

A GEL MATRIX ENERGY ABSORBING COMPOSITE FUNCTIONALIZED BY NANOPOROUS SILICA

Yu Qiao, Lance A. Sperball, Venkata K. Punyamurtula: yqiao@ucsd.edu
 Department of Structural Engineering, University of California at San Diego
 La Jolla, California 92093-0085, USA

Keywords: *Nanoporous, Gel, Energy absorption, Infiltration*

1 Introduction

Energy absorption materials (EAM) such as epoxy composites, polymer and metal foams, and Ti-Ni alloys have been widely used for car bumpers, blast-resistant containers, protective layers, among others. However, because of the relatively low energy absorption efficiency, the protection systems based on them are often bulky and heavy. Over the years, continuous efforts have been made to search for new energy absorbing mechanisms.

Based on recent research on pressure induced infiltration [1-3], it has been demonstrated that the ultra-large surfaces of nanoporous materials can be utilized to amplify the well-known capillary effect, forming nanoporous energy absorption systems. For instance, by forcing water into hydrophobic nanoporous silica particles, a large amount of external work can be converted to the solid-liquid interfacial tension. While the absolute value of the excess interfacial energy $\Delta\gamma \approx 0.06 \text{ J/m}^2$ is relatively low, due to the high specific surface area $A \approx 250 \text{ m}^2/\text{g}$, the energy absorption efficiency of this system $E^* = \Delta\gamma A \approx 15 \text{ J/g}$ is much higher than that of ordinary EAM. For example, the energy absorption efficiencies of polymer foams, metal foams, and shape memory alloys are around 0.1-1 J/g, 1-3 J/g, and 0.5 J/g, respectively. If nanoporous materials of smaller pores are used, E^* can be further increased by another order of magnitude.

However, since the nanoporous particle-water system contains a liquid phase, it must be sealed appropriately, making it quite incompatible with most of conventional protection devices. In order to minimize the difficulty in implementing this concept in engineering practice, it is desirable to develop a solid-like system consisting of hydrophobic nanoporous particulates dispersed in a gel matrix. Under ambient condition, the system can

be placed and handled as a normal EAM; under a high pressure, water molecules become highly mobile in the gel matrix and can be “compressed” into the nanopores, activating the energy absorption process. Such a system can actually be regarded as a composite material, with the gel matrix being functionalized by the nanoporous particulates.

One of the most promising candidates for the gel matrix is superabsorbent. Superabsorbents are polyelectrolytes that can form stable confining networks. The commonly used superabsorbents include polyacrylic acid, poly(styrene sulfonate), etc. In this article, we investigate the energy absorption behavior of nanoporous particles in a polyacrylic acid gel.

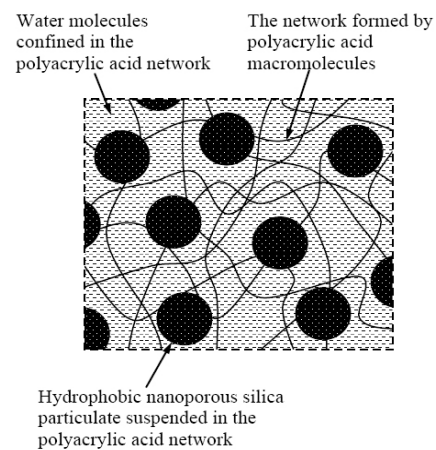


Fig.1 A schematic of the gel matrix NMF composite.

2 Experimental Results

Figure 1 depicts the microstructure of the specimen. By dispersing Sigma 100 C₈ reversed phase nanoporous silica particulates in distilled water, a liquid energy absorption system was formed. By adding polyacrylic acid, the liquid phase was solidified into a gel, and the silica particulates were embedded in it, forming a gel matrix composite material, as shown in Fig.2.

