Diffusivity and Climatic Simulation of Hybrid Foams

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Abstract: Hybrid composite phenolic foams reinforced with glass and aramid fibers were prepared and evaluated as potential materials for insulation and cladding applications. In particular, moisture uptake, flammability, and accelerated aging experiments were performed. A statistical approach was employed to model and predict the moisture absorption of the foams. Hybrid foams exhibited much lower diffusivity of water molecules and moisture content compared to unreinforced foam. The properties of hybrid foams were also compared to commercial expanded polystyrene (EPS) foam. The flammability properties of hybrid foams were markedly superior to EPS. Accelerated aging test revealed excellent dimensional stability of hybrid foams even under extreme conditions. Compressive stiffness of hybrid foams was retained even after aging.

Key words: foams, fibers, insulation, climatic simulation

1. INTRODUCTION

Energy conservation is an increasingly important aspect of modern building designs. Among the factors that the building designer must consider, energy conservation by use of thermal insulation is most effective [1]. Creating a low-cost structural insulation material is also important for environmental reasons. As energy costs rise, energy conservation in buildings is becoming increasingly important. A large reduction in heat loss, however, can be realized by insulating attics and ceilings [2]. Khemani has compared heat losses for an uninsulated and insulated house during heating and air-conditioning periods. The article shows that insulation can save on energy costs by

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up to 50%, with rooftops being the most effective locations to place insulation [3]. However, multiple factors must be considered when choosing an insulation material.

Table 1. Embodied energy of common insulation materials http://www.afcee.brooks.af.mil/gree/case/accsfguide.pdf).

Material	Embodied energy (MJ/kg)
Cellulose	3.5–18.6
Extruded polystyrene	1171.25
Polyurethane foam	721.34
Fiberglass	302.2
Mineral wool	151.05
Expanded polystyrene	1115.5
Phenolic foam	799.03

The choice of insulation is among the most important factors affecting the environmental impact of a building. Although insulation reduces building energy consumption and provides other ongoing environmental benefits throughout a building's lifetime, insulation materials greatly differ in their environmental advantages. As the United States Department of the Interior notes, insulation manufacturing processes generate pollution as a result of fossil fuel combustion (http://www. afcee.brooks.af.mil/gree/case/accsfguide.pdf). The simplest way to assess manufacturing impact is to compare the manufacturing energy required or embodied energy (2008). Table 1 reveals significant differences in embodied energy costs of commonly used insulation materials (http:// www.afcee.brooks.af.mil/gree/case/accsfguide.pdf). The table shows that expanded polystyrene (EPS) has an embodied value over 35 times greater than cellulose. The data suggests that use of natural, locally available or recycled material can drastically reduce embodied energy costs. Cellulose, mineral wool, fiberglass, EPS, and polyurethane foam (PU) are among the most commonly used insulation materials.

Cellular plastics, because of the intrinsic low mass, low thermal conductivity, low cost and include a vast variety of polymer foams with a range of densities, elastic properties, and strengths are obvious choices for core materials in insulating panels for buildings. The properties of foams depend on the density of the foam, the foam material, and the cell structure. Popular choices of commercial foams for the purpose of insulation are EPS and PU, although both have their drawbacks. For example, embrittlement and dusting of PU foam insulation has been reported in the living space of homes [4]. In addition, exposure of PU foam samples to high temperature and humidity conditions reportedly causes deterioration similar to that which can occur in service [5]. Second, PU and EPS foams are flammable. As the standards for fire, smoke, and toxicity (FST) properties become increasingly stringent worldwide, the limitations of conventional structural foams may preclude their continued use. However, as shown in Table 1, phenolic foams have an embodied energy value of 799 MJ/kg, which is 28% less than the value for EPS. Further the R-value of phenolic foam is higher compared to EPS and PU foams as shown in Table 2, and thus making it an excellent candidate for insulation purposes.

Table 2. R-value of common materials.

Material	R-value
Wood	0.91
Polystyrene (EPS)	3.85
Polyurethane foam	6.88
Phenolic foam	8.30
Concrete	0.3
Fiberglass	3.90

Hybrid composite phenolic foam reinforced with glass and aramid fiber is considered in the current research [6]. The mechanical properties of these hybrid foams in compression and shear are superior to EPS and PU foams [6]. Phenolic foam also has other distinct advantages relative to other polymeric foams. It has excellent FST properties, low thermal conductivity, and is less expensive polymer foam [7].

