Characteristics of Glass-Polyurethane Beads Mixtures as Function of Weight Ratios: Experimental Approaches

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Abstract. In this study, a series of laboratory tests is conducted to examine the characteristics of mixtures composed of glass beads (GB) and polyurethane beads (PB) in different size ratios ($s_r = D_{50\text{-}GB}/D_{50\text{-}PB}$). Specimens are prepared in the same relative density but in various weight ratios between GB and PB called polyurethane content, PC (= $W_{PB}/W_{Mixture}$ = 0, 0.5, 1.0, 2.0, and 5.0%). Small-strain shear modulus G_{max} is estimated by the shear wave velocity measured by bender elements installed in an oedometer cell with various confinements under K_0-loading condition. The normalized shear modulus (G/G_{max}) is also measured by a resonant column test. It is found that the behavior of mixtures could be divided into two regions as the contact control and the stress control by a value of "stress threshold" that decreases with an increase in PC due to the large deformation of polyurethane particles. Additionally, with the participation of PB, the mixtures experience a sudden rise in Λ factor incorporated with a small value of ζ exponent in the $G_{max} = \Lambda(\sigma_v/1 \text{ kPa})^\zeta$ at polyurethane content, PC $\approx$ 0.5–2%, indicating the optimum packing and minimum sensitivity to confining pressure of the mixture. Although PB works as a low stiffness material, they play an important role to enhance inter-particle contact behaviors, resulting in an increase of stiffness degradation at low stress range. However, the deformation of PB at high confinement causes a reduction in G/G_{max} curves.

Keywords: K_0-loading · Mixtures · Compressibility · Shear modulus
Polyurethane content (PC)

1 Introduction

Binary material mixtures generally consist of the large grains and fines or of different stiffness particles. The behaviors of the binary mixtures composed of sands and plastic/non-plastic fines have been attracted enormous interests in recent years [2, 9, 10, 13, 16]. Previous studies revealed that the inclusion of fine particles significantly effects on the engineering characteristics of unreinforced sand grains [3, 5, 13]. Additionally, adding of plastic fines into the sand leads to transitional engineering behaviors in compressibility [9, 10], and in shear modulus and damping ratio [1, 7]. In most above researches, clean sands were used as the host-rigid particle without considering the shape effect, however, particle shape could also significantly affect properties of soils [4, 8].

In this study, comprehensive laboratory experiments were performed to explore the effect of plastic grains on the engineering behavior of rigid-host particle by using polyurethane (PB) and glass bead (GB). The experimental study including materials, sample preparation, devices, and test procedures will be firstly under commanded. The compressibility and dynamic properties of the mixtures are investigated with polyurethane content (PC) and size ratio (s_r) between two particles.

2   Experimental Study

2.1   Materials

Two different sizes of glass beads (GB100 and GB400) purchased from Doosung Chemis Corporation were selected as the host rigid particles in this study. Median particle size (D_{50}) of GB100 and GB400 are 0.08 mm and 0.23 mm, respectively. Polyurethane bead (B&K MEDIA company) with $D_{50} = 0.08$ mm was used as the plastic particle. The size ratios ($s_r = D_{50\text{-GB}}/D_{50\text{-PB}}$) are 1.0 and 2.8 for GB100 and GB400, respectively. Table 1 shows the fundamental properties of GB and PB.

Table 1. Fundamental characteristics of GB and PB.

Index properties	GB100	GB400	PB	Device/Technique
Specific Gravity (G_s)	2.47	2.48	1.05	ASTM D854
Extreme void ratio				
e_{max}	0.67	0.68	–	ASTM D4254
e_{min}	0.56	0.55	–	ASTM D4253
Median particle size (mm)	0.08	0.23	0.08	ASTM D422
Coefficient of uniformity (C_u)	1.54	1.09	1.52	ASTM D422
USCS	SP	SP	–	ASTM D422
Modulus (MPa)	70 000	70 000	3000–4000	[15, 17]

2.2   Sample Preparation and Testing Program

Table 2 shows the testing program in this study. Pre-determined amounts of PB were mixed with GB to form the mixtures with various polyurethane contents (PC = weight of polyurethane/total weight) = 0, 0.5, 1.0, 2.0 and 5.0%. Specific gravities (G_s) of mixtures were then evaluated based on PC, and extreme void ratios (i.e. e_{max} and e_{min}) were measured according to ASTM D4253 and D4254 as listed in Table 2.

