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Recycling and Reinforcing of Expanded Polystyrene by Woven Mat and Short E-Glass fibers

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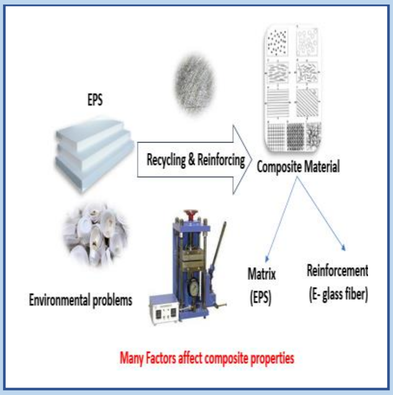
Abstract: Expanded polystyrene (EPS) polymers are widely used in insulation and packaging applications. If their waste hasn't been managed well and due to their long degradation time, they will cause severe environmental problems for human beings, plants, and animals. Therefore, recycling could be one of the acceptable solutions to overcome such problems in addition to reinforcing them to recover the decay in properties resulting from recycling. In this work two types of EPS have been recycled at different temperatures from 140 to 260°C, and then reinforced by E-glass fibers in mat form and as random short fibers with varied composition from 5 to 25 wt%. The samples have been prepared by homemade thermal press and the tensile properties such as strength, modulus, and ductility have been investigated showing an obvious enhancement of these properties upon an increase in temperature to certain level and with fiber content and length exceeding their critical lengths. Furthermore, interfacial adhesion has been studied by estimating the strength and modulus efficiency factors. The results show that the E- glass fibers could improve the strength with more than 300%.



Keywords: Expanded polystyrene, Fiber mat, short fiber, thermal press, strength efficiency, and modulus efficiency

Introduction

Expanded polystyrene (EPS) is a light, solid foam plastic that is frequently employed in building, insulation, and packaging. Although EPS is a flexible and affordable material (1), it poses serious disposal and environmental impact issues. EPS occupies a lot of area in landfills and can linger in the environment for hundreds of years due to its low density and bulky makeup.(2) Recycling could be used to address the issue of EPS waste. Many other methods can be used to recycle EPS, including mechanical recycling, which entails grinding the substance into tiny beads that can be utilized to make new items. Another option is chemical recycling, which entails disassembling EPS into its chemical components and utilizing those components to produce new materials. (3) Another method for enhancing the characteristics of EPS is fiber reinforcement. The composite material that results from the addition of fibers to EPS can be strengthened, more resilient, and better able to endure shocks and pressures.(4) Glass fibers, carbon fibers, and natural fibers like hemp and bamboo are frequently utilized to reinforce EPS. (4, 5)

Glass fibers are available in different forms and shapes such as:

1. Continuous glass fibers: Made up of long, continuous strands of glass, these fibers are frequently utilized in high-performance applications where toughness and longevity are crucial. (6)
2. Chopped glass fibers: These are shorter strands of glass that are frequently utilized in less demanding applications, such as consumer items and automobile parts. (7)
3. Glass fiber mats: These mats are created by joining together strands of glass that are randomly arranged. These mats can be used to strengthen composite materials like EPS. (8)
4. Fabrics made of woven glass: Fabrics made of woven glass are created by weaving glass strands together to create a fabric. EPS and other composite materials can be strengthened with the help of these fabrics. (9) The exact application and desired EPS composite qualities will determine the glass fiber shape to be used. When choosing a glass fiber form for EPS fiber reinforcing, factors including strength, durability, and cost must all be taken into account.

The reinforcing of EPS with fibers depends on several factors, such as:

1. Fiber type: The type of fiber employed can significantly affect the composite material's reinforcing properties. For instance, natural fibers like hemp and bamboo are lighter and more sustainable while carbon fibers are known for their high strength and rigidity. (10)
2. Fiber content: The amount of fiber added to the EPS can have an impact on the composite material's ability to provide

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reinforcement. The strength and stiffness of a composite material are normally increased by adding additional fibers, but doing so may also make it more brittle. (11)

3. Fiber length: The length of the fiber can also affect the composite material's reinforcement capabilities. Although longer fibers may be more challenging to digest, they typically offer more strength and stiffness. (12)
4. Fiber orientation: The reinforcing qualities of the composite material can also be influenced by the orientation of the fibers within the EPS matrix. The strength and stiffness of the material can be increased along an axis, for instance, by aligning the fibers in that direction. (13)
5. Processing conditions: The EPS composite's reinforcing qualities may be impacted by the processing circumstances used to create it. Temperature, pressure, and curing time are only a few variables that may affect the material's ultimate qualities. (14, 15)
6. Matrix characteristics: The EPS matrix's characteristics may also contribute to the reinforcement of the composite material. The density, porosity, and chemical makeup of the EPS, among other things, can all have an impact on the ultimate qualities of the composite material. (16)

In general, adjusting these variables necessitates extensive thought and experimentation to get the necessary reinforcing qualities in EPS composites. Overall, EPS recycling and fiber reinforcing are important areas of research and development as we work towards more sustainable and environmentally friendly solutions for the use and disposal of plastics.

