Shear wave velocity and its anisotropy of biocemented glass sand

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ABSTRACT

The paper presents a series of experimental studies on the anisotropic small strain stiffness of a biocemented glass sand. Multidirectional shear wave velocities were measured on the isotropic consolidated samples in a triaxial cell. The biotreatment method, shear wave velocity, and its anisotropy of the biocemented sand were reported. It is found that the shear wave velocity increases with the increase of cementation level and the stiffness anisotropy firstly increases then decreases with the increase of cementation level. The paper aims to provide a new way to simulate the undisturbed state of sandy soils in laboratory with the microbially induced calcite precipitation technique.

Keywords: Shear wave velocity; biocementation; MICP; anisotropy.

1. Introduction

Natural sand is sometimes cemented by the precipitates of salts in water environment or from chemical and biological reaction in long geological process (Joshi et al., 1995). The composition of bond in natural cemented sand depends on the environment it deposits. For example, the formation of natural sandstone in tropical and subtropical marine area is mainly attributed to the supersaturation of seawater and the precipitates are mostly high-Mg calcite (Molenaar and Venmans, 1993). The engineering behavior of cemented sand are more complex than pure sand and the bonds among grains paly the dominant roles in the soil strength, stiffness and other mechanical properties(Abdulla and Kiousis, 1997, Consoli, 2014, Consoli et al., 2010, Huang and Aire, 1998, Liu et al., 2019). Due to the high cost and inconveniences of sampling cemented sand on-site (Huang and Huang, 2007, Viana da Fonseca et al., 2022), attentions were paid to replicating the cementation with binding materials in laboratory (Consoli et al., 2007). The most common one is Portland cement since it is easy to control the cementation degree with changing the content and the cementation procedure is simply achieved by mixing host sand with cement ahead of specimen reconstitution.

Shear wave velocity is an efficient parameter for evaluating the properties of cemented sands since it is sensitive to the change of soil fabric (Lin et al., 2020). It can be increased with binding sand grain and decreased with the failure of the bonds. Studies have shown that the development of shear wave velocity is able to indicate the state of cementation for cemented sands. For the sand cemented with Portland cement and subjected to loading, the increase of shear wave velocity with stress is inhibited until bonds fail. After that, shear wave velocity could drop hugely then increase in the same step with the uncemented sand, meaning that bond lost its efficiency in supporting soil fabric. Recently, sands cemented with MICP (Microbially Induced Calcite Precipitation) were extensively studied and shear wave velocity was used as an indicator to reflect and monitor the process and level of cementation (Montoya and DeJong, 2015). However, due to the complex reaction of MICP, shear wave velocity seems has more development models for biocemented sands, as reported by Lin et al. (2016). What's more, the physical properties of sand, such as particle shape, particle size and gradation, etc., which affect the shear wave velocity of uncemented sand (Altuhafi et al., 2016), still play important roles in the behavior of cemented sand (Consoli et al., 2007). To date, the small strain stiffness of biocemented sands, which can be represented with shear wave velocity, is rarely reported. The fabric and grain morphology, which are vital for small strain behavior, could be changed with the participate of biocementation and requires to be deeply studied.

In this paper, a series of bender element tests are performed on biocemented sands under isotropic consolidation. The shear wave velocity in both vertical and horizontal planes are measured. Then the development of small strain stiffness and stiffness anisotropy are investigated for the sands under the treatment of MICP.

2. Test material

Glass sand was used in the tests. The physical properties of the sand are shown in Table 1. The particle size gradation of this sand is shown in Figure 1.

The specimens were prepared with dry tamping method, as detailed in (Shi et al., 2021). The dimension is 50 mm in diameter and 95 mm in height. Tests were performed in a triaxial cell with three pairs of bender elements, enabling the measurement of shear wave velocities in both vertical and horizontal planes, V_{hh}, V_{hv} and V_{vh}, where "hv" mean horizontal propagation and vertical polarization of shear waves, as shown in Figure 2. The initial consolidation pressure is 40 kPa for CO_2

flushing, MICP treatment and back pressure saturation. The back pressure used here is 300 kPa. After saturation, tests were continued with a step of 50 kPa in loading and unloading consolidation. The largest consolidation pressure is 400 kPa.

