# Energy absorption of a nanoporous system subjected to dynamic loadings

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(Received 6 June 2005; accepted 25 August 2005; published online 12 October 2005)

In a previous study [X. Kong and Y. Qiao, Appl. Phys. Lett. **86**, 151919 (2005)], we analyzed the energy absorption behaviors of a nanoporous system subjected to quasi-static loadings. In this work, the performance of similar systems under dynamic loadings is investigated through a Hopkinson bar experiment. The energy absorption efficiency increases significantly with the loading rate, which is attributed to the effect of internal friction. © *2005 American Institute of Physics*.
[DOI: 10.1063/1.2106002]

In order to develop smaller-sized and lighter-weight protection and damping systems, for many decades a large number of energy absorption materials and structures have been investigated extensively, including various polymer-based composites and shape memory alloys.[1,2] Recently, a novel high-performance nanoporous energy absorption system (NEAS) has drawn increasing attention.[3,4] The functional component of a NEAS is a liquid suspension of nanoporous particles. The liquid should be nonwetting to the pore surfaces, and can enter the nanopores when the applied pressure is sufficiently high. As the pressure is lowered, in a system of appropriate porous structure and surface properties, the confined liquid would remain in the nanoenvironment, resulting in a significant hysteresis of sorption isotherm. The specific energy being absorbed during the loading-unloading process can be assessed as $U=\Delta\gamma\cdot A$, where $\Delta\gamma$ is the effective excess solid-liquid interface energy, and $A$ is the specific surface area. Since for a nanoporous material, $A$ is usually in the range of 100–1000 $m^2/g$, the energy absorption efficiency of a NEAS can be higher than that of conventional protection systems by orders of magnitude.

However, most of current studies in this area are focused on quasi-static responses, and shed little light on the actual system performance under dynamic loadings. For instance, one important yet still unanswered question is whether the characteristic time of infiltration, $t_i$, is smaller than that of wave propagation, $t_{wp}$. If $t_i < t_{wp}$, the nanopores can be infiltrated as the impact wave bypasses a nanoporous particle, and the energy absorption capacity of NEAS can be fully utilized; otherwise, the utility factor would be smaller than 1.0. Both $t_i$ and $t_{wp}$ are dependent on a variety of factors, such as the pressure of incident pulse, the size and the microstructure of nanoporous particles, among others. In this work, by using a Hopkinson bar testing system, we investigate the high strain rate performance of a mesoporous silica, for which the quasi-static behaviors have been documented elsewhere.[3,4]

The nanoporous material under investigation was a Fluka 100 $C_8$ reversed phase nanoporous silica, with the average pore size of 7.8 nm, the standard deviation of 2.4 nm, and the surface coverage of 10–12%. The particle size is 10–30 $\mu$m. Both the pressure-induced infiltration experiment and the Berrett–Joyner–Halenda measurement have shown that the specific pore volume is 0.5 $cm^3/g$. The material has a relatively simple end-capped porous structure. Under quasi-static loadings, the energy absorption efficiency is about 15 J/g in distilled water,[3] indicating that $\Delta\gamma$ is 92 $mJ/m^2$. Note that in the nanoenvironment, there is no well-defined interface zone. The effective interface energy contains the contributions from the solid-liquid interaction and the chemical potential difference of gas and liquid phases.[5]

The testing sample was produced by sealing 0.3–0.8 g of nanoporous silica particles and 7 g of distilled water in a stainless-steel cylinder, as depicted in Fig. 1. The inner diameter of the cylinder is 19.05 mm, and the outer diameter is 38.1 mm. Under atmosphere pressure, because the silica particles are hydrophobic, the solid and liquid phases were separate. By using a Type 5569 Instron machine, the piston was compressed into the cylinder at a constant rate of 2 mm/min. Once the pressure-reached about 17 MPa, the pressure induced infiltration began in relatively large pores. As the pressure increased to about 20 MPa, the infiltration was completed and the porous space was filled. The unloading curve was quite linear, indicating that the confined liquid remained in the nominally energetically unfavorable nanoenvironment. The sample was then annealed in a controlled-temperature bath at 80 ° C for 30 min, which led to the thermally aided defiltration and thus the energy absorption capacity was fully recovered.[6] After the thermal treatment, the silica particles were uniformly dispersed in the liquid phase.

