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Hybrid Matrix Using Polyester Resin to Improve the Physical and Mechanical Properties of Recycled Expanded Polystyrene Matrix

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ABSTRACT

In this study, an innovative hybrid matrix based on recycled expanded polystyrene (EPS), dissolved in gasoline, and polyester resin (PR) is developed. The aim is to improve the physical and mechanical properties of the dissolved EPS, used previously by the authors as a matrix in composite materials. A rate of 20, 30, 40, 50, and 60 wt% of PR were added in the EPS/PR hybrid matrix. Two processes were used for drying the hybrid matrix, namely ambient temperature (ATDP) and thermal drying process (ThDP) at 60C°. Pycnometer and three-point bending measurements with a characterization by scanning electron microscopy (SEM) were carried out in order to determine: the bulk density, the flexural modulus, and the maximum stress and also to observe the EPS/PR morphology. The results showed that the addition of PR increases the physical properties of the EPS/PR hybrid matrix in both drying processes with a drastic improvement of 3 to 6 times in the mechanical properties. Using ThDP at 60°C makes the matrix lighter and more resistant even at 20 wt% of PR than using ATDP. Otherwise, using ThDP can increase the density from 7 to 16% and improve the tensile strength from 11 to 64% of the dissolved EPS. It was concluded that the elaboration of the innovative hybrid matrix EPS/PR with ThDP at 60°C improves the physical and mechanical properties of the EPS. Thus, the authors recommend the use of solar flat plate collectors as a renewable drying process.

1. INTRODUCTION

New materials with good characteristics and high lightness, mechanical requirements, durability, and flexibility are needed for industries and technological advancements worldwide. Nowadays, environmental factors and cost play an essential role in developing materials in different fields, such as automobiles, aircraft, engineering applications, and other engineering designs that use composite materials.

Researchers have given increased attention to composite materials from the viewpoint of their potential uses in mechanical applications and their unique and extensive specifications, characteristics, and qualities, which have high capacities compared to traditional materials, such as metals, ceramics, and pure polymers. In addition, composite materials, strength, weight, process, and formulation are crucial parameters in choosing a material and its application. The mechanical properties of a composite material are linked to the properties of their compositions such as the reinforcement and the matrix. For this reason, improving the properties of the reinforcements and the properties of the matrices is essential to have more efficient composite materials. Composite materials are currently oriented towards to use a hybrid reinforcement to improve their physical, mechanical, and thermal characteristics [1-3]. The importance of hybrid reinforcement is the combination of different reinforcement (shapes, types, and sizes of fillers) to form a constituent with lower weight and cost [4]. On the other hand, for the improvement of the matrix other solutions have been proposed such as the use of hybrid matrices in the development of composite materials.

Recently, a new concept of hybrid matrix, composed by combining a different matrix [5], has developed a second generation of composite materials. Hybrid matrices are attractive materials for mechanical, multifunctional, medical, energy, and industrial applications. In addition, the composite based on hybrid matrix can be used in several areas such as automotive and marine applications (hulls), aeronautical applications, aviation applications and safety equipment (ballistic protection and corrosion protection layer) [6].

Moreover, other hybrid matrix solutions have been proposed to produce new materials with improved capacities. Among the solutions, the hybrid matrix is composed of a thermosetting resin and thermoplastic resin [7, 8]. The thermosetting matrix improves mechanical resistance (Tensile or bending) and the thermoplastic matrix makes the material ductile [7, 8]. Combining the two matrices, thermosetting and thermoplastic, can improve mechanical, thermal, and chemical characteristics, impact resistance, adhesion, and printability [9, 10]. New studies on these types of hybrid matrices have been carried out to determine their physical, mechanical, and chemical properties [4, 11, 12].

From the literature, several thermoplastic polymers have been discovered to be useful as modifiers to increase the tensile strength of cured epoxies, including polyphenylene oxide, poly-methyl-meth-acrylate (PMMA), poly-ether-ether-ketone (PEEK) [4, 13, 14]. Remiro et al. [12] produced a hybrid matrix based on epoxy and poly (ε-caprolactone). Furthermore, Fenouillot et al. [15] proposed a hybrid matrix composed of polyethylene terephthalate and polybutylene terephthalate.

In this paper an innovative approach is presented with the idea of combining polyester resin (PR) with recycled expanded polystyrene (EPS). To the authors' knowledge, no work has been reported in the literature on this innovative hybrid matrix. However, PR has been used previously in hybrid matrices to improve the properties of hybrid polymer composites. For example, Cherian et al. [16] developed a Hybrid Polymer Networks (HPNs), composed by unsaturated polyester resin (UPR) and epoxidised phenolic novolac epoxy resins (EPN), to improve the toughness and impact resistance. Likewise, Gökçe et al. [17] investigated the properties of hybrid polymer composites produced with different unsaturated polyesters and hybrid epoxy. The use of fourier-transform infrared spectroscopy (FT-IR) and scanning electron microscopy (SEM) showed that the use of the binary and ternary resin in the production a hybrid matrix can enhance their properties [17].

