Polymer/Clay Aerogel-Based Glass Fabric Laminates

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ABSTRACT: Laminates of polymer/clay aerogels and glass fabric sheets were prepared with varying epoxy adhesion application levels. A poly(amide-imide) and an epoxy (1,4-butanediol diglycidyl ether/2,6-diaminopyridine) were chosen as the two "foam core" polymers; both single-layered and double-layered glass fiber laminates were investigated. The adhesion between polymer clay aerogels and glass fibers was quantified using the T-peel method. The peel strength properties were found to increase as adhesive loading increased up to an optimal value, after which peel strength declines. Flexural and compressive testing of the laminates was also performed as a way of measuring mechanical strength. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 124: 2945–2953, 2012

Key words: laminate; aerogel; glass; epoxy; imide

INTRODUCTION

Polymeric matrix composites reinforced with woven fabrics have challenged metals and other traditional construction materials, especially in applications where light weight, corrosion resistance, and minimal environment impact are primary performance parameters.[1,2]

Polymer/clay aerogels have recently been shown to be potential replacements for polymer foams used in packaging, insulation, and structural applications.[3–5] Although poor mechanical properties are obtained if aerogels are produced solely from clay, incorporation of polymers into the compositions can lead to the production of strong/light/durable foam replacement materials, using an eco-friendly freeze-drying process whose only effluent is water vapor.[4] Because 90–96% of the volume of polymer/clay aerogels are occupied by air, the thermal and mechanical properties of the composite, to a great extent, depend on the properties of the incorporated polymer.[5]

The present work focuses on designing a proper process of laminating polymer clay aerogel with glass fabric. A poly(amide-imide) and an epoxy (1,4-butanediol diglycidyl ether) were chosen as the two polymers to be incorporated into the foam-like aerogel structures. Poly(amide-imide) polymer provides a high degree of processability and high use temperatures; these materials can also exhibit high impact strength and excellent retention of the mechanical properties in a high temperature environment. Epoxy resins are known for being an important class of polymeric materials with a wide range of applications such as metal coatings, adhesive, aerospace composites, and fiber-reinforced plastic materials. Cured epoxy resins provide thermosets with excellent mechanical strength and toughness, high chemical, moisture and corrosion resistance, good thermal, and electrical properties.[6]

The interfacial adhesion between polymer/clay aerogels and glass fiber relies on the penetration of adhesives into the aerogel as well as possible chemical interactions between adhesives and aerogel. Before this study, such layered structures and associated peel strengths had not been investigated. For civil engineering applications, peeling/delamination might well be an important mode of failure, and so peel tests of the materials described herein were carried out. Flexural tests of the laminates were also performed, as such a bending force could also play a role in structural failure.[7] It is hoped that polymer clay aerogels could serve as replacements for traditional foam cores currently used in composite structures.

MATERIALS

Sodium montmorillonite (Na^+- MMT) (Nanocor, PGW grade), poly(amide-imide) (Torlon® AI-30; Solvay Advanced Polymers LLC), diethylaminoethanol (DEAE, 99.5%), 1,4-butanediol diglycidyl ether (BDGE, 95%) 2,6-diaminopyridine (DAP, 98%; Sigma-Aldrich), and the epoxy infusion resin system: EPIKOTE resin RIMR 135 (4,4′-isopropylidenediphenol-epichlorohydrin copolymer (70–90%) and 1,6-hexanediol diglycidyl ether (10–30%) mixture) and

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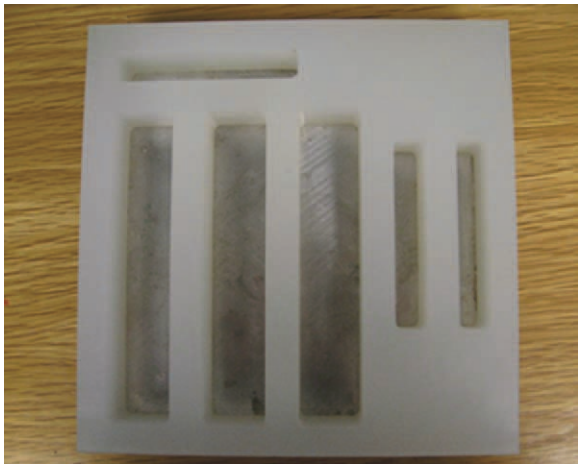

Figure 1 Designed mold for freeze-drying clay-aerogel samples. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

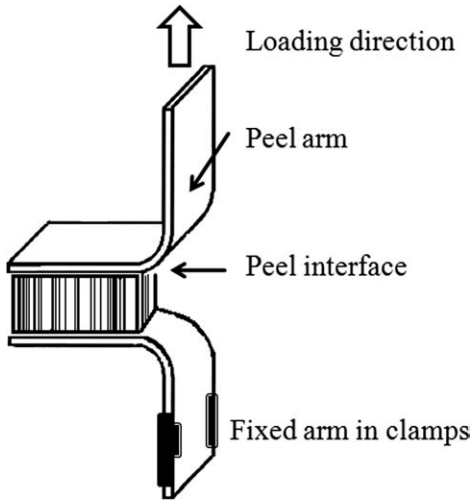

Figure 2 Schematic of the T-peel test. Peel arm and static arm both refers to fiberglass sheet. In between is polymer clay aerogel sample.

