

Flammability Properties and Mechanical Performance of Epoxy Modified Phenolic Foams

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ABSTRACT: This work has been mainly focused on the development and optimization of the processing methodology to produce epoxy modified phenolic foams. This study analyzes the relation between the composition and the structure as well as the mechanical and flammability performance of epoxy-phenolic (E-P)-based foams. Phenolic foams modified with different types and compositions of epoxy resin were successfully synthesized and characterized, showing uniform pore structure. Two epoxy resins were used for this approach. One is regular diglycidyl ether of bisphenol A (Epon 826) type and the other is a brominated bisphenol A (DER 542), which has halogen groups in the structure to improve the flammability properties of the resulting foams. Cone calorimeter (ASTM E 1354) was used to measure the heat release rate, the time to ignition, and other

flammability properties of the E-P foams with different types of epoxy resins, under well-controlled combustion conditions. The mechanical performance of the system was studied and compared with competing foams, such as phenolic, epoxy, and polyurethanes, in aspects of compression, friability, and shear performances. Compared with conventional phenolic foams, E-P foams exhibit significant improvement in mechanical performance, lower friability and similar resistance to flame. These results demonstrate the potential of the E-P foam as a flame resistant and high performance core material for sandwich structure. © 2007 Wiley Periodicals, Inc. *J Appl Polym Sci* 104: 1399–1407, 2007

Key words: foams; epoxy-phenolic; flame retardance; flammability; mechanical properties

INTRODUCTION

Among sandwich core materials, structural thermoset foams are often selected because of the extremely low density, low cost, and acceptable mechanical performance.^{1–3} They are widely used in a broad range of applications including building materials, automobiles, and aircraft. They are often a substitute for more expensive honeycomb core materials, although the performance of foams is substantially inferior. Thus, there is a cost and performance gap in lightweight core materials, an issue that can be addressed by developing lower cost honeycomb, or by enhancing the performance of existing foams. Polymer foams that are lightweight, affordable, and strong will find immediate application in commercial and military structures. In particular, high-performance composite foam materials could provide an attractive alternative to hon-

eycomb core materials commonly used in aircraft sandwich structures.

Currently, polyurethane (PU) and polyvinyl chloride (PVC) foams are popular choices for sandwich cores for structural applications. However, the use of these foams is precluded in applications with strict requirements for flame, smoke, and toxicity (FST). As FST standards become stricter in other applications, conventional structural foams may be precluded from their continued use. Unlike most structural foams, phenolic foams exhibit excellent FST properties and low production cost. As a result, phenolic foams are particularly attractive for aircraft, civil construction, and electronic applications, where FST performance is critical. However, phenolic foams are brittle and friable.^{4,5} These properties have severely limited most structural applications, and presently limit the use of phenolic foams to insulating applications. To more fully exploit the desirable properties of phenolic foam, the toughness must be improved.

Over the past few decades, different approaches have been developed to toughen phenolic foams, and these fall into three categories: chemical modification, inert fillers, and fiber reinforcement. Because inert fillers produce much denser and heavier foam, this approach has gradually lost appeal. The other two

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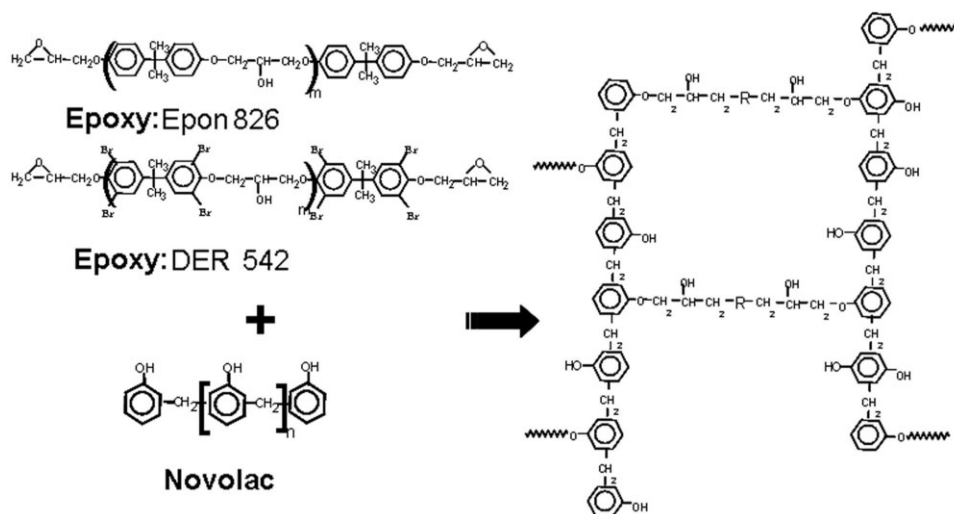


Figure 1 Schematic of the E-P foam synthesis reaction.

approaches offer the best chance of enhancing the toughness of phenolic foams without sacrificing the good FST properties. Several works^{4–8} provide detailed descriptions of reinforcement methods, models, and properties of different types of composite foams. One of the primary challenges inherent in this approach is achieving uniform dispersion and mixing during foam synthesis.⁹ Fibers, even relatively short ones in small proportions, greatly increase melt viscosity, interfering with the mixing and with the subsequent expansion of the foam.