Furthermore, the use of recycled composite materials has recently become a trend, allowing for unique characteristics and attributes for particular uses such as electrical, mechanical, and optical. Polymers and similar materials are the main components of recycled composite materials. However, polymer waste from common applications, including construction and packaging, accumulates and poses environmental problems. Among these polymer wastes, polystyrene (PS) is known for its characteristics as a lightweight material and resistant to environmental conditions. This allows it to be recycled and makes it practical for use as a matrix in composite materials [18-21]. As a thermoplastic polymer [22], PS is softer than epoxy matrix, so it can improve the fracture toughness of epoxy by allowing plastic deformation [23]. Thus, one of the main disadvantages of pure PS is its low strength and porosity, and drying after recycling takes time. In addition, recycled expanded polystyrene (EPS) is a material from the PS family, widely used especially in construction (thermal and sound insulation) and the packaging of industrial products. Using EPS in the construction or packaging of products generates a massive amount of waste. Therefore, recycling EPS is the best option to reduce or eliminate the volume of EPS waste [24, 25]. However, EPS has many disadvantages and unsatisfactory mechanical properties, notably its fragility, low heat resistance, and especially its low tensile strength [26].

In several works, EPS is recycled and used as a matrix to develop composite materials [18-21]. In previous works [19-21, 27, 28], the authors dissolved the EPS in gasoline to obtain a matrix for developing their composites. It was found that the mechanical properties of the composite materials obtained were relatively low. The drying operation of the recycled EPS matrix in the composite takes a long time. In addition, the EPS matrix presents a porous structure with many air bubbles [27, 29], particularly when the preparation of the matrix, or the composite, is carried out under atmospheric pressure. In this context, and in order to overcome these disadvantages, this study presents a new hybrid matrix based on the EPS dissolved in gasoline.

The aim of this paper is to improve the physical and mechanical properties of the dissolved EPS by adding a polyester resin (PR) to form a new hybrid matrix. This valorisation of EPS wastes has an obvious environmental impact and makes the cost of the hybrid matrix competitive to similar matrix materials. To achieve these objectives, different weight proportions of PR resin are added to the EPS/PR hybrid matrix. Two processes are used for drying the hybrid matrix, namely: (i) ambient temperature drying process (ATDP) and (ii) thermal drying process (ThDP) at 60°C. The investigation of the ThDP will make it possible to evaluate the use of solar flat plate collectors, previously investigated by the authors in the region of Biskra (Algeria), as a renewable drying process.

2. MATERIALS AND METHOD

2.1 Materials

2.1.1 EPS/PES hybrid matrix

In this study, a hybrid matrix was developed based on expanded polystyrene waste (EPS) dissolved in gasoline [19-21] and polyester resin (PR).

The EPS waste used in this study is mainly used as thermal insulation in the building industry. It insulates walls, floors, and roofs and has a 25 kg/m^3 density. EPS was dissolved within gasoline [19, 20, 30]. The literature indicates that a weight ratio of 3 is considered between gasoline and EPS waste in preparing recycled EPS [22, 27]. The recycled EPS and gasoline were mixed to obtain a homogeneous mixture with constant viscosity. The density of the recycled EPS matrix is in the range of 460-500 kg/m^3 [21, 31], with a Young modulus of around 125 MPa [18], tensile strength of 14-18.5 MPa [18], and flexural strength of 6.5MPa [29], using different recycling methods.

To prepare the EPS/PR hybrid matrix, the commercial PR is added to the dissolved EPS. Polyester resins are increasingly used as resin matrices for composite materials such as advanced polymer composites and hybrid composites. Polyester resin is a fragile resin despite its high performance in many areas, but it is widely used as a highly cross-linked material in many applications requiring exceptional performance. The young modulus and the tensile strength of the used commercial PR are 1.8 GPa and 24 MPa, respectively, with a density of 1300 kg/m^3.

To evaluate the effect of the PR on the physical and mechanical properties of the EPS/PR hybrid matrix, different weight proportions between EPS/PR (80/20, 70/30, 60/40, 50/50, and 40/60) were prepared. Table 1 summarize the composition of all studied EPS/RP hybrid matrix. The mixture composed by the recycled EPS Matrix (EPS/gasoline) and PR was mixed for 10 minutes under open-air atmospheric pressure. To accelerate the drying process of the hybrid matrix, a quantity of 1% hardener was added to the mixture during the mixing operation.

The EPS/PR hybrid matrix was dried using two processes. The first process was at ambient temperature drying (ATDP) for 15 days. The second process, the Thermal drying process (ThDP) at 60°C, was carried out using an oven for 72 hours [20, 21]. The investigation of the ThDP will make it possible to evaluate the use of solar flat plate collectors, previously investigated by the authors in the region of Biskra (Algeria) [32-35], as a renewable and ecological drying process. The renewable and ecological drying process with recycling EPS waste reduces the cost of production of the EPS/RP hybrid matrix and makes it economic and competitive to other industrial matrix.

Table 1. Composition of recycled EPS/RP hybrid matrix

	Recycled EPS Matrix (wt%)*	PR (wt%)
EPS/PR Hybrid matrix	80	20
	70	30
	60	40
	50	50
	40	60

Note: * Recycled EPS Matrix prepared with 33 wt.% of EPS waste and 67 wt.% of gasoline

2.1.2 Test specimens

This study used tensile test, bending test, hardness, density, and scanning electron microscopy (SEM) to characterize the EPS/PR hybrid matrix.

To prepare the tensile test specimens, a silicone mold is made to obtain a test specimen with dimensions according to EN ISO 527-1 standard [36]. Figure 1 shows the mold and the obtained tensile test specimens.

