STIFFNESS AND DAMPING OF NON-HOMOGENEOUS ENGINEERED PARTICLES

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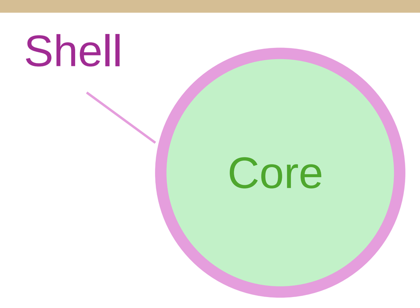
FOCUS: FUNCTIONALIZING GRAINS

The response of granular materials is controlled by numerous factors including current and past stress conditions, pore fluid properties, particle size distribution, packing arrangement and the characteristics of the grains themselves. In particular, the morphology and composition of the individual grains are known to affect interparticle interactions and ultimately the behavior of the full granular assembly. Inspired by this notion, this study sought to develop a novel highly dissipative granular material composed of a rigid core encapsulated in a soft solid shell. Measurements of the small strain shear modulus (G_{max}) and damping ratio (D_0) performed using the resonant column apparatus are used to explore the behavior of these engineered particles.

MODEL MATERIALS

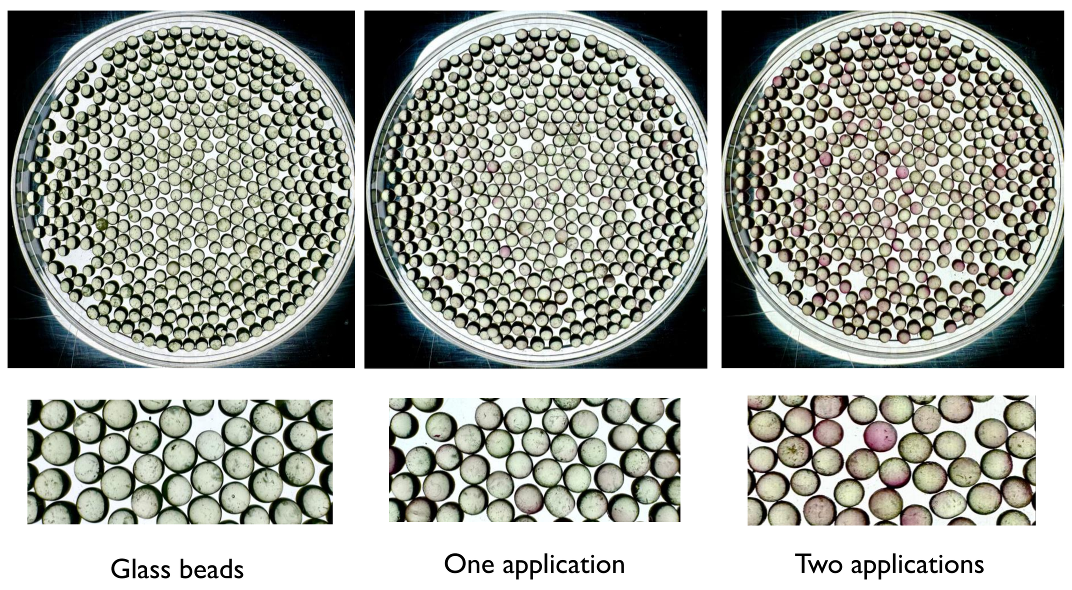


Engineered particles (EP)

Glass beads (*GB*): 3.3-3.9 mm diameter soda-lime glass

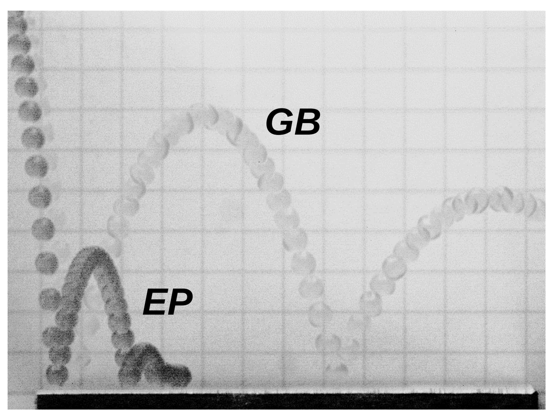
Engineered particles (*EP*): glass bead cores with a soft platinum-cure silicone shell

$G_{silicone}$ (~60 kPa[1]) << G_{Glass} (~ 29 GPa)



The *EP* coating process allows for gradual application of the soft silicon and control of the shell thickness. Oil paint is mixed with the silicone to serve as a visual indicator of shell thickness, as the hue of the engineered particles becomes more intense with additional applications.

