Composite Foams for Sandwich Structures

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ABSTRACT

Recent work at USC has focused on strategies to enhance the toughness and overall mechanical performance of polymer foams for use in lightweight sandwich structures. Both mechanical and chemical approaches have been employed with reasonable success. Fiber reinforcement, though difficult from a processing perspective, can lead to substantial enhancements in toughness and strength, while reducing friability. Chemical modifications are also challenging from a processing perspective, but can produce similar enhancements in performance. Efforts to enhance performance of phenolic foam and PVC foam through fiber reinforcement and chemical modification are described, along with the resulting enhancements in performance.

Key words : Composite, Sandwich structure, Phenolic foam, PVC foam

1. Introduction

Polymer foams are among the lowest density engineering materials available and are commonly used as packing materials to absorb impact energy.[1] They also exhibit good insulating properties, although the strength and stiffness levels are low compared with other structural materials. Several natural materials are also porous (e.g., wood and bone), and are highly efficient materials in terms of performance per unit weight. Some foams are suitable for structural applications, and are typically laminated between high-strength skins in assemblies called sandwich structures. A typical sandwich structure comprised of a foam core laminated between two composite skins is shown in Fig. 1. The function of the foam core is to carry transverse loads as shear stresses, while the skins carry bending moments as in-plane tension and compression stresses.[2] These sandwich structures are highly efficient structures used in a wide range of applications, including aerospace structures, transportation vehicles, cardboard, and natural plants. Surprisingly, many engineers know little about them.

Sandwich structures are analogous to I-beams. Flanges and webs of I-beams are simply replaced by skins and cores. The performance of the sandwich structure is dependent on the properties of the components, and the integrity of the joint between them. The core is typically an ultra-lightweight material substantially thicker than the skins, and is intended to resist compression and shear loads. The stiffness of the assembly increases exponentially with core
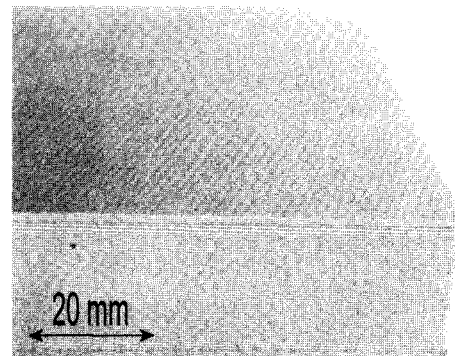
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Fig. 1. Typical foam core sandwich structure built of a phenolic foam core (density=112 kg/m^3=7 pcf) and glass fiber-phenolic composite skins.

thickness.[1,2] The highest performance levels are achieved in practice by honeycomb cores, which effectively extend the one-dimensional I-beam form to two dimensions. Foam cores are also used in instances where cost is an over-riding concern, insulation is a factor, and mechanical performance is not as critical. Thus, honeycomb cores offer substantially higher levels of performance than foams, but at substantially higher costs. This gap in performance and cost affords an opportunity for materials engineers. Honeycomb costs are likely to remain high, as the manufacture is labor-intensive and time-consuming. Logic dictates that opportunities to narrow the gap are most likely to lie with improving foam performance.

Efforts to boost the performance of foams through fiber reinforcement face seemingly insurmountable processing difficulties. This is not a new concept, and a quick review of the literature reveals numerous attempts to tap the potential of fiber reinforcement that is used so effectively in polymer composites. However, conventional manufacture of
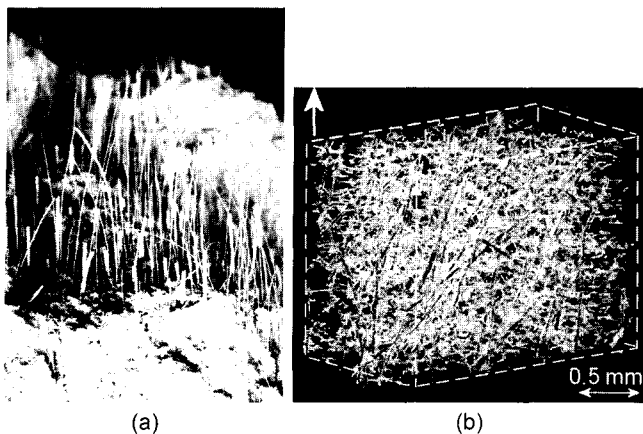
Fig. 2. (a) The cross section of a palm frond reveals a fiber-reinforced porous material with a density of 3.4 pcf (54 kg/m³) and (b) A CT image of composite phenolic foam (5 pcf) made at USC.

