CHEMICAL ENGINEERING TRANSACTIONS

VOL. 57, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš, Laura Piazza, Serafim Bakalis

ISBN 978-88-95608- 48-8; **ISSN** 2283-9216

DOI: 10.3303/CET1757224

Determination and Evaluation of Flexural Strength and Impact, Flammability and Creep Test through DMA, (Dynamic Mechanical Analysis) for Mixing Expanded Polystyrene and Polypropylene from Municipal Solid Waste

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The growing generation of urban solid waste versus limited use options that enable reincorporating materials into the production cycle and the use of landfills as the primary destinations of solid waste generated are some of the main priorities of municipal administrations within the comprehensive management of solid waste. An example of this is plastic waste, which contains large quantities of different types of polymers and makes up a considerable percentage of total waste generated. This is the case with expanded polystyrene, that while having alternative uses, ends up being sent to landfills as few municipal administrations choose to implement recovery strategies and methods of this material so it can be reincorporated into the recycling chain, primarily due to its volume-to-weight ratio, which generates low commercialization value. Therefore, this research project sets out to characterize materials through the following laboratory tests: bending strength, impact resistance, flammability and a creep test through DMA (dynamic mechanical analysis) to determine the viability of the mixture and afterwards, design future applications.

1. Introduction

This research work is based on the use of two types of plastic waste, the first of which is expanded polystyrene (EPS) and the second being polypropylene, both of which are recovered through separation at the source; homes and businesses. Expanded polystyrene is made up of 95% polystyrene and 5% gas, usually pentane, which forms bubbles that reduce density of the material. Its main applications are building insulation, packaging material for fragile products and thermal and acoustic insulation. It is also used as sports clothing due to its floating properties as well as in the manufacturing of life jackets and other items for water sports. As a result of its lightweight and damping properties, it is used in the production of bicycle helmets and insulated cups that keep drinks at their proper temperature for long periods of time due to its insulating capacity (CIT, 2011). Even though used expanded polystyrene is classified as useable solid waste, the problem lies in the fact that EPS is not a financially attractive material for use due to its volume-to-weight ratio and furthermore, carrying out the collection and transport of this material represents a high cost in addition to occupying large amounts of space at landfills by being disposed there. It is also very contaminating due to its biodegradation time and the severe environmental impact its production generates. On the other hand, polypropylene does not have the same problem for its use as is the case of EPS, as its weight is greater than its volume, which makes it viable for reuse and commercialization.
Currently, effort has been focused on plastic reuse due to the problem that it represents, such as the increase in plastic generation, the large variety of these types of materials as well as possible combinations of plastics in one piece of waste. The most widely used methods for plastic recycling and reuse are chemical and mechanical recycling, the latter being the most widely used due to its low cost and reliability (Hamad et al. 2013). Energy recovery has also become a cost-effective solution not just for polymers present in general and municipal solid waste (Al-Salem et al. 2009), but as well for the majority of solid waste generated in cities where the most widely used energy recovery methods include heat treatments such as incineration,

Please cite this article as: Solano J.K.M., Orjuela D.Y., Betancourt D.J.S., 2017, Determination and evaluation of flexural strength and impact, flammability and creep test through dma, (dynamic mechanical analysis) for mixing expanded polystyrene and polypropylene from municipal solid waste, Chemical Engineering Transactions, 57, 1339-1344 DOI: 10.3303/CET1757224