Table 2. Extreme void ratios of tested mixtures.

Type		PC = 0.5%	PC = 1%	PC = 2%	PC = 5%
GB 100	e_{max}	0.676	0.694	0.705	0.724
	e_{min}	0.576	0.593	0.593	0.597
GB 400	e_{max}	0.682	0.682	0.668	0.618
	e_{min}	0.577	0.581	0.569	0.524

2.3 Zero-Lateral Strain Compression Tests with Shear Wave Velocity Measurements

A zero-lateral strain oedometer cell equipped with bender elements was used to evaluate the compressibility and to measure shear wave velocity (V_s) of the mixture with varying s_r and PC in this study (Fig. 1). Well-mixed specimens were carefully scooped into the cell and then slightly tamped to obtain predetermined initial relative density (Dr) of ~60%. Prepared samples were applied vertical effective stresses ranging from 7 to 448 kPa. Settlements and shear wave signals were measured at the end of each loading step by an LVTD and a pair of bender elements installed in the top cap and the bottom plate of the oedometer cell [6, 11].
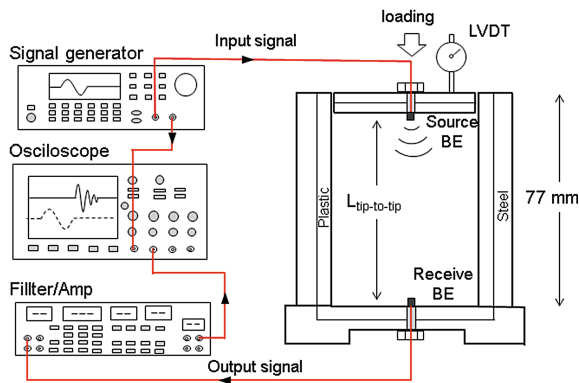

Fig. 1. Modified zero-lateral strain oedometer cell.

2.4 Resonant Column Test

In this study, shear moduli (G) with shear strains were measured by using a fix-based resonant column device (Fig. 2). Samples were prepared into a membrane with a diameter of 50 mm and fixed height of 110 mm to get the relative density D_r = ~60%. Isotropic stresses of 100, 200, and 300 kPa were applied.

3 Experimental Result
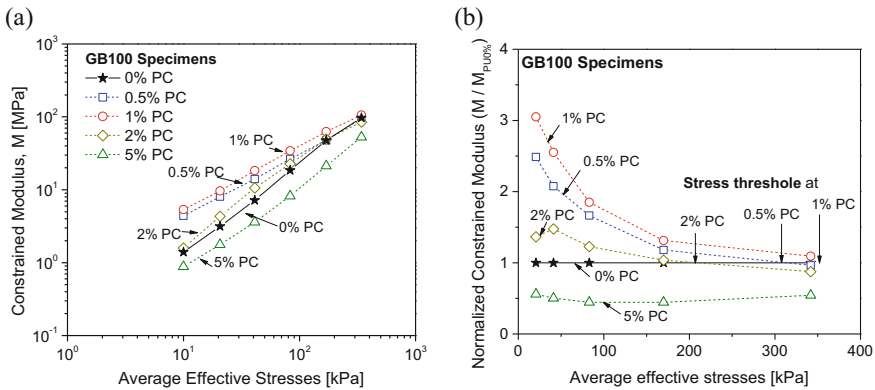
3.1 Compressibility of GB-PB Mixtures

The compressibility of specimens can be expressed in term of the constrained modulus (M), which is defined as the amount of stress induced a unit vertical strain at each loading step. Figure 3(a) illustrates the measured constrained modulus for GB100 mixtures. As shown in Fig. 3(a), the specimen with PC = 1% shows largest M values in tested stress ranges and the mixture of PC = 5% shows smallest values of M in tested PC ranges. To emphasis on the effect of the polyurethane inclusion, normalized constrained modulus ($M_{mixture}/M_{pure\ GB}$) was plotted as a function of the average
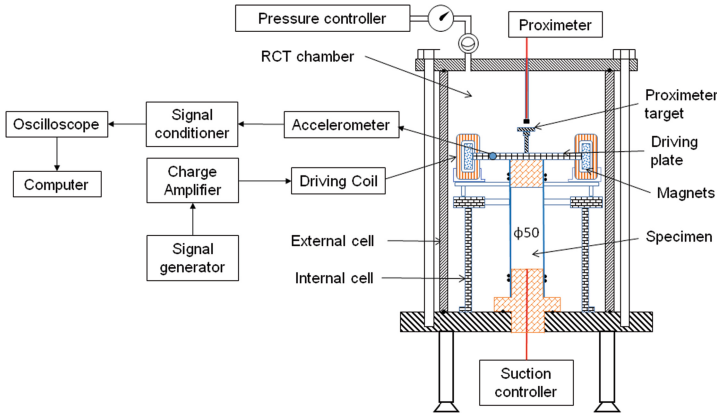
Fig. 2. Resonant column test device.