foams involves expansion by using a blowing agent that is mixed with a liquid and activated to evolve gas bubbles. Fiber additions, even modest volume fractions, greatly increase viscosity and interfere with foam expansion. Dispersing the fibers uniformly is also a challenge. Thus, the development of composite foams awaits a breakthrough in process technology, and the disparity between the mechanical performance of honeycomb and foam cores persists.

Interestingly, some natural materials exhibit fiber reinforcement of porous polymers, suggesting that Mother Nature made this breakthrough in process technology millions of years ago. Fig. 2 shows a cross section of the base of a common palm frond, which is the leaf of a palm tree. The section is taken from the woody base of the stem. This stem is a natural sandwich structure that consists of a porous core encapsulated within a hard, dense skin. The presence of aligned fibers in the core is apparent. The overall density is about 54 kg/m³ (3.4 pcf), comparable to typical manmade phenolic foams used in commercial sandwich structures. Shown next to the palm frond is an x-ray CT image (computed tomography) of a similar composite foam. However, this material is a glass fiber-reinforced phenolic foam made by a new process recently developed at USC. The foam density is 80 kg/m³ (5 pcf), and the foam contains 5 w/o glass fibers.

In the present work, recent progress in composite foam processing is reviewed. Two types of foam technology are considered. Phenolic foam is a low-cost material with excellent fire-resistant properties, but it is extremely brittle and friable. The latter limitation not only limits the service life of the material, but makes it difficult to handle during manufacture of sandwich panels. Consequently, unreinforced phenolic foam is not suitable for structural applications. Past efforts to improve the mechanical performance have generally compromised the fire-resistant attributes, limiting the utility. We describe our efforts to introduce short fibers to enhance toughness and friability.[3,4]

The second technology might be described as a binder-less

syntactic foam. The motivation for developing this technology stemmed from a need for a high-performance foam that could be thermoformed and that was not prohibitively expensive. The process relies on expandable thermoplastic microspheres that are dry-blended with continuous fiber preforms, then expanded by heating in a closed mold. No blowing agent is used, and unlike syntactic foams, no binder is used, as the expanding spheres fuse to each other and to the fibers to produce the composite foam. Initial results indicate that property levels meet or surpass the performance of leading commercial foams.[5,6] Prospects for further improvement and commercialization are briefly discussed.

2. Experimental

2.1. Foam Synthesis

Phenolic foam samples were fabricated with a patent pending technology. The formulation was typically comprised of phenolic resol resin (solid content >80%) 100 parts, surfactants 2 parts, Phenol Sulfate Acid (PSA) 4 parts, and appropriate amounts of pentane to achieve desired foam densities. When fiber reinforcements were introduced, the amount of PSA was slightly reduced to allow more time for dispersing fibers. To facilitate comparisons between properties of different foams, all foams were formulated to achieve a density of 80±10 kg/m³ (5±0.5 pounds per cubic foot). The chopped fibers included glass strand and aramid fibers, each having lengths of 1.5 mm and 6.4 mm. The glass fibers made by Owens-Corning Inc. were about 14 microns in diameter and included a phenolic compatible sizing. Aramid fibers (Nomex®) were obtained from DuPont, and were about 12 microns in diameter.

PVC foam synthesis was accomplished by vibration infiltration, as described in.[9] A blended mixture of expanded and unexpanded PVC microspheres (Expancel, Inc.) with average original diameters 40 and 10 μm, respectively, was combined with the treated fiber pre-form cut from webbing stock to match mold dimensions. Once infiltrated, the assembly was placed in a closed mold and heated to 150°C for 20 minutes to expand the microspheres and fuse them together into composite foam.