EPIKURE curing agent RIMH 1366 [alkyl ether amine (25–50%), isophorone diamine (20–25%), aminoethyl piperazine (<20%) mixture] (Hexion specialty chemicals) were used as received.

Deionized water was prepared using a Barnstead RoPure reverse osmosis system. Glass fiber fabric (E-glass; Sweet Composites, Bethesda, MD) and a vacuum bagging system (EZ-Vac bagging kit) were used in laminate preparation.

Preparation of poly(amide-imide)/clay aerogel solutions

Aqueous solutions of poly(amide-imide) were prepared by mixing 5.22 g diethylaminoethanol and 166.2 mL deionized water.[8] The amine solution was heated to 95°C before slowly adding 28.6 g poly(amide-imide) polymer. About 10 wt % clay gels were prepared by mixing 20 g Na^+-MMT and 200 mL deionized water using a Waring model MC2 mini laboratory blender. Then 2.5% poly(amide-imide)/5% clay solution was made by slowly adding the polymer solution to the clay gel while stirring by a hand mixer. The solution was poured into a 7″ × 7″ × 1″ mold-containing flexural test (0.5″ × 3″) and peel test (1″ × 5″) test cavities (Fig. 1).

Preparation of BDGE/clay aerogel solutions

About 17.5 g of Na^+-MMT clay was added to 200 mL of deionized water and mixed in Waring model MC2 mini laboratory blender for about 3 min. About 55 g of BDGE and 15 g of DAP were added to 150 mL of deionized water and stirred gently by hand before mixing it using a hand mixture to avoid the formation of bubbles and foamy structure. Both mixtures (200 mL and 150 mL) were added together in 500 mL flask and combined using a hand mixer to prepare the 20% BDGE/5% Na^+-MMT clay aerogel. The resulting polymer/clay aerogel were poured into a rectangular polypropylene mold (Fig. 1).

Freeze drying process of polymer/clay aerogels

Both polymer-clay aerogel solutions were frozen using liquid nitrogen/solid carbon dioxide bath. The freeze-drying process was carried out using a Virtis Advantage Model EL-85 lyophilizer. For poly(amide-imide) clay aerogels, the initial shelf temperature of −10°C, and it was increased to 25°C after full vacuum attained. For BDGE clay aerogel, the shelf temperature was constant at 25°C. The freeze-drier process was stopped when reaching an ultimate pressure of 5 μbar.

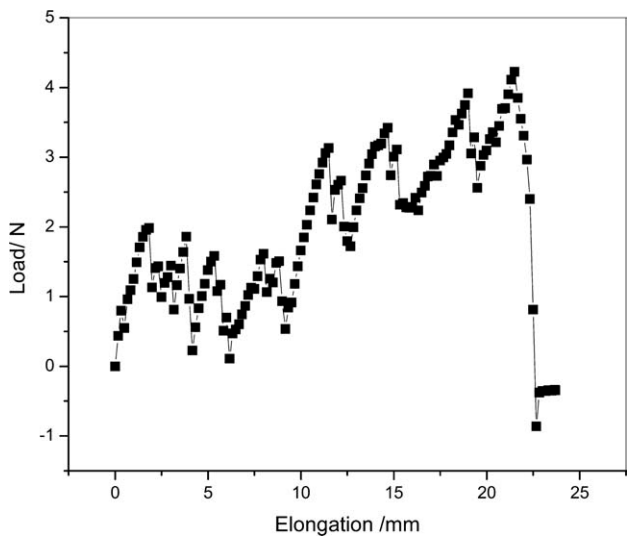

Figure 3 Peel curve of poly(amide-imide) clay aerogel/single-layered glass fiber laminate.

TABLE I
Peel Test Results of Poly(amide-imide) Clay Aerogel/ Single Layered Glass Fiber Laminate(n=5)

Sample#	ρ(Aerogel) (g/cm^3)	*m* (Epoxy)(g)	Peel strength/ (N/m)
1	0.09	1.09	110
2	0.09	2.60	85(fiber break)
3	0.09	3.00	120
4	0.09	3.49	170
5	0.08	7.07	83

Curing process of polymer/clay aerogels

After freeze-drying, all samples were removed from the mold and cured in a vacuum oven. For poly(amide-imide) clay aerogels, 210°C/6 h were required to convert the poly(amide-amic acid) to poly(amide-imide) and to remove DEAE from the samples. For BDGE clay aerogels, 80°C/48 h was used to fully cure the epoxy.

Preparation of epoxy adhesives

Epikote resin MGS RIMR 135 and Epikure curing agent MGS RIMH 1366 were mixed using a 100 : 30 weight ratio and cured at the recommended 25°C temperature.[9] The resins were used after mixing for 2 h, providing for an optimal viscosity and a limited depth penetration into the clay aerogel. The curing time depends on the quantity of the resin and the thickness of the laminate; for our samples, 24–48 h were allowed for curing, consistent with manufacturer data.