However, to use a foam or cellular material for insulation, several other factors have to be taken under consideration, such as long-term durability and stability under extreme environmental conditions, especially for service conditions involving extreme heat and humidity. The thermal conductivity of the entrapped gas in the cell represents an important contribution to overall foam thermal conductivity because approximately 50% of the heat transfer through the foam occurs by conduction through the gas phase [8]. A major problem in foam materials involves the decrease in insulation value over time and the lack of dimensional stability. Air diffuses into the cells during the service life of foams, and a high molecular weight blowing agent diffuses out primarily in case of extruded polystyrene, which modifies the cell gas composition and ultimately causes a gradual decrease in thermal resistivity of the foam. Thus, the diffusion behavior in foams is important because the mass transfer of gases in the air control the cell gas composition for short to intermediate times, whereas the mass transfer of the blowing agent controls long-term composition changes in the foam. Condensed vapor is generally not taken into consideration in the optimizing insulation thickness; however, condensed vapor not only damages the building structures but also it has an energy that causes a loss in its transferring [9–13]. For this purpose, the relative humidity (RH) that affects the condensation process must be studied carefully. This parameter affects the living condition, namely, 'thermal comfort'. To get thermally comfort conditions in buildings, temperature and indoor RH must be arranged between 18 °C and 22 °C and 40–70%, respectively. The reference state is the most important parameter to determine the optimum insulation thickness. In this sense, temperature and RH of ambience described with the concept of reference state are the characteristics of the regions and spaces.

Efforts to develop predictive models for the effective diffusivity of foam have met with limited success. Bart and Du Cauze De Nazelle [13] developed a discrete model to predict the effective

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diffusivity of foam. However, this and other discrete models reported in literature are not realistic in describing the diffusion through foams, mainly because of the basic assumption of a steady state in the cell walls that is not necessarily valid. In this article, we apply Fick's second law of diffusion to predict the moisture content and diffusivity of hybrid foams. A statistical approach is employed to analyze the foam behavior and to predict moisture absorption. The flammability of phenolic foam with different fibers is measured and compared to commercial EPS foam. Accelerated aging of these hybrid foams is analyzed to determine if extended exposure to intense heat and humidity weakens the material. Compressive properties of composite foam are compared before and after accelerated aging to study environmental stress and effects on foam properties and performance. The present study also determines structure–property relations and the effects of fiber reinforcement on foam morphology. Cell lengths before and after climatic simulation are compared to study moisture absorption in composite foams.

2. EXPERIMENT

2.1. Materials and Foam Preparation

Phenolic foams were synthesized using a proprietary formulation [14] and a patented technology [15]. The formulation was typically composed of phenolic resole resin (solid content 480/100 parts) and appropriate amounts of pentane (3–7 wt%) to achieve desired foam densities. Polysulfonic acid (PSA) was used as a catalyst for the reaction. When fiber reinforcements were introduced, the amount of PSA catalyst was slightly increased to allow more time for dispersing fibers. All foams were formulated to achieve a density of 50 kg/m3 (3 pcf). The foams were synthesized at low density to compete with existing insulation materials such a PU and EPS.

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Resin was blended with fibers, blowing agent, and catalyst. Synthesis and mixing were performed using a high-speed, dual-axis mixer (Keyence HM-501). Finally, fibers (glass and aramid) were incorporated into the mixture, which was blended at high speed for several minutes. The foam slurry was poured into a mold and held at 1 h at 80 °C to allow foaming of phenolic foam. The foam was allowed to cool to room temperature and then neutralized overnight in a closed ammonia chamber. The test specimens were then sectioned from foam slabs using a diamond band saw. Special attention was given to the cutting direction with respect to the foam rise direction, and the edges of foam blocks were avoided. All samples were cut and tested in the foam rise (parallel) direction. Table 3 summarizes the weight percentage of fibers used for various foams studied. For comparison purposes, hybrid foams reinforced with glass and aramid fibers (fiber ratio 1 : 3 and 3 : 1) were produced, foam with only aramid fibers (1 wt%), foam with only glass fibers (1 wt%), and unreinforced foam.

