International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:9, No:1, 2015

Enhanced Dimensional Stability of Rigid PVC Foams Using Glass Fibers

Nidal H. Abu-Zahra, Murtatha M. Jamel, Parisa Khoshnoud, Subhashini Gunashekar

***Abstract*—**Two types of glass fibers having different lengths (1/16" and 1/32") were added into rigid PVC foams to enhance the dimensional stability of extruded rigid Polyvinyl Chloride (PVC) foam at different concentrations (0-20 phr) using a single screw profile extruder. PVC foam-glass fiber composites (PVC-GF) were characterized for their dimensional stability, structural, thermal, and mechanical properties. Experimental results show that the dimensional stability, heat resistance, and storage modulus were enhanced without compromising the tensile and flexural strengths of the composites. Overall, foam composites which were prepared with longer glass fibers exhibit better mechanical and thermal properties than those prepared with shorter glass fibers due to higher interlocking between the fibers and the foam cells, which result in better load distribution in the matrix.

***Keywords*—**Polyvinyl Chloride, PVC Foam, PVC Composites, Glass Fiber Composites.

I. Introduction

POLYMER foams are a unique class of materials that are widely used due to their light weight, low cost, and good formability along with load bearing and insulation capabilities. The cellular structure of the foam determines its mechanical and physical properties, and hence its performance and applications [1], [2]. Rigid Polyvinyl Chloride (PVC) foam and their composites have been used as an excellent replacement for wood in the building industry in the form of profiles, sheets, and pipes due to their low cost, low density, fire retardancy, and high insulation and damping properties. However, rigid PVC foams lack adequate dimensional stability when they are exposed to high and low temperatures. Certain applications of PVC foam products require excellent dimensional stability; such as in exterior mouldings, siding, decking and railing applications. Solid fillers, such as calcium carbonate, talc, glass fibers, carbon fibers, and wood fibers have been reported as effective PVC reinforcement additives in many publications [3]-[5]. The selection process of an effective reinforcement filler depends on its compatibility with the polymer matrix and the governing relationship between structure, property, and performance for the composite.

The use of glass fibers (GF) as a reinforcement filler for improved dimensional stability in non-foam polymer composites has been studied and reported extensively. Raj et al. [6] studied the effect of heat exposure on the mechanical and thermal properties of glass fiber, mica and wood fiber reinforced low density polyethylene (LDPE); they reported that tensile strength and dimensional stability of the GF reinforced LDPE increased with increasing GF content. Canova et al. [7] studied GF (3.2 mm) and Mica filled Polypropylene (PP) composites; they reported high dimensional stability and shrinkage reduction in GF-PP composites with higher filler contents. Jang et al. [8] prepared poly(butylene terephthalate) (PBT) filled GF composites using extrusion process. They reported enhancement in mechanical properties only when using sufficient coupling agents in order to improve the interfacial interaction between glass fibers and the polymer matrix. They also claimed that the loading amount and length of glass fibers, as well as the extrusion conditions determine the final mechanical properties of PBT-GF composites. Hassan et al. [9] prepared PP reinforced glass fibers using maleic anhydride polypropylene (MAPP) as a coupling agent in extrusion and injection molding. They reported modest increase in the melting temperature of the composites with increasing GF and MAPP contents. Dynamic mechanical analysis (DMA) showed an improvement in the viscoelastic properties of the composite with low GF loadings in the presence of the coupling agent.

Although short glass fibers are known to yield lower enhancement in their composites when compared to their longer counterparts, they are still widely used in polymer composites due to their processing advantages [10]. Ozkoc et al. [11] studied the effect of surface treated short GF content and extrusion conditions on the mechanical properties of acrylonitrile-butadiene-styrene (ABS). In this work, polyamide-6 (PA6) was used at different levels to improve the interaction between GF and the matrix. They reported that the tensile strength, tensile modulus, flexural modulus, and impact strength of the composites are lower when using shorter glass fibers. However, mechanical properties improved slightly when using higher amounts of short GF and PA6. Thomason et al. [12] studied the effect of the length, diameter, and content of GF on the impact properties of polyamide 6,6 reinforced with GF using notched and un-notched impact samples. They reported that the impact properties of the notched samples were more sensitive to the fiber length and content; while the fiber diameter and content were the main parameters affecting the impact strength of the un-notched samples. Jiang [13] studied the influence of short (0.8 mm) and long (6.4 mm) glass fibers on the impact strength of PVC/wood flour/glass fibers at a constant loading level of 5%.