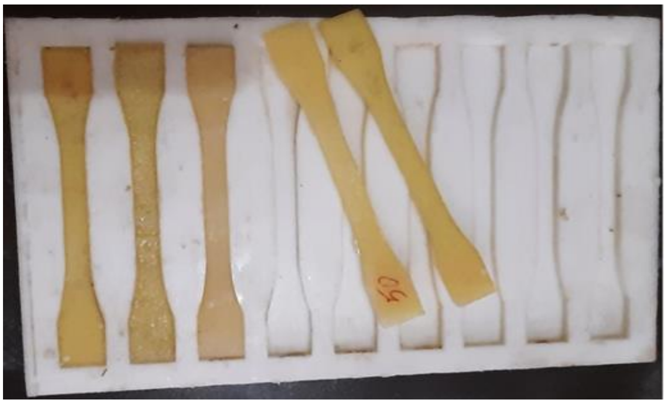

Figure 1. The tensile test specimens

Figure 2. The bending test specimens

A silicone mold is also made to prepare the bending test specimens, obtaining a plate with dimensions 200×200×4 mm (Figure 2). After drying, the plate was cut to get a specimen with dimensions lb=80 mm, h=4 mm, and width b=10 mm according to the EN ISO 14125 standard [37].

2.2 Methods

A pycnometer of 100 ml measured the bulk density of the EPS/PR hybrid matrix according to ISO 1183-1:2019 standard [38]. In each case, measurements were taken to define the mean value and standard deviation.

The tensile properties of the EPS/PR hybrid matrix, such as Young's modulus (E) and tensile strength (σ_{max}) were determined using an Instron 5969 universal testing machine. A loading speed of 2 mm/min with a gauge length of 50 mm was considered. The mechanical properties of the tensile test were calculated according to the ISO 527-1: 2019 standard [36]. Five samples were used in each case, and the average values with standard deviation were reported. Figure 3 shows the dimensions of the tensile test specimen.

The bending properties of the EPS/PR hybrid matrix, such as flexural modulus (E_f) and flexural strengths ($\sigma_{f_{max}}$) were determined using an Instron 5969 universal testing machine (Figure 4). A 5 mm/min loading speed with a support span length L_0= 64 mm was considered. The mechanical properties of the bending test were calculated according to the standard EN ISO 14125 [37]. Three samples were used in each case, and the average values with standard deviation were reported.

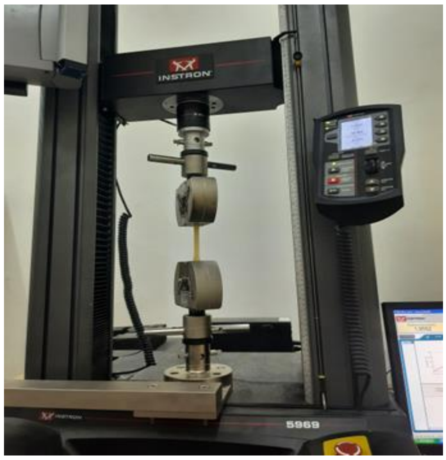

Figure 3. Tensile test

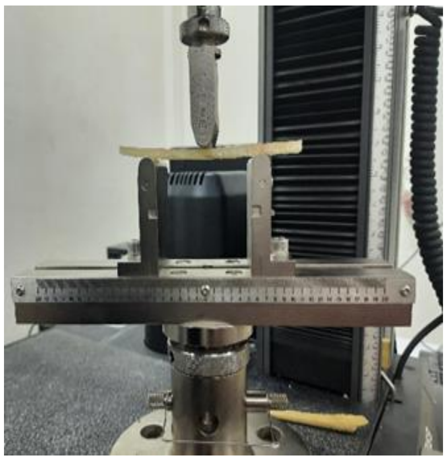

Figure 4. Three-point bending test

The Shore-D hardness measurement was carried out on rectangular samples in different locations according to the ASTM D2240 standard [39]. Five measurements defined each case's mean value and standard deviation.

Morphological analysis was carried out using a Scanning Electron Microscope (SEM). The cross-sections of the samples were analyzed to get information about the structure of the EPS/PR hybrid matrix and the adhesion between the EPS and PR.

3. RESULTS AND DISCUSSIONS

3.1 Bulk density

Figure 5 represents the effect of the weight proportion of the PR in the EPS/PR hybrid matrix. From the figure, the increase in the weight proportion of the PR increases the density of the EPS/PR hybrid matrix using both ATDP and ThDP processes. The density is in the range of 742-977kg/m^3 using the ATDP and in the range of 626-886 kg/m^3 using ThDP; with a standard deviation varied from 7 to 67 kg/m^3 and from 26 to 76 kg/m^3 respectively. The density of EPS/PR hybrid matrix is between the density of polyester and the density of recycled EPS (457-495) [21, 40]. In this last case, the density of the EPS/PR hybrid matrix becomes lower, with a rate of weight loss varying from 7 to 16%. The authors explain this phenomenon by the weight loss of the EPS/PR hybrid matrix using the ThDP. The loss in the weight is due to the heat which serves to evaporate the solvent remaining in the hybrid matrix. In the work of Abdulkareem and Adeniyi [41], the same phenomenon was found using the same recycled EPS as matrix and bamboo wastes as reinforcement. Abdulkareem and Adeniyi [41] found weight loss in the range of 1-3.5%, with an average weight loss of 2.3%. Abdulkareem et al. explain the weight loss by the release of volatile gases as the composites cure to a stable mass. The same observation was also mentioned by Hittini et al. [40].