An alternative approach to toughening phenolic foam is chemical modification, although the primary challenge of this approach is to retain the intrinsic FST properties of phenolics. Unfortunately, most chemical modifications that improve toughness severely compromise the FST performance. For example, one obvious class of additives—epoxy resins—offers high toughness and strength, although they are highly combustible. However, recent reports indicate that certain epoxy-modified novolac type phenolic resins can exhibit both high fracture toughness and excellent flame resistance.^{10–14} Furthermore, recent work in our laboratory has shown that epoxy-phenolic (E-P) foams can be made without an acidic or alkaline curing agent, thus eliminating corrosiveness in the resultant foam. In this work, we present a unique approach to produce phenolic-based epoxy foams, which combines the intrinsic flame resistance and low cost of phenolic foam with the superior strength and impact properties of epoxy resins. These fixtures provide a unique combination of flame-resistance and mechanical performance sufficient to compete with high performance structural materials.

This article focuses on the development of E-P-based foams modified with different types of epoxy resins. The flame resistance of the different E-P sys-

tems is evaluated by cone calorimetry, and the mechanical performance is evaluated and correlated with composition and structural features. Also, the behavior of E-P foam is compared with competing foams, including conventional phenolic, epoxy, and polyurethane foams, to evaluate the potential as an alternative foam for structural applications.

EXPERIMENTAL

Materials and sample preparation

Two types of E-P foams were synthesized by reacting a novolac type phenolic resin (Georgia Pacific, laboratory grade reagent, $M_n \sim 1049$ g/mol, 11.4 phenolic groups per molecule) with one of two epoxy resins. The first epoxy was a diglycidyl ether of bisphenol A (Epon 826, equivalent weight: 178 g/equiv.), while the second was a brominated bisphenol A epoxy (DER 542, equivalent weight: 333 g/equiv.). In both cases, 0.3 wt % of triphenylphosphine was used as catalyst (Fluka A.G., analytical reagent). The amount of catalyst added was based on the weight of epoxy. In these systems, the curing reaction proceeds via nucleophilic addition of the phenolic hydroxyl onto the epoxy group.¹⁴ A schematic of the synthesis of the E-P from the reaction of the epoxy and the novolac is shown in Figure 1.

The E-P foams were produced by addition of nonane as blowing agent in a weight proportion of 3.5 wt %. Peltstab (2 wt %) and Dabco (0.75 wt %) were used as surfactants. All the materials were used as received. The cure reaction was carried out at 140°C in an oil bath and before the gel time the mixture was placed in an oven at 180°C for 1 h and postcured at 200°C for 0.5 h. The reaction was carried out with the epoxy phenolic ratios shown in Table I.

TABLE I
E-P Foams Formulation

Foam formulation	Epoxy utilized	E-P (wt %/wt %)	E-P (equiv./equiv.)
Epoxy(100/0)	Ren 1774	100/0	–
E-P(50/50)	Epon 826	50/50	1/2
E-P(35/65)	Epon 826	35/65	1/4
E-P(20/80)	Epon 826	20/80	1/8
E(Br)-P(50/50)	DER 542	50/50	1/4
E(Br)-P(35/65)	DER 542	35/65	1/7
Phenolic(0/100)	–	0/100	–

Considering the chemical structure of the monomers, the crosslinking density of the resultant networks should decrease as the phenolic resin is added in increasing excess with respect to the epoxy groups. At the same time, there is an increase in intramolecular forces due to an increase in hydrogen bonding formation from the large amount of unreacted phenol.¹⁴

To compare the properties of the E-P foams with competing foams, pure epoxy and phenolic foams were also prepared. Epoxy foams were formulated using a commercial system REN 1774 (Epoxy, amino hardener and polydimethylsiloxane as chemical foaming agent) supplied by Ciba-Geigy (K.R. Anderson, USA). The epoxy foam was synthesized with a ratio epoxy : hardener : blowing agent of 100 : 25 : 1.2 (by weight), respectively.^{3,15} The phenolic foam was a thermally cured cresol network, synthesized by conventional means.^{4,5}

Table I shows the weight and equivalent weight percentage of epoxy-to-phenolic in the foams. Also shown are the identification codes assigned to the foams produced and the commercial name of the epoxy used. Unless otherwise specified, all foams were produced with a density of 200 kg/m³. A foam slab was produced, and test samples were cut from the slab after edge removal using a band saw.