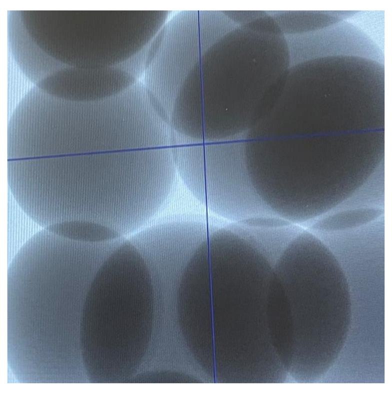
Two applications of the silicone yield a coating that is ~ 3.5-4% of the mass of the glass core, corresponding to an average shell thickness of ~ 50-70 μm.



Coefficient of restitution (measured on hardened steel)
***GB**: ~ 0.94*
***EP**: ~ 0.37*

Effect of soft shell on coefficient of restitution

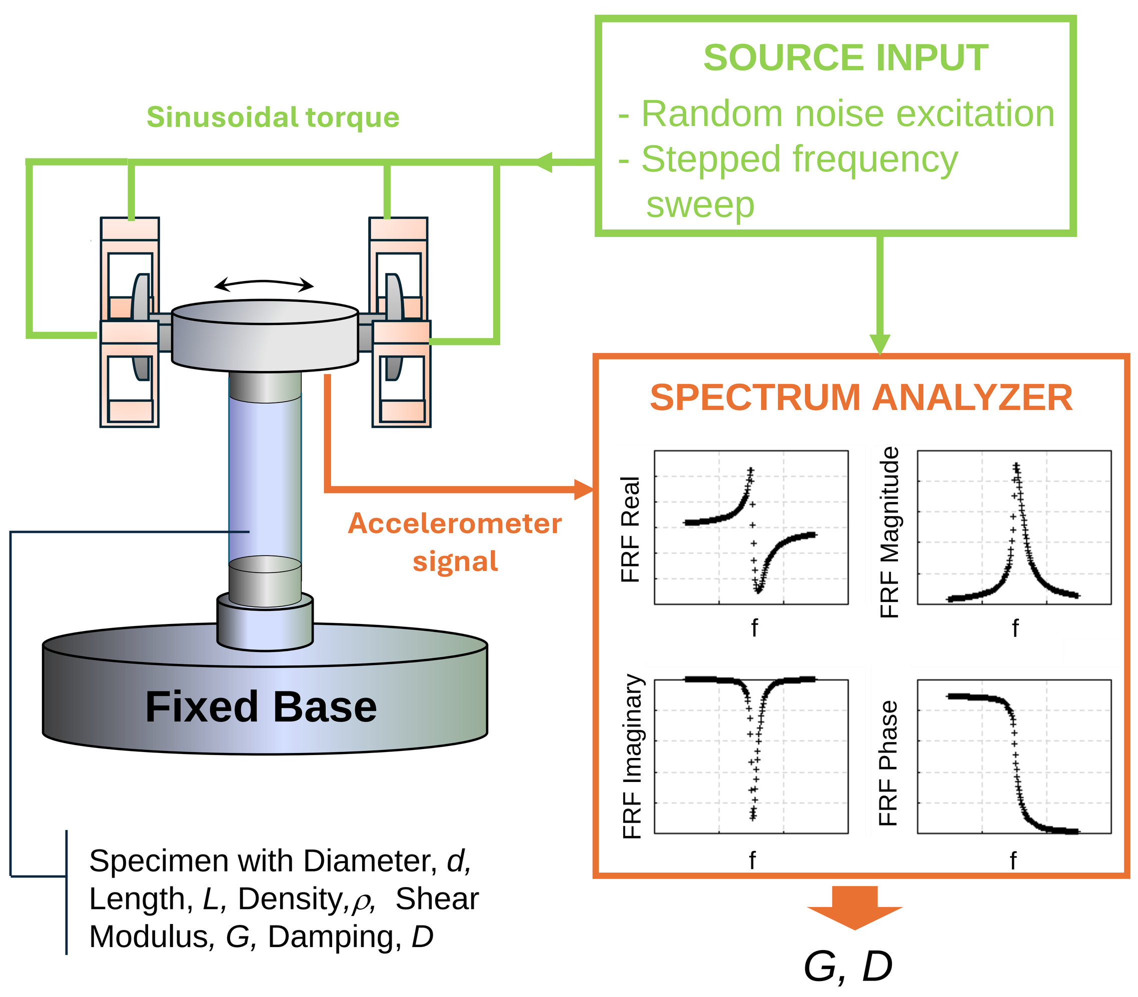
(test performed with initial horizontal velocity for visualization purposes)