effective stress in Fig. 3(b) for GB100. At low stress level, mixtures with PC = 0.5%, 1%, and 2% are experienced higher M values than pure glass bead specimen, however, at high stress range, all mixtures are exhibited a similar M value. It could be attributed to the enhancement of the contact behavior due to the inclusion of PB. At low stress, the inclusion of PB helps to increase the inter-particle contacts, resulting in increasing in M. However, at high stress level, the reduction in M is observed due to the high deformation of PB in the mixture. The mixture with 1% PC shows highest "stress threshold", which is defined as stress value when $M_{mixture}/M_{pure\ GB} = 1$, and it gradually reduce in 0.5%, 2% PC specimens (Fig. 3(b)).


Fig. 3. Compressibility for tested mixtures of GB100: (a) measured constrained modulus with effective stresses; (b) normalize constrained modulus with effective stresses.

3.2 Shear Wave Velocity (V_s) and Small Strain Shear Modulus (G_{max})

The stress dependent behavior of shear wave velocity can be expressed by a power equation [10, 14] as:

$$V_s[m/s] = \alpha \left(\frac{\sigma'_v}{1kPa} \right)^{\beta} \tag{1}$$

where α [m/s] factor is a shear wave velocity of tested specimen at unity effective stress; and β exponent indicates the stress sensitivity of V_s. The empirically measured α and β plotted in Fig. 4(a) are well fitted with the empirical equation proposed in [12] for different geo-materials.
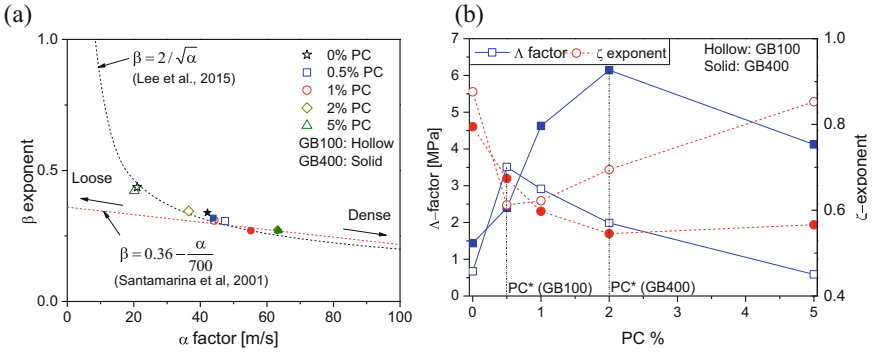
Fig. 4. (a) Relationship between α factor and β exponent; and (b) functions of Λ factor and ζ exponent to PC.

The stress-dependent behavior of G_{max} can be expressed as:

$$G_{max} = \Lambda \left(\frac{\sigma'_v}{1\,k\,Pa} \right)^{\varsigma} \tag{2}$$

where Λ factor expresses G_{max} at 1 kPa confinement, which is controlled by packing condition including contact behavior, material properties, and coordination number; and ζ exponent shows the sensitivity of G_{max} on stress, which affected by size, shape, and structure of particles [10, 14]. The experimentally determinced Λ factor and ζ exponent are plotted as a function of PC in Fig. 4(b). In this study, the optimum polyurethane content (PC*) is defined as the ratio at which mixtures exhibit highest Λ factor with lowest ζ exponent, representing the optimum packing of the mixture [1]. PC* for GB100 and for GB400 mixtures were defined at 0.5% and 2%, respectively.

