Thermochemical study of the briquetting process of mattress foams

María A. Garrido, Rafael Font, Juan A. Conesa*

Department of Chemical Engineering, University of Alicante, P.O. Box 99, E-03080
Alicante (Spain)

*Email: mangeles.garrido@ua.es

Graphical abstract

Abstract

The production of flexible polyurethane foam (FPUF) briquettes has been tested at four different temperatures (160, 170, 180 and 190°C) and with four different compacting pressures (17, 24, 35 and 48 MPa), selecting 180°C and 35 MPa as the best briquetting conditions. In addition, heterogeneous briquettes have been moulded employing 10, 18 and 25% of viscoelastic

memory foam (VMF) with FPUF and the same proportions for latex foam (LATEX) with FPUF, at 180°C and 24 and 35 MPa of compacting pressure. For VMF+FPUF briquettes mixtures of up to 18% of VMF showed high quality, whereas this proportion decreased by up to 10% for LATEX. The FTIR and TG-IR analyses were conducted to investigate the mechanism of adhesion bonding in heterogeneous briquettes considering that the FPUF acted as a binder. The temperature (180°C) and pressure (35 MPa) selected to mould the heterogeneous briquettes seem to be enough to achieve the break of part of the urethane bond present in the FPUF improving the mobility of long polymeric chains which allowed the bonding of different materials.

Keywords: Flexible polyurethane foam; viscoelastic memory foam; latex foam; briquette, FTIR analysis, TG-IR analysis

1. Introduction

The economic and technological development, as well as the demographic rise, have brought about an increase in waste production every year. In 2011, the total waste production in the European Union (EU) was 2.5 billion tonnes, of which only an average of 40% of municipal waste was recycled, 23% incinerated and 37% landfilled. Nevertheless, some Member States exceed 90% of landfilled waste [1]. This assumes that it is necessary to improve the resource efficiency in order to reduce the raw material dependency and greenhouse gas emissions. To achieve these objectives, in July 2014, the European Commission (EC) published the modification of six existing waste directives among which was Directive 1999/31/EC on the landfill of waste. In addition, the range of wastes considered “municipal waste” was widened, including in this group bulky waste (white goods, furniture, mattresses). The targets proposed by the EC in relation to landfill were:

- After 1 January 2025: only 25% of non-hazardous waste generated the previous year could be landfilled.
- After 1 January 2030: the rate will be reduced up to 5%.

With this new legislation, the EC is forcing alternative options to be considered for the management of wastes such as mattresses which besides the fact that they are high volume wastes, they are also very difficult to decompose in natural conditions [2].

The European Bedding Industries Association (EBIA) presented the real situation of recycling mattresses in the General Assembly in Budapest on September 2014, remarking that from the 30 million mattresses that reach the end of life every year, 60% go to landfill and 40% are incinerated, which means that for the moment recycling has not been considered as a possible solution for the end of life of these wastes. The production of mattresses in Europe in 2013 was distributed in the following manner: 45% spring mattresses, 42% polyurethane foam (PUF), 11% latex and the rest of other compounds. Spring mattresses need to be dismantled before recycling. On the other hand, PUF and latex are two thermoset materials that cannot be re-melted and re-moulded once cured [3].

With respect to polyurethane foam mattresses, two different materials are involved: flexible polyurethane foam (FPUF) and viscoelastic memory foam (VMF), also known as memory foam. Flexible polyurethane foam is obtained from the reaction between a diisocyanate (toluenediisocyanate (TDI) or diphenylmethane diisocyanate (MDI)) and a hydroxyl-polyether. Carbon dioxide is employed as the blowing agent that comes from the reaction between diisocyanate and water. The apparent density of FPUF for mattresses ranges from 18 to 48 kg/m³ [4]. Viscoelastic memory foam is produced with the same raw materials as FPUF, but adding certain additives to provide the property of regaining its original shape after undergoing a deformation. This fact is that responsible for the term viscoelastic memory foam, but other expressions are employed to refer to these types of foam: memory foam, slow recovery foam and controlled recovery foam. The typical range of apparent density for these kinds of foam is from 32 to 96 kg/m³.