2.2. Moisture Absorption and Diffusivity Model

Foam plate samples (5x50x50 mm) were used for moisture absorption tests, in accordance with ASTM D5229. The samples were dried in a vacuum oven at 60 °C until no weight change was observed. Dried specimens were placed in an environmental chamber and maintained at 80% RH at room temperature. The weight of these samples was monitored until specimens reached equilibrium. Table 3 summarizes the results of moisture absorption over time. The mechanism of moisture diffusion can be described by Fick's second law using diffusivity constant (D), which normally represents Diffusivity and Climatic Simulation of Hybrid Foams 465 Downloaded from cel.sagepub.com at UNIV OF SOUTHERN CALIFORNIA on August 17, 2015 non-steady-state diffusion in a polymer in three dimensions as follows [16]:

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$$\frac{M_t}{M_\infty} = 1 - \sum_0^\infty \frac{8}{(2n+1)^2 \cdot \pi^2} \cdot \exp\left[\frac{-D \cdot \pi^2}{4 \cdot l^2} \cdot (2n+1)^2 \cdot t\right] \qquad (1)$$

Here, M_t is the weight gained at time t, and M_∞ is the maximum weight gained at the equilibrium state. In the present work, one-dimensional diffusion through a sample of thickness 2l was measured, and thus, the relative moisture uptake was approximated by the following expression (where only the terms for n=0 appear) [16]:

$$\frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2} \cdot \exp\left[\frac{-D \cdot \pi^2}{4 \cdot l^2} \cdot t\right] \qquad (2)$$

An expression similar to Equation (1) was used to predict the moisture content given by the following:

$$\frac{M_t}{M_\infty} = 1 - \exp\left[-7.3 \cdot \left(\frac{D \cdot t}{4 \cdot l^2}\right)^{0.75}\right] \qquad (3)$$

Fick's second law is based on a linear relationship between the moisture gain (M_t/M_∞) and time ($t^{1/2}$). Consequently, the diffusivity coefficient can be determined from the resultant slope of the following equation for small values of times ($M_\infty/M_t \leq 0.5$):

$$\frac{M_t}{M_\infty} = 4 \cdot \left(\frac{D \cdot t}{\pi \cdot 4 \cdot l^2}\right)^{0.5} \qquad (4)$$

In this study, the diffusivity value of composite foams was determined, and the non-steady-state moisture absorption was also considered.

Table 3. Moisture absorption test.

Time (h)	1% Nomex	1% glass	Unreinforced	1% glass, 3% Nomex	3% glass 1% Nomex
0	6.916	6.740	7.025	6.855	7.183
2	6.930	6.758	7.046	6.868	7.192
7.75	6.941	6.771	7.059	6.877	7.202
31.5	6.945	6.782	7.074	6.889	7.219
55.417	6.947	6.790	7.088	6.906	7.230

79.63	6.958	6.799	7.101	6.909	7.238
151.63	6.965	6.806	7.111	6.914	7.245
175.67	6.970	6.811	7.113	6.916	7.246
198.33	6.975	6.814	7.113	6.920	7.251
246.33	6.977	6.817	7.116	6.921	7.253
390.3	6.978	6.819	7.117	6.921	7.254
411.3	6.978	6.819	7.118	6.921	7.254
701.3	6.978	6.819	7.118	6.921	7.255
843.3	–	–	7.118	–	7.255

2.3. Flammability Test

Vertical burn tests were performed in accordance with UL 94 to measure flammability (http://www.ul.com/plastics/standards.html). Samples were loaded into the metal chamber, and a Bunsen burner was lit and positioned beneath the sample (Figure 1). The flame was applied to samples for two 10 s intervals separated by the time it took (if any) for the combustion to cease after the first application. The length of time that the sample retained flame for each application was measured. Three samples were tested per specimen. In addition to combustion time, the volume of each sample was measured before and after the test to determine the volume of material consumed.

Figure 1. UL 94 burn test.

2.4. Climatic Simulation: Accelerated Aging

Accelerating aging was performed in accordance with ASTM D2126 [17]. Aged samples were subsequently prepared for compression and shear tests, and for cell measurement. Samples were first conditioned in an oven for 24 h at 508C. Next, samples were placed in a humidity oven. Controls were set at 40 °C and 85% RH. Samples were conditioned for 6 weeks, then removed and weighed.

Variations of the standard aging were also performed. Compression samples were prepared by sectioning to 25.4x25.4x25.4 mm. No preconditioning was performed on these foam samples to extract moisture. Three samples were placed in the aging chamber for each fiber type so that results of the postconditioning tests could be averaged after 6 weeks.

2.5. Mechanical Tests

Test specimens were sectioned from foam slabs using a diamond blade band saw. Special attention was given to the cutting direction with respect to the foam rise direction, and the edges of foam blocks were avoided. Compression tests were performed using a universal testing machine (INSTRON 5564 system) in accordance with ASTM standards. Specimens, 30 mm square by 25.4 mm thick, were placed between steel platens, and load was applied with a crosshead speed of 0.5 mm/min. Compressive modulus was determined from the steepest initial slope of the stress–strain curve, and strength was determined from the maximum load (in a range of strain < 10%). At least five replicates were tested for each material, and the results were presented as the average value of all replicates.