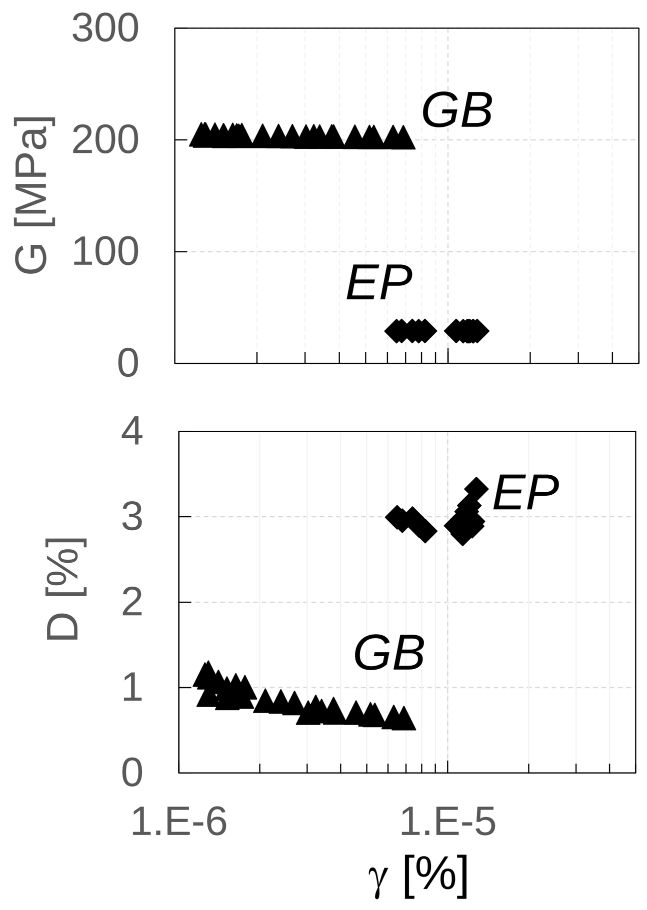
Engineered particles as seen using X-ray tomography

OFF-RESONANCE MEASUREMENTS IN RESONANT COLUMN APPARATUS

Measurements are performed using a Drnevich type resonant column device leveraging recent developments that allow analysis of off-resonance data and semi-continuous characterization of *G* and *D* with shear strain under a single excitation. Small amplitude random noise torsional vibrations are used to probe the small strain response of the *GB* and *EP* specimens after isotropic loading and unloading to σ'_c = 35-350 kPa. G_{max} and D_0 are derived from the real and imaginary components of the complex frequency response function reported by the spectrum analyzer following the method described in [2].