The standard composite foam used for the majority of experiments was comprised of 10 wt% unidirectional fiber webbing, 3% phenolic resin, and 87% PVC microspheres, and the foam density was 100 kg/m³ (6 pcf). Variants of the composite foam were synthesized to investigate specific parametric effects. Two unreinforced PVC foams of equal density were selected as baseline materials for comparison purposes. One foam was synthesized from expandable microspheres, and the second was cross-linked PVC foam (Divinycell H-100, DIAB Corp.).

2.2. Mechanical Testing

Climbing drum peel tests were performed in accordance with ASTM D1781, except that the specimen width was reduced to 25.4 mm (1 inch). Phenolic foams were first cut to

bars 25.4 mm wide, 31.8 mm thick, and 177 mm long. Then aluminum tape facings (25.4 mm wide and 0.2 mm thick) were bonded to both sides of the foam bars using an epoxy film adhesive. The adhesive was cured at 120°C for 3 h, and consolidated under a vacuum bag. The peel strength was obtained by averaging the force exerted over the entire peeling distance, and was expressed in N·mm/mm.

Friability was measured with a tumbling box custom-made in accordance with ASTM C421. For each specimen, twelve foam cubes of 25.4 mm (1 in.) side length were mixed with twenty-four oak cubes of 19.0 mm (¾ in.) side length. Samples were measured to an accuracy of one milligram before and after tumbling. Prior to each weighing, each foam cube was cleaned with pressurized air to remove surface dust. Tumbling times were 10 min at 60 rpm, as specified by the standard. Images of each specimen were documented before and after the test.

The tensile, flexural, and compression testing of foam samples was carried out in accordance with ASTM standards D 1623–78, D–790, D 1621–73, respectively. Because of the difficulty in attaching tensile specimens to conventional grips, a special test fixture was developed for holding dog-bone shaped tensile specimen. Shear tests were performed according to the C-273 standard using a custom-built fixture. The fixture ensures parallel motion of upper and lower platens to produce conditions of pure shear. All mechanical measurements were performed at room temperature. Crack resistance and damage tolerance were assessed by three-point bend testing of edge-notched foam beams. A razor blade was used to introduce notches 0.2 mm wide and ~1 mm deep. The stress-strain energy density was calculated for tensile and shear tests, and the total energy was evaluated for flexural tests according to ASTM standard procedures. All mechanical tests were performed at ambient conditions using an Instron 8500 universal test machine. For each material, at least three replicates were tested for every specimen and the final data were given as the average of all replicates within a 95% confidence limit.

3. Results and Discussion

3.1. Phenolic Foam

Peel strength is a critical performance indicator for sandwich structures, as many failures originate from or involve the skin-core interface. Moreover, the peel test is recognized measure of interfacial fracture toughness.[3] The addition of 3 wt% chopped aramid fibers (6 mm) to the foam core significantly alters the failure mode during peel, as evidenced by the pair of micrographs in Fig. 3. The image on the left shows the peel surface of the neat foam, while the image on the right shows the peel surface of the composite foam. The composite foam surface is substantially rougher and more textured, indicating that the crack path frequently deviated from the interface and extended into the composite foam. As expected, the crack deflections resulted in substantially more energy absorption and a peel strength that was 6–7
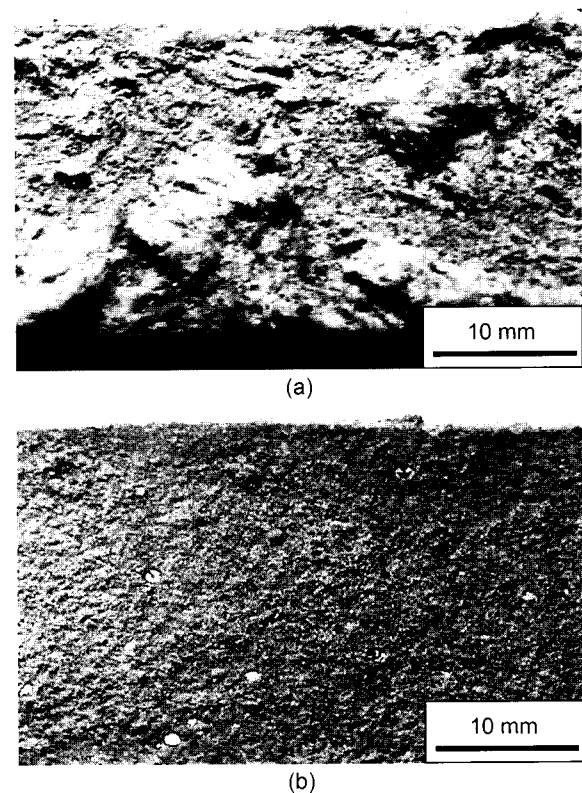