Cone calorimeter test

Flammability was assessed using a cone calorimeter. The tests were performed at an incident heat flux of 50 kW/m², a value typical of a well-developed fire, in accordance with ASTM E 1354. The tests were conducted on samples cut from panels to dimensions of 100 × 100 × 12.7 mm³. Each foam sample was mounted horizontally on a weighting device and ignited by a spark igniter. The time to sustained ignition, peak heat release rate (PHRR), evolution of CO and CO₂, were recorded. The cone data reported here are the averages of three replicates.

Sol and gel fractions

The sol and gel fractions of completely cured samples were determined by placing the samples in acetone for

a specified time and monitoring the changes in the weight. The extraction of soluble material was continued in renewed solvent until constant sample weight was reached.

Mechanical tests

The compression testing was done using universal testing machine (INSTRON 8531). The test specimens used were of dimensions 30 × 30 × 25.4 mm³, in accordance with ASTM D1621. Specimens were compressed between two stainless steel platens, and load was applied with a crosshead speed of 2.5 mm/min. Special attention was given to the cutting direction with respect to the foam rise direction. Two loading directions, perpendicular and parallel to the foam rise direction, were used. Figure 2(a) shows the test configuration and the specimen geometry for the compression test. Compressive modulus was calculated as the initial slope of the linear portion of the compression-loading curve. The compression yield stress was determined from the maximum of the stress–strain curve. The results pre-

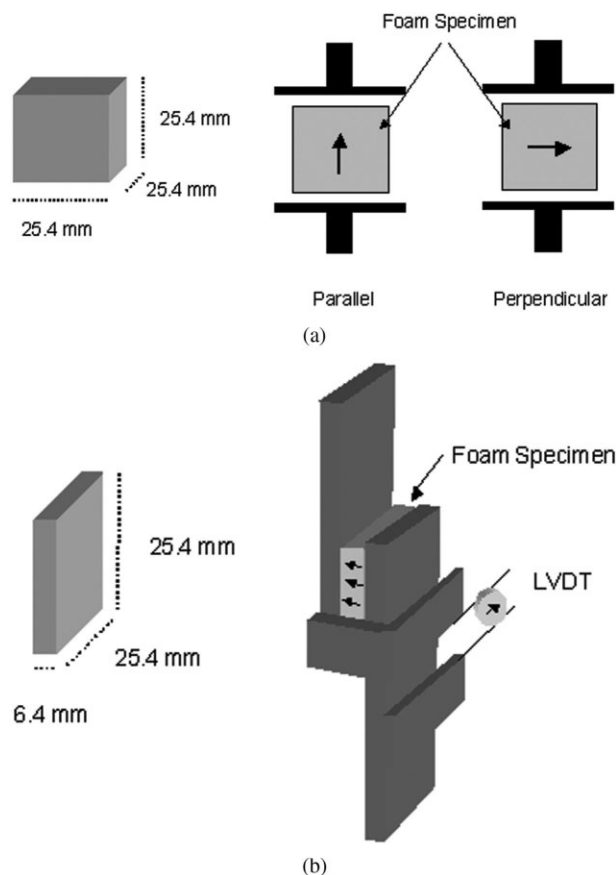


Figure 2 Compression (a) and shear (b) specimen geometry and test configurations. The arrows indicate the foaming direction.

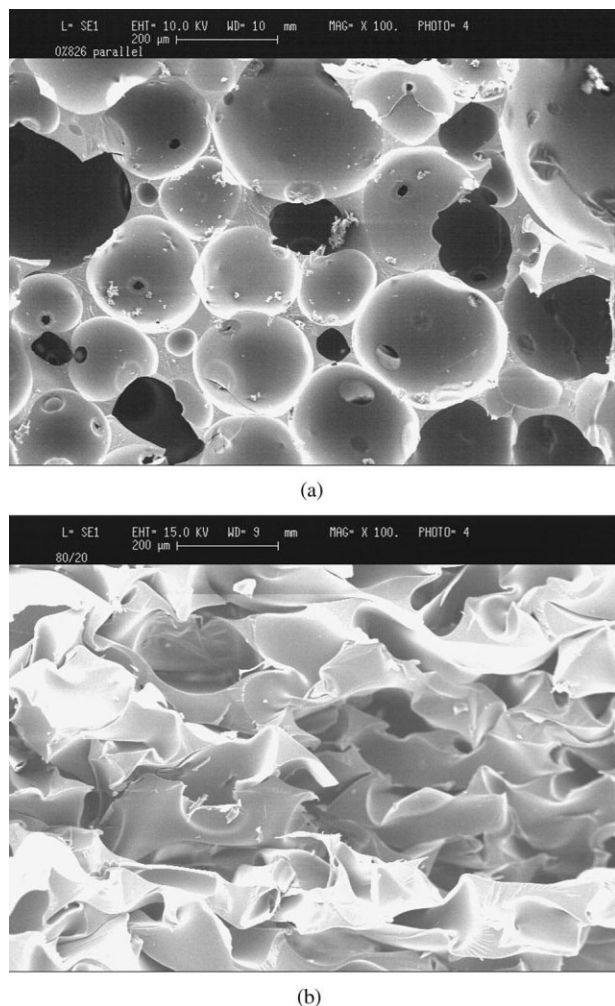


Figure 3 SEM micrograph of E-P foams with different epoxy/phenolic ratio: (a) E-P (35/65), (b) E-P (20/80).

sented here are average values from a minimum of five replicates.