Nidal H. Abu-Zahra is an associate professor in the Materials Science and Engineering Department at the University of Wisconsin-Milwaukee. 3200 N. Cramer St., Milwaukee, WI 53201, USA (phone: 414-229-2668; fax: 414-229-6958; e-mail: nidal@uwm.edu).

Murtatha M. Jamel, Parisa Khoshnoud, and Subhashini Gunashekar are graduate students in the Materials Science and Engineering Department at the University of Wisconsin-Milwaukee. 3200 N. Cramer St., Milwaukee, WI 53201, USA.

It was reported that the long glass fiber improved the impact strength while maintaining flexural properties, whereas the short glass fiber did not show any significant improvements. However, it has been reported elsewhere that the addition of glass fibers to PVC composites improves dimensional stability and mechanical strength regardless of their length [14], [15].

Deanin et al. [16] investigated the effect of adding GF on the dimensional stability of Poly(butylene terephthalate) foam composites. They reported enhancement in the dimensional stability of the composites when using coupling agents and surface treatments to enhance the interaction between the glass fibers and polymer matrix. Similarly, Laurent et al. [17] studied the effect of surface treatment on the mechanical properties of foamed and un-foamed PVC reinforced with wood fibers. They observed a reduction in tensile modulus and tensile strength of the composites at higher GF loading, which was attributed to higher void fraction in the composites structure and weak interaction between the matrix and glass fibers. Mengeloglu et al. [18] studied the mechanical properties of extruded foam PVC/wood-flour composites and reported similar results to Laurent et al. [17]. Tungjitpornkull et al. [19] prepared E-chopped glass fiberfilled wood/PVC composites at different glass fiber loadings, 10, 20 and 30 phr, with various fiber lengths 3, 6 and 12 mm. They concluded that the most critical parameter in determining the tensile and flexural properties of the composites is the glass fiber loading.

Based on our literature review, there is no reported work on the effect of glass fibers on the dimensional stability of PVC foams. In this study, the effect of glass fibers content and length on the dimensional stability, as well as the mechanical, microstructural, and thermal properties of PVC foam composites, is investigated.

II. Experimental Method

Rigid PVC resin was acquired from Shintech, USA; it had an inherent viscosity of 0.74 (ASTM D1243); bulk density of 36.3 lb/ft^3 (ASTM D 1895), and maximum volatiles of 0.12% (ASTM D3030). A commercially available thermal stabilizer, Thermolite T-137, and processing aids, Plastistrength P530 and P770, were provided by Arkema, USA. Other ingredients used in preparing the samples are Lubricants Loxiol 2986 and 2987 produced by Oleochemicals; paraffin wax Petrac 215 produced by Ferro Corp.; Calcium Stearate COAD 10 produced by Norac Corp.; chemical blowing agents Azodicarbonamide (ADC) produced by Season Corp.; and Sodium Hydrogen Carbonate (FICEL SBH) produced by Hughes Polymer Additives Corporation. The specific content of each ingredient is considered proprietary; however the amount of each ingredient follows a common formulation used in making rigid PVC foams. Two types of milled and saline treated E-glass fibers, with lengths of 1/16" and 1/32" and diameter of 16 microns, were purchased from Fiber Glast Developments Corporation.

PVC foam compounds, shown in Table I, were prepared using a high shear mixer (Gunther Pepenmeier, Type: TSHK). Initially, the PVC resin was added to the mixer at room temperature. Then, the stabilizer was added at 52ºC, glass fibers and processing aids were added at 58ºC. Finally, the lubricants and the blowing agents were added at 66ºC. When the temperature reached 100ºC, the compound was collected from the mixer and allowed to cool down to room temperature before extrusion.

The compounds were extruded using a 1.25 inch, 20:1 (L/D) single screw extruder (Themoplas Extrusion Machine) at a screw speed of 60 rpm. The heating zones temperatures were in the range of 158 ºC to 175ºC. A rectangular profile die was used to extrude the samples. The extruded stream was air cooled prior to feeding through an aluminum sizer (1" x 0.28") placed in a vacuum chilled water tank. Finally, the extruded stream is cut into 12" pieces using an automated cutter.

