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Characterization of a Composite Material Composed by Rubber Tire and Expanded Polystyrene Wastes

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ABSTRACT

This study aims to valorise industrial waste of Expanded Polystyrene Packaging waste (EPS) and used tire waste, in the production of a new composite material. The new composite material RTPC (Rubber Tire Polystyrene Composite) is a mixture of rubber particles from used tires, as reinforcement, and a matrix obtained by recycling EPS with gasoline. In this study, several matrix/reinforcement weight proportions (25%, 30% and 35%) and several reinforcement particle sizes (2-3, 3-4 and 4-5 mm) were considered. Physical, mechanical and thermal characterization were carried out in order to determine the density, the flexural modulus, the maximum stress and the thermal conductivity of the composite material. According to the obtained results, the RTPC material obtained is considered as a light material with a density between 500 and 600 kg/m^3. The thermal characterization tests of the RTPC material also showed that the RTPC is an insulating material with thermal conductivity between 0.22 and 0.23 W/m.K. On the other hand, the three-point bending tests showed that the RTPC material has poor bending properties. The RTPC material can be used in the field of building construction as a good thermal insulator. The RTPC material can be used in other applications as a structural component in sandwich structures if its mechanical properties will improve.

1. INTRODUCTION

Tires are an essential part of the economy of each country that relies on road and/or air transport. Although the global rubber sector, which is the basic material for the production of tires, is very small compared to other economic sectors, tire production represents an important part of international and national trade [1]. The world production of tires, for various types of vehicles, is increasing rapidly due to the significant growth of the population and the development of transport [2].

The annual world production of rubber has reached about 3.3 million tons. Consumption by the automotive industry represents 75% of world rubber production, of which approximately 60% is used for the manufacture of tires for passenger cars, utility vehicles and trucks. The remaining 15% is intended for the production of non-pneumatic automotive products, including appearance elements, belts, hoses, housings, mouldings, rings, seals [1]. Therefore, a tire is an essential and most regularly used element among rubber products, because the majority of the total rubber consumption is used to deliver tires [3].

According to Raffoul et al. [4], industrial tire waste is almost proportional to tire production. Every year, 3 million tones that correspond to 1000 million of used tires are generated by the tire industry. Thomas et al. [5] estimates that by 2030, the number of tire out of use would reach 1200 million tires per year. Unfortunately, most used tires are not recycled due to the nature of rubber [6]. Storage and elimination of used tires have become an urgent word preoccupation from the environmental point of view [7].

The green development concept has been accepted since 2000 by more and more people. This concept, which intrinsically require us to pay more attention to the importance of the environmentally friendly disposal and resource utilization of waste tires in the economic development [8]. In a context of sustainable development on a global scale, it seems essential to be able to know and exploit the potential of our waste in order to make the most of it. Out of use tires (OUT) are considered waste when the tread rubber is too worn for the tire to maintain its performance; this does not mean that the remaining rubber is unusable. The residual rubber extracted from a used tire still has excellent mechanical properties, opening the way to multiple applications [6]. The three major current method of recycling of the used tires are [6]: i) Energy recovery by incineration with around 40% of used tires; ii) Landfill of used tires represent 25%; and iii) Material recovery: The vast majority of current materials recovery uses OUT as a simple filler, without added value. Tire shreds of a few centimetres are used to replace traditional construction materials such as gravel or sand. The advantage of this type of material is its lower density, good drainage properties and better thermal insulation. The first two recycling methods inevitably cause serious second-pollution to environment and health damage [8]. Material recovery is one of the possible solutions for the use of waste tire rubber, in particular to incorporate it into the production of composite material, to replace some of the natural aggregates. This attempt could be environmental friendly and economically viable [5].