2.6. Scanning Electron Microscopy

A scanning electron microscope (SEM) was employed to observe the fracture surfaces of foam specimens. Samples were cut from the freshly peeled surfaces using a razor blade. Gold sputtering onto the sample surface was used to impart electrical conductivity. The operation voltage of the SEM was 15 kV. SEM images were recorded in a high-resolution electronic format and processed later with computer software.

3. RESULTS AND DISCUSSION

3.1. Foam Diffusivity and Moisture Absorption

The model described in the section 'Moisture Absorption and Diffusivity Model' was used to predict the saturated humidity content of the composite foams. Fiber-reinforced composite foams exhibited lower moisture absorption rate compared to the unreinforced counterpart. Figure 2(a) and (b) show plots of weight gain as a function of square root of time for composite foam. Clearly, fiber reinforcement reduced the rate of moisture absorption for composite foams. Hybrid foams (glass : aramid – 1 : 3) at the saturation limit showed almost 31% less weight gain compared to unreinforced foam of similar densities.

The effective diffusivity values predicted by Fick's second law for phenolic foams are displayed in Figure 3. A ~25% reduction in effective diffusivity relative to the unreinforced phenolic foam was predicted in hybrid foams with addition of glass and aramid fibers. In general, the effective diffusivity decreased with increasing fiber content because moisture absorption of reinforced composites involves complex internal stress phenomena [18]. For example, the effective diffusivity for glass-reinforced phenolic foam is influenced by cross-linking and the cell size reduction that results from fiber addition. Note that phenolic foam with 1 wt% aramid fiber exhibits a ~45% increase in effective diffusivity with respect to unreinforced phenolic foam because of the hydrophilic character of the fibers. The results suggest that selection of fiber type is a critical factor that affects foam diffusivity.

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3.2. Flammability

Figure 4 shows the flammability results for phenolic foam compared to commercial EPS foam. Fiber reinforcement in phenolic foam had no effect on the fire properties. However, phenolic foam overall showed significantly greater fire resistance compared to EPS. EPS lost more than 70% volume after flame exposure, whereas phenolic foams (both unreinforced and reinforced) exhibited less than 6% volume loss during this test.

Table 4 also shows results obtained by using the classification system defined by testing standard UL 94, in which V0 is a superior and V1 is inferior. For foams identified with V0 rating, the burning stopped within 10 s after two applications of 10 s each of a flame to a test bar, whereas burning stopped within 60 s after two applications of 10 s each of a flame to a test bar for foams with V1 rating. V0 rating for phenolic foam further highlights its superior flammability properties.

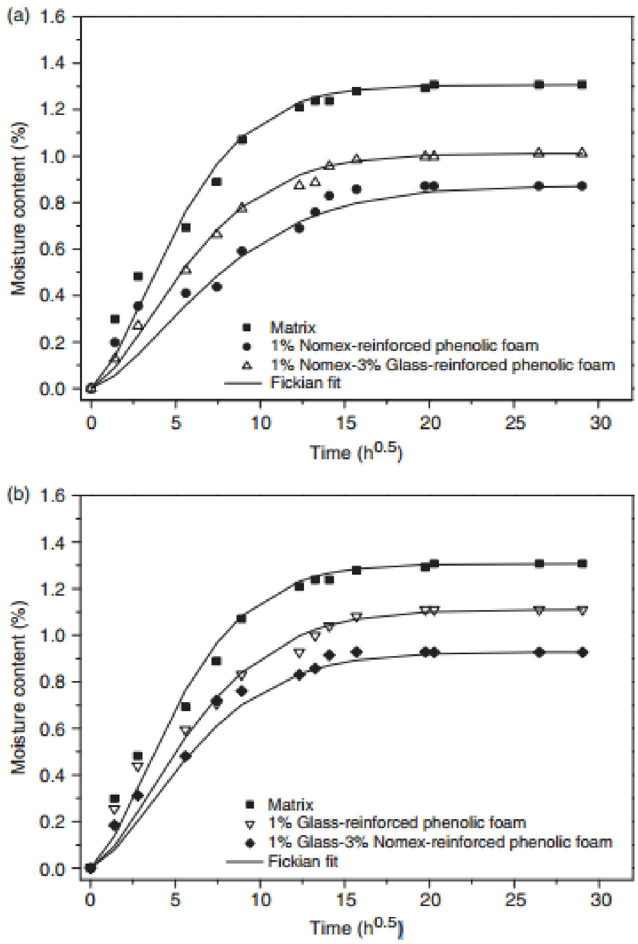

Figure 2. (a–b) Plots for weight gain vs square root of time for composite foams.