TABLE I
PVC-GF FOAM COMPOSITES FORMULATION

Sample Number	Glass Fiber (wt%)		PVC Resin (wt%)
S0	0		92.5
S1	1/16"	5	87.5
S2		10	82.5
S3		15	77.5
S4		20	72.5
S5	1/32"	5	87.5
S6		10	82.5
S7		15	77.5
S8		20	72.5

Thermal properties of the foam composites were analyzed using: (1) TA Instrument SDT 2960 thermo-gravimetric analysis equipment (TGA) in the temperature range of 25 to 800°C at a heating rate of 10 °C/min under argon atmosphere; and (2) Differential Scanning Calorimetry (DSC) measurements using TA Q2000 analyzer (TA Instruments, U.S.). Foam composite samples weighing 5 to 10 mg were heated in standard aluminum pans in the temperature range of 25 to 260°C at a heating rate of 10 °C/min.

Dynamic Mechanical Analysis (DMA) was performed on TA Instrument Q800 to evaluate the viscoelastic properties (storage modulus, loss modulus, and tanδ) of composites in the solid state. A three-point bending mode was used at a test temperature range of 25 to 120°C and a constant heating rate of 3 °C/min at 1Hz frequency of dynamic force.

The dimensional stability of the foam composites was measured according to American Architectural Manufacturers Association (AAMA) procedure. Extruded samples were heated in an oven at 82°C for 30 min. The original dimensions of the foam composites were 12" x 1" x 0.28". The change in length was measured after 4 hours and reported as a shrinkage percentage according to (1), where l_o and l_f are the initial and final lengths; respectively:

$$\%\, Shrinkage = \frac{l_o - l_f}{l_o} \times 100 \quad (1)$$

Heat resistance of the composites was determined using an oven at 141ºC for 30 min. The original dimensions of the foam composites were 12"x 1"x 0.28". Visual inspection on the samples was done to determine the presence of any flaws or distortion after cooling down for four hours on the dry and

clean surfaces. Tensile properties were determined using an Instron 3365 universal testing machine on rectangular specimens measuring 12"x1"x0.265" at a crosshead speed of 0.5 in/min. Flexural properties were determined using Instron 3365 with a three-point bending test set-up on rectangular specimens measuring 8"x1"x0.265" at a crosshead speed of 0.5 in/min. The span length was kept at 4 inches. The flexural stress and strains were calculated using (2) and (3):

$$\sigma_f = \frac{3PL}{2bd^2} \quad (2)$$

$$\varepsilon_f = \frac{6Dd}{L^2} \quad (3)$$

where, σ_f and ε_f are the respective flexural stress and strain at the midpoint, and P, L, b, d, D are the load, span length, specimen width, specimen thickness and midpoint deflection; respectively. The flexural strength was determined using the maximum stress value recorded before sample fracture and flexural modulus was determined by the slope of the initial linear region of the stress-strain curve. Charpy impact properties were determined using Tinus Olsen impact testing machine (model IT 504) according to ASTM D 6110. Four samples of each composite were tested. The dimensions of the impact testing samples were 5" x 0.5" x 0.28" with a 45º notch at the middle.

Topcon SM-300 SEM was used for imaging and microstructural analysis of the extruded PVC-GF foam composites.The specimens were fractured in liquid nitrogen and coated using a sputter coater to minimize the charging effect and to improve the conductivity of the samples prior to analysis.

III. Results and Discussion

The dispersion and surface bonding of the solid phase with the host polymer matrix affect many important characteristics such as mechanical properties and dimensional stability. Therefore, it is important to study the fiber-matrix interface in order to explain the characteristics and behavior of these composites. Fig. 1 shows the dispersion of 15%wt of 1/16" GFs in the PVC foam matrix at 50x magnification; whereas Fig. 2 shows the dispersion of 15%wt of 1/32" GFs in the PVC foam matrix at 150x magnification. One can observe in both micrographs the random orientation and dispersion of glass fibers in the matrix, and the penetration of the long fibers through the closed cell walls. It was also noticed that shorter fibers tend to agglomerate more than the longer fibers during processing due to the liquid additives used in the compounding process.