Among the waste treatment procedures for used tires, grinding is the most important method for converting the waste rubber into ground material. By way of example, it can be used in combination with other materials such as asphalts, concrete, mortars, rubber and thermoplastic matrices, and epoxy resins to produce a composite material for surfaces of athletic tracks or games [7]. Furthermore, the waste of used tires can be used in the Public Works concerned in the form of powder (or other recycled elastomers) in the asphalts. These modified asphalts or RMA (Rubber Modified Asphalt) have better resistance to cracking and digging fatigue. However, even this last recycling process makes little use of the intrinsic mechanical properties of tire rubber, which is a high-performance material designed to withstand high stresses over long periods of time [6]. Aoudia et al. [7] have used tire waste, in the form of aggregate, in the development of a composite with an epoxy matrix. It appeared that epoxy composites filled with Devulcanized Ground Tire Rubber (DGTR) have better mechanical properties than those filled with untreated GTR.

In the literature, other industrial wastes have been recycled for the development of ecological and low-cost materials, such as expanded polystyrene (EPS) which is used in packaging. In all countries of the world, the expanded polystyrene is commonly used in many applications, especially in packaging and insulation materials [9]. The most industries use EPS because of its dimensional stability, versatility, clean nature and low cost [10]. The use of expanded polystyrene generates important quantities of non-bio-degradable wastes which usually ends up in landfills or is incinerated, causing serious environmental problems [9, 11]. For the exploitation of Expanded Polystyrene Packaging waste, Masri et al. [12-14] used recycled expanded polystyrene using gasoline for use as a matrix in the development of a composite material with natural reinforcement.

According to the above literature, there have been several studies of combining waste rubber with other materials to form composite material with better thermal and mechanical behaviour. On the other hand, expanded polystyrene (EPS) waste can be considered as good matrix in the development of composite material. In this context and in order to valorise industrial waste such as used rubbers tire and polystyrene packaging wastes, this work proposes a composite material, using purely industrial wastes, based on the rubber of used tires, and the recycled expanded polystyrene wastes to obtain an ecological and low cost material for construction applications. Physical, Mechanical and thermal behaviours are studied in detail in order to test the main characteristics of the new material.

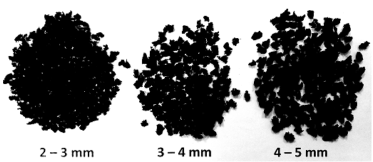


Figure 1. Sizes of rubber tire reinforcement

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Reinforcement preparation

Rubber particles (granulate) obtained from used tires are recycled as reinforcement in the preparation of the composite material. For this purpose, used tires were cleaned and grinded using a gear grinder. The raw material was filtered to separate the metallic fibres and the rubber aggregates. This process makes it possible to obtain rubber aggregates with a particle size range 2 to 5 mm. To study the effect of particle size on the mechanical, physical behaviour three sizes were considered in this paper: 2-3 mm, 3-4 mm, and 4-5 mm.

The sieving of the reinforcement was carried out using a sieving machine (Retsch AS200). To have a similar distribution of particles reinforcement in each case, an amount of 500 g was sieved for 10 min with a sieving amplitude equal to 1.5. Figure 1 show the different particle sizes used to elaborate the composite material.

2.1.2 Preparation of matrix

Masri et al. [12-14] used a matrix obtained from the recycling of expanded polystyrene (EPS). In the elaboration of the composite material the same matrix was used. The matrix is obtained by dissolving the EPS waste, with a density of 15 kg/m^3, in gasoline with a mass ration defined as follows:

$$\frac{m_{gasoline}}{m_{Polystyrene}} = 3 \tag{1}$$

where, $m_{gasoline}$ is the mass of gasoline and $m_{polystyrene}$ is the mass of the EPS.

2.1.3 Preparation of RTPC test specimens

In this study, three-point bending test and thermal conductivity measurements are carried out. For the preparation of bending and thermal conductivity RTPC (Rubber Tire Polystyrene Composite) test specimens, two wood moulds have been manufactured, a 240x110x40 mm^3 dimension for bending specimens and a 40x40x30 mm^3 dimension for thermal conductivity samples (Figure 2).