3.3. Accelerated Aging

Results of accelerated aging tests are also summarized in Figure 5. Mass loss as a percentage of initial mass was calculated by subtracting the final mass of each specimen after 6 weeks in the environmental chamber from the initial mass, then dividing by the initial mass and multiplying by 100. The unreinforced phenolic foam showed mass loss >10% over the 6 weeks at 40 °C and 85% humidity.

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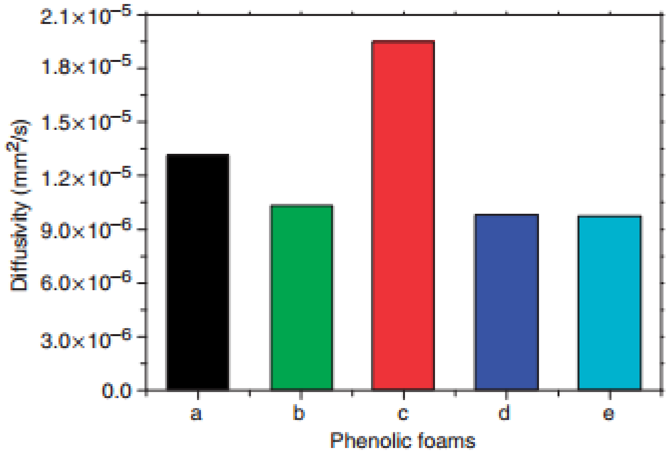

Figure 3. Evolution of moisture diffusivity for composite foams (a) unreinforced foam, (b) 1 wt% glass fibers, (c) 1 wt% aramid fibers, (d) hybrid foam – 3 wt% glass and 1 wt% aramid fibers, and (e) hybrid foam – 3 wt% glass and 1 wt% aramid fibers.

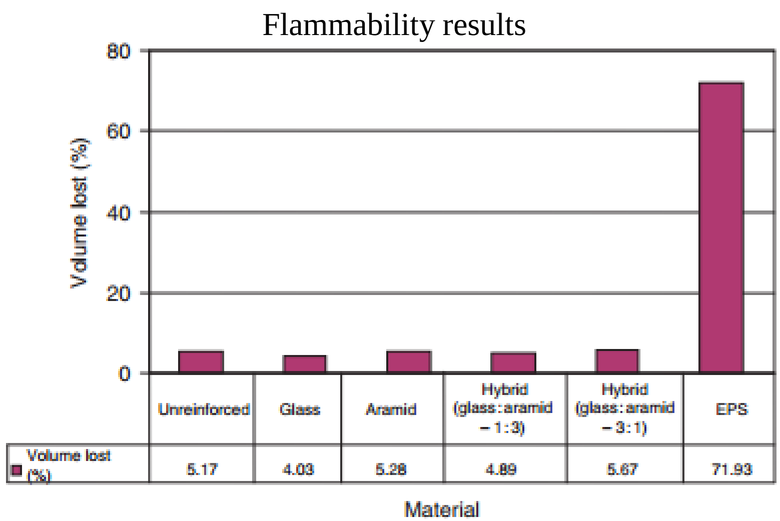

Figure 4. Flammability test results: volume lost as a percentage of initial volume.

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Fiber reinforcement significantly reduced mass loss in phenolic foams. For example, almost 300% less mass lost was observed in hybrid foams (aramid:glass–3:1) compared to unreinforced foam. EPS although lost 25% less mass than unreinforced phenolic foam but lost almost 110% more mass over time in comparison to hybrid foams. The results highlight hybrid foams long-term durability and its ability to withstand extreme environments. Also, foams with higher percentages of aramid fibers exhibited least mass loss compared to other composite foams. These findings indicate that selection of fiber type and proportion of fibers influences the aging process of composite foams. Thus, selection of foam composition for insulation applications will be critical in service conditions with high temperature and dry conditions.

Table 4. Flammability test results: UL 94 ratings assigned to materials.