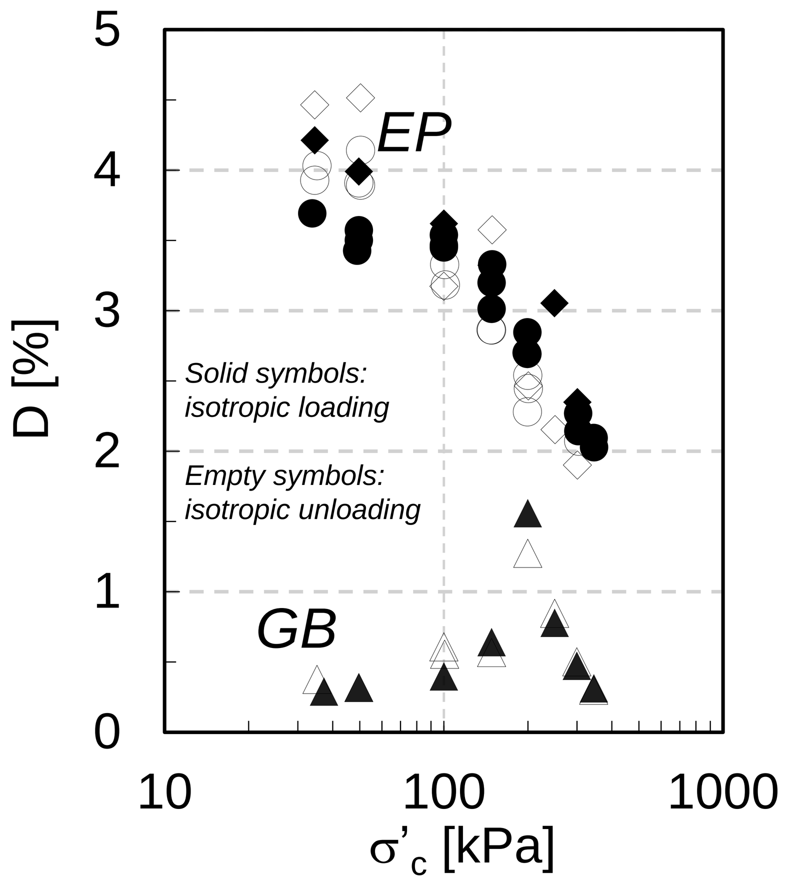
Testing method for off-resonance measurements



Example of data from random noise excitation

(σ'_c =150 kPa - 20 mv amplitude)

EFFECT ON D_0



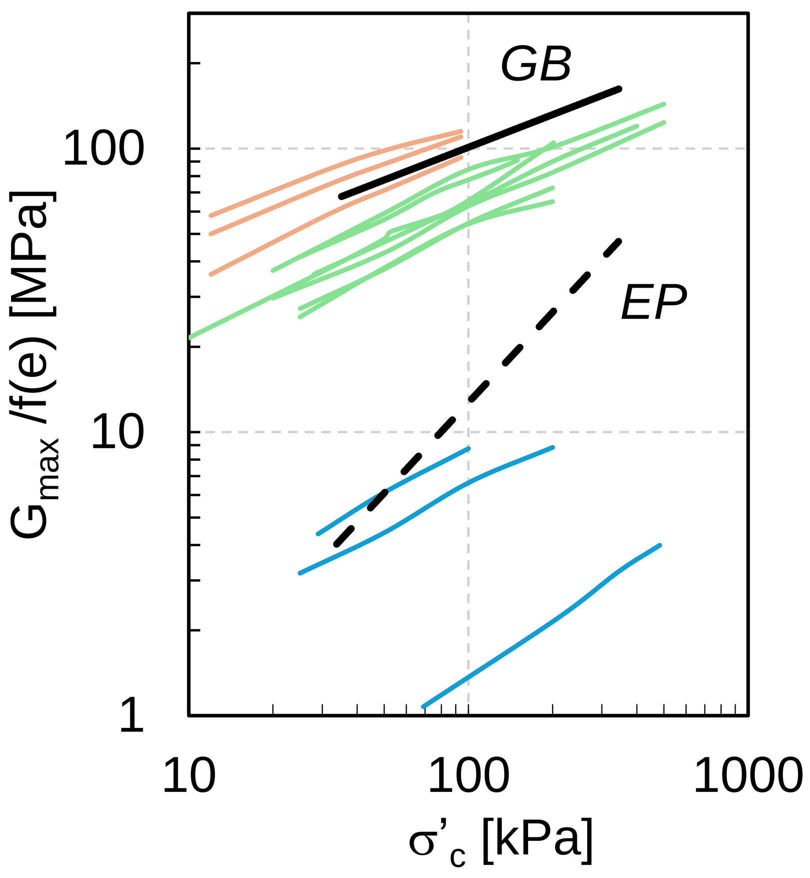
EP exhibit: :

- tenfold increase in D_0 relative to *GB*
- marked decrease of D_0 with σ'_c
- D_0 values at low σ'_c exceed those measured on sand-rubber mixtures with replacement exceeding 35% [6].

Damping data for *GB* are consistent with those for silicate granular materials.