(a)

(b)

Fig. 3. Peel test fracture surfaces of unreinforced phenolic foam (bottom) and composite phenolic foam (top). The composite foam fracture path is more tortuous and extends into the foam, away from the bondline.[3]

Table 1. Peel Strength of Phenolic Foams, in N·mm/mm^{3}

Loading (%)	Plain foam	Glass filled		Aramid filled	
		1.5 mm	6.4 mm	1.5 mm	6.4 mm
0	5.0	–	–	–	–
3	–	8.4*	14.5	14.7	25.3
5	–	–	15.7	–	36.2

*: 2.5 wt%

times higher than the neat foam. Table 1 shows typical peel data for the composite and control foams. All results show that fiber reinforcement significantly enhances the toughness of phenolic foam.

As mentioned previously, the friability of phenolic foam constitutes a major limitation, as the foam can be easily damaged by handling during manufacture. Friability involves microfractures from abrasion and repeated light impact events, and is regarded as another indicator of toughness for low density materials.[4] The property can be measured by weight loss during tumbling in accordance with ASTM C421. The composite foam reinforced with aramid fibers exhibits superior friability, as shown in Fig. 4. The mass loss drops from 25% for plain phenolic foam, to less than 5% for the composite foam with 10 wt% aramid fibers, a five-fold decrease. The dramatic improvement in friability confirms the enhanced toughness of the reinforced foam as shown previously in the peel test results. As foam
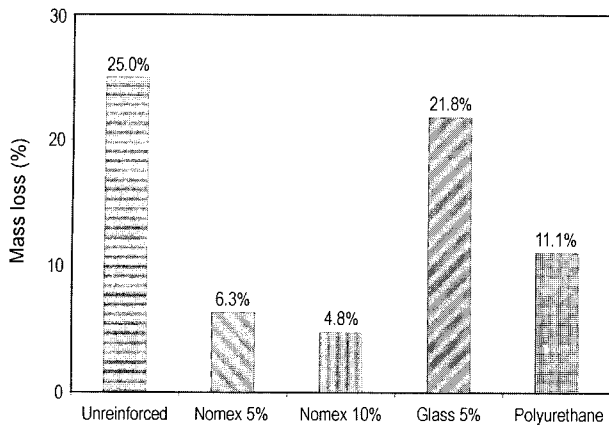
Fig. 4. Mass loss during friability test for different foams. Note that some composite foams outperform a commercial polyurethane foam.[4]
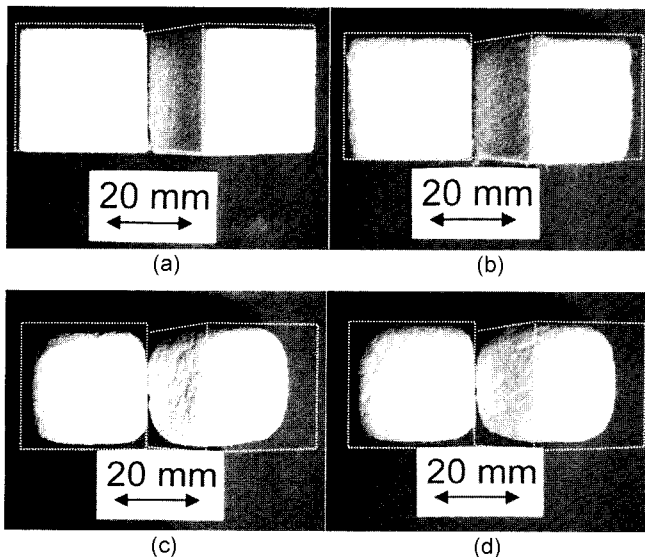