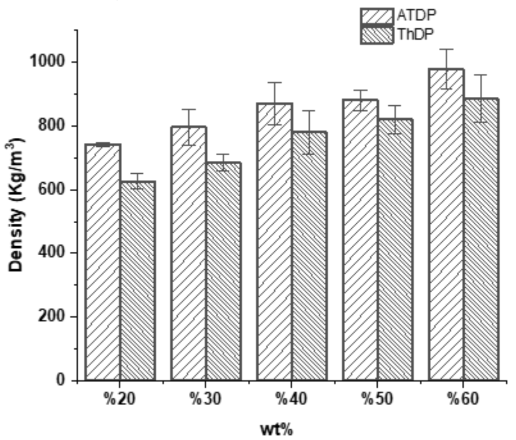

Figure 5. The bulk density of the EPS/PR hybrid matrix

3.2 Tensile test properties

The tensile tests determined Young's modulus (E) and the tensile strength (Maximum stress, σ_{Max}) of the EPS/PR hybrid matrix. Figure 6(a) and Figure 6(b) represent the stress/strain curves of the EPS/PR hybrid matrix dried using ATDP and ThDP at 60°C, respectively. Different weight ratios of polyester (20 to 60 wt%) were carried out to evaluate its effect on the mechanical properties of the EPS/PR hybrid matrix. From Figure 6 (a) and (b), increasing the weight ratio of polyester increase the mechanical properties of the EPS/PR hybrid matrix in all samples. This improvement on the mechanical properties of the EPS/PR hybrid matrix is due to the high mechanical properties of polyester compared to the mechanical properties of EPS. It is also observed that the EPS/PR hybrid matrix has a ductile rupture when the weight ratio of polyester varies from 20 to 40wt%. Beyond these values (50wt% and 60wt%), the behavior of the EPS/PR hybrid matrix has a brittle fracture. From the literature, it has been found that the use of some solvents to recycling the EPS give a low characteristic [29], which explains the ductile behavior of the hybrid matrix obtained at a low polyester content (20% to 40%). Moreover, it is observed that the ThDP (at 60°C) makes the EPS/PR hybrid matrix more rigid than the drying at the ambient temperature (ATPD). Schmidt et al. [29] has been found that the recycling process at a high temperature improves the recycled EPS strength and the recycled EPS become more fragile. We conclude that the ThDP improves the mechanical properties of the EPS/PR hybrid matrix.

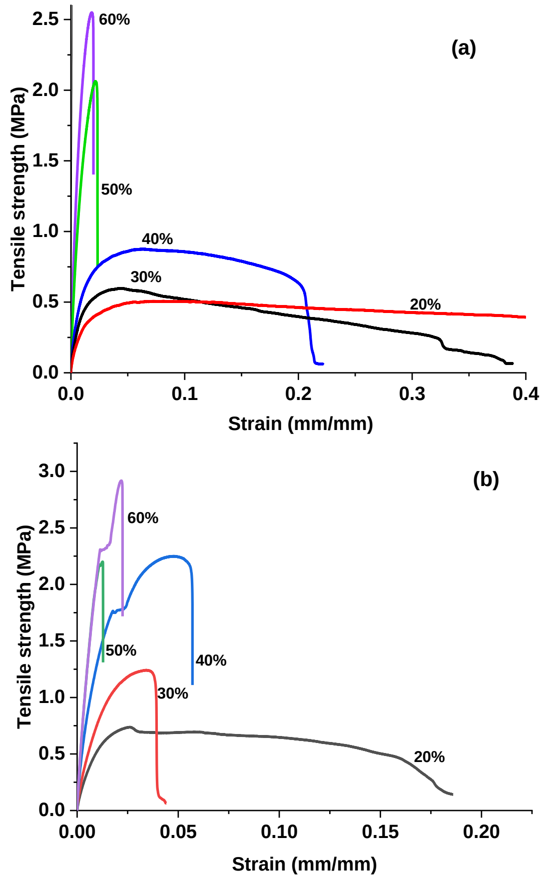

Figure 6. Stress-strain type curves of the EPS/PR hybrid matrix tensile tests: (a) Ambient temperature drying process (ATDP) (b) Thermal drying process (ThDP) at 60°C

Figure 7(a) and Figure 7(b) represent Young's modulus and the tensile strength of the obtained EPS/PR hybrid matrix. According to the results, Young's modulus and tensile strength increases with increasing PR weight ratio in the EPS/PR hybrid matrix. In the first process using ATDP, an improvement in matrix stiffness was observed and the Young's modulus increases more than 3 times from 104 MPa (20 wt%) to 327 MPa (60 wt%), with standard deviation in the range of 2 to 18 MPa. Also, the PR increases the tensile strength of more than 5 times from 0.47 MPa (20 wt%) to 2.60 MPa (60 wt%) with a standard deviation between 0.03 and 0.11 MPa.

However, the use of ThDP at 60°C can improve more than 6 and 3 times of the Young's modulus and the tensile strength from 59 MPa (20 wt%) to 407 MPa (60 wt%) and 0.77 MPa (20 wt%) to 2.89 MPa (60 wt%), respectively. According to Muzher et al. [31], the addition of the EPS, with a low weight ratio, decreases the mechanical properties of the hybrid matrix. This main the recycled EPS has lower mechanical properties than epoxy resin. This justifies the improvement in the EPS/PR hybrid matrix properties obtained with a high weight proportion of EPS compared to PR. In addition, a loss in rigidity was observed when the quantity of PR is less than or equal to 50 wt%. Beyond 50%, the ThDP at 60°C gives a better rigidity (407 MPa) than the ATDP (327 MPa), i.e. an improvement of 25%.