gasification and other methods such as anaerobic digestion for example (Fodor and Klemeš. 2011). It is estimated that between 1.03 and 1.55 TWh of electricity can be produced annually if all plastic and other mixed waste are processed in pyrolysis and the respective technologies for obtaining fuel derived from waste (Varbanov et al. 2015). For this project, mechanical recycling was selected as the extraction method of the polymer mixture.
Regarding the mixture of plastic waste, the use of recovered expanded polystyrene has not been widely used, as the mixtures that contain high-density polyethylene (HDPE), low-density polyethylene (LDPE) and polypropylene (PP) are the most widely studied due to their large consumption. Stress, compression and rupture tests have been performed on all of the above, in which acceptable strength and stiffness were found for light-weight construction applications, demonstrating non-linear behavior and plastic deformation (Bajracharya et al. 2016). These plastic materials are used all over the world in applications such as bags, games, containers, piping (LDPE), household appliances, wrappers, industrial films, gas lines (HDPE), battery cases, as well as automatic and electric components (Achilias et al. 2007). One application that is considered viable for the reuse of recycled plastic waste and materials is in concrete mix as an environmental-friendly construction material that has caught the attention of researchers in recent years and several studies have been published on the behavior of concrete that contains recycled plastic waste and materials (Gu and Ozbakkaloglu, 2016).
For the specific mixture of the two materials that this study focuses on, stress-strain and hardness tests have been performed, and thermogravimetric analyses were carried out, in which the polypropylene is virgin and only has expanded polystyrene as recovered material from urban solid waste, achieving favorable tests results, especially with regards to hardness (Betancourt and Solano).
For this reason, PP was selected as the mixing material with EPS, therby complementing these types of studies with a mixture analysis of these two completely recovered plastic materials and to develop other types of tests for them, such as bending strength, impact resistance, flammability and creep tests through DMA, which help to characterize the newly obtained materials and thus being able to determine a wide range of possible applications, in which it is expected that main applications could focus on the construction industry, automotive parts manufacturing and different objects that require the use of plastics in their production.

2. Materials and Methods

2.1 Variable selection

Even though for this type of research in which the main variables to be taken into account are the components' particle size and the composition of the mixture, in previous studies that involved these two variables, particle size is non-determining for the characterization of this specific type of mixture (Betancourt and Solano, 2016), which is why tests based on the compositions: 50% PP - 50% EPS, 90% PP - 10% EPS, 70% PP - 30% EPS, 90% EPS - 10% PP and 70% EPS - 30% PP, were established.

2.2 Rod specimen production

For both expanded polystyrene and polypropylene, recovered material from urban solid waste was used for the production of the rod specimens, both of which met the quality conditions for the process. Once the materials were obtained, the preparation of the rod specimens began, and in accordance with the experimental design, the rod specimens were developed through the following phases:
Phase 1, Material Mixture: 45 grams of the polypropylene and polystyrene mixture are added to an internal mixer, depending on the proportions defined in the experimental design, under the following torque variables: $>$10 newton meters and an average temperature of 190ºC. The materials are mixed through two counter-rotating screws, one of which rotates three times faster than the other, which delivers as a result, a homogenous mixture of the two materials.
Phase 2, Material Cutting: The homogenous mix from the internal mixer is added to a knife mill, in which the blades shred the material, which now homogenous in particle size, falls onto a mesh, thus creating the granulated material for the production of the rod specimens.
Phase 3, Compression Molding: 150 grams of the material are added to a 0.1mm thick aluminum mold, after which the mold is taken to a molding press, where the material is preheated for 12 minutes with a distance of 14mm between plates to ensure the mold’s heating, then the material moves to the fusion phase, where it is heated to 190ºC with an initial pressure of 15 BAR for 2 minutes and then to 85 BAR for another 2 minutes. Once the material is fused, it is left to cool for 12 minutes until it reaches 37ºC, then it is taken from the mold, thus obtaining the standardized rod specimens in accordance with the ASTM D 638-02a test method, with which the mixture's physical and mechanical properties are analyzed.

2.3 Performing tests to characterize the mixtures.

Once the rod specimens were obtained, and in accordance to the experimental design, the respective characterization tests were performed. For the flexure test, the ASTM D 790-07 “Standard Test Methods for Flexural properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials” was applied using the Instron 3367 Universal Testing Machine. For the impact test, the NTC 943 Plastics methods were applied to determine the grooved plastic rod specimens’ pendulum impact strength, and the ASTM D256-10 "Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics" were applied. With respect to the plastics horizontal flammability test, the ASTM D635-14 “Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position” was applied and the DMA Q800 V20, 24 Build 43a Double Cantilever flexure test classification machine was used for the Creep Tests through DMA (Dynamic Mechanical Analysis).

3. Results and Discussion

3.1 Flexure Test

Table 1 presents the results from the flexure test of the proposed mixture. It can be seen, that as the EPS percentage increases in the mixture, the maximum deflection stress decreases and deformation at maximum stress, while the modulus of elasticity increases, exhibiting a fragile behavior for all the proposed compositions. This behavior may be directly related to EPS properties, which become brittle and crystalline when trying to obtain a rod specimen from just this compressed material.