EP data for double coated particles

EFFECT ON G_{max}



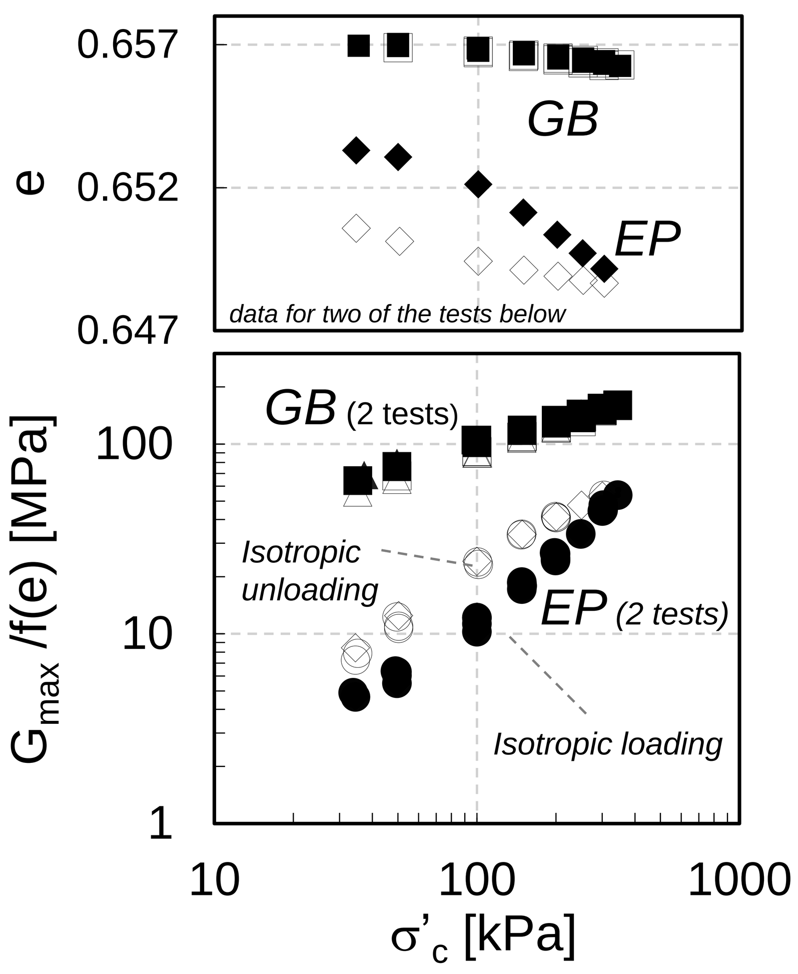
$$G_{max} \propto OCR^m\, f(e)\, \sigma_c'^n \qquad f(e) = 1/(0.3 + 0.7e^2)$$

Material	n	Source
Gravels	0.34-0.46	[3]
Silicate Sands	0.41-0.54	[3-6]
Sand + Rubber	0.50-0.68	[6-7]
Glass Beads	0.38	this work
Engineered Particles	1.06	

EP exhibit:

- lower G_{max} relative *GB* particles (by over an order of magnitude at low σ'_c).
- greater stress sensitivity than all other reference materials including sand-rubber mixtures.

The behavior of *GB* is comparable to that of similar size geomaterials.



EP data for double coated particles

In the EP specimens only, G_{max} measured during unloading exceeds values measured during loading by as much as a factor of 2, even accounting for differences in void ratio.

This behavior can be attributed to visco-plastic deformations at the contacts similarly to what has been reported for lead shots[8].

This hypothesis is supported by the permanent volume changes measured upon unloading.

Grain contacts between beads compressed in a track

CONCLUSIONS

The findings of this work showcase the vast potential for the development of novel functional granular materials through proactive design of particle level attributes. In particular, the work demonstrates that it is possible to engineer particles with highly dissipative behavior through encapsulation of the grains in a soft shell that represents less than 4% of the particle mass. This is demonstrated through tests on a model granular material consisting of glass beads coated with soft platinum-cure silicone.

Engineered particle assemblies exhibit: lower shear modulus relative to specimens consisting exclusively of rigid cores, higher sensitivity to confining stress compared to that reported for granular materials, and stiffening upon preloading. Most significantly, values of the damping exceed those measured on sand-rubber mixtures with replacement exceeding 35%. This enhanced dissipative behavior is attributed to the modification of the majority of particle contacts, with a notably lower mass of damping medium.

REFERENCES

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