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Aerogel-reinforced polymer nanocomposites

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Carbon aerogels are lightweight, mesoporus, solid-state materials that can be used to reinforce composites and to enhance their thermal and mechanical properties.

Polymer nanocomposites—materials that consist of a polymer matrix containing individually dispersed nanosized fillers (commonly natural and synthetic clays, nanostructured silica, nanoceramics, nanocalcium carbonates, and carbon nanotubes)—are an important class of materials that serve as an alternative to conventionally filled polymers. These composites exhibit performance superior to pure polymers, and to their conventional composites, and can thus compete with traditional materials. Such characteristics include increased modulus and strength, toughness, thermal endurance, flame retardance, liquid and gas barrier properties, improved solvent and abrasion resistance, reduced shrinkage and residual loss, as well as altered electrical and optical properties.[1–5] For many applications, however, it would be desirable to reduce energy and material consumption, and it is thus necessary to reduce the weight of the nanocomposites.

To date, an effective approach to reducing both the mass and density of bulk materials has been the generation of pores during composite synthesis or postprocessing.[3] Nonetheless, mesoporous nanofiller forms offer a novel and lightweight alternative for reinforcing agents in several engineering polymer nanocomposites. These nanofiller forms are suitable because of their high surface area and their organized mesoporosity. The mesoporosity of the fillers means they can trap polymer chains, and consequently, a higher level of interaction between the polymer and the fillers can be achieved.[6–11] For example, aerogels are an intriguing type of mesporous, solid-state material that possess unique properties (e.g., extremely low density, large open pores, and high surface area). They are composed of a 3D solid network, with a large number of air-filled pores in the form of a highly cross-linked structure.[12–14] Aerogels are therefore comparable with mesostructured fillers and can be used as the reinforcing agent for polymer nanocomposites. Indeed, it is thought that aerogels may promote the effective fabrication of multifunctional nanocomposite materials (i.e., where the aerogel would first be prepared and optimized, and the polymer matrix would subsequently be backfilled into its network).[6, 15]

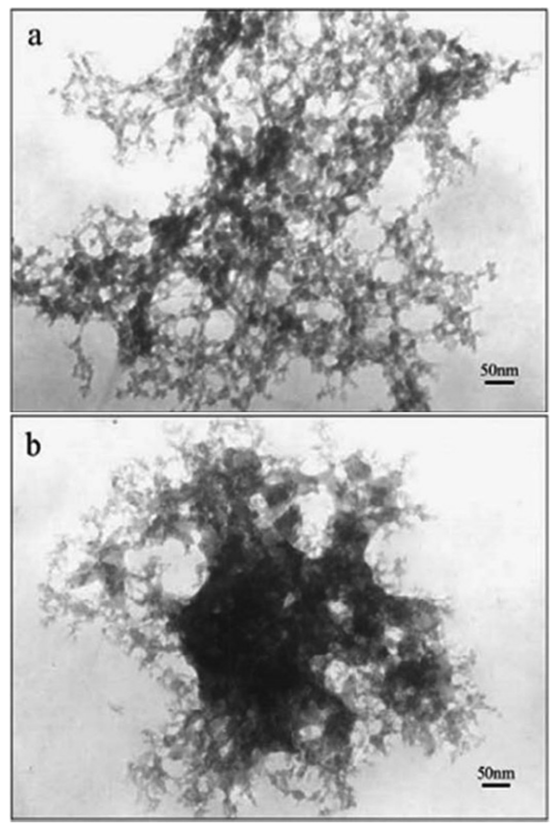

Figure 1. *Transition electron microscopy images of (a) silica aerogel and (b) a silica aerogel/epoxy nanocomposite.[16]*

Although there have been several previous reviews of layered-silicate- and carbon-nanotube-reinforced polymer nanocomposites, as yet, aerogel-reinforced polymer composites have not been examined in a similar manner. We have therefore recently presented an overview of the state of the art in the use of aerogel as a reinforcement for polymer nanocomposites.[16] In particular, we focused on identifying fundamental structure–property relationships of the materials. In this work, we briefly examine how the structure and morphology of carbon aerogel/epoxy nanocomposites can be assessed. We also present the

