Technical Note

Viscoelastic Behavior of Silica Particle Compacts under Dynamic Compression

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Abstract: The viscoelastic behavior of model sandy soils in the form of silica particle compacts under dynamic compression (0.2–10.0 Hz) is reported. The solid content ranges from 24 to 28% by volume, as controlled by compaction. Both viscous and elastic characters are largely governed by the solid part of the compact. The elastic character stems from the stiffness of the silica, while the viscous character stems from the interparticle movement. The elastic character of the solid part (the storage modulus and solid content) is essentially independent of the degree of compaction, indicating validity of the rule of mixtures. The viscous character of the solid part (the loss tangent and solid content) decreases with increasing degree of compaction, indicating decreasing ease of interparticle movement as the degree of compaction increases. The loss modulus and solid content is essentially independent of the degree of compaction. All quantities decrease with increasing frequency. A low degree of compaction is recommended for fast decay of the vibration amplitude; no particular degree of compaction is recommended for mechanical energy dissipation. **DOI:** 10.1061/(ASCE)MT.1943-5533.0000831.

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Introduction

Silica (SiO_2) particles constitute a major component of soil, particularly sandy soil. A silica particle compact can be considered as a model soil. The silica particle size and the degree of compaction can be controlled in the compact in the absence of any other ingredient (e.g., water, clay, organic carbon), thus enabling controlled systematic study at a level that is not possible by studying real soils.

The viscoelastic behavior of soil is relevant to the performance, vibration damping, durability, and seismic resistance of foundations and soil embankment structures (Ambrosini 2006; Anastasiadis et al. 2012), including pavements, ballasts, foundations, embankments, piers, and levees. The damping ability also relates to the tendency for settlement (Omar et al. 2011). Sound damping, which is akin to vibration damping, is increasingly needed due to the noise emitted by trains, particularly high-speed trains. How soil is affected by dynamic mechanical forces (Ahn et al. 2011) is relevant to soil stabilization (Ali 2012), which relates to the bearing capacity of the foundation of a structure built on soil and to the stability and safety of soil embankment structures. It also relates to soil compaction (Bragov et al. 2006; Lukas 1997).

Silica particles are widely used as a low-cost reinforcement in cement–matrix and polymer–matrix composites. With the silica particles bound by a matrix, the particle–matrix interface rather than the particle–particle interface is important. In contrast, the particle–particle interface is important in a particle compact. Nevertheless, information on the particle–particle interface in a compact can shed light on the mechanical behavior of a particle composite that involves a degree of particle clustering, which is quite common due to the imperfect dispersion of the particles.

Prior work addressed the dynamic mechanical behavior of polymer–matrix and cement–matrix composites containing silica particles under dynamic flexure (Reddy and Das 2006a, b; Chen and Chung 2013), tension (Zhao et al. 2012), or shear (Chonkaew et al. 2011; Ladouce-Stelandre et al. 2003; Ward et al. 2003), but not compression. This is due to the difficulty of dynamic compressive testing of stiff monolithic materials, the surface of which is never perfectly smooth. The surface topography results in high local compressive stresses at the hillocks and deformation that mainly occurs at the hillocks. However, for soft materials or particle compacts, the specimen surface conforms to the topography of the piston (the surface of which is never perfectly smooth) used to apply the compressive force. In a particle compact, the interparticle movement involves friction, which results in damping (Cui et al. 2011).

The viscoelastic behavior of dry soil relates to that of wet soil. Relatively little attention has been given to the viscoelastic behavior of dry soil (Anastasiadis et al. 2012).

The storage modulus E' is the dynamic elastic modulus and is defined as

$$E' = (\sigma_o/\varepsilon_o)\cos\delta \tag{1}$$

where σ_o and ε_o = stress and strain amplitudes, respectively. The loss modulus E'' is the dynamic viscous modulus, which relates to the amount of mechanical energy dissipated per unit volume, and is defined as

$$E'' = (\sigma_o/\varepsilon_o)\sin\delta \tag{2}$$

The loss tangent ($\tan\delta$, where δ is the phase angle between the stress and strain waves) is defined as

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$$\tan\delta = E''/E' \quad (3)$$

The behavior is purely elastic when $\delta = 0°$ and is purely viscous when $\delta = 90°$.