Fig. 3 shows a close up image of a fiber-matrix interface at 1000x magnification. The orientation of this particular fiber is along the fracture surface, whereas the majority of fibers which are present in the foam matrix are across the fracture surfaces. However, the fracture surface shown in Fig. 3 seems to be clean, which indicates poor bonding between the two surfaces. In addition, the diameter of the glass fiber seems to be close to the thickness of the cell wall, or higher at some locations. Both these observations may be significant to the effect of glass fibers on the mechanical and thermal performance of the composite matrix, as is discussed later.

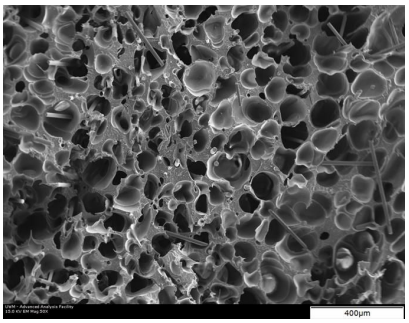

Fig. 1 SEM micrographs at 50x of 1/16" 15% GF-PVC

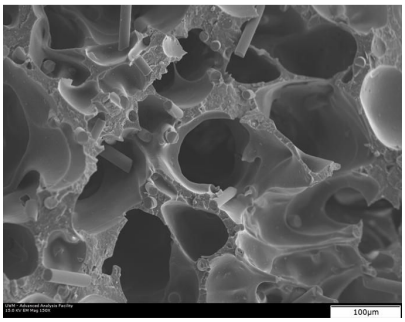

Fig. 2 SEM micrographs at 150x of 1/32" 15% GF-PVC

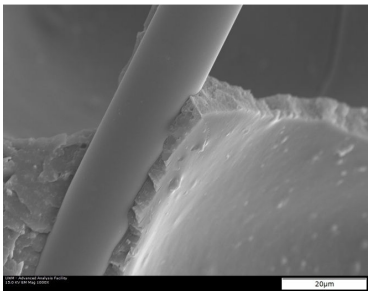

Fig. 3 SEM image at 1000x of GF interface with PVC foam

Dimensional stability of the foam composites was measured as a percentage of shrinkage and the effect of GF lengths and loading is presented in Fig. 4. The percentage of shrinkage decreases by 22.5% and 28.4% when adding 5phr of 1/32″ and 1/16″ GF; respectively, compared with pristine samples. It is also evident that dimensional stability increases significantly with increasing the glass fiber content in the composites. This is due to the higher solid content in the polymer matrix, which has higher resistance to thermal expansion and/or contraction. A comparison between the samples made with the same filler content at different GF lengths reveals that the composites containing longer glass fibers (1/16") exhibit higher dimensional stability improvement than those with shorter glass fibers. This may be attributed to a higher interlocking and bonding between longer glass fibers and the foam matrix

along the fiber length. Since glass fibers have lower coefficient of thermal contraction than the polymer matrix, higher interaction between the fibers and the matrix improves dimensional stability of the composites.