Preparation of polymer clay aerogel/glass fiber laminates

The thickness of polymer clay aerogel samples were 5 mm for the peel tests and 10 mm for the flexural tests. The laminates were typically fabricated by laying a sheet of glass fabric on each face of the aerogel, saturating these mats with adhesives, and allowing the adhesives and reinforcement fabric to harden.[10] The quantities of adhesive resins applied to the surfaces were recorded and reported in the figures herein, which correlate various mechanical properties with that adhesive weight; the penetration of the adhesive compound depends on the wetting qualities of the adhesive as well as the qualities of the aerogel surface.[11] The glass fiber/aerogel core structures coated with tacky adhesive were placed into a vacuum bag under ambient temperature and connected to a small vacuum pump; laminates were removed from the vacuum bag after full solidification of the resin.

TABLE II
Peel Test Results of Poly(amide-imide) Clay Aerigek/ Double Layered Glass Fiber Laminate (n=5)

Sample#	ρ(Aerogel) (g/cm^3)	*m*(Epoxy total)(g)	Peel strength/ (N/m)
1	0.08	0.67	43
2	0.08	0.75	40
3	0.08	0.99	25
4	0.08	1.51	15
5	0.08	1.85	6

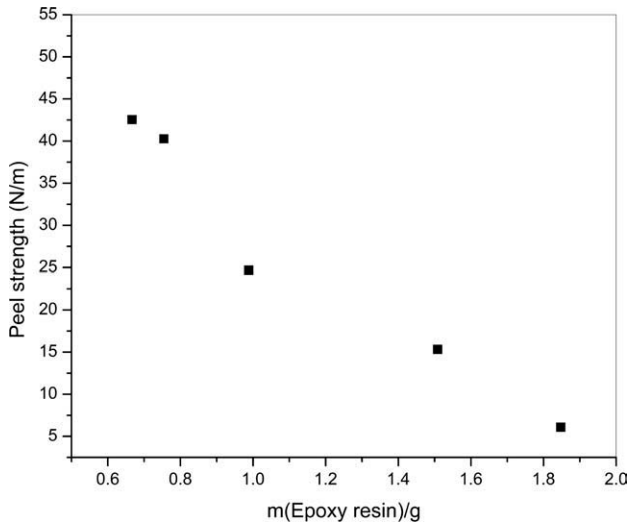

Figure 4 Peel strength of poly(amide-imide) clay aerogel/double-layered glass fiber laminate versus epoxy adhesive content.

The preparation method of the laminate with two layers glass fiber was described earlier, except that a second layer of glass fabric was placed on the tested surface of the one layer glass fiber/polymer clay aerogel laminate and adhesives were applied on the surface of the second glass fabric. Afterward, the two glass fiber layer laminate was put into a vacuum bag for the adhesive to harden.

CHARACTERIZATION

T-peel test

A peel test was used method for the determination of interfacial adhesion between fiberglass sheet and clay aerogel. According to ASTM D903-98, the

TABLE III
Flexural Test Results of Poly(amide-imide) Clay Aerogel/ Single Layered Glass Fiber Liminate (n=5)

Sample#	ρ(Aerogel) (g/cm^3)	*m*(Epoxy) (g)	Flexural modulus(MPa)
1	0.08	0	0.3
2	0.08	0.95	13.1
3	0.07	1.06	13.1
4	0.09	1.12	7.0
5	0.07	1.69	12.7
6	0.09	1.96	24.7

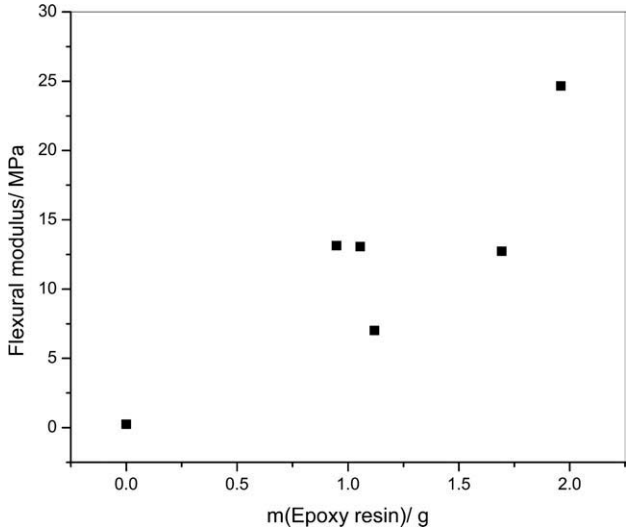

Figure 5 Flexural modulus of poly(amide-imide) clay aerogel/single-layered glass fiber laminate versus epoxy resin content.

adhesion peel strength was examined using an Instron model 5565 universal testing machine at an extension rate of 10 mm/min. Laminates with different epoxy contents were tested. Both glass fiber sheets were mounted in the clamps; one was as the peeling arm and the other was static in the clamp (instead of the more fragile polymer clay aerogel). Figure 2 shows the schematic representation of the test. The load and extension data from each peel test for each laminate sample was plotted, and peel strength values were obtained for each sample.

Flexural tests

Three-point bending test was used to investigate the flexural properties of the laminates. Samples were tested according to ASTM-790 using an Instron model 5565 universal test machine with a span distance of 50 mm with a moving crosshead speed of 1 mm/min. The load and displacement data from each flexural test were plotted, and flexural moduli were determined by calculating the slopes of the linear portion of the load-displacement curves.