Fig. 5. Shape changes of phenolic foam cubes as result of friability test. (a) Original shape, 1 inch cube, (b) 5 wt% Nomex reinforced, (c) unreinforced, and (d) 5 wt% glass reinforced. The dashed line frames represent original shapes and sizes.[4]

friability is reduced, shape retention of the samples improves, as shown in Fig. 5. The shape of aramid fiber-

reinforced foam cubes is virtually unchanged by the friability test (specimen b). In contrast, unreinforced foam samples exhibit pronounced edge-rounding (specimen c). The friability performance of the composite phenolic foam also surpasses the performance of the commercial polyurethane foam, which exhibits an estimated mass loss of 11.1% (65 kg/m^3 in density, 4 PCF).[4]

Compression and shear properties of phenolic foam are also enhanced by fiber reinforcement. Table 2 summarizes the compressive test results for phneolic foams.

When the compression force is applied parallel to the foaming direction the phenolic foams with 5 wt% and 10% aramid fiber show modulus and strength comparable to the unreinforced conterpart. However, glass fiber additives show a much greater enhancement in compression properties. In particular, at 10 wt% loading of glass fiber, the modulus rises to almost twice the value for unreinforced foam, and this is accompanied by a 31% increase in strength.

Both of the reinforced phenolic foams display higher shear moduli than unreinforced foams, and shear strengths comparable to the unreinforced foam.[4] However, glass fiber reinforcements again produce a greater increase in shear stiffness than the aramid fiber counterparts at the same fiber loading. Adding more fibers helps elevate both shear modulus and shear strength significantly.

Table 2 also includes some data for commercial polymer foams. Generally, phenolic foams are stiffer (having higher modulus) than polyurethane foam at the same density, but not as stiff as PVC foam. Although the compressive strength of unreinforced phenolic foam is lower than that of polyurethane and PVC foam, the reinforced phenolic foam is comparable in strength. This indicates that fiber reinforced phenolic foam can be competitive with these structural foams in certain engineering applications, particularly those applications requiring fire resistant properties. Like the trend in compression performance, the shear modulus of all phenolic foams is intermediate between polyurethane and PVC foams, while the shear strength is lower than both.

The ultimate proof of foam performance comes from bending tests on sandwich beams. The flexural behavior of sandwich beams with different cores is depicted in Fig. 6, which

Table 2. Compressive Properties of Foams at Density of 80 kilograms/m^3 [4]

| Properties | Parallel* | | Perpendicular* | | Modulus anisotropy |
Foam formulations	Modulus (MPa)	Strength (MPa)	Modulus (MPa)	Strength (MPa)	ratio $E_{//}/E_{\perp}$
Unreinforced	31.8	0.76	15.2	0.65	2.09
5% Nomex reinforced	29.1	0.90	26.8	0.71	1.09
10% Nomex reinforced	31.0	0.71	–	–	–
5% glass reinforced	33.9	0.90	19.7	0.59	1.72
10% glass reinforced	62.7	1.1	–	–	–
Polyurethane*	26.5	0.92	14.9	0.60	1.78
PVC(Divinycell®H80)*	85	1.2	–	–	–

*Loading direction with respect to foam's original foaming direction.
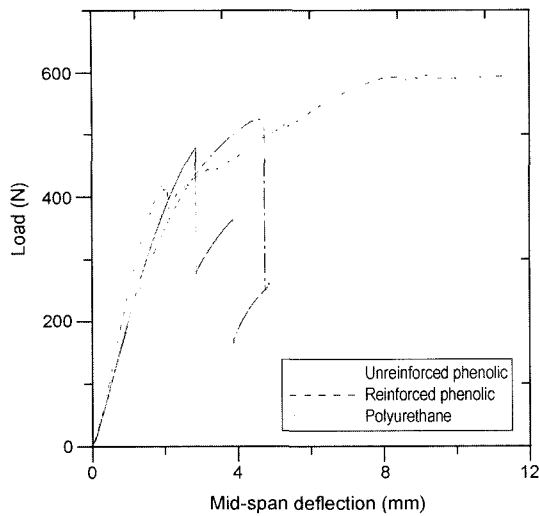*Data from the manufacture datasheets.[5]