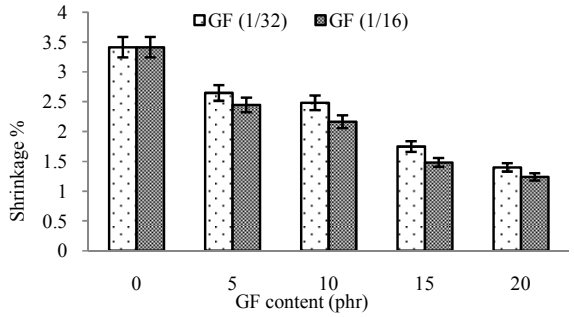

Fig. 4 Dimensional stability of PVC-GF foam composites

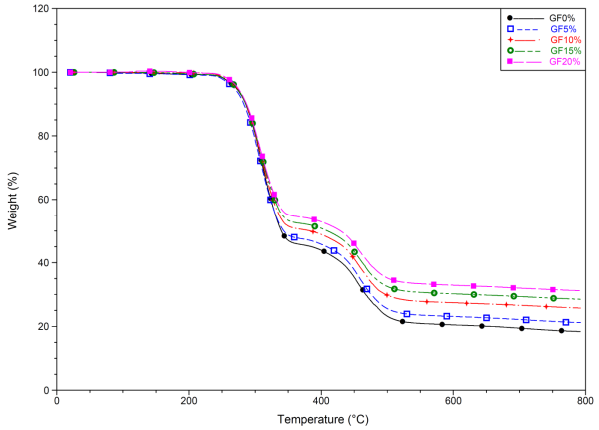

Fig. 5 (a) TGA analysis for PVC-1/32" GF composites

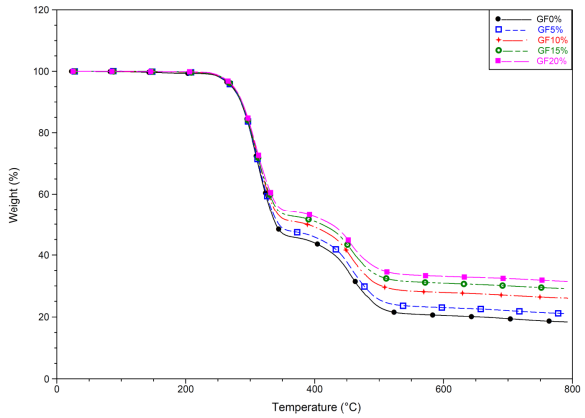

Fig. 5 (b) TGA analysis for PVC-1/16" GF composites

The results from TGA analysis of PVC-GF foam composites using short glass fibers (1/32") and long glass fibers (1/16") are presented in Figs. 5 (a) and (b); respectively. The average Primary Degradation Temperature (PDT) of the foam composites begins around 277ºC, while the average Secondary Degradation Temperature (SDT) is around 440ºC. Increasing glass fibers content increases the secondary decomposition temperature of the composites, which means that it takes more energy to break the hydrocarbon backbone of the polymer matrix [20]. On the other hand, the primary degradation temperature of the composites, which indicates the start of the separation process of chlorine from the polymer chains, decreases slightly by increasing the GF content. This can be attributed to the higher thermal conductivity of GF, which results in faster heat transfer into the PVC matrix and thermal degradation starting at lower temperatures.

Heat resistance was evaluated qualitatively by visual inspection for surface flaws and shape distortion of the extruded samples after subjection to heating and cooling cycles. Pristine samples did not show any flakes or cracks on the surface, however, some distortion was observed on the sides in the form of swelling. The addition of glass fibers in the matrix reduced the amount of swelling, where the composites containing 1/16" GFs exhibited higher heat resistance when compared with those containing shorter GF lengths. Meanwhile, the addition of glass fibers did not seem to affect the glass transition temperature (Tg) of the PVC foam composites, around 83ºC.

Thermo mechanical properties of the PVC-GF composites were determined by DMA analysis. Variations in the storage modulus (E'), which represents the elastic behavior, and the loss modulus (E"), which represents the viscous behavior, with temperature, are shown in Figs. 6 and 7; respectively. The magnitude of E' and the peak intensity of the GF filled samples increase with the addition of glass fibers up to 15 phr. This is attributed to the enhancement in the energy dissipation ability as a result of the presence of solid filler in the polymer matrix and the increase in the polymer-filler and filler-filler slippages at Tg. However, at 20phr GF concentration, the magnitude of E' decreased. This may be attributed to the agglomeration of GF fibers at higher concentrations. This leads to higher friction between the fibers and less interaction between the reinforcing phase and the host matrix.