Table 1: Flexure Test for the PP and EPS mixtures.

Sample	Maximum Deflection Stress (MPa)	Deformation at Maximum Stress (%)	Modulus of Elasticity (MPa)	Observations
90% PP - 10% EPS	41.350 ± 4.073	3.692 ± 0.671	1796.312 ± 97.013	The sample exhibits brittle behavior.
Uncertainty (95% confidence level) ±	8.229	0.733	130.802	
70% PP - 30% EPS	25.595 ± 1.045	1.571 ± 0.069	1964.186 ± 81.844	The sample exhibits brittle behavior.
Uncertainty (95% confidence level) ±	3.906	0.729	189.984	
50% PP - 50% EPS	21.917 ± 2.142	1.256 ± 0.126	2121.699 ± 153.160	The sample exhibits brittle behavior.
Uncertainty (95% confidence level) ±	5.633	0.429	256.459	
30% PP - 70% EPS	18.911 ± 3.640	1.571 ± 0.069	2481.109 ± 236.398	The sample exhibits brittle behavior.
Uncertainty (95% confidence level) ±	7.424	0.493	195.408	
10% PP - 90% EPS	27.062 ± 3.239	1.215 ± 0.097	3160.905 ± 94.694	X
Uncertainty (95% confidence level) ±	6.952	0.442	249.055	

3.2 Impact Test

Just as with the flexure test, as the percentage of EPS in the mixture increases, the values of the measured properties decrease; in this case the decrease is in impact toughness, with type C defects appearing, in accordance to the reference standard, which consist of a complete rupture in the sample, breaking into one or more pieces as is presented in Table 2.

Table 2: Impact Test for the PP and EPS mixtures.

Sample	Impact Toughness (J/m)	Type of Defect	Observations
90% PP - 10% EPS	19.16 ± 2.57	C	Complete break, total separation of the parts
Uncertainty (95% confidence level) ±	5.046		
70% PP - 30% EPS	10.46 ± 0.34	C	Complete break, total separation of the parts
Uncertainty (95% confidence level) ±	0.674		
50% PP - 50% EPS	13.12 ± 2.79	C	Complete break, total separation of the parts
Uncertainty (95% confidence level) ±	5.475		
30% PP - 70% EPS	11.74 ± 2.50	C	Complete break, total separation of the parts
Uncertainty (95% confidence level) ±	4.899		
10% PP - 90% EPS	10.92 ± 1.92	C	Complete break, total separation of the parts
Uncertainty (95% confidence level) ±	3.767		

3.3 Horizontal Flammability Test

As presented in Table 3, the 90% PP - 10% EPS mixture did not show visible signs of combustion once removed from the ignition source during this test, while the flame surpassed the 25mm reference mark for the 50% PP - 50% EPS mixture, it did not reach the second reference mark of 100mm. For the mixture's other proposed compositions, they cannot be classified according to the reference standard.

Table 3: Flammability Test for the PP and EPS mixtures (continue)

Sample	(T1) Time up to 25mm (s)	(TAE) Time up to 100mm or self-extinguish (s)	(DSQ) Distance without burning between 25-100 (mm)	(DQ) Distance burnt between 25-100 (mm)	(TC) = (TAE - T1) Combustion time (s)	Material classification
90% PP - 10% EPS	36.92 ± 3.72	37.30 ± 3.50	75 ± 0.0	0	0.77 ± 0.65	No visible signs of combustion once removed from the ignition source
Uncertainty (95% confidence level) ±	7.29	6.87	0.0		1.28	
70% PP - 30% EPS	19.69 ± 4.25	88.82 ± 53.52	23 ± 33.0	51.9 ± 33.0	69.13 ± 53.31	No Classification
Uncertainty (95% confidence level) ±	8.33	104.91	64.7	64.7	104.49	
50% PP - 50% EPS	34.65 ± 5.33	143.19 ± 44.04	10 ± 26.5	65.0 ± 26.5	108.54 ± 42.46	The front of the flame surpasses the 25mm reference mark, but does not reach the second 100mm reference mark.
Uncertainty (95% confidence level) ±	10.45	86.32	51.9	51.86	83.22	