Prior work on particulate materials under dynamic compression addressed glass spheres, polyethylene, rubber, and sand of average particle size ranging from 169 to 4,417 μm (Yanagida et al. 2002, 2003a, b). These sizes are large, resulting in small values of the interparticle interfacial area and hence little contribution of the interface to the viscoelasticity. Thus, prior work (Yanagida et al. 2003b) reported no effect of particle size on the loss tangent. In contrast, this paper addresses particles that are approximately 0.2 μm in size, so the interface becomes more important. In the prior work (Yanagida et al. 2002, 2003a), glass and sand give relatively high values of the modulus of elasticity but relatively low values of the loss tangent, whereas rubber and polyethylene give relatively low values of the modulus of elasticity but relatively high values of the loss tangent. These results are consistent with the dominance of the contribution from the particle interior. In contrast, the addition of silica particles of average size around 0.2 μm (as in this paper) to cement increases the loss tangent and the storage modulus (Chung 2002; Chen and Chung 2013), indicating the significant role of the silica–cement interface.

High values of the storage modulus and loss tangent are necessary for energy dissipation because (1) a high storage modulus enables a high force to be borne, and (2) a high loss tangent enables fast reduction of the vibration amplitude (Chen and Chung 2012; Chung 2001).

This paper is directed at studying the viscoelastic behavior of model sandy soils in the form of compacts of silica particles in the absence of any other ingredient, including water. In particular, the effect of the degree of compaction on the viscoelastic behavior is addressed.

Experimental Methods

The silica particles of true density 2.1 g/cm^3 are silica fume (Elkem Materials Inc., Pittsburgh, microsilica, EMS 965), as used in prior work on cement–matrix composites (Chung 2002; Chen and Chung 2013). The particle size ranges from 0.03 to 0.5 μm, with average size 0.2 μm. It contains >93% by weight SiO_2, <0.7% by weight Al_2O_3, <0.7% by weight CaO, <0.7% by weight MgO, <0.5% by weight Fe_2O_3, <0.4% by weight Na_2O, <0.9% by weight K_2O, and <6% by weight loss on ignition.

Specimens are obtained by manual compaction in a stainless steel cylindrical cup of inside diameter 18.0 mm. The thickness in the direction of the compressive stress is 3.5 mm, as measured for each specimen. The bulk density is obtained from the measured mass and volume. Specimens are tested at bulk densities ranging from 0.50 to 0.59 g/cm^3, which correspond to solid volume fractions ranging from 24 to 28%. Dynamic compressive stress is applied by using a stainless steel circular plate of diameter 15.0 mm such that the plate is parallel to the bottom plane of the cup and is centered at the axis of the cup. Three specimens are tested for each combination of specimen type and loading condition.

Dynamic compressive testing ASTM D4065-12 (ASTM 2012; this method is commonly used for obtaining dynamic mechanical data) using a sinusoidal stress wave at controlled frequencies of 0.2–10 Hz is conducted at room temperature using a dynamic mechanical analyzer (DMA7E, Perkin Elmer Corp., Shelton, CT, http://www.perkinelmer.com/Catalog/Category/ID/Measuring%20Systems%20for%20DMA%207). The phase lag between the input stress wave (as controlled by a load cell) and the output strain wave (as measured by a displacement transducer) is measured, thus giving the loss tangent. The amplitude of the stress wave divided by that of the strain wave gives the storage modulus. The dynamic stress σ_d ranges from 70 to 73% of the corresponding static stress σ_s. The stresses are chosen so that different specimens are tested at comparable values of the static strain and deformation amplitude, which is kept below 10 μm in order to avoid other vibration modes. The wall of the cup does not interfere with the measurement due to the low amplitude. The static stress ranges from 500 to 1,200 Pa, the dynamic stress ranges from 300 to 900 Pa, and the static strain ranges from 0.93 to 1.93%. The frequency is far from any vibration resonance frequency.