Fig. 6. Load vs midspan deflection relationships for 4-point bending test of short sandwich beams with foam cores.[4]

shows plots of total load *vs.* the mid-span deflection for the different beams. The behavior of the beam with 5 wt% aramid fiber-reinforced phenolic foam core is distinct from the other materials. Unlike the other beams, which exhibit drastic decreases in load-bearing capacity once initial failure occurs, the aramid fiber-reinforced foam core sandwich beam maintains load-bearing capacity even after the damage initiation, continuing up to much higher loads and deflection. The slight load drop at 400 N corresponds to minor cracking in the foam core (Fig. 6(a)), representing the initiation of shear damage in the aramid fiber-reinforced phenolic foam. However, as previously seen in shear tests, the crack is stable and does not propagate quickly because of fiber bridging along the crack wake (Fig. 6(b)). Thus, the cores strong resistance to shear cracking damage leads to a "tough" sandwich structure that does not exhibit catastrophic collapse. Instead, the structure recovers the capacity to carry load, and the load increases substantially as the beam continues to deflect. This feature indicates the potential of fiber-reinforced foam cores to tolerate damage and to significantly reduce the risk of catastrophic failure of sandwich structures.

3.2. Composite Foam from Expandable PVC Microspheres

Unlike most methods to produce foam, a new technique developed at USC is a "dry" process in which thermoplastic microspheres are blended with long fibers, then heated in a closed mold to expand the foam.[6] The expanding microspheres fuse together at contact points, creating the composite foam. In this section, we describe some of the properties of such foams, which are substantially enhanced by the presence of long continuous fibers.

Tensile tests conducted on composite PVC foams with 4 and 10% fiber loadings showed substantial improvements in modulus and strength compared with unreinforced foams,
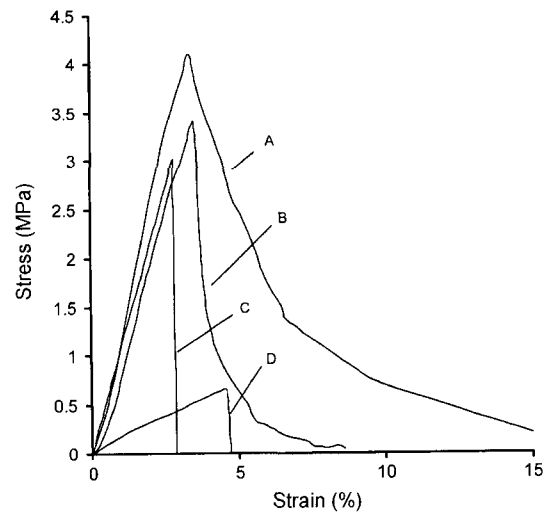

Fig. 7. Tensile stress-strain plot for PVC foam samples with density=100 kg/m^3: (A) Foam reinforced with 10 wt% aramid fibers treated with 3 wt% phenolic resin, (B) Foam reinforced with 4 wt% aramid fibers treated with 1.2 wt% phenolic resin, (C) Cross-linked commercial PVC foam, and (D) Unreinforced PVC foam based on microspheres.

as demonstrated by the stress-strain curves in Fig. 7.[7] The curves also indicate significant differences in failure behavior. The unreinforced foams fail in a brittle manner there is an abrupt loss of load-carrying capacity after the peak stress. In contrast, the composite foams demonstrate an ability to carry a large fraction of the peak load to strains well beyond the ultimate stress. This behavior indicates a potential for greater damage tolerance, higher energy absorption capacity, and more graceful failure modes in sandwich structures.

The stress-strain data, summarized in Table 3, provide a basis for quantitative comparison of the foams. For the composite foam with 4 wt% fibers, the tensile strength and modulus is increased factors of 5 and 6.5 compared with the unreinforced control foam. The composite foam with 10 wt% fibers shows improvements in strength and modulus of 6.2× and 7.8×. Increasing the fiber loading from 4 wt% to 10 wt% causes an additional increment in modulus and strength of only 20%. When compared with the control foam, a commercial cross-linked PVC foam (Devinycell), the two composite foams show increases in tensile strength by factors of 1.1 and 1.4.