Table 3: Flammability Test for the PP and EPS mixtures

30% PP - 70% EPS	12.63 ± 1.30	102.71 ± 6.87	0	75.0 ± 0.0	90.08 ± 8.00	No Classification
Uncertainty (95% confidence level) ±	2.56	13.46	0,0	0.01	15.69	
10% PP - 90% EPS	26.97 ± 5.87	134.31 ± 9.49	0	75.0 ± 0.0	107.34 ± 3.72	No Classification
Uncertainty (95% confidence level) ±	11.5	18.59	0	0.01	7.29	

3.4 Creep Test through DMA (Dynamic Mechanical Analysis)

The creep test measures the deformation of the sample over time after applying a fixed voltage (deformation from creep), and afterwards it monitors the recovery of the deformation of the sample after eliminating the stress (recovery from creep), (Smith and Petty, 2015). Table 4 shows the results of this test for the different proposed compositions, where it can be seen that the change of values for the percentage of constant deformation per minute in the creep zone, and the deformation percentage in the relaxation zone, while maintaining the temperature at 25°C, is not significant when modifying the composition percentage of the mixture.

Table 4: Creep Test through DMA for the PP and EPS mixtures.

Sample	Creep compliance (%/ MPa)	Recovery compliance (%/ MPa)	Observations
90% PP - 10% EPS	0.0017	0.0564	In the creep zone from minute 26.79, a constant deformation percentage rate per minute is observed. In the relaxation zone from minute 50.22, a constant deformation percentage rate per minute is observed.
Uncertainty (95% confidence level) ±	0.00020	0.00930	
70% PP - 30% EPS	0.0108	0.0974	In the creep zone from minute 26.39, a constant deformation percentage rate per minute is observed. In the relaxation zone from minute 50.05, a constant deformation percentage rate per minute is observed.
Uncertainty (95% confidence level) ±	0.00141	0.02676	
50% PP - 50% PS	0.0046	0.0661	In the creep zone from minute 26.39, a constant deformation percentage rate per minute is observed. In the relaxation zone from minute 49.93, a constant deformation percentage rate per minute is observed.
Uncertainty (95% confidence level) ±	0.00052	0.01218	
30% PP - 70% EPS	0.0026	0.0557	In the creep zone from minute 26.50, a constant deformation percentage rate per minute is observed. In the relaxation zone from minute 50.05, a constant deformation percentage rate per minute is observed.
Uncertainty (95% confidence level) ±	0.00029	0.0091	
10% PP - 90% EPS	0.0016	0.0463	In the creep zone from minute 26.45, a constant deformation percentage rate per minute is observed. In the relaxation zone from minute 49.99, a constant deformation percentage rate per minute is observed.
Uncertainty (95% confidence level) ±	0.00018	0.00683	

4. Conclusions

The synthesis of these two polymers to obtain mixtures of recovered EPS and PP in different composition percentages allows us to demonstrate a viability indicator for the study of the material's main physical and mechanical properties. However, the homogeneity of the mixture must be ensured, for which carrying out a scanning electron microscope (SEM) test is recommended to determine the distribution of the phases in the synthesis. The values of the properties measured for the proposed mixtures of PP and EPS decrease as the EPS percentage increase, as a result the 90% PP - 10% EPS mixture has the highest values. Therefore, more detailed studies must be performed, taking into account this composition and its variations in values close to these percentages, which will enable a detailed revision of possible applications of the suggested mixture, thus introducing this material to the recycling chain. Even though the mixture had better values in the properties analyzed, it only contains 10% EPS, a waste problem. It is important to stress that this mixture improves upon the flammability characteristic and would allow for a type of waste, which has a low rate of commercialization and a high environmental impact, to be used when it is available at landfills, thus ensuring alternatives to introduce this material into the production cycle. However, the percentage could be increased to close to 10%, for which it is necessary to continue analyzing the properties of this mixture close to this value.

Due to the fact that PP and EPS are combustible materials, from the values obtained in the 90% PP - 10% EPS mixture during the horizontal flammability test, it can be inferred that this mixture significantly improves the characteristics of the material on the grounds that it does not show visible signs of combustion once it is removed from the ignition source. Likewise, taking into account the obtained values for the flexure and impact tests in the same mixture proportions, the material could be used to manufacture light-weight materials as well as automotive or construction parts.

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