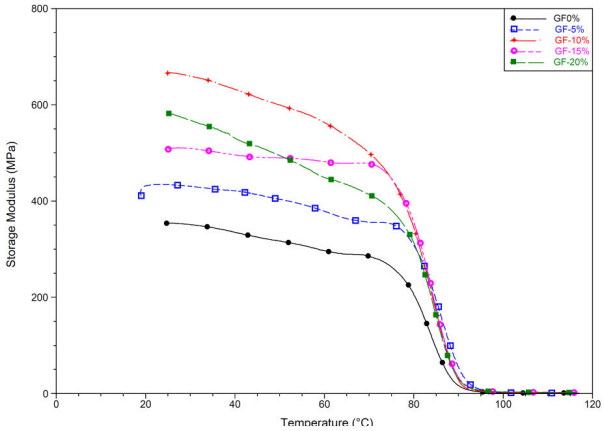

Fig. 6 (a) Storage Modulus (E') for 1/16" GF

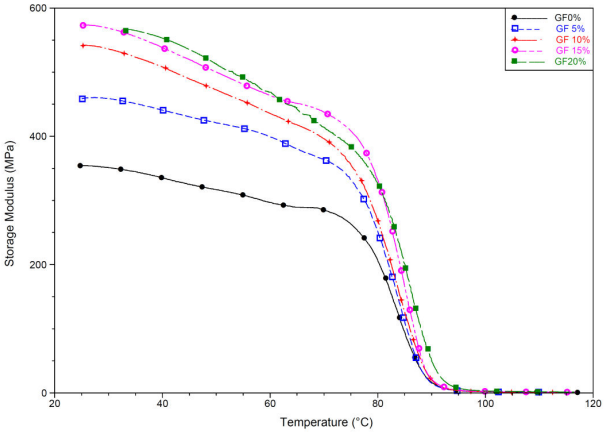

Fig. 6 (b) Storage Modulus (E') for 1/32" GF

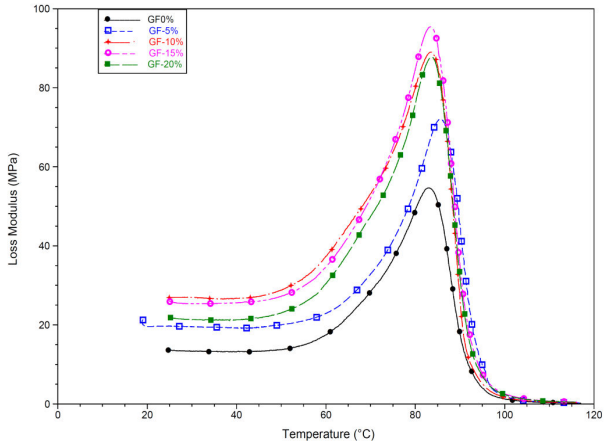

Fig. 7 (a) Loss Modulus (E") for 1/16" GF

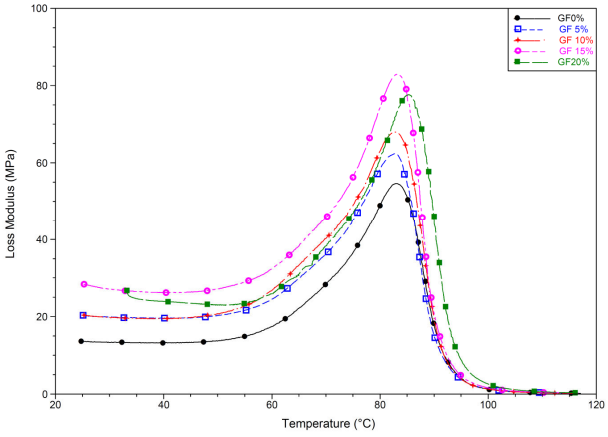

Fig. 7 (b) Loss Modulus (E") for 1/32" GF

The effect of glass fibers content on the mechanical properties of PVC-GF composites depends on the geometry of the reinforcement phase, such as the length and diameter of the glass fibers. The ultimate tensile strength (UTS) of the composite foams, shown in Fig. 8, seems to maintain its value at different loadings of GF. Meanwhile, the composites made with longer glass fibers (1/16") seem to have slightly higher UTS at all loading levels. Since the bonding between GFs and the polymer foam occurs only through the cell walls, the enhancement in the foam strength is limited and is greatly affected by the bonding strength between the two surfaces. However, longer fibers are likely to have more bonding sites due to higher penetration through the walls of the closed cell foams. A similar effect of the glass fibers length on the mechanical properties is also visible with the flexural strength measurements are shown in Fig. 9.