TABLE IV
Flexural Test Results of Poly(amide-imide) Clay Aerogel/ Double Layered Glass Fiber Liminate (n=6)

Sample#	ρ(Aerogel) (g/cm^3)	*m*(Epoxy total)(g)	Fleexural modulus(MPa)
1	0.10	0.69	12.9
2	0.10	0.64	2.8
3	0.10	0.61	14.5
4	0.10	0.63	1.3
5	0.12	1.00	2.4
6	0.11	0.80	76.9

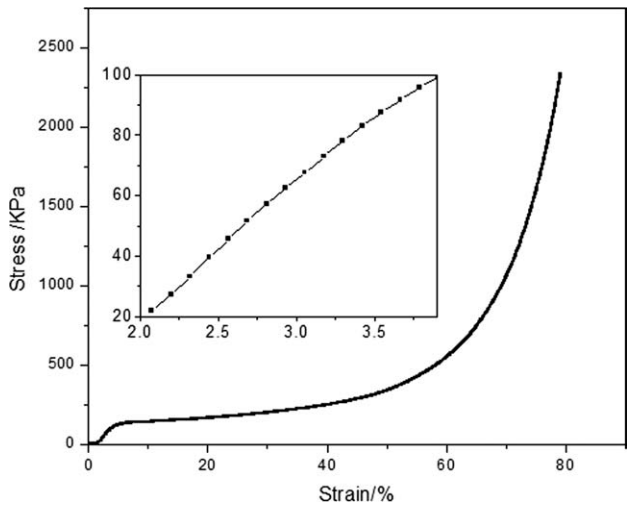

Figure 6 Compressive curve of poly(amide-imide) clay aerogel/single-layered glass fiber laminate.

Compressive tests

Compressive tests were performed to study the robustness of the laminates. Samples were tested according to ASTM D695 using an Instron model 5565 universal test machine with a moving crosshead speed of 1 mm/min. The tests were terminated upon reaching 80% strain deformation.

Density measurements

Densities of the aerogel samples were determined by weighing the samples with an analytical balance and measuring physical dimensions using a digital caliper.

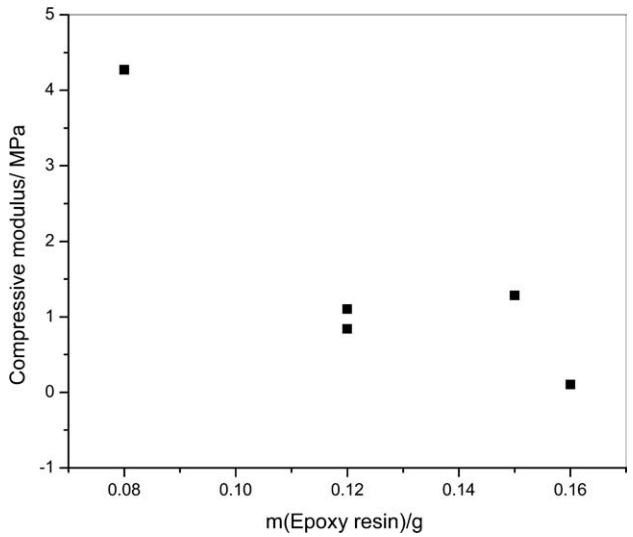

Figure 7 Compressive modulus of poly(amide-imide) clay aerogel/single-layered glass fiber laminate versus epoxy resin content.

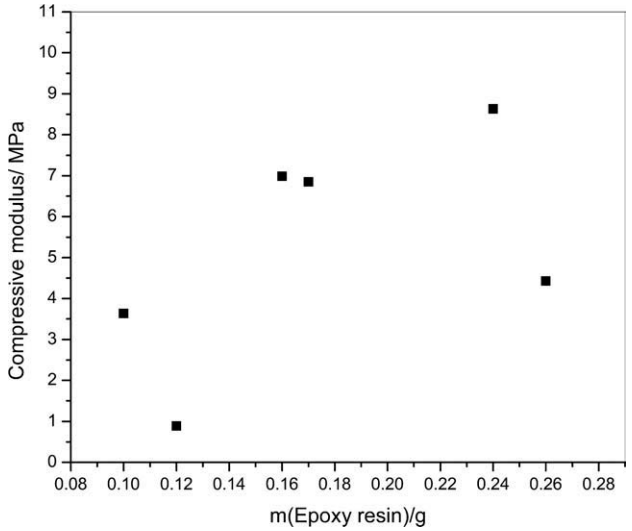

Figure 8 Compressive modulus of poly(amide-imide) clay aerogel/double-layered glass fiber laminate versus epoxy resin content.