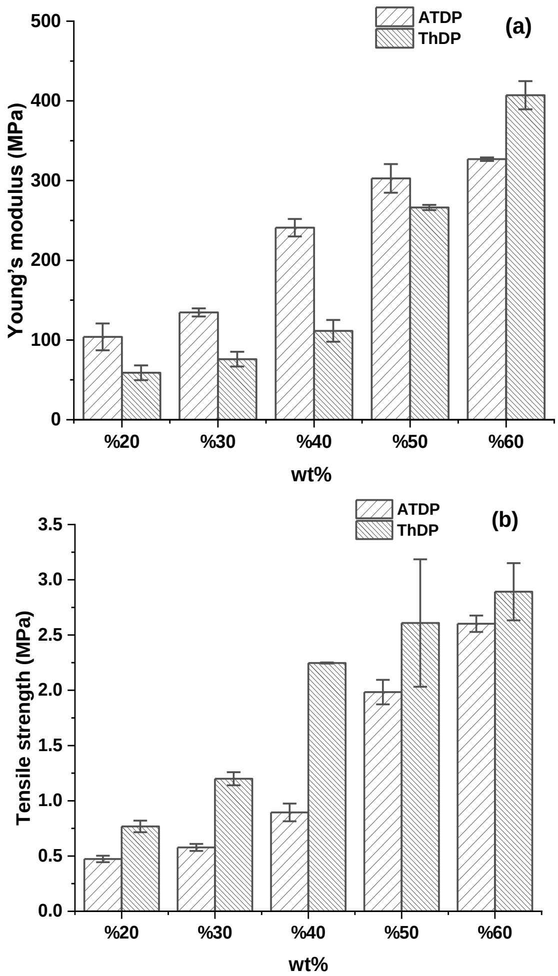

Figure 7. Effect of polyester weight ratio on (a) the Young's modulus and (b) the tensile strength of the EPS/PR hybrid matrix

According to the two processes, generally, the ATDP improves the stiffness and decreases the tensile strength of the EPS/PR hybrid matrix. On the other hand, the ThDP, at a temperature of 60°C, makes the material more resistant with an increase in tensile strength compared to ATDP, i.e., an improvement in the range of 11 to 64%.

3.3 Bending test properties

The bending tests determined the flexural modulus E_f and the flexural strength $\sigma_{f\,max}$ (Maximum stress) of the EPS/PR hybrid matrix. Figure 8(a) and Figure 8(b) show the typical stress-strain curves of the bending tests using the ATDP and ThDP, respectively.

From Figure 8, increasing the weight ratio of polyester increases the mechanical flexural properties of the EPS/PR hybrid matrix in the two processes. Moreover, the same slopes (rigidity) of the curves have been observed when the weight proportion of polyester is equal to or exceeds 40 wt% in the EPS/PR hybrid matrix. Comparing the two processes, the ThDP at 60°C improves flexural properties compared to ATDP.

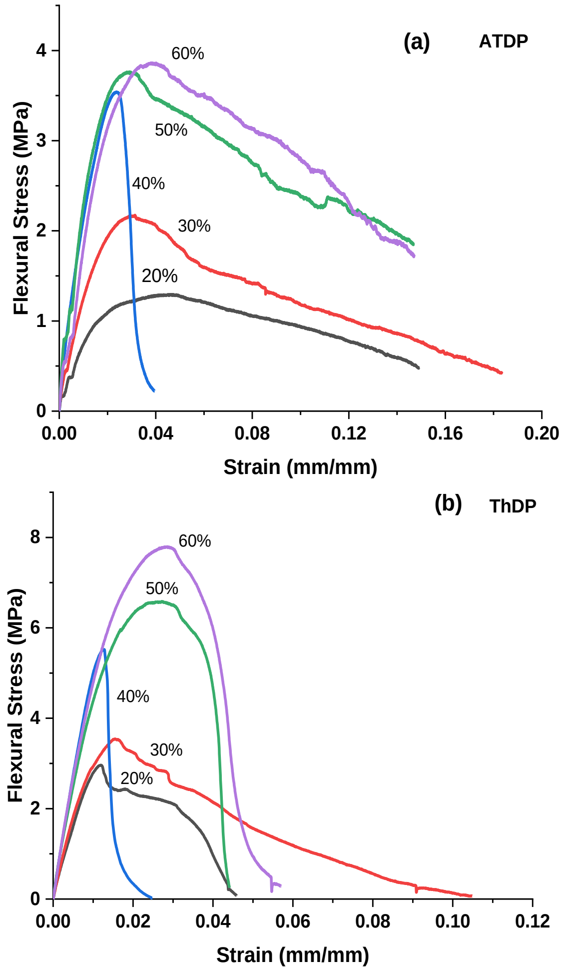

Figure 8. Stress-strain type curves of the EPS/PR hybrid matrix obtained from bending tests using (a) ADTP and (b) ThDP processes

Figure 9(a) and Figure 9(b) present the effect of the PR weight ratio on the flexural modulus and flexural strength, respectively. Figure 9(a) and Figure 9(b) show that increasing the quantity of polyester in the EPS/PR hybrid matrix increases the flexural modulus and flexural strength for the used processes. Furthermore, the ThDP (at 60°C) improves the flexural properties of the EPS/PR hybrid matrix more than the ATDP. The flexural modulus and the flexural strength of EPS/PR hybrid matrix are in the range of 116-590 MPa 1.20-6.80 MPa with a standard deviation varies from 12-38 MPa and 0.14-1.4 MPa, respectively,

For the ATDP, the flexural modulus and the flexural strength range from 116-391 MPa and 1.19-3.93 MPa, respectively. On the other hand, the flexural modulus and the flexural strength obtained by the ThDP (at 60°C) varied from 382 to 590 MPa and 3 to 6.8 MPa, respectively. However, it has been found that at 30 wt% of polyester, using the ThDP, we achieve equivalent flexural properties using 60 wt% of polyester with ATDP. This main, the reduction of 50 wt% of polyester quantity.