Table 1. Physical properties of the tested sand

Sand	maximum void ratio	minimum void ratio	specific gravity	coefficient of uniformity	mean particle size
Glass sand	0.549	0.444	2.5	1.212	0.7

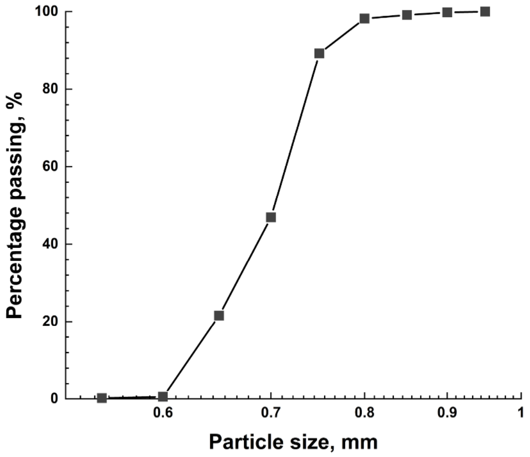


Figure 1. Particle size gradation of tested sand

Sporosarcina Pasteurii was used for the MICP treatment in this study and the bacteria cultivation was implemented using 2 g/L of soy peptone, 1 g/L of ammonium chloride, 0.5g/L of magnesium sulfate and 1.2 g/L of nickel chloride. After that, one-phase solution containing the mixture of bacterial and 0.1 Mol/L, 0.3 Mol/L and 0.5 Mol/L calcium chloride with pH of 5 was flushed through the specimens for 30 min. Then, back pressure was applied to specimen immediately and kept for 12 h for the completion of saturation and reaction.

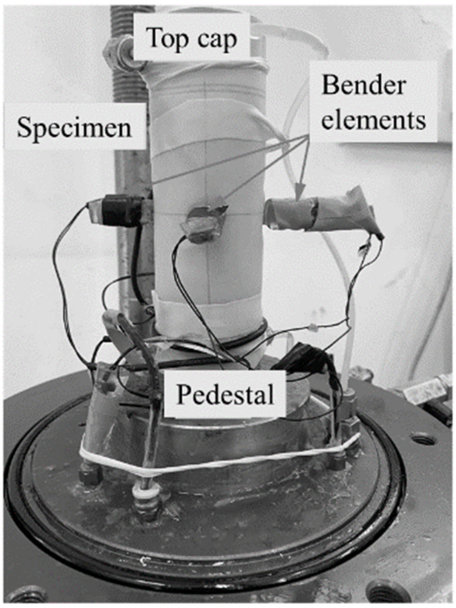


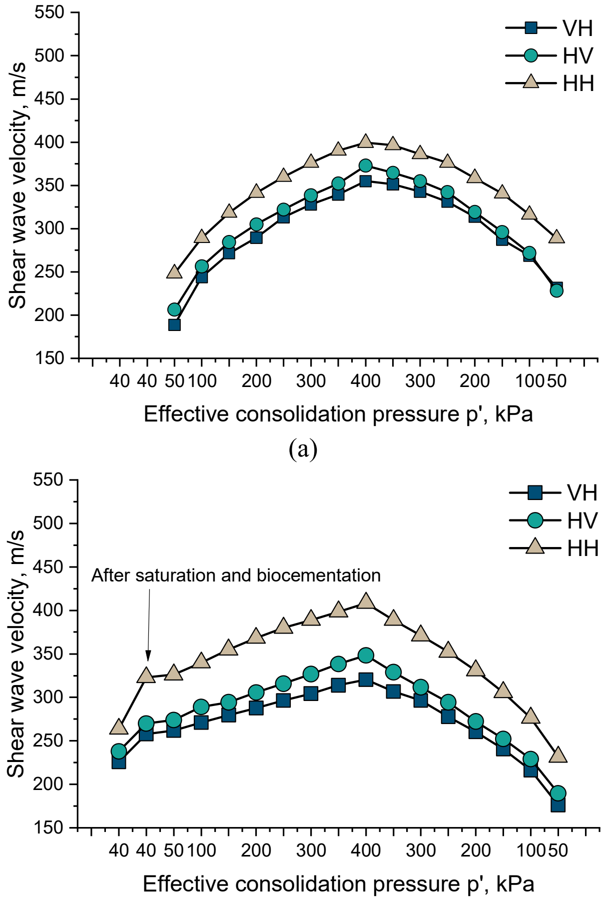
Figure 2. Specimen with bender elements

Two pairs of horizontal bender elements were mounted at the middle height of specimens to measure Vhh and Vhv. One pair of bender elements was installed in the pedestal and top cap to measure Vvh. All shear wave velocities were measured at the end of each testing stage and loading step. The shear waves were excited at a frequency of 15 kHz and an amplitude of 20 V. Peak to peak method was used for signal interpretation.