Results and Discussion

Table 1 shows that the loss tangent decreases slightly with increasing solid content, while the storage modulus increases with increasing solid content and the loss modulus increases slightly, if at all, with increasing solid content. These quantities describe the behavior of the compact. On the other hand, the loss tangent and solid content (which relates to the loss tangent of the solid part of the compact) decreases with increasing solid content and the loss modulus and solid content (which relates to the loss modulus of the solid part of the compact) decreases slightly, if at all, with increasing solid content, while the storage modulus and solid content (which relates to the storage modulus of the solid part of the compact) is essentially independent of the solid content. This means that the viscous character of the solid part decreases as the solid content increases, while the elastic character of the compact is essentially independent of the solid content. This observation means that the interparticle movement in the solid part contributes largely to the viscous behavior of the compact and that the movement is more difficult when the solid content is increased. In contrast, the elastic character of the solid part is essentially independent of the solid content, so the rule of mixtures is obeyed. Hence, both the viscous and elastic characters are largely governed by the solid part of the compact. The loss tangent, storage modulus, and loss modulus all decrease with increasing frequency from 0.2 to 10.0 Hz as is typical of viscoelastic deformation, which takes time to complete.

In practice, a low degree of compaction is recommended for fast decay of the vibration amplitude (loss tangent) and no particular

Table 1. Effect of Bulk Density on the Dynamic Compressive Properties of Silica Particle Compacts at the Frequency of 0.2 Hz

Bulk density (g/cm^3)	0.50 ± 0.01	0.55 ± 0.01	0.59 ± 0.01
Solid content (% by volume)	24 ± 1	26 ± 1	28 ± 1
Static strain (%)	1.85 ± 0.07	1.93 ± 0.14	1.91 ± 0.06
Amplitude (μm)	8.7	8.8	8.1
Static stress (Pa)	800	1,200	1,200
Dynamic stress (Pa)	500	800	900
Loss tangent	0.098 ± 0.002	0.088 ± 0.002	0.084 ± 0.007
Storage modulus (10^4 Pa)	1.97 ± 0.11	2.24 ± 0.05	2.44 ± 0.10
Loss modulus (10^3 Pa)	1.93 ± 0.07	1.98 ± 0.06	2.03 ± 0.08
Loss tangent/solid content	0.41 ± 0.03	0.34 ± 0.02	0.30 ± 0.03
Storage modulus/solid content (10^4 Pa)	8.2 ± 0.8	8.6 ± 0.5	8.7 ± 0.7
Loss modulus/solid content (10^3 Pa)	8.1 ± 0.6	7.6 ± 0.5	7.3 ± 0.5

Note: Comparison is made at comparable values of the static strain and amplitude, as obtained by adjusting the static stress and dynamic stress.

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degree of compaction is recommended for mechanical energy dissipation (loss modulus). A low frequency is preferred for both functions.

For glass spheres of size ranging from 80 to 4,000 μm, prior work (Yanagida et al. 2003a) reported that the storage modulus is significantly increased by increasing the compressive stress, whereas the loss tangent is only slightly decreased, if at all, upon increasing the stress. The effects of stress observed in this paper for the storage modulus and loss tangent are basically consistent with those reported previously (Yanagida et al. 2003a), though the effect of stress on the loss tangent is more clearly observed in this paper than in prior work.

Conclusion

New information on the viscoelastic behavior of model sandy soils in the form of compacts of submicrometer silica particles under dynamic compression (0.2–10.0 Hz) is provided. The solid content ranges from 24 to 28% by volume as controlled by compaction. The viscoelastic behavior is relevant to vibration damping. Both viscous and elastic characters are largely governed by the solid part of the compact. The elastic character stems from the stiffness of the silica, while the viscous character stems from the interparticle movement. The elastic character of the solid part (described by the storage modulus and solid content) is essentially independent of the degree of compaction, indicating the validity of the rule of mixtures. The viscous character of the solid part (described by the loss tangent and solid content) decreases with increasing degree of compaction, indicating decreasing ease of interparticle movement as the degree of compaction increases. The loss modulus and solid content is essentially independent of the degree of compaction. The loss tangent, storage modulus, and loss modulus all decrease with increasing frequency. In practice, a low degree of compaction is recommended for fast decay of the vibration amplitude (in relation to the loss tangent) and no particular degree of compaction is recommended for mechanical energy dissipation (in relation to the loss modulus), with a low frequency being preferred for both functions.

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