Shear tests were performed in accordance with ASTM C273. Foams specimens were bonded to steel plates with an epoxy adhesive, and an extensometer attached to the shear fixture provided a measure of in-plane shear deformation with accuracy to 1 μm . The shear modulus was taken as the initial slope of the stress-strain curve, and the strength was measured from the peak stress. All results were the average of five samples. Figure 2(b) illustrates the shear configurations and specimens, with the foam rise direction marked (arrow).

Friability was measured using a custom tumbling box in accordance with ASTM C421. For each measurement, twelve foam cubes (25.4 mm side length) were mixed with twenty-four oak cubes (19.0 mm side length). Sample weights were measured before and after tumbling with accuracy of 1 mg. Tumbling times were 10 min at 60 rpm. Images of the specimen were recorded before and after testing.

RESULTS AND DISCUSSION

Morphology of E-P foams

The morphology of E-P foams with different compositions is shown in Figure 3. Foam E-P (35/65), shown in Figure 3(a), has a uniform dispersion of spherical cells that are $\sim 200 \mu\text{m}$ in diameter. The foam density is 200 kg/m^3 . Dimples on the cell walls represent the areas of contact between adjacent cells. These contact areas are continuous, thin polymer films, which form the walls that enclose the cells. The walls are extremely thin, and are estimated to be less than $2 \mu\text{m}$.

Foam E-P (20/80) had a totally different microstructure, as shown in Figure 3(b). The cell structure was completely collapsed. Because the phenolic concentration was high, there was insufficient epoxy to connect the phenolic chains, leaving a large number of dangling chain ends. Considering the reaction that occurs in the E-P foam system (Fig. 1), when equimolar amounts of phenolic and epoxy are used, highly crosslinked materials are expected to form. For E-P (20/80) foam, the equivalent weight percentage of epoxy to phenolic is $1/8$, and the crosslinking density is thus low. The hydrogen bonding in those unconnected phenolic chains results in brittle foam with drastically reduced property levels. Thus, the structure collapses after the foaming process. These observations provide insight into processing-structure relations of E-P foams.

To produce foams with a large excess of novolac groups, small samples were immersed in acetone at room temperature for a month. Figure 4 shows the fractional solids content for the foam samples. Samples prepared with near-stoichiometric ratio showed no weight gain, while the sol fraction grew when the novolac was in excess. This figure illustrates that as the phenolic concentration increases, the crosslinking density decreases, and thus the sol fraction increases.

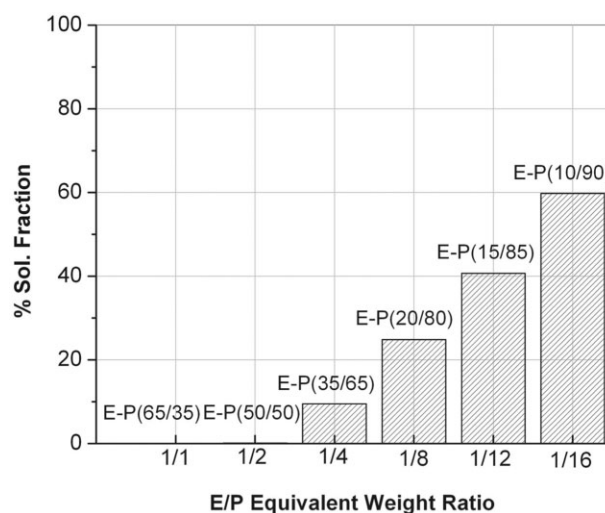


Figure 4 Sol and gel fractions for the E-P networks.

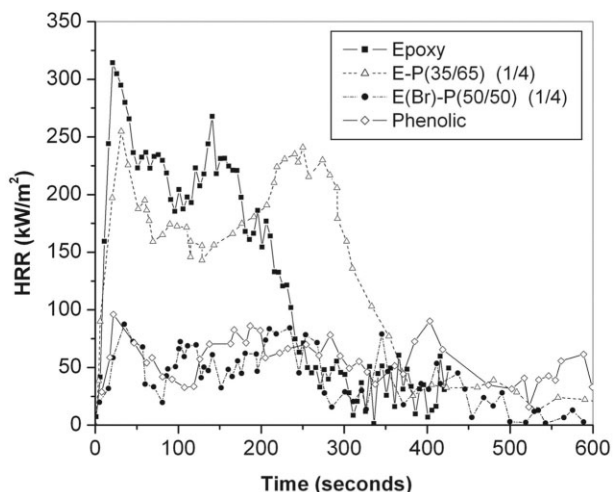


Figure 5 Comparison of the heat release rates (HRR) plots for pure the E-P foams and pure phenolic and epoxy systems.