RESULTS AND DISCUSSION

Poly(amide-imide) clay aerogel/glass fiber laminates

Peel strength testing

A T-peel test was used to evaluate the epoxy-resin-adhered glass fabrics-aerogel composite. For each of the test pieces, the peel strength was calculated according to the equation $G = F_{peel}/W$, where G indicates bonding peel strength, F_{peel} is the observed force that applied to separate the previously adhered parts, and W is the specimen width.[12] The adhesion properties of the laminate were analyzed by comparing the peel strength value versus the epoxy adhesive uptakes. Two typical behaviors observed include (i) crazes in polymer clay aerogel that opened up into cracks and caused polymer clay aerogel failure or (ii) delamination at the interface due to the strong adhesion of laminate leading to a broken peel arm.[13] That polymer clay aerogels would be the site of initial failure can be explained by their relatively lower fracture energy for cracking compared to that of the glass fabric/epoxy layers.[14] The observed variability in peel strengths was attributed to inhomogeneous dispersion of the adhesives. Both polymer clay aerogel and glass fiber were porous materials; thus, the interfaces for adhesives were not a complete smooth surface. Figure 3 shows peel curves for poly(amide-imide) clay aerogel/glass fiber laminate tested at an extension rate of 1 mm/min. As the elongation of the peel arm, the load fluctuated; the load for this sample was the average value of 3 and 1.5 N because of the inhomogeneous adhesive spreading. The adhesive loading level affected the peel strength of the laminates. It is desirable to prepare laminates with good adhesion; however, lower interfacial adhesion allowed the polymer matrix to yield without constraint of the glass fibers, which might debond from the matrix during deformation.

Table I shows the peel strengths of five different one-layer fiberglass laminates reported with the quantity of adhesive used quantity. The estimated trend was that in a certain range of epoxy level, higher epoxy contents yielded higher peel strength. However, these tests with only five testing samples were not reliable to represent the actual laminate peeling performance. To better examine its peel properties, a larger sample quantity would be needed. For double-layered glass fiber laminates, the aerogel core breaks for all the test samples, showing that the sufficient bonding between glass fiber and aerogel core. Figure 4 and Table II show that peel strength decreased as the total amount of epoxy glue increased.

TABLE V
Compressive Test Results of Poly(amide-imide) Clay Aerogel/Single Layered Glass Fiber Liminate (n=5)

Sample#	ρ(Aerogel) (g/cm^3)	*m*(Epoxy) (g)	Compressive modulus(MPa)
1	0.11	0	1.26
2	0.12	0.16	0.10
3	0.11	0.12	0.84
4	0.12	0.15	1.28
5	0.11	0.08	4.27
6	0.11	0.12	1.10

TABLE VI
Compressive Test Results of Poly(amide-imide) Clay Aerogel/Double Layered Glass Fiber Liminate (n=6)

Sample#	ρ(Aerogel) (g/cm^3)	*m*(Epoxy total)(g)	Fleexural modulus(MPa)
1	0.08	0.17	6.85
2	0.08	0.16	6.99
3	0.09	0.26	4.43
4	0.08	0.24	8.63
5	0.08	0.10	3.63
6	0.08	0.12	0.89

Flexural testing

Poly(amide-imide) clay aerogels were found to be easier to bend and break than their glass fabric laminate structures. The inner aerogel core was squeezed convexly while the outer glass fibers remained intact. There was no apparent delamination between fiber layer and aerogel matrix, which could be attributed to the sufficiently strong interfacial bonding in between. The flexural modulus for one layer laminate was $\sim$ 40 times higher than that of the starting polymer clay aerogel as shown in Table III. As epoxy content increased, the flexural modulus of the laminate

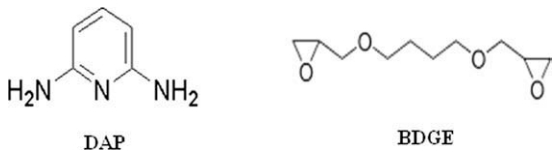

Figure 9 Chemical structures of 1, 4-butanediol diglycidyl ether (BDGE) and 2, 6-diaminopyridine.

increased (Fig. 5). This increasing trend can be explained by the dependence of materials rigidity on the fiber reinforcement, wherein adhesives content plays a significant role. When a second layer of glass fiber was applied to the laminate, the flexural modulus did not show a clear trend versus amount of epoxy (Table IV). Fiber layers buckled while the aerogel core broke during the testing. We propose that the failure was initiated when the core began yielding, which eliminated the support for the glass fibers.

Compression testing

To explore the deformation behaviors of the laminate, compression testing was performed. Poly(amide-imide) laminates were compressed until reaching its 80% strain while maintaining their starting structures. Figure 6 is a typical stress–strain curve for the laminates, which is similar to that of porous foam. The compressive stress–strain curves were observed to go through an induction region due to the uneven surfaces on the sample, an initial linear elastic region (the slope of which is defined as the compressive modulus of the test sample), a yielding deformation region, a plateau region, and a solidifying region.[15] Figure 7 shows a decreasing trend in compressive modulus, which could be a result of a more closely packed structure from the increased amount of epoxy resin. However, addition of another layer of glass fiber to the poly(amide-imide) clay aerogel laminate at least doubled compressive modulus (Fig. 8) with similar amount of epoxy glue, suggesting that glass fiber plays a dominant role in reinforcement (Tables V and VI).