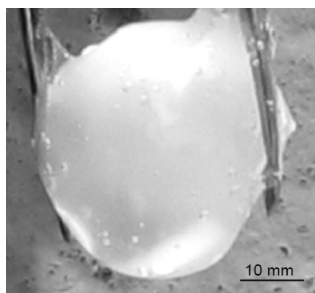


Fig.2 A photo of the testing sample.

After removal of remaining water and drying, the polyacrylic acid gel functionalized by nanoporous silica particulates was placed in a steel container. By using a type-5569 Instron machine, a steel piston was compressed into the container, applying a uniform pressure on the material. As the pressure reached about 50 MPa, further increase in pressure would not lead to detectable change in system behavior, and the piston was moved back at the same speed. The loading-unloading cycle was repeated until the sorption isotherm converged to the steady-state, as shown in Fig.3.

When dispersed in water, polyacrylic acid macromolecules can crosslink each other through charged groups and form a unified network. The water molecules are confined in the cells of the network. Hence, by adding a small amount of polyacrylic acid, typically 2-6% in weight, in water, the characteristic of fluid would be lost and the system is solidified to a soft matter. When a hydrostatic pressure is applied, if the pressure field is isotropic, the soft matter would deform and the system free energy would increase as the strain energy is stored. However, the variation in driving force of water diffusion is negligible, and consequently the gel structure is quite stable. If the stress field is not equiaxed, e.g. there exist small voids in the material, the water molecules tend to diffuse from the high-energy region (the polyacrylic acid network) to the low-energy region (the small voids), until the voids are filled. Since this process is energetically favorable, it is governed by kinetics instead of thermodynamics.

In the gel matrix composite material functionalized by nanoporous particulates, on the other hand, the nanopores are hydrophobic. Therefore, the applied pressure must be sufficiently high so that the capillary effect can be overcome. Initially when the pressure is low, water molecules cannot infiltrate into nanoporous silica, and, except for the initial concave ramp caused by the loading

system, the sorption isotherm curve increases quite linearly. As the pressure reaches 14.3 MPa, the sorption isotherm becomes highly nonlinear, indicating that the pressure induced infiltration begins. Due to the pore size distribution, the slope of the infiltration plateau of sorption isotherm is positive. When the pressure reaches 27.2 MPa, most of the pores are saturated and the system compressibility decreases rapidly.

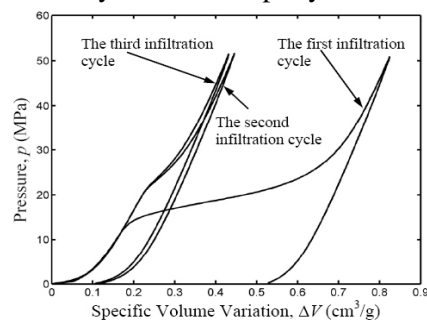


Fig.3 Load-displacement curves.

The unloading behavior of the polyacrylic acid gel matrix composite material is quite linear, similar to the pure water based nanoporous system, which is compatible with the previous experimental observation that under ambient condition most of the confined water molecules cannot come out of the nanopores. That is, the increased system free energy associated with the water infiltration cannot be released, resulting in the significant energy absorption. The energy absorption efficiency of the current material, which can be calculated as the area enclosed by the first infiltration cycle of sorption isotherm, is about 14 J/g, nearly the same as that of the water based system (15 J/g) [1]. Since most of the porous space remains being filled, from the second loading-unloading cycle the energy absorption capacity of the composite material is largely reduced, i.e. the material is suitable for one-time protection applications.

References

- [1] Kong X, Qiao Y. Improvement of recoverability of a nanoporous energy absorption system by using chemical admixture. *Appl. Phys. Lett.* 2005; 86: 151919.
- [2] Surani FB, Kong X, Qiao Y. Energy absorption of a nanoporous system under dynamic loadings. *Appl. Phys. Lett.* 2005; in the press.
- [3] Kong X, Surani FB, Qiao Y. Effects of addition of ethanol on the infiltration pressure of a mesoporous silica. *J. Mater. Res.* 2005; 20: 1042.