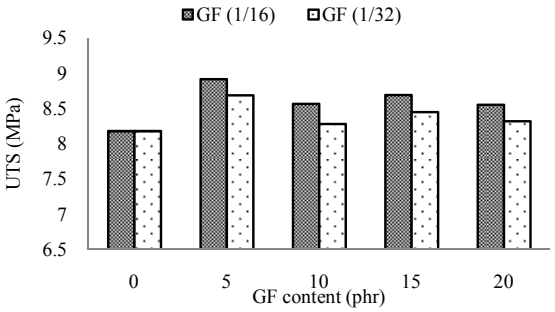

Fig. 8 Ultimate tensile strength (UTS) PVC-GF foam composites

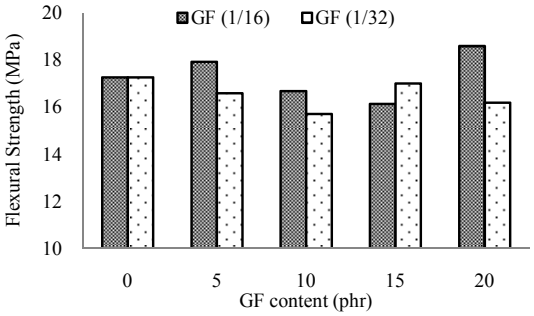

Fig. 9 Flexural strength of PVC-GF foam composites

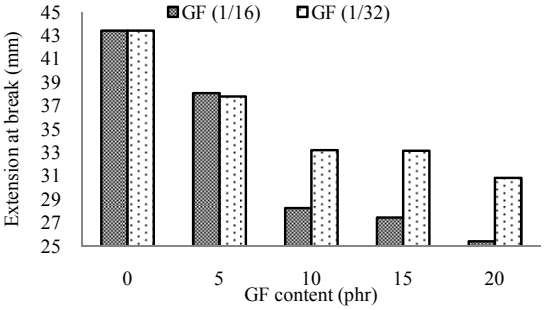

Fig. 10 Extension at break of PVC-GF foam composites

The ductility of the PVC-GF composites, measured by the extension at break, was noticed to decrease in the presence of glass fibers, as shown in Fig. 10. Higher amounts of GFs in the polymer matrix render the composite more brittle and prone to brittle fracture as they are dispersed in the matrix with no specific orientation. Longer glass fibers (1/16") exhibit higher reduction in ductility compared to the shorter

fibers; this is also attributed to the higher penetration of the longer fibers in the walls of the closed cell foams which increases the stiffness of the structure.

The impact strength of the PVC-5%GF composites, shown in Fig. 11, increased slightly for both lengths. This is mainly attributed to the increase in the cell walls' strength when reinforced with GFs. However, the effect of the GF length on impact strength is marginal since the failure is due to brittle fracture starting at a notched edge, which is independent of the glass fibers length. Further increase in the loading of GFs in the polymer matrix exhibits a proportional decrease in the impact strength of the extruded material due to the higher brittleness of the matrix. Under high loading, longer fibers (1/16") seem to exhibit slightly better performance than their shorter counterpart due to higher intersection between the fibers and the cell walls, and hence better load distribution.

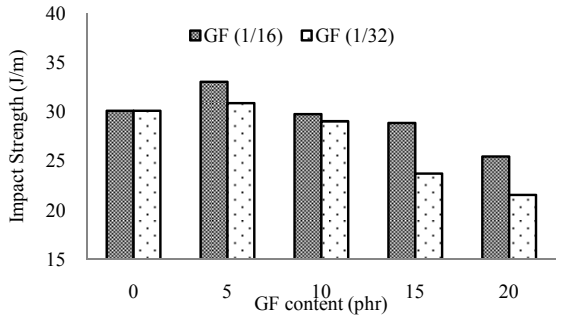

Fig. 11 Impact strength of PVC-GF foam composites

IV. Conclusions

SEM images of the cellular structure of the composite foams show that the glass fibers are randomly distributed in the matrix; the connections between GF and the matrix are only through the walls of foam-matrix. Therefore, longer fibers are more effective in distributing the load in the matrix. Higher GF content hinders the enhancement in mechanical properties due to agglomeration and friction between the fibers.

Thermal stability of PVC-GF composites, measured by heat shrinkage and shape distortion show a significant improvement with the addition of glass fibers. Longer fibers exhibit better performance than shorter fibers due to higher interaction with the foam cells. Similarly, viscoelastic properties measured by storage and loss moduli show an improvement with the addition of glass fibers; better performance is evident in the case of longer fibers.

The addition of glass fibers maintained the original tensile and flexural strengths of the foam composites. Longer glass fibers show higher improvement in tensile strength due to higher interlocking between the fibers and the foam cells, which results in better load distribution in the matrix. Ductility was shown to decrease with increasing the amount of GFs in the composites for both sizes. Impact strength seems to improve slightly with low content of GFs in the matrix (5% wt.) and decreases with higher content afterwards. Both these behaviors; i.e. ductility and impact strength, were attributed to the high brittleness of glass fibers in the matrix.