Figure 2. Wood moulds for three-point bending test and thermal conductivity measurements

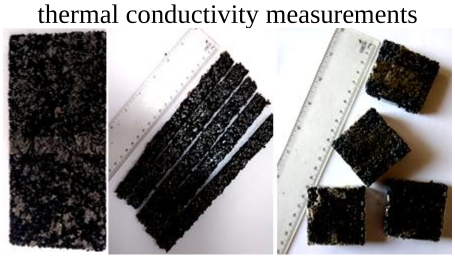


Figure 3. The plate, specimens and the parallelepipeds of elaborated composites

Table 1. Various RTPC tested samples

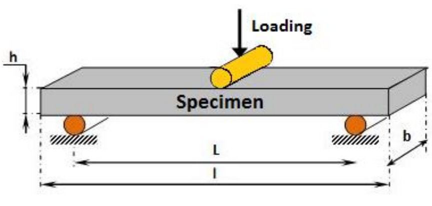
RTPC Samples	Size of the reinforcement (mm)	Matrix (wt%)	Reinforcement (wt%)
A1		25	75
A2	2-3	30	70
A3		35	65
B1		25	75
B2	3-4	30	70
B3		35	65
C1		25	75
C2	4-5	30	70
C3		35	65

In this work, nine combinations of weight proportions of the matrix/reinforcement (25/75, 30/70 and 35/65 wt%) with three different particle sizes of reinforcement (A, B, and C) have been prepared to obtain the RTPC materials (Table 1).

The RTPC material is obtained by mixing the recycled EPS matrix with the rubber particles tires. Afterwards, the mixture is poured into the two moulds, one for the three-point bending specimens and the other for the thermal conductivity samples. For a good distribution of the reinforcement in the matrix, pressure is applied and maintained for 10 minutes [15, 16]. As the nature of the rubber of the tires is very elastic and to avoid the elastic return of the material which will create vacuum faults, the pressure applied is low and equal to 0.5 Bar. After compression, the plates and the parallelepipeds obtained are dried in an oven at a temperature equal to 60° for 72 hours. After drying, the plates will be cut to obtain specimens with dimensions of 200x10x15 mm^3 according to EN ISO 14125 [17] (Figure 3).

2.2 RTPC characterizations

The three-point bending tests of the RTPC material were carried out on a universal testing machine model Instron 5969 with standardized dimensions specimens (Figure 4).



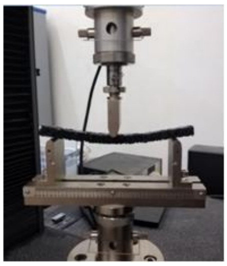


Figure 4. Specimens dimension and three-point bending test configuration

Figure 5. Test of the thermal conductivity measurement

According to standard EN ISO 14125 [17] ($l=200^{-0}_{+10}$ mm, L=160±1 mm, h=10±0.2 mm and width b=15±0.5 mm). For each sample, five similar specimens were tested with a loading speed equal to 2 mm/min.

The three-point bending test allowed to determine the flexural properties of the RTPC material such as the flexural modulus E_f and the maximum stress σ_{Max}.

The bulk density of material was measured by a pycnometer of 500 ml according to ISO 1183-1: 2012 standard [18]. On the other hand, a pycnometer of 50 ml was used for the measurement of the density of the dry matrix (Recycled EPS) and the rubber of the tires in order to use as references.

The thermal conductivity of RTPC material was measured, at a temperature of 28°C and at humidity of 21%, using the HotDisc TPS 500 model (Figure 5). The TPS 500 gives measurements witch an accuracy of 5% and also meets the ISO 22007-2 standard [19]. The type of sensor used is Kapton with a diameter equal to 19.8 mm. As recommended by the manufacturer, the dimensions of the thermal conductivity samples, cited above, must be greater than the diameter of the used Kapton sensor.