Material	Unreinforced foam	Phenolic foam with glass fibers	Phenolic foam with aramid fibers	Hybrid foam (glass : aramid – 1 : 3)	Hybrid foam (aramid : glass – 1 : 3)	EPS
Total flaming combustion	Less than 10 s	Less than 10 s	Less than 10 s	Less than 10 s	Less than 10 s	Greater than 10 s
Cotton ignited by flaming drips	No	No	No	No	No	No
Rating	V0	V0	V0	V0	V0	V1

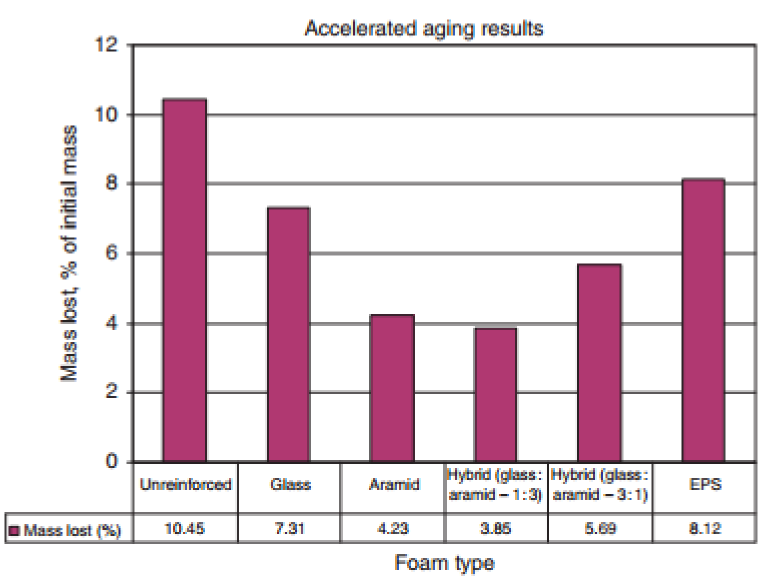

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Figure 5. Accelerated aging results: mass lost as a percentage of initial mass.

3.4. Mechanical Performance

Figures 6 and 7 show the compressive modulus and strength of foams before and after 6-week aging. The compressive modulus and strength of unreinforced phenolic foam decreased by 35–40% after aging. EPS foams were weaker than phenolic foams of similar density, and the modulus and strength of EPS foam was almost 66% and 35% less than unreinforced phenolic foam after undergoing the aging test. Hybrid foams again outperformed the other types of foam studied here. For example, the hybrid foam with aramid : glass ratio of 1 : 3 was stiffer than unreinforced foam, EPS foam, and phenolic foams with aramid fibers even after 6 weeks of aging, and the modulus and strength of this foam was decreased by only 17% and 4%, respectively. Although the mechanical performance of foams at low densities is not of prime importance for insulation and cladding applications, the preliminary results obtained for compressive properties indicate that hybrid foams with varied proportions of glass and aramid fibers could be used as a load bearing member in structural components of buildings. This is particularly true for foams of medium to high density (160–275 kg/m^3). The suitability of hybrid foams structural application is presently speculative, and further studies are required to validate the properties of hybrid foams for building materials.

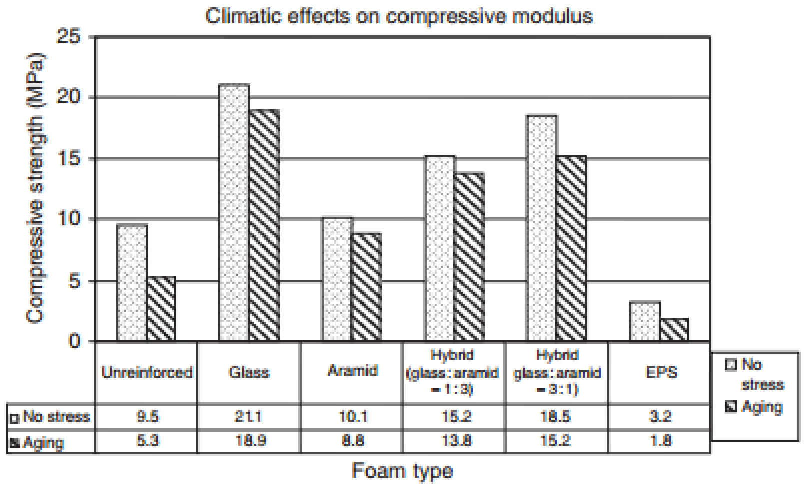

Figure 6. Climatic effect on compressive modulus.

3.5. SEM Analysis

Microscopic examination of foams revealed that fiber additions resulted in a reduction in cell size. For example, for hybrid foams (aramid : glass – 1 : 3), the average cell size was found to be almost 100% less compared to unreinforced foam. These results are consistent with previous reports [6]. Glass fiber additions had a similar effect. The glass fibers used for this study were treated with silane coupling agent and that led to the formation of covalent bonds within the surface and the development of cross-linked silane films [19]. Thus, the coupling agent bound the organic material (phenolic foam) to the inorganic glass fibers and resulted in extensive cross-linking [19].