Latex mattresses are produced using natural latex (called natural rubber, NR) as well as synthetic latex. The first material comes from the liquid extracted from the rubber tree that originates in regions around the Equator. Synthetic latex on the other hand, is mainly styrene butadiene rubber (STB) obtained from the polymerization of styrene and butadiene [5]. The latex apparent density is typically around 64 kg/m³ and higher.

The recycling of mattresses has not been developed up to now mainly due to the high costs associated and the hygienic problems related to dismantling. However, for years a number of recycling and recovery methods for polyurethanes, which account for 42% of the mattress production, have been developed. These techniques can be classified into four groups: mechanical recycling, chemical processing, thermochemical processing and energy recovery. Mechanical recycling basically consists in employing the waste as a filler of new polyurethane products which involves a reduction in raw material costs. The first step in mechanical recycling is regrinding (or powdering) polyurethane into powder employing special knife cutters or different types of mills up to a final particle size between 200 and 100 µm [6]. After that, a limited percentage of the powder is mixed with raw material and binders and this mixture is subjected to heat and pressure

to achieve other products with good properties. This technique presents the disadvantage that it can only be applied to some cheap products which means that it has a limited market.

The polymerization of polyurethanes is an irreversible process however, employing chemical reagents, catalysts and heat, it is possible to obtain monomer polyol and isocyanate with a very high purity. This is the basis of different chemical recycling methods such as glycolysis, hydrolysis, the amine method and the phosphate ester method; glycolysis is one of the most studied processes in recent years [7-13]. Monomers recovered in chemical recycling processes may replace up to 50% of virgin materials [14], but to achieve this purity of final monomers the process should be really well optimised involving a high cost in the final products. This fact means that chemical recycling is less economically competitive than production with only virgin materials [15]. On the other hand, the long lifetime of polyurethane materials, 10 years [16], and the rapid change of the markets make it difficult to achieve the correct optimisation of the chemical recycling process [17].

Different thermochemical recycling process can be considered. Pyrolysis, which consists of using the waste stream to obtain fuel, some monomers and other chemicals by heating the polyurethane under an oxygen-free atmosphere [18]. Air gasification assumes the presence of a poor oxygen atmosphere and would produce an exothermic process where ashes and synthesis gas are evolved [19]. Hydrogenation, which is between both pyrolysis and gasification, where the heat effect and the high pressure of hydrogen are employed to produce gases and liquid products.

Finally, energy recovery should be selected only when the polyurethane waste cannot be recycled by another method, although it is preferable to landfill as demonstrated by Lanoë et al.[20] in their study of the environmental impact factor of the life cycle of bedding products. However, the high calorific value of polyurethanes near to coal [2], the reduction of the waste volume around 99% and the destruction of harmful foam agents [17] make burning a good method for high volume polyurethane waste such as mattresses without any environmental risks [21].

Regardless of the recycling technology employed, the transport costs from the collection point to the recycling industry play a key role in feasible polyurethane recycling, due to the low apparent

density and the high volume of polyurethane foam. This means that firstly the densification of the foam should be dealt with independently of the selected recycling method; briquetting and baling are the common techniques for compacting rigid and flexible polyurethane foam, respectively [16]. Briquetting is the most known compacting process by employing the mechanical and chemical properties of materials to achieve a compact block (briquette) without binders or additives, only pressure and heat. This technology is mostly employed for compacting biomass [22-24], but it can also be used to produce briquettes from the mixture of plastic waste and biomass [25-27], municipal solid waste [28] or mixtures of plastic wastes [29, 30].

Baling is the most used process to compact flexible polyurethane foam and consists of pressing the material, without heat, until the final dimension is achieved and then the bale is bound in order to prevent it from expanding again. Some authors postulated [16, 30] the high volumes of this type of foam could not maintain the compressed shape due to this elastic memory, making baling necessary immediately after the compression.

In conclusion, the densification of flexible foam is extremely important in its management, not only during transportation but also by the increase of the burning characteristics. It would be an advantage in energy recovery or thermochemical recycling.