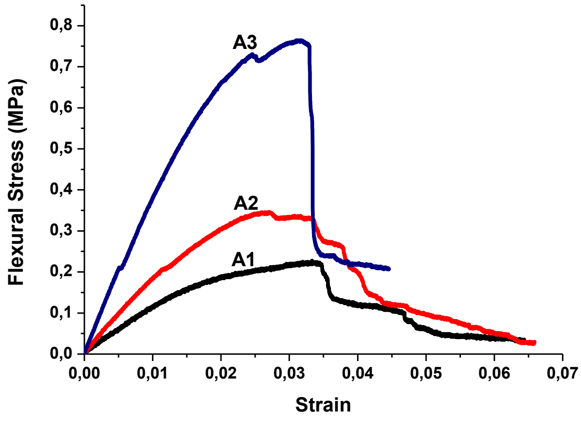
3. RESULTS AND DISCUSSION

3.1 Three bending test properties

The flexural modulus E_f and the maximum stress σ_{Max} of the RTPC Material were determined by three-point bending tests. Figure 6 shows the effect of the matrix/reinforcement weight ratios and the dimensions of the reinforcement on the mechanical behaviour of the RTPC material.

In general, Figure 6 shows that bending stress as a function of deformation is characterized by two major parts. The first part is limited by the maximum bending stress and the second part identifies the type of failure (ductile or brittle) of the material. Moreover, the first part presents a linear zone followed by a second non-linear zone. The linear part characterizes the flexural modulus. Before the maximum stress, a nonlinear zone is observed. In A3, B2 and C3 cases, where the mechanical properties are better, a damping of the curve is observed due to the pre-cracking of the composite.

For each size range of reinforcement, Figure 6 shows that two cases can be observed on the slope values of the curves. In the first case A, with a small grain size (2-3 mm), the slopes of the curves increase with increasing the quantity of the matrix in the RTPC material, the same behaviour was found by Tang et al. [20]. On the other hand, in cases B and C the values of the slopes of the curves increase with the increasing the quantity of the matrix up to 30% then the slope decreases at 35% of the matrix (Cases B3 and C3). Generally, the RTPC material exhibits ductile failure in the majority of cases. This behaviour is already observed in the literature for the plastic composites [21, 22].



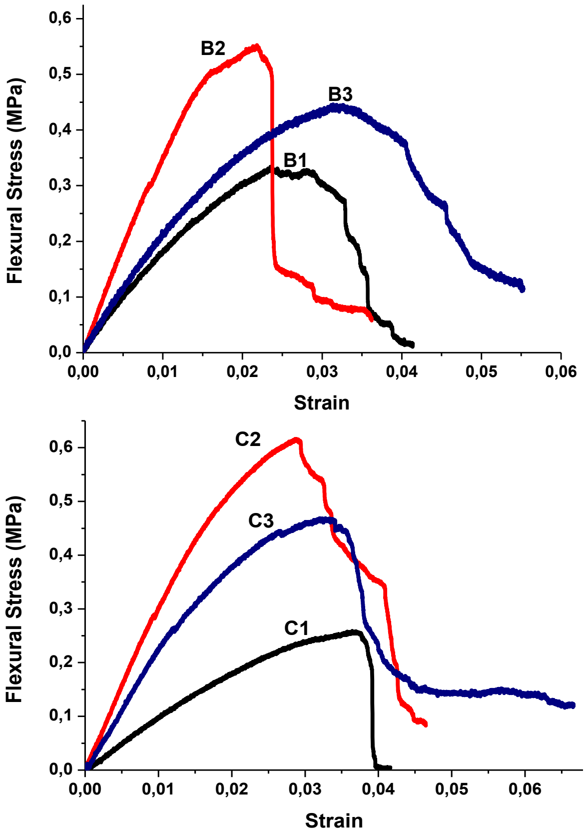


Figure 6. The stress-strain type curves of the three bending tests of the RTPC material