3. Test results

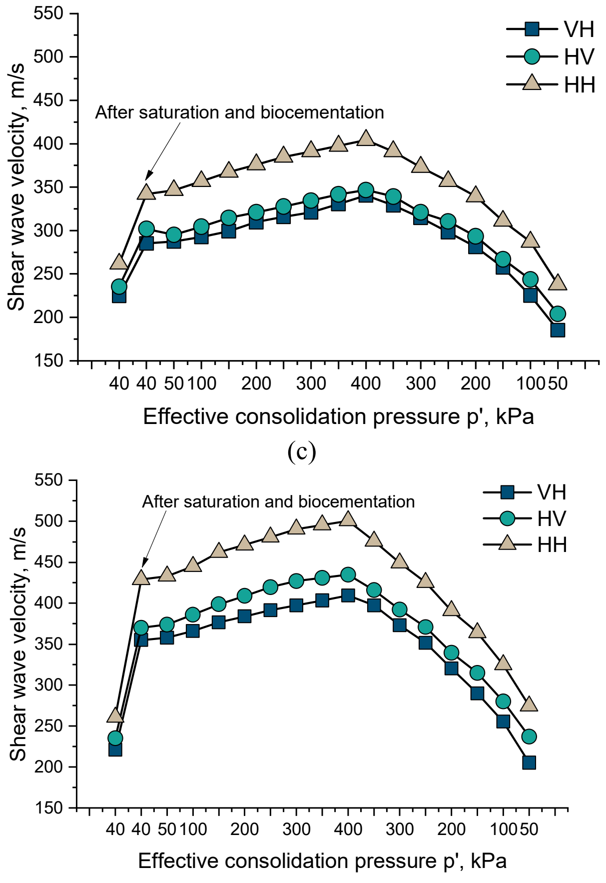
Figure 3 shows the development of shear wave velocity at the saturation, reaction, loading and unloading stages for the specimens treated with the three cementation levels. The void ratios of the untreated, 0.1 Mol/L, 0.3 Mol/L and 0.5 Mol/L after consolidation, without considering the calcium carbonate precipitate, are 0.967 0.961, 0.956 and 0.957, respectively.

It is seen that after the MICP reaction, shear wave velocities were promoted significantly and the increment for V_{hh}, V_{hv} and V_{vh} are in the similar amplitudes. For highly cemented sands, the stiffness ahead of the bonding failure might keep constant until reaching the threshold stress (Fernandez and Santamarina, 2001). This is not observed for the biotreated sands in this study. During the loading stage, shear wave velocities increase continuously with stress.In the unloading stage, shear wave velocities are even lower than those at the same stress level in the loading stage, which is more significant for the higher treatment level. This indicates that the bonds from biotreatment are destroyed after loading and more bonds can be generated with increasing treatment level, leading to more deduction of soil stiffness.



(a)

(b)



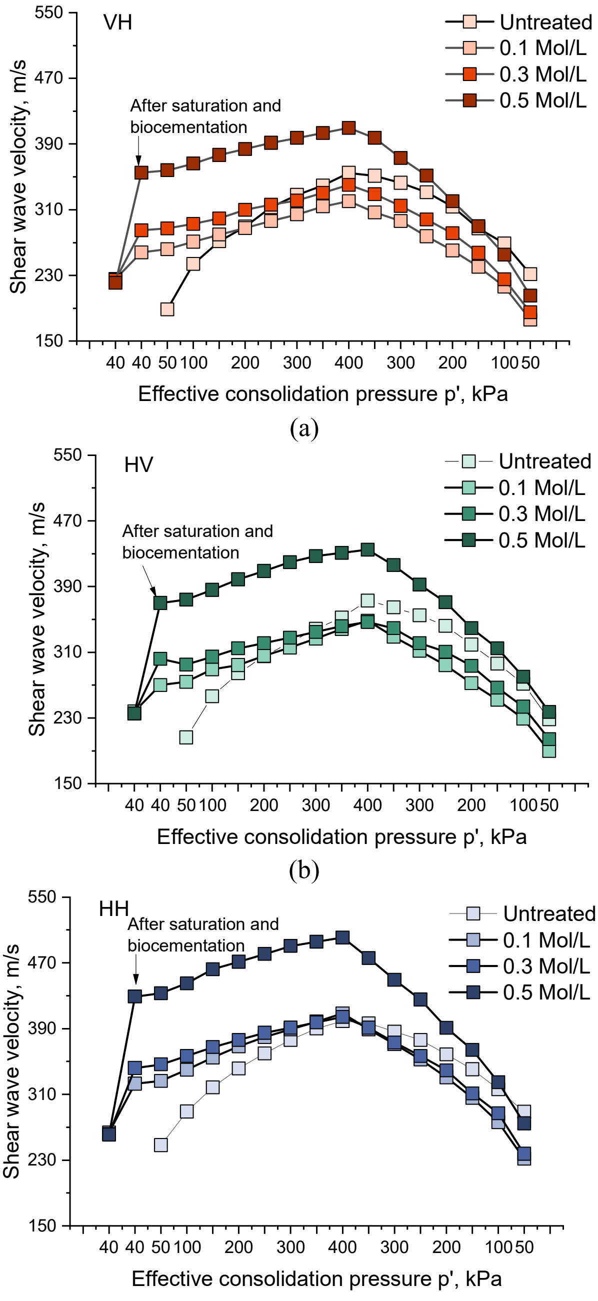
(c)