Using the ThDP, an improvement of 100% to 150% in the flexural properties is obtained when the quantity of polyester is between 20% and 30 wt% compared to the ATDP. Beyond 30 wt%, an improvement from 65% to 75% is obtained.

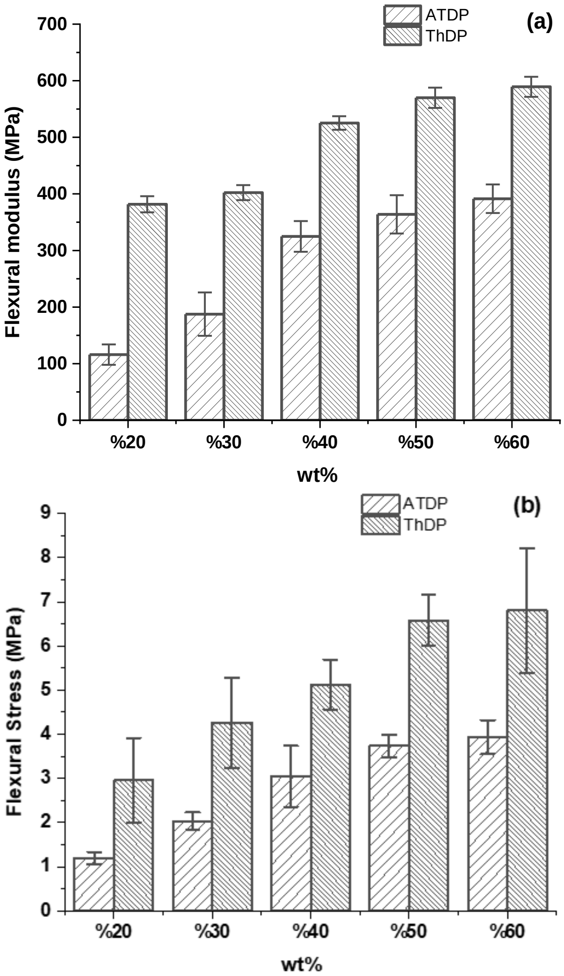

Figure 9. Effect of weight ratio of polyester (PR) on (a) the flexural modulus and (b) the flexural strength of the EPS/PR hybrid matrix

3.4 Shore-D hardness test results

Figure 10 shows the Shore-D hardness results of the EPS/PR hybrid matrix. It represents the effect of the polyester's weight ratio on the hardness of the EPS/PR hybrid matrix. Indeed, for the two processes, there is a proportional relationship between the quantity of polyester and the hardness of the EPS/PR hybrid matrix, with a prominent improvement at low weight proportions (20 wt% and 30 wt%) of polyester. The hardness of the EPS/PR hybrid matrix developed varies from 63 to 95 with a standard deviation between 1.2-3.8.

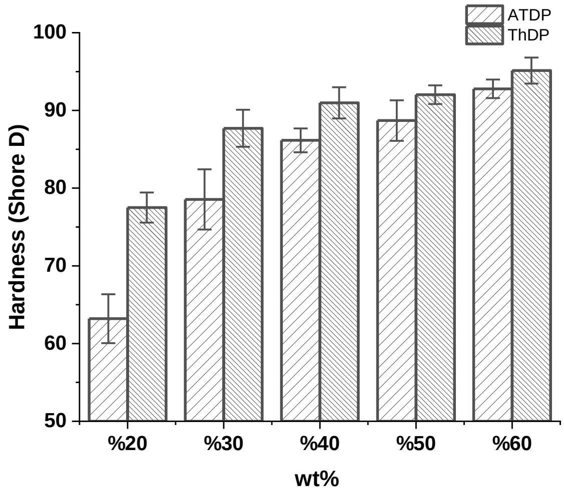

Figure 10. Effect of PR weight ratio on the Hardness of EPS/PR hybrid matrix

The Shore-D hardness of the EPS/PR hybrid matrix, using the ATDP, varies from 63 to 93, with an improvement of 47%. Moreover, using the ThDP, the Shore-D hardness of the EPS/PR hybrid matrix varies from 78 to 95, with an improvement of 23%. The authors explain this improvement by increasing the quantity of PR; the EPS/PR hybrid matrix gradually acquires the hardness of PR. By comparing the two processes, we found that the ThDP gives butter hardness than the ATDP, with an average improvement of 10%.

Table 2 summarizes the physical and mechanical properties of the obtained EPS/PR hybrid matrix.