On the other hand, in Spain only one factory recycles mattress waste, which means that to achieve the rates proposed by the EC [1] for reducing landfilled waste, it would be necessary to promote other waste management such as thermochemical recycling or energy recovery. The reduction of the volume of mattress waste is essential to make these techniques more economically attractive, and the briquetting process could be a good option.

Therefore in this study, the authors propose to establish the best conditions (pressure and temperature) to obtain homogeneous briquettes made of FPUF and heterogeneous briquettes from different mixtures of FPUF with VMF and LATEX.

2. Material and Method

2.1. Materials

Flexible polyurethane foam (FPUF) latex foam (LATEX) and viscoelastic memory foam (VMF) were obtained from a landfill in Alicante (Spain). The apparent density was determined following the UNE-EN ISO 845:2009 method [31]. For the determination of the Net Calorific Value, an AC-350 LECO Calorimetric Bomb was used. The results are shown in **¡Error! No se encuentra el origen de la referencia.**, where it can be seen that the FPUF has the lowest apparent density and calorific values, meanwhile latex presents an apparent density three times higher than FPUF and a calorific value up to six times higher.

Table 1

These materials were cut into pieces of 1 cm side square section and about 2 cm in height for the briquetting process.

2.2. Briquetting process

The apparatus employed to make briquettes consists of a heated cylinder with 5 cm in diameter, a base which can be removed to remove the briquette from the bottom of the cylinder and a piston which is introduced into the cylinder; the material/briquette becomes trapped between the piston and the base. The briquetting system is inside a furnace with temperature control; the thermocouples are very close to the sample. A hydraulic system pushes the piston towards the base of the cylinder to compact the material with the desired pressure.

Four different temperatures, 160, 170, 180 and 190°C and four pressures, 17, 24, 35 and 48 MPa were selected to study the compaction of 20 g of flexible polyurethane foam.

The material was preheated at a selected temperature for 5 minutes before applying pressure. Afterwards, the pressure was increased progressively to achieve the desired value which was maintained for 2 seconds.

Heterogeneous briquettes were obtained by mixing flexible polyurethane foam with viscoelastic memory foam or latex foam (secondary foam) in proportions of 10, 18 and 25% in weight of secondary foam; the total mass of the blends was 20 g. The compaction temperature used in these runs was 180°C and two different pressures, 24 and 35 MPa.

The briquettes were weighed and their diameter and length were measured to determine the apparent density. In some samples, the bottom of the briquettes had a curvature, in such a way that the height in the middle of the briquette was higher than at the edge. Therefore, bearing in mind the shape of the briquette, the apparent density was calculated employing the following equation (1):

$$\rho_b = \frac{m_b}{V_b} \left[\frac{kg}{m^3} \right] \quad (1)$$

where:

- V_b = briquette volume (m^3) considering the shape of the briquette
- m_b = briquette weight (kg)

The compaction ratio was obtained for the FPUF briquettes as the quotient between briquette density and the initial density (2):

$$\text{Compaction ratio} = \frac{\text{Briquette density}}{\text{Initial density}} = \frac{\rho_b}{\rho} \quad (2)$$

In order to evaluate the quality of the briquettes, the curvature ratio at the bottom of briquette was calculated by the following expression (3); the briquettes were better when this parameter was nearer to 1

$$\text{Curvature ratio} = \frac{H_m}{H_e} \quad (3)$$

where:

- H_m = briquette height in the middle (cm)
- H_e = briquette height at the edge (cm)

In order to verify the mechanical resistance of the briquettes obtained, a similar procedure to that employed by Antwi-Boasiako et al. [32] to determine the shatter index of sawdust briquettes was performed in this study. The shatter index records the percentage of material retained on the sieve after dropping the briquettes from a specific height and gives information from the briquette resistance to handling and transportation. In this case, the briquettes were dropped three times from a height of three metres, with impact energy with the floor of 0.6 J each time.

In addition, the high calorific values were calculated for briquettes considering the apparent density of the briquettes and the initial mass of each type of foam.