Flammability properties

Cone calorimetry was used to assess the flammability and potential fire safety of the experimental E-P foams. Heat release rate (HRR) curves were measured as a function of time, showing the different burning behavior of the Epon 826 and DER 542 E-P cured foams (Fig. 5). The shapes of the curves are representative of the type of epoxy used in the network. Because of environmental concerns, the brominated epoxy has been used in this study for purposes of understanding and comparison. The peak heat release rates of the Epon 826 E-P foams were higher than those of the DER 542 epoxy cured foam at similar compositions. The halogen groups on the DER 542 contributed to a decrease of the peak heat release rate (PHRR). This sample shows a behavior similar to the pure phenolic foam. However, the peak heat release rates of the Epon 826 E-P foams were lower than those of pure epoxy foam. These foams were based on a commercial epoxy system and thus already contained fire retardant additives. Therefore, the PHRR value reported here (314 kW/m^2) is much less than what

additive-free pure epoxy foams would exhibit. For example, the PHRR of neat epoxy resin is reportedly $\sim 1200 \text{ kW/m}^2$.^{11,12} For this reason, larger differences are expected when the E-P system is compared with neat epoxy foams.

The results of the cone calorimeter test for the different E-P formulation are summarized in Table II. Individual values for the PHRR, average heat release rate at 300 s, time to ignition (TTI), percent weight loss, and CO/CO₂ yield during the fire test are included for each material. Values in the Table indicate that networks containing higher novolac contents showed lower peak heat release rates. This is because novolac contributes to flame retardance. The high flame retardancy was achieved primarily by the formation of a stable foam char layer. The stability of the char layer derives from the high pyrolysis resistance of the compounds after curing. Furthermore, the addition of excess phenol groups improved the flame retardancy by (a) facilitating the formation of the char layer by decreasing the crosslinking densities, and (b) reducing the amount of flammable substances generated from the foam compounds during combustion. Higher char yields are desirable because char forms an isolation layer, which generally improves flame properties, shielding the transfer of heat to the inside of the specimen during the ignition process.

The foams containing brominated epoxy in the main chains displayed far greater flame retardance than those containing conventional epoxy resin. Thus, lower peak heat release rates were observed for the brominated networks. Surprisingly, the E(Br)-P (35/65) sample showed a superior behavior compared to pure phenolic foam. The ignition time was longer, and the HRR curve was lower over the total time measured. However, these foams showed a higher CO/CO₂ yield in combustion gases, a potential cause for concern. Masatoshi Iji and Yukihiro Kiuchi¹⁶ demonstrated that the halogens, such as bromine in E(Br)-P foams, decompose during burning. The decomposed halogens then retard combustion by trapping radicals generated from the decomposing resin and forming a gas phase barrier against oxygen. However, the use of

TABLE II
Combustion Properties of E-P Foams Measured with Cone Calorimeter

Foam formulation	Peak heat release (kW/m ²)	Average heat release rate at 300s (kW/m ²)	Ignition time (s)	Mass loss (%)	CO/CO ₂ yield
Epoxy(100/0)	314	195	2.3	100	0.023
E-P(50/50)	258	179	4	89	0.052
E-P(35/65)	253	174	3.8	84	0.026
E-P(20/80)	247	170	3.6	91	0.063
E(Br)-P(50/50)	91	24	7	65	2.51
E(Br)-P(35/65)	66	22	–	69	0.5
Phenolic(0/100)	106	54	6	84	0.026

TABLE III
Compression Test Data of E-P Foams
(Density: 200 kg/m³)

Foam formulation	Parallel ^a		Perpendicular ^a	
	Modulus (MPa)	Strength (MPa)	Modulus (MPa)	Strength (MPa)
Epoxy(100/0)	48.01	1.89	21.12	1.69
E-P(50/50)	44.32	2.64	24.22	2.05
E-P(35/65)	72.23	2.87	52.6	2.28
E-P(20/80)	8.40	0.62	–	–
Phenolic(0/100)	53.42	2.17	49.37	1.85
Polyurethane ^b	106.05	3.39	79.87	3.27

^a Loading direction respect to foam's original direction.

^b Data from the literature.¹⁸

such halogen-bearing materials poses a problem. During burning, the compounds can generate toxic substances that pose a health hazard.¹⁷

The mass loss behavior of the two types of foams differed considerably. The Epon 826 E-P foams burned almost completely, losing ~90% mass, while the brominated E-P foams showed behavior similar to phenolic foam, with ~70% mass loss. Higher char yields are desirable with respect to fire retardance because char forms an isolation layer. The isolation layer retards the transfer of heat inside the specimen during the ignition process, thus improving flame properties.