Table 2. Physical and mechanical properties of the EPS/PR hybrid matrix

Processes	EPS/PR	Tensile Test		Bending Test		Hardness Test	Density
	wt(%)	E (MPa)	σ_{max}(MPa)	E_f (MPa)	$\sigma_{f_{max}}$(MPa)	Shore D	(Kg/m^3)
ATDP	80/20	103.93±16.83	0.47±0.03	116.04±18.00	1.19±0.14	63.20±3.15	741.37±6.83
	70/30	134.55±5.09	0.58±0.03	187.50±38.30	2.03±0.19	78.55±3.87	795.61±55.92
	60/40	240.88±10.96	0.89±0.08	324.90±27.07	3.05±0.69	86.15±1.53	870.02±67.18
	50/50	302.76±17.94	1.98±0.11	363.85±33.83	3.73±0.24	88.70±2.61	880.96±31.89
	40/60	326.87±2.24	2.60±0.07	391.41±25.23	3.93±0.38	92.78±1.20	976.95±62.75
ThDP	80/20	58.92±9.30	0.77±0.05	381.62±14.25	2.96±0.96	77.50±1.94	626.43±25.75
	70/30	75.97±9.27	1.20±0.06	402.25±13.29	4.26±1.01	87.70±2.38	685.27±27.44
	60/40	111.45±13.62	2.25±0.01	525.24±12.01	5.12±0.56	90.98±2.01	781.15±68.21
	50/50	266.24±3.24	2.61±0.58	569.89±17.94	6.58±0.57	92.03±1.20	821.26±44.28
	40/60	407.11±17.68	2.89±0.26	589.29±17.71	6.80±1.40	95.13±1.67	886.42±75.62

3.5 Scanning electron microscopy (SEM) characterization

The SEM figures give helpful information about the EPS/PR hybrid matrix structure and the adhesion between the EPS and polyester. Figure 11 show that the EPS/PR hybrid matrix structure comprises bubbles of different diameters representing polyester. EPS totally or partially coats these polyester bubbles with the presence of a few air bubbles. The different components of the EPS/PR hybrid matrix have a random distribution.

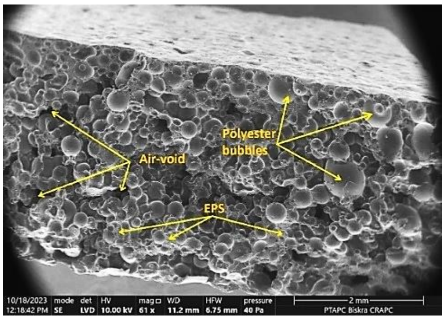

Figure 11. Scanning electron microscopy (SEM) image showing the structure of EPS/PR hybrid matrix with 50 wt% of PR

Figure 12 shows the SEM visualization of EPS/PR hybrid matrix samples with different weight proportions between the recycled EPS and polyester (20 wt%, 30 wt%, 40 wt%, 50 wt%, and 60 wt%). Figure 12 shows that increasing the PR quantity in the EPS/PR hybrid matrix increases the quantity of PR bubbles, and the volume of some PR bubbles produced becomes larger (see Figure 12(a) - (e)). Li et al. [34] found the same observation using the same EPS matrix with polycarbonate (PC).

In the case of a low PR quantity (20 wt% and 30 wt%), we observe the presence of a significant separation between the EPS matrix and the PR bubbles. This separation generates poor cohesion between the two components of the EPS/PR hybrid matrix.