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Table 1. *Glass transition temperature (T_g) and mechanical properties of epoxy/carbon aerogel nanocomposite samples containing 0.0–0.5wt% aerogel.*[17]

Carbon aerogel (wt%)	T_g (°C)	Young's modulus (GPa)	Tensile strength (MPa)	Fracture toughness (MPa $m^{1/2}$)	Fracture energy (J m^{-2})
0.0	147.8±1.5	2.77±0.02	79.3±0.5	0.76±0.03	125.0±3.2
0.1	146.8±2.0	2.83±0.03	80.2±0.3	1.39±0.06	199.8±14.0
0.2	147.2±3.2	2.84±0.01	83.2±1.8	1.47±0.05	246.7±6.32
0.3	145.3±1.8	2.84±0.03	84.1±0.9	1.53±0.12	255.9±10.2
0.4	146.5±2.6	2.85±0.02	82.0±1.6	1.31±0.10	231.6±12.0
0.5	145.5±3.8	2.94±0.03	81.2±1.1	1.31±0.08	219.5±8.9

thermal and mechanical properties of a set of carbon aerogel/epoxy nancomposites with a range of aerogel contents (0–5wt%).

To characterize the properties of aerogel-polymer nanocomposites and to characterize their response to external stimuli (such as stress gradients or thermal cycling), it is important to understand the structure and morphology of the materials. For instance, transition electron microscopy can be used to assess the microstructural characteristics of the nanocomposites (see Figure 1). From these two images we can observe that although the nanopores of the silica aerogel—shown in Figure 1(a)—have been immersed by epoxy in the nanocomposite—Figure 1(b)—its 3D net structure has been preserved.

The effect of particle loading on the mechanical properties of aerogel/epoxy nanocomposites can be observed from the results presented in Table 1.[17] We see a monotonic increase in the Young's (elastic) modulus of the samples with increasing aerogel content (i.e., from 2.77GPa for the neat epoxy to 2.94GPa for the 0.5wt% aerogel sample), but this relationship is nonlinear. We also find that incorporating a small amount of aerogel into the epoxy significantly affects the tensile strength of the nanocomposites. In contrast, a relatively high content of carbon aerogel (i.e., more than 0.3wt%) causes a decrease in the tensile strength of the composites. Moreover, we note that the tensile strength depends on the uniform dispersion of the aerogel in the epoxy matrix. The maximum tensile strength value (84.1MPa) occurs at 0.3wt%, which is thus determined to be the optimum aerogel content. Indeed, increased aerogel loading above 0.3wt% does not improve the fracture toughness of the materials. The results also indicate that the maximum fracture energy value (255J m^{-2}) occurs at a 0.3wt% aerogel loading (and decreases with increased aerogel content).

In summary, aerogel-reinforced polymer composites exhibit enhanced thermal and mechanical properties because of the high surface area of aerogel, and the favorable interfacial interaction that occurs between the polymer matrix and the aerogel surfaces. Aerogel therefore has great potential for use in polymer-based nanocomposites, and fabrication of aerogel/polymer nanocomposites is a relatively simple way to obtain ultralight foam-like materials, with unique properties, for many applications (such as for damping and insulation purposes). Aerogel-reinforced composites may also be suitable for medical (e.g., orthopedic and dental) and sustainable-energy applications. Hybrid aerogel/fiber polymeric nanocomposites are another interesting topic for future study in this field, and we are particularly keen to see production of an aerogel polymeric nanocomposite fiber in the near future. In our upcoming work—to be conducted in collaboration with the Swiss Federal Laboratories for Materials Science and Technology (Empa)—we will investigate the rheology and thermodynamic properties of silica aerogel/epoxy nanocomposites.

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Saeed Salimian is a PhD student whose research is focused on mesostructured materials, specifically mesoporous silica–polymer hybrid nanocomposites. He also has experience in the synthesis of mesoporous silica (aerogel), which is used as a reinforcement in polymer-based nanocomposites.

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