Mechanical performance

The compressive modulus and strength for the E-P foams, measured in perpendicular and parallel directions with respect to the foaming rise, are summarized in Table III. As expected, the addition of epoxy in the E-P foam formulations improves the compression modulus and strength. This is attributed to the widely known phenomenon that an increased crosslink density (caused in this case by increasing the epoxy concentration) causes the network strands to become shorter and the modulus and strength to increase. However, the compressive strength and modulus have a maximum value for the sample E-P (35/65). This phenomenon can be attributed to the fact that while the crosslinking density of this sample is decreasing, the intermolecular force (hydrogen bond) produced by the excess phenolic groups is increasing.¹⁴ Nevertheless, there is a critical amount of phenolic that can be incorporated into the samples. If the amount of phenolic in the foam increases beyond this critical value, the foam will become fragile and weak. This is the case for the E-P (20/80) foam shown in Figure 3(b). A complete collapse of the structure of these samples was observed after the foaming process. The dominant effect is the extremely low crosslinking density, while the increased intermolecular force produces only a minor enhancement of mechanical prop-

erties. This leads to the final poor performance of these materials.

The compressive properties of the E-P (35/65) are superior to pure phenolic foams of comparable density, and approach those of commercial polyurethane foams. Comparing first with phenolic foam, along the parallel direction, the E-P (35/65) foam shows a 36% increase in modulus, from 53 to 72 MPa, and a 32% increase in strength from 2.17 to 2.87 MPa (when measured parallel to the foam rise direction). The data in Table III show that the E-P foams are not as stiff and strong in compression as rigid PU foams of the same density. However, the E-P foams have not been fully optimized, and are superior with respect to FST performance. Consequently, E-P foams can be competitive with structural foams in certain applications, especially those requiring good fire resistance.

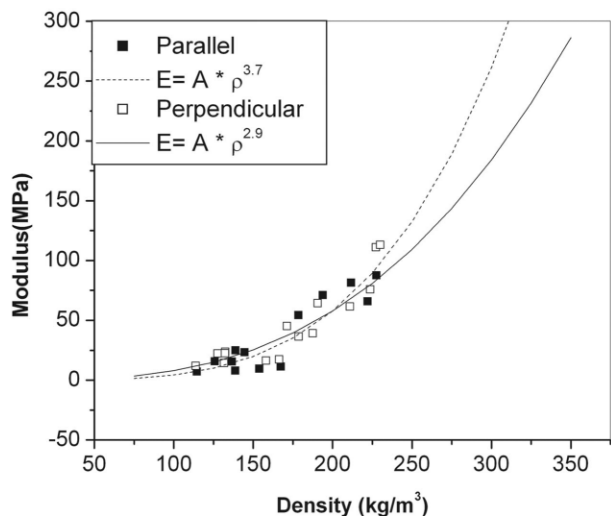
The modulus and the compressive strength of E-P (35/65) are plotted versus foam density in Figures 6(a) and 6(b). As the amount of the blowing agent increases, the density of the foam decreases, resulting in lower mechanical properties. The modulus and the strength data exhibit power-law dependence with respect to foam density, given by

$$E = A\rho^m \quad (1)$$

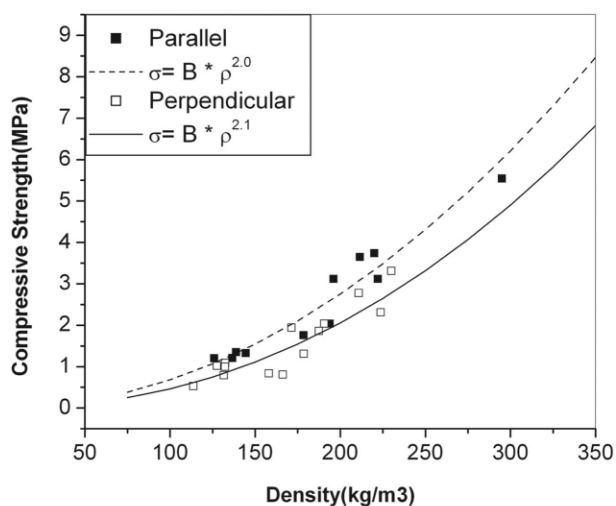
$$\sigma = B\rho^n \quad (2)$$

where E and σ are the modulus and compressive strength of the foam, respectively, ρ is the foam density, A and B are constants related to the physical properties of the resins, and m and n are density exponents associated with the structure and deformation mechanics of the cellular materials.^{3,19} Over the range of density shown in the plots, the data are well fit along the parallel direction. Similar trends are observed for properties measured perpendicular to the rise direction. For other compositions, all the compressive data conform to similar power-law expressions with respect to foam density. The characteristic values of m , n , A , and B are presented in Table IV.