The composite foams show distinctly different performance after reaching the peak stress. Note that the strain at peak strength for all foam samples is similar, although the ultimate strain is significantly higher for the composite foams. However, for composite foams with 10 wt% and 4 wt% fibers, the strain-to-failure increases by factors of 3.3 and 1.6, respectively, compared with the control foam. Furthermore, the area under the stress-strain curves is far greater for the composite foams. The integrated area provides a measure of energy absorbed during fracture, and

Table 3. Tensile Properties

	Strength (MPa)	%	Modulus (MPa)	%	Strain energy density (J $10^{-6}/$ m^3)	%
Unreinforced foam	0.66	100	15	100	1.5	100
Foam reinforced with 4 wt% fibers	3.4	515	97	646	7.6	507
Foam reinforced with 10 wt% fibers	4.1	621	120	800	20	1333
Cross-linked PVC commercial foam	3.0	455	104	693	4.3	287

thus crack resistance.[8,9] This quantity, normally referred to as the strain energy density, is tabulated in Table 3. The results show that composite foams have much higher strain energy density than the unreinforced control foam (factors of 5 and 13) and the cross-linked PVC foam (factors of 1.8 and 4.6).

Examination of the composite fracture surfaces revealed long fibers extending from the foam matrix which evidently bridged the crack prior to pulling out, as shown in Figure 8. The fibers extended at various angles to the fracture surface, a consequence of the absence of strict fiber orientation in the web structure, as described previously. The exposed
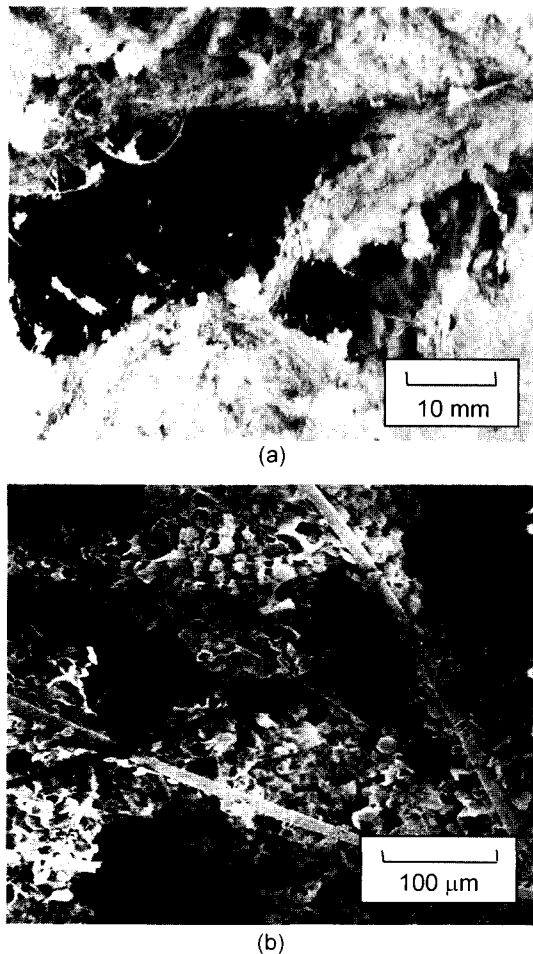
fiber lengths were typically several millimeters, but were significantly shorter than the average length of the chopped fibers (75 mm), indicating that the remaining lengths were embedded within the foam structure. Earlier work showed that similar long fibers embedded in foams may break rather than pull out during fracture, suggesting effective load transfer and fiber-foam adhesion.[6]