The reduction in cell size due to addition of fibers also influenced the water absorption in composite foams. Hybrid phenolic foams exhibited lower water absorption and diffusivity relative to unreinforced foams, and also compared to foams reinforced with only glass or aramid fibers. The reduced water absorption in the composite foams was obviously attributed to the cell size reduction associated with fiber additions resulting in inhibited cell growth [6]. We predict that enhanced nucleation along with inhibited cell growth was responsible for reduced cell size in hybrid foams.

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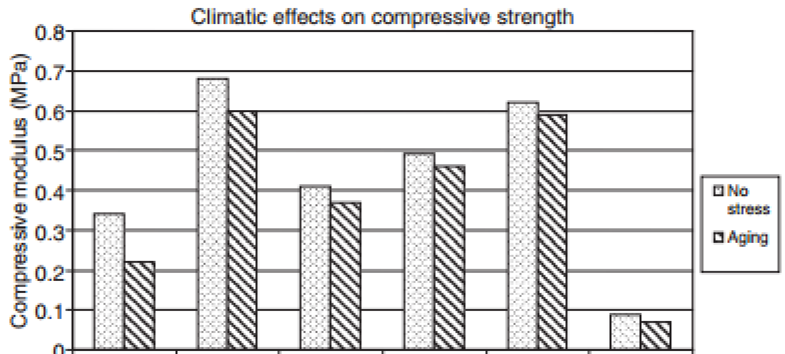

	Unreinforced	Glass	Aramid	Hybrid (glass : aramid − 1 : 3)	Hybrid glass : aramid − 3 : 1)	EPS
No stress	0.34	0.68	0.41	0.49	0.62	0.088
Aging	0.22	0.6	0.37	0.46	0.59	0.069

Foam type

Figure 7. Climatic effect on compressive strength.

Microscopic examination of foams before and after temperature humidity exposure was performed. Figure 8 shows the SEM images of foams before and after moisture absorption tests. The glass fiber ends protrude from the foam matrix, which shows evidence of cracking in foam vicinity. Whereas several small fragments of phenolic foam are found adhering to aramid fibers in hybrid foams indicating a strong cohesive strength that forces a combination of interface and matrix failure [6]. It is observed from Figure 8 that of all the foams studied here, unreinforced phenolic foams have the largest average cell size. The average cell size for each of these foam samples was calculated before and after moisture absorption test and is reported in Figure 9. From data in Figure 9, it is revealed that unreinforced phenolic foam has average cell size almost 55% greater than hybrid foams. Also, it is observed that the average cell size for EPS foams is comparable to hybrid foams at same density. As expected, no change was observed in cell size of foams after undergoing 6 weeks of temperature humidity exposure in the environmental chamber.