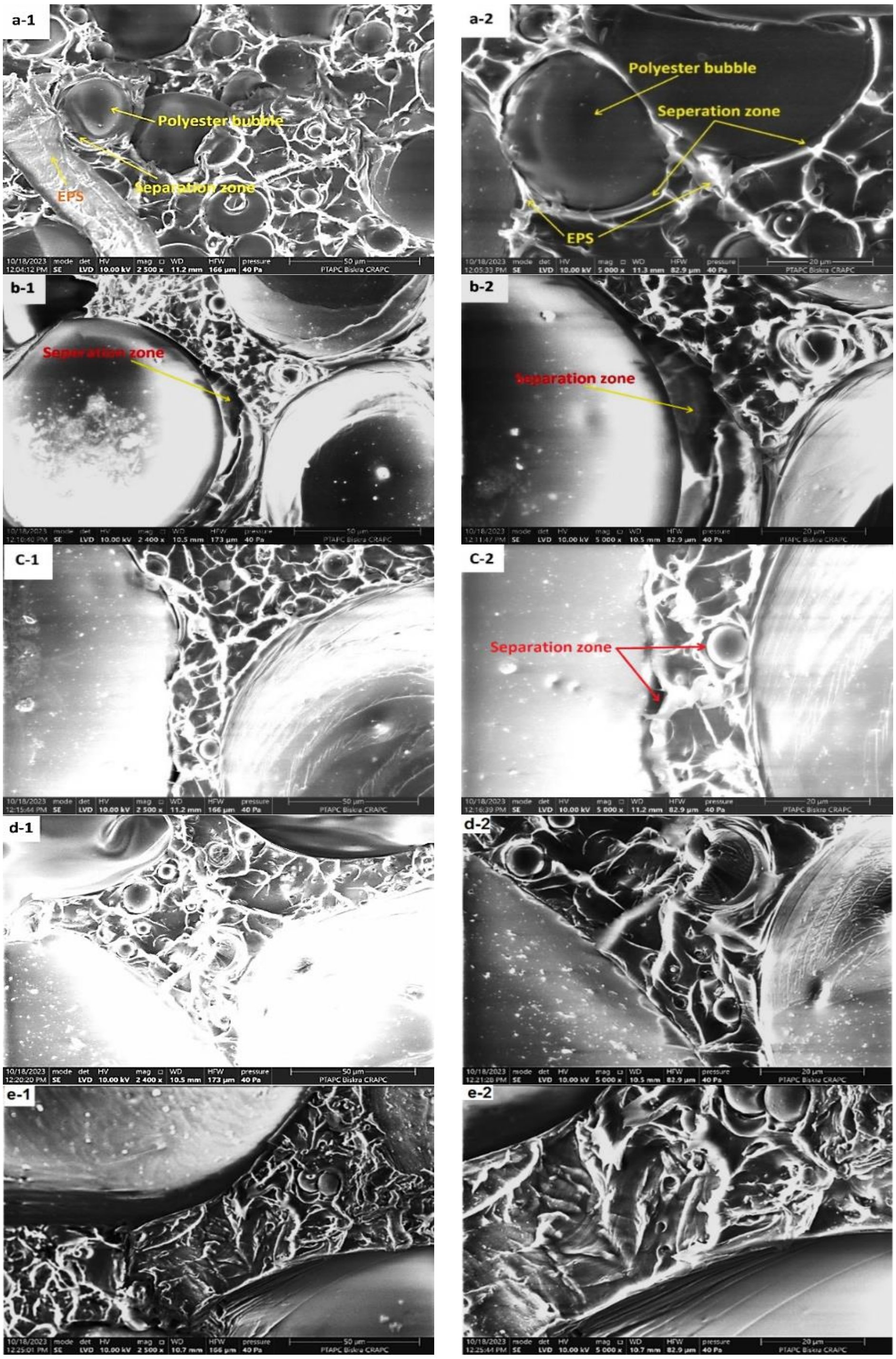

Figure 12. SEM figures of EPS/PR hybrid matrix with different weight proportions of PR
Note: (a) 20 wt%, (b) 30 wt%, (c) 40 wt%, (d) 50 wt%, and (e) 60 wt% of PR

In addition, when the quantity of PR is low, the number of PR bubbles in the EPS/PR hybrid matrix increases, and their diameters decrease. This increases the contact perimeter between EPS and the PR bubbles, which causes an increase in delamination areas and lowers the material's mechanical properties. This behaviour explains the low mechanical properties of the EPS/PR hybrid matrix obtained, mentioned previously, of the tensile and bending tests.

Beyond 40 wt% of PR, an improvement in the mechanical properties of the EPS/PR hybrid matrix is obtained. This improvement is due to the reduction of separation zones, which generates good cohesion between the elements constituting the EPS/PR hybrid matrix. Moreover, Cherian et al explain the improvement of mechanical properties by the better crosslinking and longer chains of polymers produced by using the binary and ternary mixtures of matrix and the polymerization reaction was produced in all mixtures. In addition, the binary and ternary resin mixtures have developed higher energy absorption compared to single resin composites.

4. CONCLUSION

To improve the physical, mechanical, and morphological properties of recycled polystyrene matrix (EPS), used previously by the authors as a matrix in composite materials, an innovative hybrid matrix based on recycled EPS and polyester resin (PR) is developed in this study. The valorisation of EPS wastes through the elaboration of a new hybrid matrix has an obvious environmental impact and makes its cost competitive to similar matrix materials., the EPS/PR hybrid matrix comprises EPS waste dissolved in gasoline, used as a thermoplastic matrix, and the polyester resin (PR) used as a thermosetting matrix. Different weight proportions (20, 30, 40, 50, and 60 wt%) between EPS and PR were considered to obtain the physical, mechanical, and morphological properties of the EPS/PR hybrid matrix. In the elaboration of the EPS/PR hybrid matrix, two processes were used for drying the hybrid matrix: the ambient temperature drying process (ATDP) and the thermal drying process (ThDP). From the results, increasing the PR weight proportion increases the physical and mechanical properties of the EPS/PR hybrid matrix using the ATDP and ThDP.

The use of ThDP at a temperature of 60°C showed that the material became more resistant with an increase in tensile strength compared to ATDP, i.e., an improvement in the range of 11 to 64%. Moreover, from the bending results, using ThDP with 30 wt% of PR gives the equivalent flexural properties using 60 wt% of PR with ATDP with a reduction of 50 wt%. Furthermore, the EPS/PR hybrid matrix becomes lower using the ThDP, with a weight loss from 7 to 16%. In addition, when the PR quantity is between 20 wt% and 30 wt%, an important improvement in the physical-mechanical properties was obtained using the ThDP.

Scanning electron microscopy (SEM) images showed that the EPS/PR hybrid matrix structure comprises polyester bubbles, recycled EPS matrix, and voids. The SEM morphological study shows that the EPS/PR hybrid matrix has a porous structure which decreases with increasing PR.

In conclusion, the addition of PR made it possible to improve the physical and mechanical properties of the EPS/PR hybrid matrix in both drying processes with a drastic improvement of 3 to 6 times in the mechanical properties. The explored ThDP at 60°C shows the possibility of using solar flat plate collectors, previously investigated by the authors in the region of Biskra (Algeria), as a renewable drying process which is an ecological process and which reduces the cost of the product. The developed hybrid matrix can be used as a binder, additive or a matrix in several areas such as automotive and marine applications (hulls), aeronautical applications, aviation applications and safety equipment (ballistic protection and corrosion protection layer). The hybrid matrix can be also used to improve the mechanical properties of new construction materials, composite materials, sandwich panel cores for various applications such as for example the materials already studied by the authors like date palm leaflet-polystyrene composite and Rubber tire-polystyrene composite

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