In this work collected EPS from two different recourses were collected, recycled, and reinforced by two forms of E-glass fibers, woven mat, and randomly short fibers at different lengths (10, 20, and 30 mm). The effect of processing temperature, and fiber content on the mechanical properties of used matrix and prepared composites have been studied. Furthermore, the interfacial adhesion between matrix and reinforcement in the mat form has been investigated by calculation of strength and modulus efficiency factors KS and KE

Experimental Work

Materials: Expanded polystyrene (EPS) from insulation-used panels (iEPS) and food packages (fEPS) were collected from the local market and used as a matrix in the prepared composite sheets. E-glass fibers in a woven mat form of around 38 mm in length and 10.6 µm diameter r supplied by VOSSCHEMIE were used as a reinforcement for both types of matrices.

Sample Preparation: Rectangular metallic frame made from stainless steel of thickness (1 mm) was used to maintain the thickness and the shape of the composite sheet produced from EPS and glass fibers and, 4 EPS sheets were used in the preparation of each sample, they were filled with glass fibers, so 2 sheets below fibers and 2 above. The sheets were covered with aluminum foil and pressed using thermo-stamp press mold apparatus at different pressing temperatures. Firstly, the EPS from both sources were collected and cleaned from any contaminants, and processed (recycled) at different temperatures (140, 160, 180, 200, 220, 240, 260 ˚C) and pressed for 15 minutes to form sheets as reference matrix. On the other hand, the E-glass/EPS composites were prepared at different temperatures and as aforementioned. The glass fibers' weight percent was in the range of 28-33%, (the values of weight percent have been estimated from the mass of the selected fiber (in mat form) to the total mass of polymer and fiber). The variation 28-33% is related to the difference in the woven mat thickness. All samples were cooled to room temperature by constant flowing water. Furthermore, short glass fiber-reinforced EPS composites (iEPS and fEPS) were prepared for different fiber weight percent (5, 10, 15, 20, and 25%) and with varied fiber lengths (10, 20, and 30 mm). The weighed short fibers had been distributed randomly between two prepared EPS sheets and pressed between the two halves of the press mold at 180°C for 15 minutes and then cooled to room temperature with water. See Figure 1

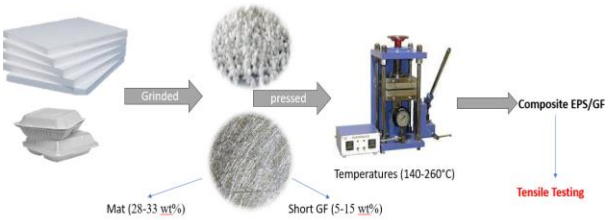

Figure (1): Sample Preparation Summary.

Tensile Testing: Tensile test was carried out by using the Gunt Hamburg apparatus WP 310 machine at a constant speed of 5 mm/min. and at room temperature. Five trials of each sample were taken. The samples were (20mm × 1.5mm) gauge dimensions and 130 mm gauge length. A tensile test was done to measure the tensile modulus, strength, and ductility (as a percentage of elongation). The obtained-recycled sheets (composites) were cut into five-equal pieces for each and the thickness & the neck width for each specimen were measured.

Results and Discussion

Processing of EPS in the absence of E-glass fibers

Samples from both EPS (iEPS and fEPS) were prepared at different temperatures and their tensile properties (Tensile strength, Elastic Modulus, and Ductility as %EL) have been estimated.

Figures 2 a, b, and c illustrate the tensile strength, elastic modulus, and ductility, respectively for both iEPS and fEPS at different temperatures.

