-strain shear modulus (Gmax) at 28 days and 56 days curing, respectively for Saccharomyces cerevisiae treated with: (a) 10% cement; (b) 15% cement; (c) 20% cement

Figure 4 illustrates the variation of the maximum small strain shear modulus with cement and yeast contents at 28 days and 56 days curing. It can be noted that the optimum yeast content to achieve highest stiffness is approximately 0.5% for both samples treated with 10% and 15% cement.

4 CONCLUSIONS

In this study, the effects of Saccharomyces cerevisiae on the shear wave velocity and the maximum small-strain shear modulus of cement treated kaolinite clay were examined. The laboratory tests were conducted over two months with a total number of 45 specimens prepared in order to perform the bender element tests.

The results reveal that the shear wave velocity and the calculated maximum small strain shear modulus increase with the cement content and curing time. However, the influence of Saccharomyces cerevisiae on the shear wave velocity highly depends on its content. Adopting the optimum amount of yeast (e.g. 0.5%), the shear wave velocity can be enhanced substantially in the long term, while excessive percentage of yeast has adverse effects on the stiffness. This can be attributed to the chemical and biological reactions occurring in the course of curing process, during which, carbon dioxide generated due to Saccharomyces cerevisiae reacting with the cementing agents and generate the undissolved calcium carbonate to fill up the pores. Additionally, this study has concluded that the optimum Saccharomyces cerevisiae content depends on the adopted cement content, and it is suggested that more comprehensive investigations should be conducted to evaluate effects of Saccharomyces cerevisiae on both physical and mechanical properties of cement treated clays.

5 REFERENCES

DeJong, J.T., Mortensen, B.M., Martinez, B.C. and Nelson, D.C. 2010. Bio-mediated soil improvement. *Ecological Engineering*, 36, 197-210.

Fatahi B. Khabbaz H. and Fatahi B. 2012. Mechanical characteristics of soft clay treated with fibre and cement. *Geosynthetics International* 19 (3), 252–262.

Fatahi B. Fatahi B. Le T.M. and Khabbaz H. 2013. Small-strain propertiesof soft clay treated with fibre and cement. *Geosynthetics International* 20 (4), 286–300.

Ivanov V. and Chu J. 2008. Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil in situ. *Reviews in Environmental Science and Bio/Technology* 7, 139-153

Lorenzo, G. A. and Bergado, D. T. 2006. Fundamental characteristics of cement-admixed clay in deep mixing, *Journal of materials in civil engineering*, 18: 161-174.

Mitchell, J.K. Santamarina, J.C. 2005. Biological considerations in geotechnical engineering, *Journal of Geotechnical and Geoenvironmental Engineering*, 131 (10), pp. 1222–1233

Nguyen, L. & Fatahi, B. 2016, Behaviour of clay treated with cement & fibre while capturing cementation degradation and fibre failure - C3F Model, International Journal of Plasticity, 81, 168-195.

Paassen L. and Molendijk W. 2009. SmartSoils: A Decade of Research on Biological Ground Improvement. *Special 17th ICSMGE Alexandria*, Egypt.

Prusinski, J. and Bhattacharja, S. 1999. Effectiveness of Portland cement and lime in stabilizing clay soils, *Transportation Research Record: Journal of the Transportation Research Board*: 215-227.

Stabnikov V. Neaimi M. Ivanov V. and Chu J. 2011. Formation of water-impermeable crust on sand surface using biocement. *Cement and concrete research* 41, 1143 – 1149.

Trhlíková J. Masín D. and Bohác J. 2012. Small-strain behaviour of cemented soils. *Géotechnique* 62 (10), 943–947.