The dynamic response of the thermally recovered nanoporous system was characterized in a Hopkinson bar arrangement. The striker, with the length of $L_s=76.2$ mm and the cross-sectional diameter of $d=19.05$ mm, impacted the input piston at about 11 m/s, through which two compressive wave fronts were generated and propagated along opposite directions. The front in the striker would be reflected by the free end, forming a compressive incident pulse.[7] As the inci-

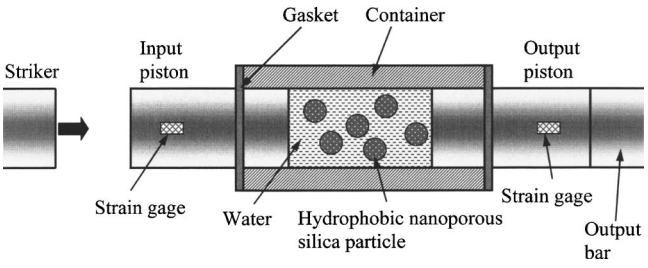


FIG. 1. A schematic diagram of the experimental setup.

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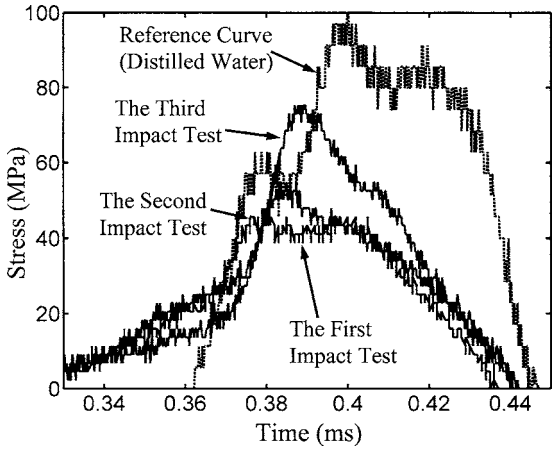


FIG. 2. The transmitted pulses measured in the output piston for a system consisting of 0.3 g of nanoporous silica particles. The reference curve is the transmitted pulse of distilled water. The curves have been moved along the time axis.

dent pulse reached the steel-liquid interface, part of it would be reflected and the rest of it would enter the nanoporous system, propagate across it, and partly transmit into the output piston. The incident pulse, the reflected pulse in the input piston, and the transmitted pulse in the output piston were measured by the strain gauges.

Due to the large impedance difference of the steel and the liquid phase, it was prohibitively difficult to obtain the effective stress-strain relation through the standard Hopkinson bar analysis. In the current study, the transmitted pulse of a system consisting of only distilled water is used as the reference curve. Since there is no nanoporous particle, the energy absorption of this system is negligible. Therefore, the variation in shapes of transmitted pulses of NEAS reflects the effect of pressure-induced infiltration, as shown in Fig. 2. Altogether three groups of samples were investigated, with the silica particle contents of 0.3 g, 0.5 g, and 0.8 g, respectively. Each sample was impacted repeatedly until the transmitted pulse converged to the reference curve. The time interval between the impact tests was less than 5 min. As shown in Fig. 3, for all the samples, the measured incident pulses and the reflected pulses were quite similar, indicating that the addition of silica particles did not cause significant changes in impedance of liquid phase.

The energy carried by a stress pulse can be obtained as

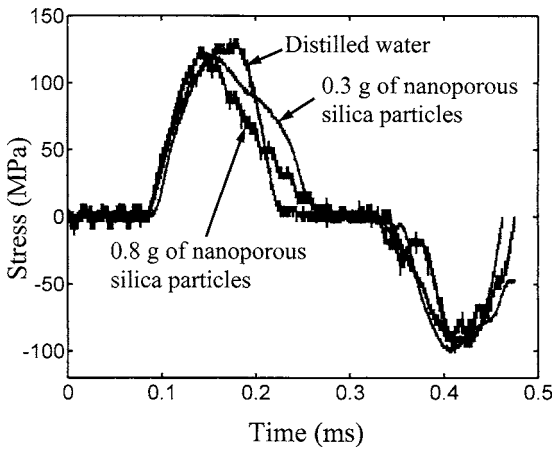


FIG. 3. The incident and reflected pulses in the input piston.