Phenolic foams are typically brittle under shear loads, and the modified E-P foams were also brittle in shear, albeit somewhat improved. Typical shear stress-strain curves for E-P foams of comparable density (200 kg/m³) are shown in Figure 7. The initial linear region defines the modulus of the foam and the maximum in the curve shear stress. The foams generally fail abruptly upon reaching a maximum stress. As expected, the epoxy content dominates the strength and stiffness of the E-P foam, as shown in Figure 7. However, the shear strength and modulus show maxima with increasing additions of phenolic because of strong intermolecular forces. As discussed above, there is an optimum amount of phenolic resin that can



(a)



(b)

Figure 6 Density dependence of the compressive modulus (a) and strength (b) of the E-P(35/65) foam.

be incorporated into the network, and beyond this point, the foam weakens and collapses [Fig. 3(b)].

Table V summarizes the shear results obtained at room temperature for the different epoxy phenolic ratios. The shear properties of the E-P (20/80) system was not tested because of poor sample quality, as explained previously. The E-P foams exhibit substan-

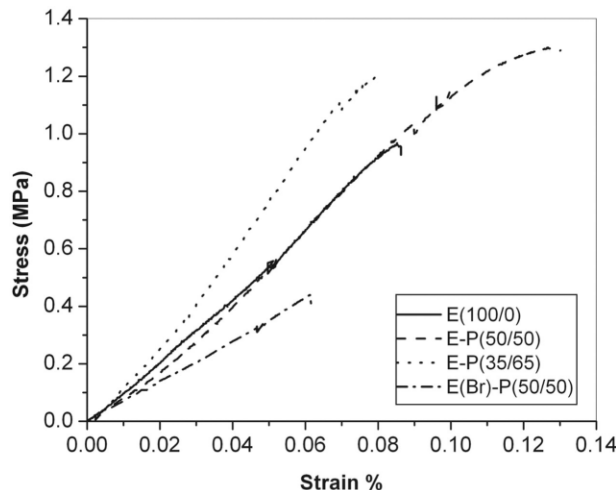


Figure 7 Shear experiments of different E-P foams. Shear plane and loading direction are perpendicular to the foam rise direction.

tial improvements compared with the pure phenolic foams. For example, the E-P (35/65) foam shows a two-fold increase in shear modulus and strength compared with pure phenolic foam.

The properties of E-P foams compare favorably with some leading commercial foams of equivalent density (200 kg/m²). Epoxy and polyurethane (PU)^{18,19} foams are crosslinked foams well-suited to use in engineering sandwich structures. Epoxy foams are among the hardest and stiffest foams available because they are highly crosslinked. On the other hand, polyurethane foams have moderate stiffness and are easy to process and affordable. Nonetheless, the shear results shown in Table V illustrate that the E-P foams have behavior comparable with these typical commercial systems. The data from Table V indicates that the E-P (35/65) is stronger and stiffer than conventional phenolic and commercial polyurethane foams.

Friability is defined as the mass loss due to surface abrasion and impact damage. It is a fundamental property for structural foams that has practical significance as well. For conventional phenolic foam, the friability is high, causing severe handling problems during manufacture and in service applications involving cyclic loads and vibrations.^{4,5} Friability also

TABLE IV
Predicted Values of the Density Dependence with the Modulus and Strength for Different E-P Foams

Foam formulation	Parallel ^a				Perpendicular ^a			
	A	m	B	n	A	m	B	n
E-P(50/50)	1.1 × 10 ⁻⁸	4.1	1.8 × 10 ⁻⁵	2.3	3.1 × 10 ⁻⁸	3.8	1.6 × 10 ⁻⁵	2.0
E-P(35/65)	1.6 × 10 ⁻⁷	3.7	6.6 × 10 ⁻⁵	2.0	1.5 × 10 ⁻⁷	2.9	2.4 × 10 ⁻⁵	2.1
E-P(20/80)	3.0 × 10 ⁻¹⁴	5.7	5.4 × 10 ⁻¹¹	4.1	-	-	-	-

^a Loading direction respect to foam's original direction.

TABLE V
Shear Test Data of E-P Foams (Density: 200 kg/m²)

Foam formulation	Perpendicular ^a	
	Modulus (MPa)	Strength (MPa)
Epoxy(100/0)	11.9	1.07
E-P(50/50)	7.9	0.82
E-P(35/65)	14.2	1.7
E-P(20/80)	5.59	0.33
Phenolic(0/100)	7.1	0.84
Polyurethane ^b	14	1.35

^a Loading direction respect to foam's original direction.

^b Data from the literature.¹⁸

makes bonding to other materials difficult and produces airborne dust particles during production. For construction applications, vibration precludes the use of phenolic foam in most structures. The friable nature of the phenolic foam derives from the brittle and fragile nature of the foam structure. This problem can be addressed by developing E-P foam formulations with enhanced toughness.