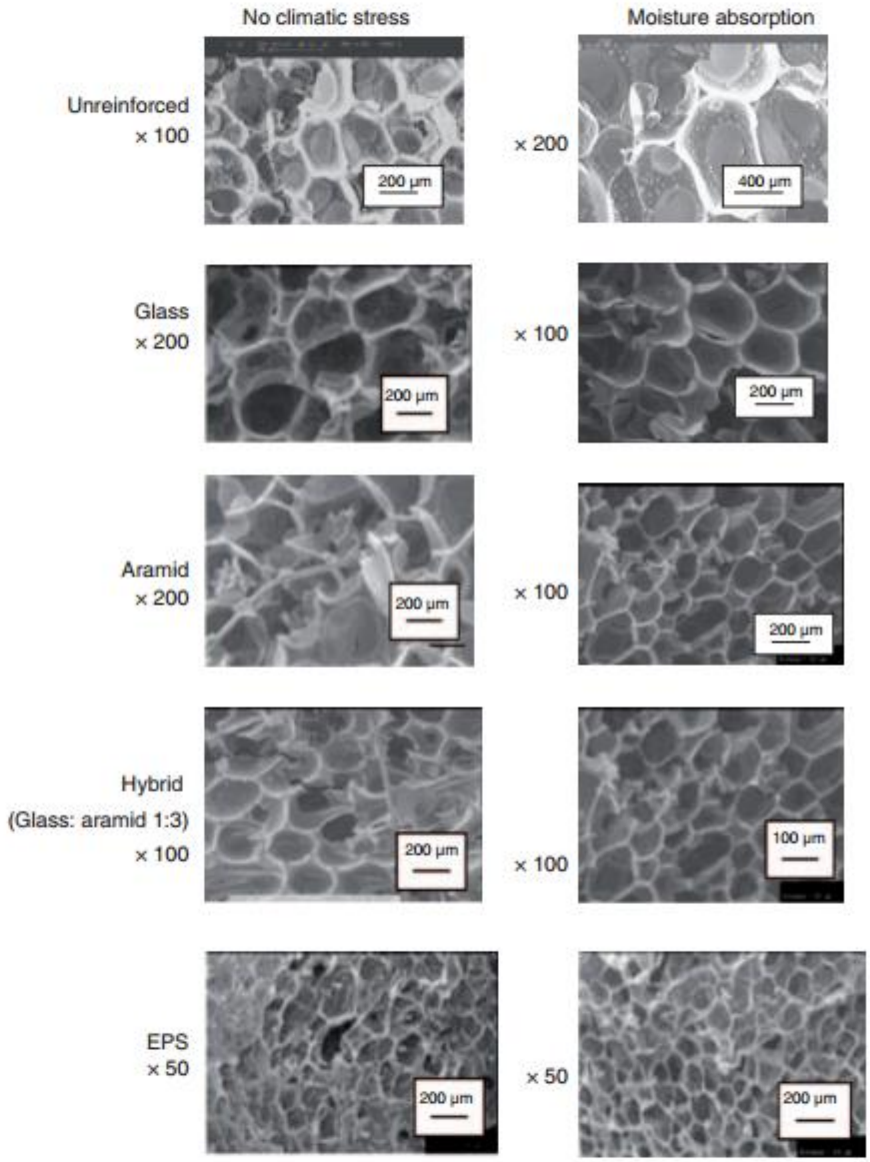

Figure 8. SEM images showing cell lengths across climatic stress.

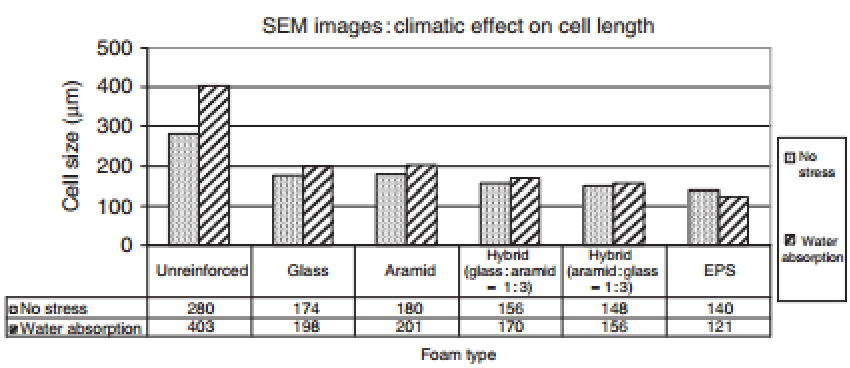

Figure 9. SEM results: cell length across climatic stress.

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4. CONCLUSIONS

The long-term durability and stability of hybrid composite foams was evaluated and compared to commercial EPS foams, which is a popular choice for insulation purposes. Measurements were performed to determine moisture sorption kinetics, flame resistance, and compressive strength.

A statistical approach along with Fick's second law was applied to predict the non-steady-state diffusivity and water absorption of the hybrid composite foams. The effective diffusivity decreased with increasing fiber content, and overall hybrid foams exhibited the lowest diffusivity and moisture absorption of all foams studied. Increased fiber loading, particularly glass fiber loading, resulted in increased crosslinking due to formation of cross-linked silane films and thus reduced the effective cell size. This finding is significant because increased water absorption in insulation materials can eventually reduce their strength over time. Hybrid composite phenolic foams lost significantly less mass in aging experiments compared to unreinforced phenolic and commercial EPS foam.

Fiber reinforcement did not affect the flammability properties of phenolic foam. As expected, all phenolic-based foams exhibited superior fire performance compared to EPS. In particular, EPS showed significant volume reduction during exposure to flame, a critical issue for service areas where weather conditions are hot and arid. The mechanical performance measured in this study coupled with earlier results [6] underscores the potential for applications of medium density hybrid foam as a fire retardant, low-cost structural element for building structures, providing both insulation and load-carrying capacity. Finite-element modeling along with failure analysis are in progress to validate behavior under applied loads and determine suitability of hybrid foams for steel stud assembly in building applications.

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