3.3   Shear Modulus Degradation (G/G$_{max}$)

Typical G/G$_{max}$ curves for mixture of GB400 - 1%PC are plotted in Fig. 5(a) and they are well matched with the Ramberg-Osgood (R.O) model. Similar to clean sands, G/G$_{max}$ increases with increasing in the confining pressure, regardless of shear strains. Figure 5(b) (c), and (d) illustrate the shear modulus degradations of GB400 with the inclusion of PB at different confining stresses of 100 kPa, 200 kPa, and 300 kPa, respectively. When the mixtures were compressed with low confining stress (i.e. 100 kPa) as shown in Fig. 5(b), G/G$_{max}$ increases with increasing in the PC under same shear strain level because of the enhancing in contact behaviors due to the inclusion of PB in mixtures. The evolutions of contact behavior could be clearly observed at high strain levels in specimens with 1%, 2%, and 5% PC. When confining stress increases, G/G$_{max}$ curves for different PC mixtures are converged into a single trend (Fig. 5(c) and (d)). Also, normalize shear modulus curves of mixtures with higher PC exhibited more reduction at high stress ranges due to large deformations by the PB inclusion.
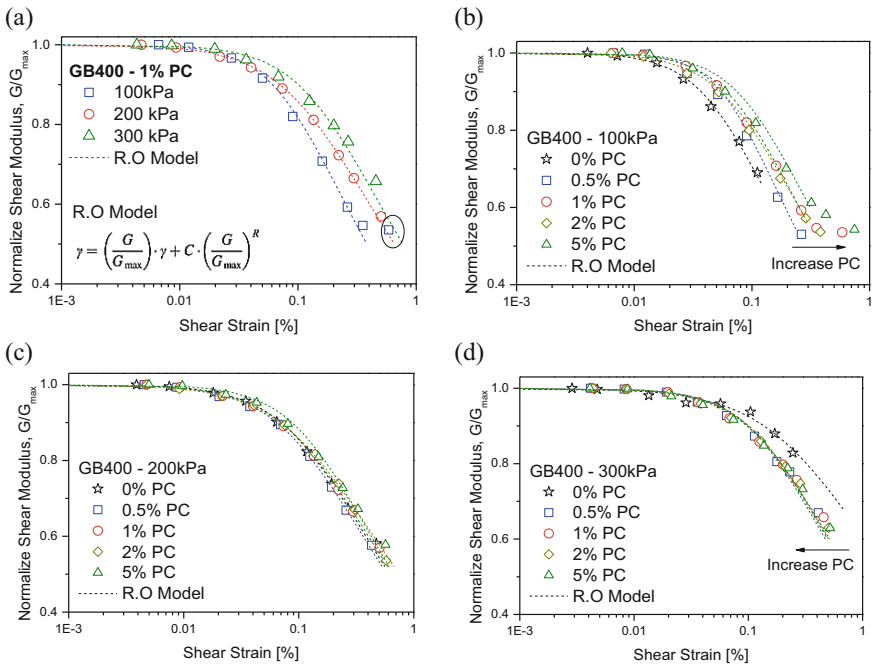
Fig. 5. Shear modulus degradation curves measured for GB400 - 1%PC (a), and for GB400 with PC from 0% to 5% at 100 kPa (b), 200 kPa (c) and 300 kPa (d).

4 Conclusion

A series of laboratory experiments were performed to investigate the characteristics of the mixtures with rigid-host (GB) and soft particles (PB). An instrumented oedometer cell was implemented to evaluate the compressibility and G_{max}, and resonant column tests were performed to explore the shear modulus degradation of mixtures. It is found that the participation of PB shows significant influences on both of compressibility and dynamic properties of the mixtures due to the enhancement of the contact behavior between GB. Behavior of mixtures could be separated into two categories as the contact controlled behavior and stress controlled behavior by the stress threshold. Optimum polyurethane contents (PC* = 1% and 2% for GB100 and GB400, respectively) are observed at which mixtures experienced the optimum packing condition, resulting in an increase both of the constrained modulus (M) and small strain shear modulus (G_{max}). It was also observed that the inclusion of PB in mixture results in an increase in the elastic threshold strain of the mixture at low confinement. The transition from contact control to stress control behaviors at high confinement leads to the reductions in both constrained modulus and shear modulus degradation in mixtures. Since the polyurethane bead is a high damping material, this study would provide a new idea for an energy absorbed layer or seismic base isolation application under the dynamic loading.

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