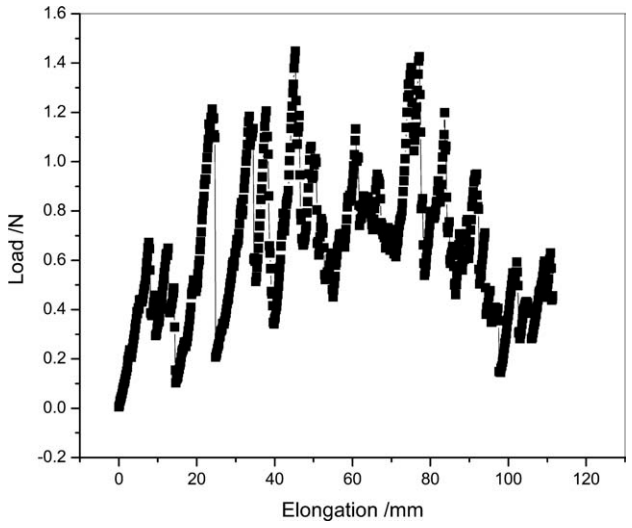

Figure 10 Peel curve of BDGE-DAP clay aerogel/single-layered glass fiber laminate.

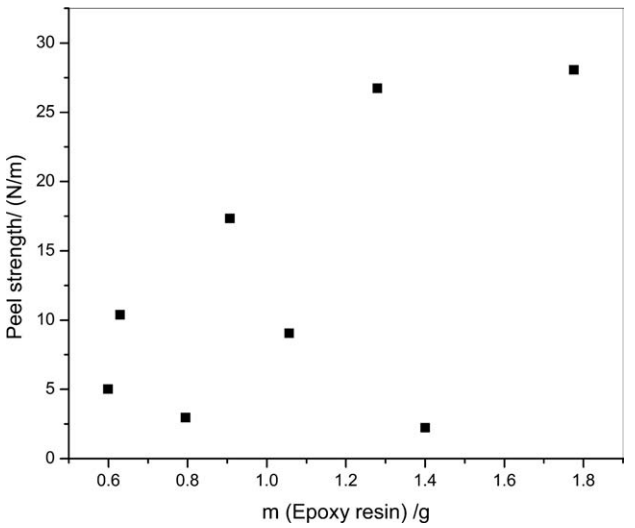

Figure 11 Peel strength of BDGE-DAP clay aerogel/single-layered glass fiber laminate versus epoxy adhesive content.

BDGE clay aerogel/glass fiber laminates

Peel strength testing

Figure 9 shows the chemical structure of BDGE that has two epoxide rings and the chemical structure of DAP that has two amine groups. A 2 : 1 mol ratio of BDGE to DAP was used to provide one amine protons to react with one epoxide ring. All the aerogel samples were strong and stiff with a brownish-yellow color.

Figure 10 illustrates a typical peel curve for a BDGE-DAP/single-layered fiber glass laminate; the test was performed at strain rate of 10 mm min^{-1}. Inhomogeneity in epoxy adhesive distribution will lead to a less than completely symmetrical peel test

TABLE VII
Peel Test Results of BDGE-DAP Clay Aerogel/Single Layered Glass Fiber Liminate (n=8)

Sample#	ρ(Aerogel) (g/cm^3)	*m*(Epoxy total)(g)	Peel strength/ (N/m)
1	0.14	1.40	2
2	0.18	0.80	3
3	0.15	0.60	5
4	0.15	1.06	9
5	0.15	0.63	10
6	0.18	0.91	17
7	0.19	1.28	27
8	0.17	1.78	28

TABLE VIII
Peel Test Results of BDGE-DAP Clay Aerogel/Double Layered Glass Fiber Liminate (n=5)

#	ρ(Aerogel) (g/cm^3)	m_1(Epoxy) (g)	m_2(Epoxy) (g)	Peel strength/ (N/m)
1	0.17	1.54	0.95	4
2	0.18	1.50	0.93	5
3	0.17	1.60	0.91	8
4	0.19	1.83	1.10	15
5	0.16	1.70	0.90	19

curve. In Figure 11, there is a general increase in peel strength with increasing epoxy resin weight in the peeled layer. Increasing epoxy resin loading have a significant effect on the mechanical properties (peel strength) of the BDGE-DAP clay aerogel laminate (Table VII). The average peel strength and adhesive load were determined to be 12 N/m and 1.05 g, respectively. The densities of the aerogels produced were found to be between 0.08 and 0.19 g cm^{-3} with an average of 0.16 g cm^{-3}. The densities of BDGE-DAP clay aerogel composites showed no significant effect on the peel strength of the laminate. No major or visible failing of the BDGE-DAP clay aerogels were observed during the peel test of all laminates, indicative of adhesive failure.

Table VIII shows that the peel strength is directly proportional to the epoxy adhesive weight in the peeled layers. The average peel strength and epoxy resin weights for the double-layered laminates were calculated to be 10 N/m and 1.63 g, respectively. Although the double-layered system contained more epoxy resin, the peel strengths for the double-layered systems were lower than with the single-layered system. This difference is thought to result from the fact that the adhesive load for the two layers was considered in our comparison and determined by the addition of the amount of epoxy resin between the aerogel and the first layer and between the first layer and the second layer. Considering the epoxy load between the aerogel and the first fiber glass layer, the average peel strength and epoxy resin weight are 10 N/m and 0.94 g, respectively. Therefore, the peel strength is proportionally related to the epoxy resin weight between the aerogel and the first fiber glass layer. The second fiber glass layer and the adhesive load between the two layers showed no effect on the peel mechanical property.