$$U = U_s + U_K = \xi \int_0^T \sigma^2(t)dt, \tag{1}$$

where $U_s$ and $U_K$ are strain energy and kinetic energy, respectively, $t$ is time, $T$ is the pulse length, $\sigma$ is the measured stress, and $\xi = cA/(2E) + \rho A c^3/(2E^2)$, with $c$ being the sound speed, $E$ the Young's modulus, $A$ the cross-sectional area, and $\rho$ the weight density. For the steel sample, $A = 285\ \text{mm}^2$, $c = 5.92 \times 10^3\ \text{m/s}$, $E = 2.11 \times 10^{11}\ \text{Pa}$, $\rho = 7.8 \times 10^3\ \text{kg/m}^3$, and thus $\xi = 9.2 \times 10^{-12}\ \text{m}^5/\text{N s}$. According to Eq. (1), the energies of the incident, the reflected, and the transmitted pulses of the reference system are, respectively, $U_{\text{ir}} = 10.8$ J, $U_{\text{rr}} = 4.9$ J, and $U_{\text{tr}} = 3.4$ J. Note that $U_{\text{ir}}$ is close to the kinetic energy of the striker, as it should be. The fraction of energy carried by the transmitted pulse across the interface between the liquid phase and the output piston can be calculated as $\alpha = U_{\text{tr}}/(U_{\text{ir}} - U_{\text{rr}}) = 0.57$.

Figure 2 shows the output pulses of a system consisting of 0.3 g of nanoporous silica particles. The energies carried by the output pulses in the first three impact tests were 0.8 J, 0.9 J, and 1.5 J, respectively. From the fourth impact test, the energy was stabilized at about 3.4 J, the same as that of distilled water, indicating that the system could not be recovered by itself. The total energy that the 0.3 g of nanoporous particles absorbed can be estimated as $\Delta U/\alpha = 12.3$ J, with $\Delta U$ being the accumulated energy difference of the transmitted pulses. Thus, the energy absorption efficiency of this system is 41.0 J/g, which is about three times higher than the quasi-static value. Similarly, the energies absorbed by the systems consisting of 0.5 g and 0.8 g of nanoporous particles can be calculated as 19.5 J and 30.0 J, respectively. It can be seen that the energy absorption capacity is quite linear to the amount of nanoporous particles, suggesting that the interaction among the particles is negligible. The increase in energy absorption efficiency with the loading rate can be related to the internal friction. For instance, it has been reported that, in shear thickening systems formed by dispersing nm-sized particles in liquids, the damping ratio can increase considerably as the strain rate exceeds a certain value.[8] The energy dissipation associated with the "flow" in nanopores can also be pronounced as a liquid penetrates into a porous material.[9]

Note that, in Fig. 2, the shapes of the transmitted pulses in the first two impact tests are quite similar. Similar phenomena were observed for all the nanoporous systems, which demonstrates that the pressure-induced infiltration took place simultaneously in nanopores of different sizes; otherwise, the pressure of the next pulse must be higher than the previous one since the larger pores were filled. This can be attributed to that, at the wave front, the local pressure increases to the peak value in a short period of time and therefore the priority of infiltration in larger pores is suppressed. However, this effect must be further evaluated by testing nanoporous materials of similar pore size distributions but different particle sizes.

In summary, through the impact experiment, it has been validated that the nanoporous system can be used for energy absorption applications under dynamic loadings. Compared with the quasi-static case, under a dynamic loading the energy absorption efficiency of the nanoporous system was much higher. The interaction among the nanoporous particles was negligible. No detectable priority of infiltration in larger pores over smaller ones was observed in the current study.

This work was supported by The Army Research Office under Grant No. W911NF-05-1-0288, for which the authors are grateful to Dr. D. M. Stepp. Special thanks are also due to Dr. M. Hoo-Fatt and Dr. R. Huang for the help with experiment and the useful discussions.

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