Figure 7-a and 7-b represent respectively the flexural modulus and the maximum stress of the studied cases. From the results, the same observations of the slopes of the curves were observed in the flexural modulus and the maximum stress. In case A, increasing the amount of matrix increases the bending modulus and the maximum stress of the RTPC material. The same behaviour was found by Homaeigohar et al. [23] and Tang et al. [20]. This behaviour is due to the nature of the EPS matrix material compared to the rubber. The dry EPS matrix has a higher mechanical property than rubber (6.5 to 13.4 MPa) [24]. Both, cases B and C show a decrease in the flexural modulus and the maximum stress if the quantity of the matrix exceeds 30%. The same behaviour was found by Abdel-Hakim et al. [25], where the mechanical properties decrease when the quantity of the matrix exceeds 40%. The authors think that this behaviour is due by the springback of tire reinforcement particles after compression with high grain sizes A and B (3-4 mm and 4-5 mm). Springback of the rubber particles after compression will create voids in the RTPC material. Moreover, increasing the particle size increases the creation of voids in the composite [20]. These void contents reduce the bending mechanical properties of the RTPC material.

Figure 7 shows also the effect of the size of the reinforcement, for each reinforcement weight ratio, on the flexural modulus and the maximum stress of the RTPC material. By taken into account in the analysis of the standard deviation, increasing the size of the reinforcement from case A (2-3 mm) to case B (3-4 mm) improves the flexural modulus and the maximum stress of the RTPC material. These properties decrease if the size of the reinforcement exceeds 4 mm (C case). The authors think that increasing the size of the reinforcement particles more than 4mm, produces lots of bulky voids at the microscopic scale. In this case, the contact surface between the particles decreases, which generate a low contact surface and poor cohesion between the reinforcement and the matrix respectively.

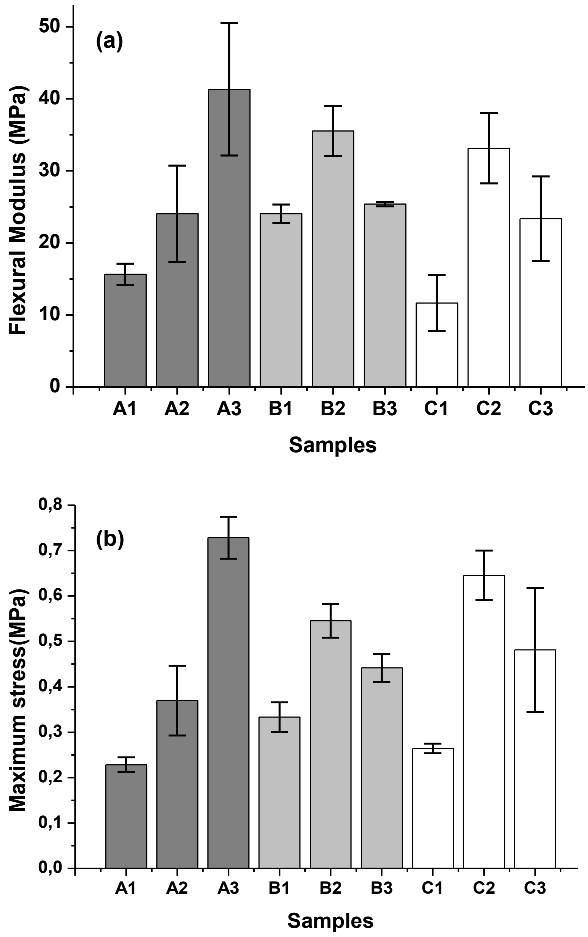


Figure 7. Effect of the particle sizes and matrix/reinforcement weight ratio on: (a) the flexural modulus and, (b) the maximum stress

3.2 The density of RTPC material

Figure 8 shows material density results from various RTPC samples as well as dry matrix and waste tire rubber. According to the results obtained, it is observed from all cases, the densities of the formulated RTPC materials are between the density of the pure dry matrix (M) and the density of the rubber reinforcement of used tires (R). Moreover, the density of the RTPC material depends on the weight ratio between the matrix and the reinforcement and also depending on the particle size of the reinforcement.