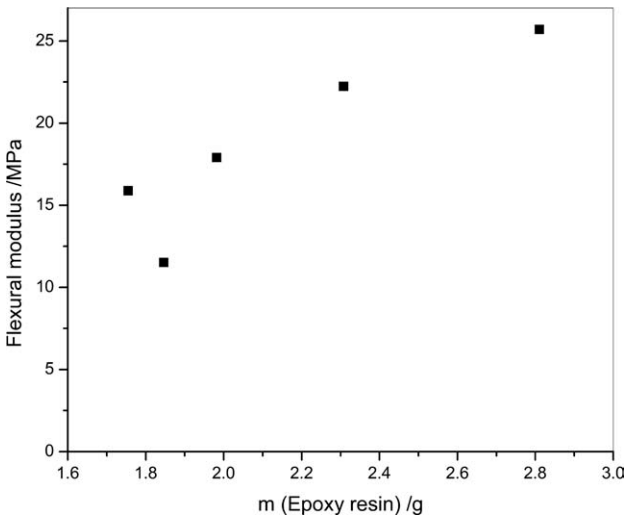

Figure 12 Flexural modulus of BDGE-DAP clay aerogel/single-layered glass fiber laminate versus epoxy resin content.

Flexural testing

The flexural test was performed on the single-layered BDGE-DAP/fiber glass laminate at strain rate of 1 mm min^{-1} (Table IX). The flexural modulus was determined by calculating the slope of the first linear portion of the stress–strain curve.

In Figure 12, an increasing trend between laminate flexural modulus and the total mass of the epoxy resin was observed. The amount of the epoxy resin added to the laminate showed an effect on the modulus of the aerogel laminate. The flexural modulus of the aerogel laminate was determined to be between 12 and 26 MPa and an average of 20 MPa, which is four times greater when compared with the flexural modulus of the epoxy aerogel. For the double-layered, the average flexural modulus of the laminate and epoxy resin weight were calculated to be 166 MPa and 1.64 g, respectively. Similar to the poly(amide-imide) clay aerogels laminates, the

TABLE IX
Flexural Test Results of BDGE-DAP Clay Aerogel/Single Layered Glass Fiber Liminate (n=5)

Sample#	ρ(Aerogel) (g/cm^3)	m(Epoxy) (g)	Flexural modulus(MPa)
1	0.17	1.90	11.5
2	0.14	1.80	15.8
3	0.14	1.90	17.9
4	0.16	2.30	22.2
5	0.17	2.80	25.7

TABLE X
Flexural Test Results of Double-Layered BDGE-DAP Clay Aerogel/Double Layered Glass Fiber Liminate (n=5)

Sample#	ρ(Aerogel) (g/cm^3)	m(Epoxy) (g)	Flexural modulus(MPa)
1	0.15	1.73	80.3
2	0.16	1.61	126.1
3	0.14	1.75	195.0
4	0.16	1.40	207.1
!5	0.16	1.72	220.0

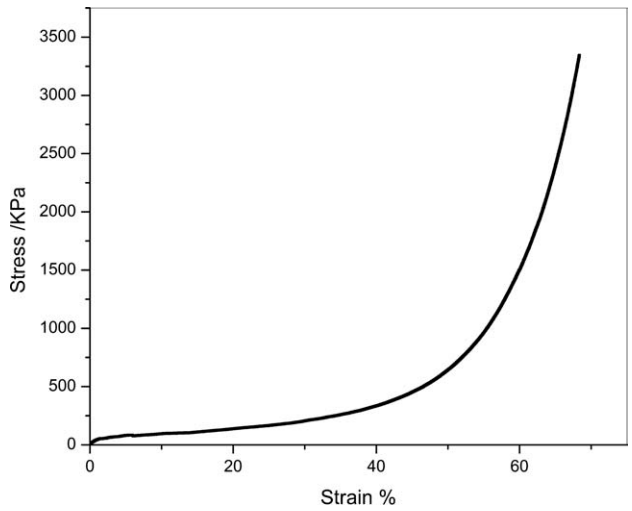

Figure 13 Stress–strain curve of BDGE-DAP clay aerogel/single-layered glass fiber laminate.

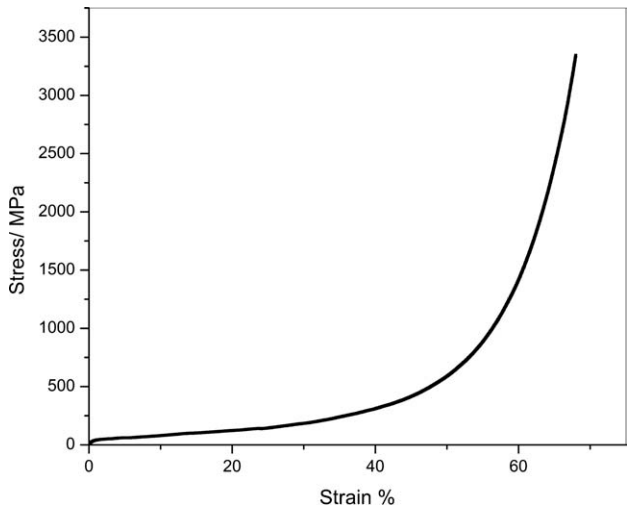

Figure 15 Stress–strain curve of BDGE-DAP clay aerogel/double-layered glass fiber laminate.

flexural modulus does not show a clear trend versus the amount of the epoxy (Table X).