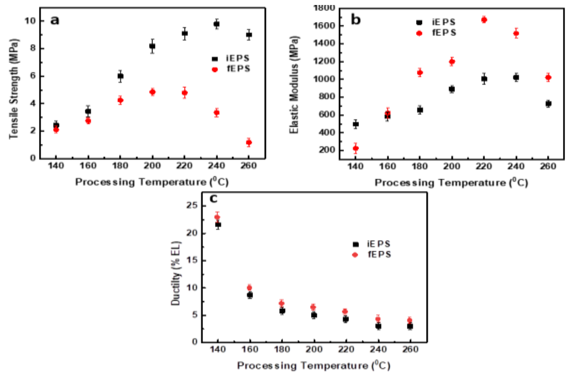

Figure (2): Tensile properties of iEPS and fEPS at different temperatures; Tensile strength (a), Elastic modulus (b), and Ductility (c)

As illustrated by Figure 2, Tensile strength and elastic modulus increased with increasing temperature up to 240 °C and 220 °C for iEPS and fEPS, respectively due to a decrease in melt viscosity and enhance flow leading to homogenous phase with a lower amount of voids. (17) Furthermore, the values then declined to lower values due to thermal degradation and decomposition of polymer covalent bonds. (18) The maximum tensile strengths are 9.8 and 4.9 MPa for iEPS and fEPS, respectively. Whereas, the obtained elastic modulus is 1023 and 1670 MPa for iEPS and fEPS respectively. The above-reported values will be used as references for the estimated mechanical properties of the fiber composite sheets. Moreover, the ductility of the polymer as shown in Fig. 2c decreases as temperature increases which is a normal relation between strength and ductility; an increase in strength causes a decrease in ductility, this because ductility is a measure of a material's ability to deform under tensile stress, and materials that are strong tend to be more resistant to deformation.(19)

EPS/E-glass fiber mat composites

The recycled EPS matrices have been reinforced by E-glass fiber mat with a weight percent between 28-33% and at different temperatures. The tensile properties have been investigated in terms of tensile strength, elastic modulus, and ductility and are illustrated in Figure 3.

As shown in Figures 3a and b, the prepared composites exhibit higher mechanical properties compared to the pristine EPS matrices. An improvement in tensile strength of about 345% has been achieved for iEPS when 33 wt.% (only 10 vol%) of E-glass mat fiber was added, nearly similar improvements can be noticed for elastic modulus and also for the other type of polymeric matrix (fEPS). Furthermore, the elastic Modulus and strength increased with increasing temperature up to 220 °C and then decreased to lower values as in the case of iEPS. On the other hand, the fEPS exhibited an increase in TS over all the temperature range while the elastic modulus decreased after reaching a processing temperature equal to 240 °C The enhancement achieved with increasing temperature could be related to the decrease in polymer melt viscosity which in its turn increases the wettability between the polymer (EPS) and the fibers. (20) The high wettability would be obtained due to an increase in polymeric melt penetration rate which is increased according to the drop in melt viscosity as can be proved by Darcy's equation (21) Eq (1):

$$pentration\ rate = \frac{KP}{\mu} \qquad (1)$$

Where P and K are constants, K is related to the porosity of the mat. As the temperature increases the viscosity μ decreases and so the penetration rate increases. After a certain temperature, the tensile modulus and strength decreased due to degradation and matrix decomposition or may be related to very low melts viscosity which would flow out of the reinforcement voids. For both EPS matrices, the addition of a fiber mat improves the ductility but with a slight drop upon the rise in processing temperature as shown in Figure 3c.

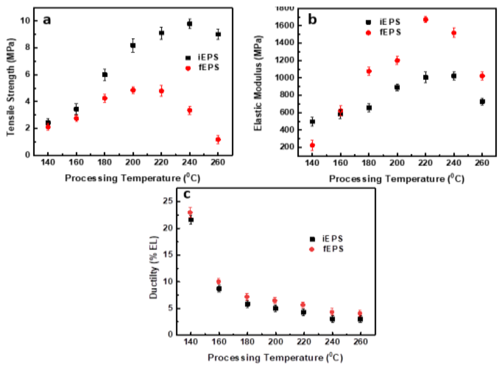

Figure (3): Tensile properties of EPS/Glass fiber mat composites for iEPS and fEPS matrices at different temperatures; Tensile strength (a), Elastic modulus (b), and Ductility (c)

Moreover, to study the degree of interfacial adhesion between polymeric matrix and the reinforcement, strength efficiency (KS) and modulus efficiency (KE) factors can be estimated for all prepared composites according to the modified rule of mixture (22) as in equations (2) and (3):

$$E_c = K_E V_f E_f + V_m E_m \qquad (2)$$

$$\sigma_c = K_s V_f \sigma_f + V_m \sigma_m \qquad (3)$$

Where E_C, E_f (72 GPa), and E_m (from Fig.2b at different temperatures), are elastic moduli of the composite, fiber, and matrix respectively. V_f, and V_m are fiber and matrix volume fractions respectively. σ_c, σ_f (3800 Mpa), and σ_m are the tensile strengths of the composite, fiber, and matrix respectively. (Values of elastic modulus and tensile strength of the E-glass fibers are obtained from the manufacturer 'VOSSCHEMIE" data sheet.