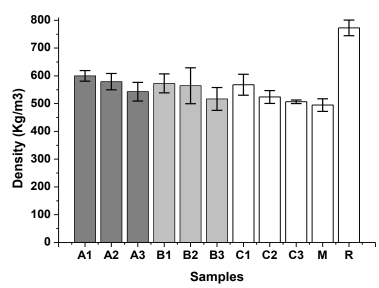


Figure 8. Density of RTCP material

Figure 8 shows that the density of the RTPC material decreases with increasing amount of matrix, this is because the dry EPS matrix measured (494.75 kg/m^3) has a lower density than the density of the reinforcement (772.71 kg/m^3). Similarly, a slight decrease in the density of the RTPC material was observed with increasing the particle size of reinforcement. Homaeigohar et al. [23] have found that the density remains constant with increasing particle size, however increasing the mass fraction of the reinforcement/matrix increases the density of the composite. The density range of the obtained RTPC material is between 506.86 kg/m^3 and 599.89 kg/m^3 with a standard deviation of 22.62 and 19.11 respectively (Cases C3 and A1).

Furthermore, the composite density calculated directly, from EPS matrix and rubber reinforcement densities, is higher than the value found experimentally. For example, the measured and calculated densities of the composite A3 are respectively 543 kg/m^3 and 675 kg/m^3. This difference is mainly due to porous structure of the final composite material; which is composed by the voids of the reinforcement particles and the voids produced after drying of the matrix.

3.3 Thermal conductivity of the RTPC material

The thermal conductivity measurements of the RTPC material obtained are in the range of 0.197-0.237 W/m.K (Cases C3 and A2 respectively). From the obtained results of Figure 9, The thermal conductivity of the RTPC material increases slightly with the increase the weight ratio between the reinforcement and the matrix (Cases A1, A2, B1, B2 and C1, C2). On the other hand, it decreases if the weight ratio between the matrix and the reinforcement exceeds 30% (Cases A3, B3 and C3). The authors justify the reduction of the thermal conductivity in the cases A3, B3 and C3 by the void created due to the elastic return of the used tires rubber particles and by increasing the particles size of reinforcement which increases the creation of voids in the composite [20]. As the void is a good heat insulator, the RTCP material becomes more insulating. In all cases, the variation in thermal conductivity value (from 0.197-0.237 W/m.K) remains very limited and the RTPC material exhibits an insulating behaviour. Table 2 summarizes the physical, mechanical, and thermal properties of the developed RTPC material and other materials of the same family.