Compression testing

Figure 13 shows a typical stress–strain curve for the single-layered epoxy aerogel laminate. The compression test was performed on 1 mm min^{-1}, and the tested was stopped at 75% strain or when the load exceeding the plate load of 1 kN. Figure 14 shows that the laminate Young's moduli were independent of the total mass of the epoxy resin added; hence, the structural materials, rather than adhesive, was found to bear the compressive stress. The stress–strain curve for the double-layered laminate is similar to that of a porous material (Fig. 15). The Young's modulus does not show a clear trend versus the amount of the epoxy resin used. The average Young's modulus for the laminate samples is 7.13 MPa compared to an average of 2 MPa for the BDGE/DAP clay aerogel. Also, the average Young's modulus for the double-layered laminate samples is 5.02 MPa, which is similar to that of the single-layered system. The extra layer of fiberglass fabric and the extra amount of the epoxy resin, therefore, showed no effect on the Young's modulus as indicated in Figure 16.

CONCLUSIONS

Polymer clay aerogel/glass fabric laminates were successfully prepared using simple composite processing methods. Both poly(amide-imide) clay aerogel

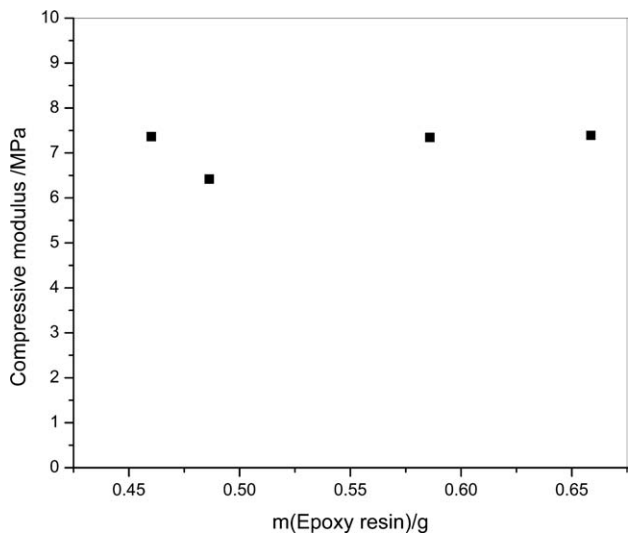

Figure 14 Compressive modulus of BDGE-DAP clay aerogel/single-layered glass fiber laminate versus epoxy resin content.

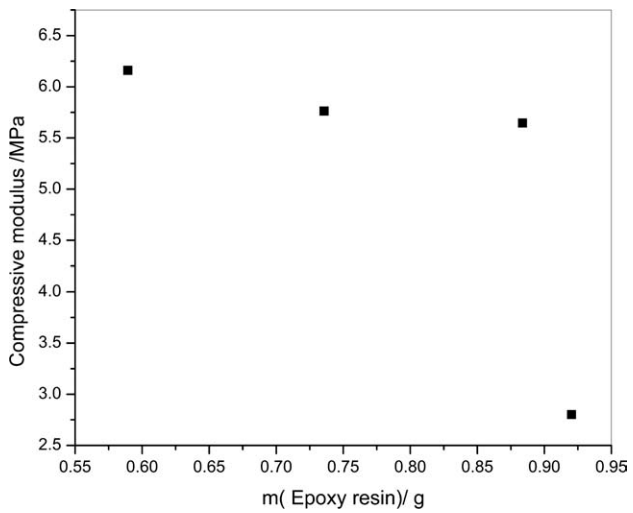

Figure 16 Compressive modulus of BDGE-DAP clay aerogel/double-layered glass fiber laminate versus epoxy resin content.

and BDGE clay aerogels were relatively stiff, foam-like materials after curing.

The polymer clay aerogel/glass fiber laminates showed enhanced flexural modulus compared to that of simple polymer clay aerogels. For poly(amide-imide) clay aerogel laminate, the flexural modulus was almost 40 times higher than that of the aerogel sample. Similar flexural properties were obtained using both poly(amide-imide) and epoxy cores. A generally linear relationship between the epoxy adhesive retained and flexural modulus was observed for both polymer aerogel/glass fiber laminate systems. The epoxy aerogel core exhibited an overall higher level of adhesive uptake.

A generally linear relationship between the epoxy adhesive uptake and the peel strengths of glass fabric and aerogel cores was retained. The absolute peel strengths were considerably higher for poly(amide-imide) samples, compared to those produced with epoxy-based aerogels.

The compressive tests for samples describe a trend that the compressive modulus decreases as epoxy amount increases.

Overall, better mechanical properties would be expected if more than one layer of glass fabric would be applied to the aerogel core surfaces and epoxy adhesive layers.

Note: Torlon® is a registered trademark of Solvay Advanced Polymers LLC.

One of the coauthors, Dr. David Schiraldi, has a financial interest in a company that is commercializing the technology investigated in this research. He is an owner and officer of the company. Case Western Reserve University also has an ownership and IP interest in this technology which, if commercialized, could result in royalties for Dr. Schiraldi and CWRU.

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