References

[1] Li Shen, JulianeHaufe, Martin K. Patel, "Product overview and market projection of emerging bio-based plastics", PRO-BIP 2009
[2] S. T. Lee, C. B. Park, "Polymeric Foams", (2006).
[3] "Mineral fillers for PVC reinforcement" British plastic and rubber, 2003
[4] Haihong Jiang and D. Pascal Kamdem "Development of poly(vinyl chloride)/wood composites. A literature review", Journal of Vinyl and Additive Technology, Vol. 10, Issue 2, pages 59–69, 2004
[5] JenöBorda, GyörgyDeák, MiklósZsuga, KálmánMarossy and SándorKéki, "Preparation and characterization of poly(vinyl chloride)–continuous carbon fiber composites", Journal of Applied Polymer Science, Vol. 124, Issue 1, pages 190–194, 2012
[6] R. G. Raj, B. V. Kokta and C. Daneault, " Comparative study on the effect of aging on mechanical properties of LLDPE-glass fiber, mica, and wood fiber composites", Journal of Applied Polymer Science, Vol. 40, Issue 5-6, pages 645–655, 1990
[7] Levy A. Canova, Larry W. Ferguson, Luke M. Parrinello, Rajgopal Subramanian, Harold F. Giles, Jr, "Effect of Combinations of Fiber Glass and Mica on the Physical Properties and Dimensional Stability of Injection Molded Polypropylene Composites", Plastics Saving Planet Earth, ANTEC 1997 Plastics
[8] Jang, S. H., Kim, Y. H., Lim, S., Choi, G. D., Kim, S. H. and Kim, W. N. "Effects of fiber characteristics on the mechanical and rheological properties of poly(butylene terephthalate)/glass fiber composites", Journal of Applied Polymer and Science, 116: 3005–3, 2010
[9] Hassan, Aziz, Rahman, NormasmiraAbd., Yahya and Rosiyah, "Extrusion and injection-molding of glass fiber/MAPP/polypropylene: Effect of coupling agent on DSC, DMA, and mechanical properties", Journal of Reinforced Plastics and Composites, Vol. 30, n 14, p 1223-1232, 2011
[10] Robert J. Young and Peter A. Lovell, "Introduction to Polymers", 3rd, 2011
[11] GuralpOzkoc, GoknurBayram and ErdalBayramli, "Short glass fiber reinforced ABS and ABS/PA6 composites: Processing and characterization", Journal of Polymer Composites, Vol. 26, Issue 6, pages 745–755, 2005
[12] J.L and Thomason, "The influence of fibre length, diameter and concentration on the impact performance of long glass-fibre reinforced polyamide 6,6", Composites Part A: Applied Science and Manufacturing, Vol. 40, Issue 2, Pages 114-124, February 2009
[13] Haihong Jiang1, D. Pascal Kamdem1, Bill Bezubic and Paul Ruede "Mechanical properties of poly(vinyl chloride)/wood flour/glass fiber hybrid composites", Journal of Vinyl and Additive Technology, Vol. 9, Iss3, pages 138–145,. 2003
[14] H.S. Katz, J.V. Mileski, "Handbook of Fillers for Plastics", 1987
[15] James Lindsay White, "Principles of Polymer Engineering Rheology", 1990
[16] Rudolph D. Deanin and Gerardo "glass-fiber-reinforced poly(butylene terephthalate) structural foam", conference proceeding
[17] Laurent M. Matuana, Chul B. Park, and John J. Balatinecz, "Cell morphology and property relationships of microcellular foamed PVC/wood-fiber composites", Journal of Polymer Engineering & Science, 2004
[18] Fatih Mengeloglu1 and Laurent M. Matuana, "Mechanical properties of extrusion-foamed rigid PVC/wood-flour composites", Journal of Vinyl and Additive Technology, Vol. 9, Issue 1, pages 26–31, March 2003
[19] S. Tungjitpornkull, K. Chaochanchaikul, N. Sombatsompop, "Mechanical Characterization of E-Chopped Strand Glass Fiber Reinforced Wood/PVC Composites", Journal of Thermoplastic Composite Material, Vol. 20 no. 6 535-550, 2007
[20] J. Qiao, A.V. Amirkhizi, K. Schaaf, S. Nemat-Nasser, "Dynamic Mechanical Analysis of Fly Ash Filled Polyurea Elastomer", J. Engineering Materials and Technology, Vol. 133, 2011.