Flexure tests were conducted on unnotched and notched beams of the standard composite foam to investigate the influence of fiber reinforcement on crack resistance and damage tolerance. Fibers were arranged parallel to the length of the beam. Representative test data are shown in Fig. 9. Unreinforced foams show brittle behavior in both the notched and unnotched conditions, and the flexural strength is significantly lower for the notched beams (Fig. 9(a)). However, the composite foam shows much higher flex
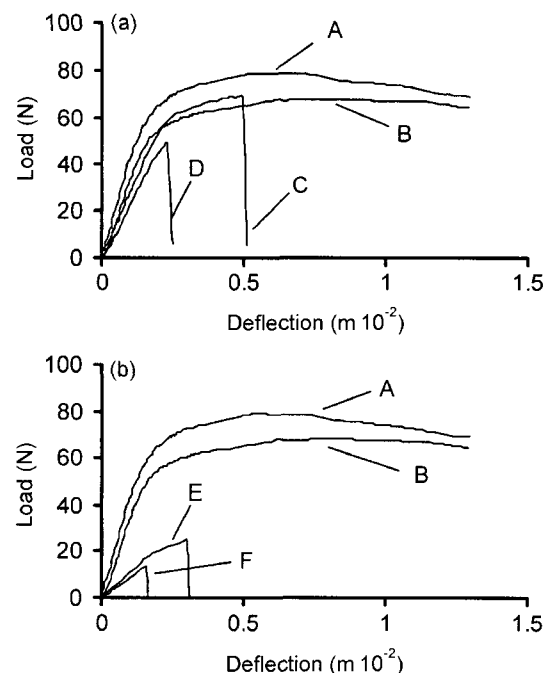

(a)

(b)

Fig. 8. Cracks in shear-tested composite PVC foam (10 wt% aramid fibers, 3 wt% phenolic resin). (a) Crack region showing fiber bridging and (b) Crack region showing fibers well-bonded to PVC microspheres.

Fig. 9. Load-deflection data from flexural tests for foam materials with density=100 kg/m^3. Part (a) compares un-notched and notched beams of PVC composite foam (curves A and B) with un-notched and notched beams of cross-linked commercial PVC foam (curves C and D) and Part (b) compares un-notched and notched beams of PVC composite foam (curves A and B) with un-notched and notched beams with un-notched and notched foam made from PVC microspheres (curves E and F).

strength and practically absence of strength decrement in the notched condition. The strength decrements for the notched unreinforced and composite foams were 37% and 1% respectively. Perhaps more significantly, both the notched and unnotched composite beams continued to carry load far beyond the yield and ultimate stress levels. This behavior derives from the fibers, which effectively carry substantial load after the foam yields.

The fibers also impart a substantial increment in energy dissipation compared with the unreinforced foam, as summarized in Table 5. Here, the total work is measured by the area under the load-deflection curve, in accordance with ASTM D 790. Calculations were based on effective cross-sections of the beams (excluding the notch area). The energy dissipated by the notched composite foam was nearly 60 times greater than the unreinforced foam, and the notch-induced decrement in energy absorption was 77% for the unreinforced foam, compared with only 15% for the composite foam.

Comparisons between the composite foam and the unreinforced commercial foam highlight some of the advantages of fiber reinforcement (Fig. 9(b)). First, both unnotched and notched samples of the unreinforced foam show brittle failure after the ultimate stress, while composite foams continue to carry loads within 10% of the peak load for strains 2–5 times greater. Second, notched beams of unreinforced cross-linked foam show substantially lower ultimate load and ultimate deflection than un-notched beams, while notched beams of composite foam retain 85% of the load-carrying capacity after peak stress, for deflection several times larger than the deflection at peak stress. Thus the notch sensitivity of the composite foam is substantially less than that of the cross-linked unreinforced foam.

4. Conclusions

Composite foams show substantial improvements over unreinforced foams, particularly in tensile and shear properties, friability, and fracture toughness. Compression properties, which are critically important for most sandwich applications, show moderate but significant enhancements.

Fiber reinforcement of foams, while not a new idea, has been given new life in recent years. Advances in process technology and availability of new material forms now make possible the production of composite foams with substantially improved performance levels. These materials will lead to expanded use of sandwich structures, as lower-cost, higher performance core materials narrow the price-performance gap between foams and honeycomb materials, making sandwich constructions more competitive as an alternative structural form. However, before sandwich structures can replace other forms, engineers must become knowledgeable in the selection of materials and the design of such structures.

Acknowledgement

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