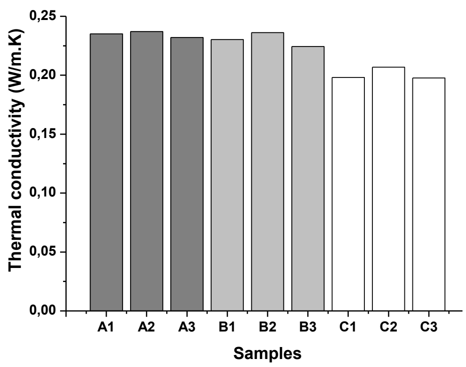


Figure 9. Thermal conductivity of RTPC material

Table 2. Mechanical, physical and thermal properties of RTPC material

RTPC samples	E_f (MPa)	σ_{max} (MPa)	ρ (kg/m^3)	λ $(W/m.K)$
A1	15.64±1.45	0.23±0.02	599.89±19.11	0.2351
A2	24.05±6.67	0.37±0.08	579.19±33.79	0.2371
A3	41.33±9.20	0.73±0.05	543.02±29.18	0.232
B1	24.05±1.27	0.33±0.03	572.87±34.13	0.2302
B2	35.54±3.49	0.54±0.04	564.44±64.66	0.2362
B3	25.39±0.32	0.44±0.03	517.12±41.08	0.2243
C1	11.63±3.90	0.26±0.01	568.12±37.75	0.1981
C2	33.13±4.87	0.64±0.05	523.92±22.99	0.2068
C3	23.36±5.84	0.48±0.14	506.86±6.41	0.1977
M	/	/	494.75±22.62	/
M [25, 26]	4.48	58.35	711-457	0.17
R	/	/	772.70±28.27	/
R [27-29]	50.00	5.3	800	0.2-0.5
DGTR [26]	2070-2620	6.43-40.49	540-580	0.16-0.25

Table 2 illustrates that, the flexural modulus of the RTPC material (11.63-41.33 MPa) is in the range of the flexural modulus of the recycled EPS matrix (4.48 MPa) [26] and waste tire rubber (50 MPa) [27]. On the other hand, the RTPC material has weak mechanical properties compared to the devulcanized rubber composite material developed by Hittini et al. [26].

Measurements of the density of the recycled EPS matrix (494.75 kg/m^3) and the rubber waste particles from the tires (772.70 kg/m^3) gave a similar result to the measurements of Hittini et al. [26] (457 kg/m^3) and Raffoul et al. (800 kg/m^3) [4]. On the other hand, the density of recycled EPS measured by Abdel-Hakim et al. (711 kg/m^3) is greater. Furthermore, the density of the developed RTPC material have the same density of devulcanized rubber composite [26].

Moreover, the thermal conductivity of the developed RTPC material obtained (0.1977 - 0.2371 W/m.K) is in the range of the thermal conductivity of the recycled EPS matrix (0.17 W/m.K) [26] and the reinforcement of the rubber waste of the tires (0.2-0.5) [28, 29]. According to the thermal conductivity results, it was found that increasing the particle size of rubber tires (cases C) makes the material more insulating. Both RTPC and devulcanized rubber composite materials are insulating materials with similar thermal conductivity.

4. CONCLUSIONS

In this study, a new composite material is studied composed by rubber tire waste as the reinforcement and EPS waste dissolved in gasoline as a matrix. Mechanical, physical and thermal measurements were performed to characterize the Rubber Tire Polystyrene Composite (RTPC) material.

The results of the bending test show that the RTPC material have a low flexural property (flexural modulus and the maximum stress) compared with some composites obtained from the literature. The RTPC material has a porous structure which has the advantage of making the material as light and insulator. The density and thermal conductivity of RTPC material were obtained respectively around 600 kg/m^3 and 0.17 W/m.K.

Tire waste can be recovered by using their rubbers in the formulation of low-cost and ecological insulating material with a 100% industrial waste composition. The RTPC material can be used in the field of building construction as a good and low cost thermal insulator. The RTPC material can be used also in other applications as a structural component in sandwich structures if its mechanical properties will improve.

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NOMENCLATURE

A	Small particle size of the reinforcement, 2-3mm
b	Width of specimen, mm
B	Medium particle size of thereinforcement, 3-4mm
C	Large particle size of the reinforcement, 4-5mm
E_f	Flexural modulus, MPa
h	Thickness of the test specimen, mm
l	Length of specimen, mm
L	Support span length, mm
$m_{gasoline}$	Mass of gasoline, g
$m_{polystyrene}$	Mass of expanded polystyrene, g
wt%	Weight proportions
y	Deflection, mm

Greek symbols

σ_{Max}	Maximum stress, MPa
ρ	Density, kg/m^3
λ	Thermal conductivity, W/m.K

Subscripts

DGTR	Devulcanized Ground Tire Rubber
EPS	Expanded Polystyrene
FDT	Fuel Derived from Tires
GTR	Ground Tire Rubber
M	Matrix
R	Rubber
RMA	Rubber Modified Asphalt
RTPC	Rubber Tire Polystyrene Composite