The values of K_S and K_E have been estimated and plotted versus processing temperature as shown in Figure 4. As shown in Fig. 4a the K_S for composites prepared from iEPS matrix increased with temperature up to 200 °C because of the enhancement that occurred due to lower melt viscosity and its ability to impregnate the fiber mat and transfer load between reinforcements and then dropped to lower values which could be ascribed to degradation of polymeric matrix or very low melt viscosity which may escape out from the mat. On the other hand, K_S for fEPS composite exhibited an increase over all the temperature range with lower values compared to those of iEPS at lower temperatures. The discrepancy between K_S values for both matrices could be attributed to the virgin polymers used in the production of EPSs and the different rheological properties of iEPS and fEPS melts at different processing temperatures. (23)

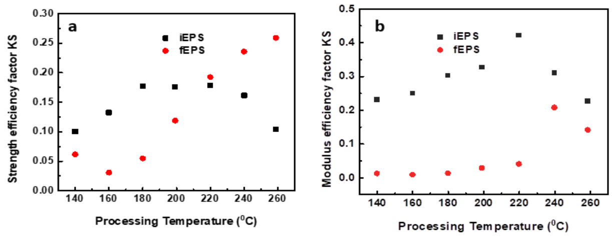

Figure (4): K_S and K_E Values of iEPS and fEPS reinforced by E-Glass Fibre Mat at Different Processing Temperatures.

Fig. 4b presents the values of K_E at different processing temperatures showing that for iEPS K_E increased dramatically with temperature up to 220°C and then decreased to lower values while for fEPS K_E increased slowly with temperature up to 240°C and then decayed to lower values. The values of both K_S and K_E indicate that the EPS matrix could be reinforced by E-glass fiber mat.

EPS/Short E-Glass Fiber Composites

The tensile properties of short glass-reinforced composites of iEPS and fEPS containing different fiber percents and lengths have been investigated. Figure 5 shows the tensile strength and elastic modulus of iEPS composites.

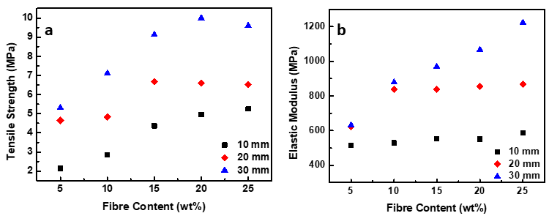

Figure (5): Tensile strength (a), and Elastic modulus (b) of short glass fiber reinforced iEPS processed at 180 °C

The tensile strength and elastic modulus of the reinforced iEPS increased as the fiber contents increased from 5 to 25%, slight decay would occur at higher fiber content related to the lack of iEPS ability to impregnate the fibers. Furthermore, a significant enhancement could be observed as the length of fibers increased from 10 to 30 mm with a significant effect at 30 mm which could be ascribed to the need of designing a composite containing short fibers with lengths larger than the critical fibre length. (24) Similar results have also been obtained for fEPS matrix as illustrated in Figure 6.

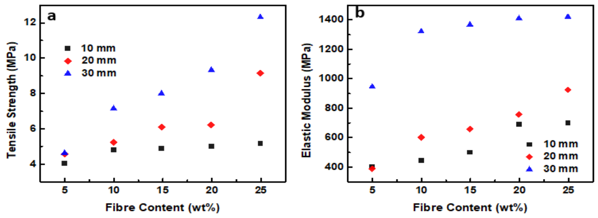

Figure (6): Tensile strength (a), and Elastic modulus (b) of short glass fiber reinforced fEPS processed at 180 °C

Conclusion

This work has proved that expanded polystyrene from different resources can be recycled with optimum properties at processing temperatures between 220 -240 °C and can be reinforced by different forms of E-glass fibers, woven mat, and randomly short fibers. The tensile properties such as tensile strength and elastic modulus are highly affected by processing temperature, fiber content, and fiber lengths. It has been concluded that increasing the fiber content up to a certain value increases the tensile properties and as the fiber length increased more than the critical length higher properties will be attained. It was obvious from the values of strength and modulus efficiency factors that there is acceptable adhesion between composite moieties; the matrix and the reinforcement.

Ethics approval and consent to participate:

Not applicable

Consent for publication:

Not applicable

Availability of data and materials

The raw data required to reproduce these findings are available in the body and illustrations of this manuscript.

Author's contribution

The author confirms contribution to the paper as follows: study conception and design, theoretical calculations and modeling, data analysis and validation. draft manuscript preparation: Sawalha Sh.

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Conflicts of interest

The author declares that there is no conflict of interest regarding the publication of this article

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