(d)

Figure 3. Shear wave velocity development during tests: (a) untreated specimen; (b) specimen treated with 0.1 Mol/L; (c) specimen treated with 0.3 Mol/L; (d) specimen treated with 0.5 Mol/L

The shear wave velocities of the specimens at different biotreatment levels were compared in Figure 4. It can be observed directly that with the increase of biocementation level, shear wave velocity is promoted. However, it is interesting to see that at the largest consolidation pressure, the untreated specimens has a larger shear wave velocity than the specimens with CS=0.3 Mol/L and 0.5 Mol/L. This might be attributed to that biocementation inhibites the sensitivity of soil to stress change.

The Scanning Electron Microscope (SEM) was used to detect the morphology of biocementation in this study, as shown in Figure 5. It is seen that glass sand particles were biocemented with slight bonds and the cementation degree is not very high.



(a)

(b)

(c)

Figure 4. Shear wave velocity development during tests: (a) VH; (b) HV; (c) HH

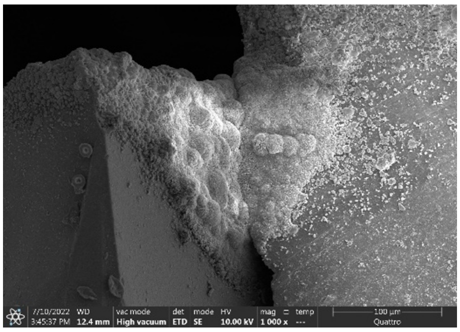


Figure 5. SEM image of biocemented sand at 0.3 Mol/L

Figure 6 shows the development of stiffness anisotropy for the untreated and the three biotreated specimens. The stiffness anisotropy can be represented by the ratio between Vhh and Vhv, as proposed by Shi et al. (2021). It is seen that for the untreated specimen, the ratios are larger than 1, indicating the significant stiffness anisotropy of the original sand. The shear wave velocity anisotropy is common within natural sand and this is given by the fabric anisotropy of soils, which was explained in Shi et al (2021). It is also noted that the ratios vary with stress by decreasing and increasing in the loading stages, respectively. This phenomenon is mitigated with the increase of biotreatment level. For the specimens with 0.5 Mol/L, stress level seems to have little impact on stiffness ratios. What's more, it is interesting to see that, the overall stiffness ratios experience an improvement at 0.1 Mol/L and then drop with the higher biotreatment level. However, the ratios are still higher than the untreated ones. It is deduced that with further biotreatment, the stiffness anisotropy might disappear and the biocemented sand could become isotropic in stiffness behavior. However, for natural cemented sand, like sandstone, anisotropic mechanical behavior does exist, as reported by Kim et al. (2016). Therefore, further study is required to investigate the anisotropic stiffness behavior at the higher biocementation level.

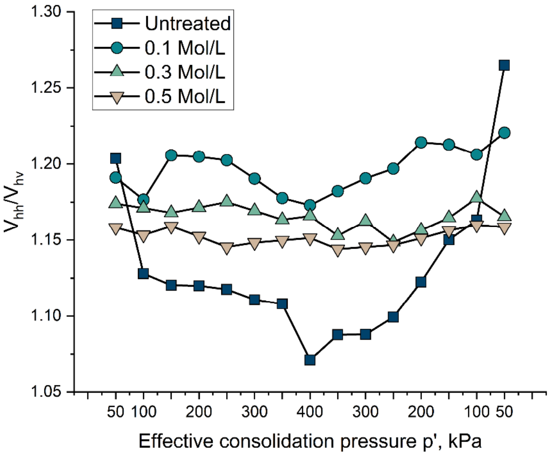


Figure 6. V_{hh}/V_{hv} versus effective consolidation pressure

4. Conclusions

This paper shows the test results of multidirectional shear wave velocities of biocemented sands at several cementation levels. The development of shear wave velocity and stiffness anisotropy with stress and cementation levels were investigated. It is found that the shear wave velocities of biocemented sands could show continuously increase with stress without sudden variation. At the end of unloading, shear wave velocity could be lower than the value at the same stress level of loading stage, implying the failure of bond. The change of stiffness anisotropy with stress is mitigated with biocementation. With the increase of biotreatment level, stiffness anisotropy increases firstly and then drops. It can be anticipated that MICP can be used as the new technique to reconstitute cemented sand in laboratory. However, the impacts of higher biocementation requires further investigation.

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