The friability test results of the E-P foams are shown in Figure 8(a). The results indicate that epoxy additions significantly improve the friability of phenolic foam. The mass loss drops from 25% for plain phenolic foam, to less than 10% for the E-P (35/65) foam. As the foam friability is reduced, shape retention of the samples improves, as shown in Figure 8(b). The shape of the E-P (50/50) foam cube is nearly unchanged after the friability test. The friability performance of the E-P foam is comparable with the performance of plain epoxy and polyurethane foams.

CONCLUSIONS

Epoxy modified phenolic foams were synthesized from phenolic and epoxy resins using triphenylphosphine as catalyst. A conventional epoxy resin and a brominated epoxy were used. The resultant E-P foams generally had a uniform, closed-cell structure. However, when phenolic additions exceeded a critical level, the resultant foam structure collapsed.

The flammability of the E-P foams was studied by cone calorimetry. E-P systems that included the halogen group in the main epoxy chain (DER 542) exhibited flame resistance superior to the corresponding Epon 828 E-P foam (without the brominated group in the chain) at the same compositions. The mechanism that produces this improvement was attributed to the formation of a pyrolysis resistant carbonaceous substance formed on the foam surface during combustion, which retarded oxygen passage and heat transfer. However, these halogen compounds produce toxic

fumes that pose a health hazard. The flame retardancy of the E-P system can be further improved by adding excess phenolic to epoxy resins to obtain nonstoichiometric compositions.

The compression, shear, and friability properties of the E-P foam were determined and discussed in terms of the crosslinking density and the network structure effects. The yield stress and compression modulus of the E-P foam had maximum values for the E-P (35/65) foams. The shear performance followed a similar trend, with a significant improvement in both shear strength and modulus compared to the conventional phenolic foam. Shear behavior is among the most important criteria for selection of core materials for sandwich structures, where the core is typically subject to significant shear loads. The friability of the E-P foams was reduced remarkably compared with pure phenolic foam, a factor that has practical implications for ease of handling and ability to withstand vibratory loads.

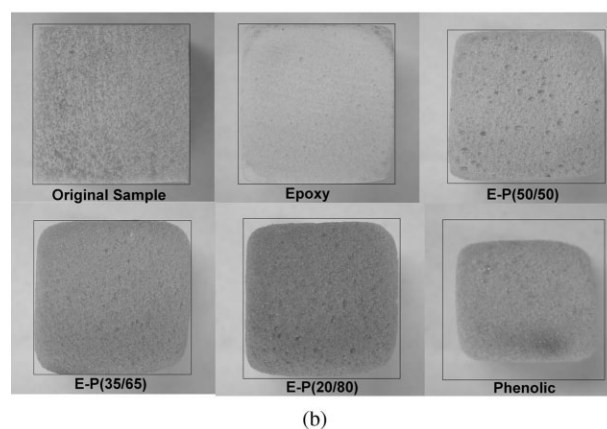
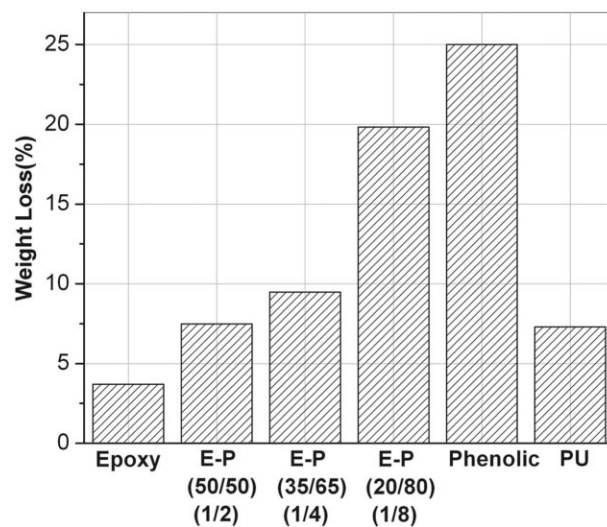


Figure 8 (a) Friability test results. (b) Shape changes of the foams as result of the friability test (original sample size 2.54 cm × 2.54 cm).

The chemical modification improves all aspects of the mechanical performance of phenolic foam considered. The E-P foam surpasses the performance of the pure phenolic foam, and is comparable to commercial PU foam of equivalent density. This approach also eliminates the corrosiveness of the phenolic foam. E-P foam has a closed cell structure that resists water ingress, which should be an asset for marine applications. While the brittle nature of phenolic foams preclude most structural applications, the results presented in this study indicate that E-P foams could be used in a variety of structural applications requiring fire resistance, moderate mechanical performance, and moisture resistance. E-P foams also may be alternatives for PU foams and even some honeycomb materials in applications demanding lower cost and improved fire retardance, such as building construction, commercial aircraft, and automobiles. An additional attribute of the E-P system is that foam properties may be tailored by varying the kind of the epoxy resins to meet various demands, and by varying the proportions of epoxy and phenolic. In the future, additional performance enhancements can be realized by fiber-reinforcement of the E-P foams, as demonstrated in similar foams systems.^{4,5}

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