2.3. FTIR and TG-IR analysis

In order to know the bonding mechanism of briquettes, the functional chemical groups of briquettes and raw material were analysed by attenuated total reflection-Fourier transform infrared spectroscopy (ATR-FTIR, Jasco FTIR-4700), acquiring the absorbance peaks in the range of 500-4000 cm^{-1} . Also, a thermogravimetric-infrared spectrometry analysis (TG-IR) was performed to study the decomposition of raw material and briquettes. For this purpose, a PerkinElmer STA6000 thermobalance and a Nicolet 6700 FT-IR spectrometer were employed using nitrogen as the carrier gas with a flow rate of 60 mL/min. About 7.5 mg of sample was placed in the crucible and heated from 30°C to 950°C with a heating rate of 10°C/min. The gases evolved were analysed by IR spectroscopy for the 4000-600 cm^{-1} region measuring the absorbance of the peaks detected.

3. Results

3.1. FUPF Briquettes

Figure 1 shows the briquettes obtained in the compaction experiments of FPUF, where it can be observed that with 17 MPa of pressure, temperatures of 160°C and 170°C were not high enough to achieve acceptable briquettes. The curvature of the bottom mentioned previously is visible in some briquettes such as those performed with 24 MPa of pressure and 160°C or 170°C, among others.

In view of these pictures, it appears to be that the temperature has a higher effect than the pressure in the compaction process, within the interval studied.

Figure 1

The calculated densities for each FPUF briquette performed are shown in Table 2. The density of FPUF briquettes increased significantly with the temperature and was higher when the pressure rose.

Table 2

Figure 2 compares the effects of pressure and temperature in the compaction ratio of FPUF briquettes. There are clearly two different tendencies. The runs performed at 160 and 170°C show

an increase with a more moderate pressure than those developed at 180 and 190°C. FPUF reached a density 37 times higher than the initial one at 190°C with 48 MPa of pressure whereas, at 160°C at the same pressure, the final density was 24 times higher. At 170°C, the briquettes were similar to those obtained at 160°C and a slight rise in the compaction ratios was obtained. This fact confirms that temperature plays a more important role than pressure in the briquetting process. Obviously, the most compacted briquettes were obtained at 190°C, but there was no important difference between these briquettes and those obtained at 180°C. Therefore, the best temperature to produce the briquettes seems to be 180°C, bearing in mind the energetic requirements. This temperature was also selected by Quadrini et al. [15] for the direct moulding of foam scraps from motorcycles seats. They made discs of 190 mm in diameter and 6 mm in thickness from 150 g of recycled particles working at 180°C and 4.2 MPa to achieve products with a density close to 1 g/cm³. It is important to remark that, in spite of the low pressure employed by Quadrini et al. [15] (4.2 MPa) to compact 150 g of foam particles (around one order of magnitude lower than those selected in the present study), they achieved an increase in the density of the material up to 14 times; in this case, the moulding time was the critical factor. While we applied the pressure to the foam for only 2 seconds, they maintained the recycled particles under 4.2 MPa and 180°C for 15 min. which could bring about a significant increase in the compacting process costs.

Figure 2

In all cases, the briquettes obtained in this research were blocks with some degree of flexibility but without grainy or filament particles; they were also stable and without large holes. Consequently, the briquetting process was successful.

With reference to the quality of the briquettes, **Figure 3** shows the curvature ratios obtained. When the pressure was lower than 24 MPa, the briquettes had a high curvature ratio which means that they were of bad quality. The temperature did not seem to be a critical factor in this parameter although, as expected, when the temperature increased, the bottom of the briquettes presented less

curvature at the same pressure. A curvature ratio of about 1.2 could be a good value for the briquettes, with a pressure of 35 MPa sufficient to achieve this quality at 180°C.

Figure 3

Only the briquettes made at 17 MPa and 160 and 170°C broke after the three falls from 3 m. whereas the rest of the briquettes passed the mechanical resistance test. Additionally, the same apparatus employed to make briquettes was used to analyse the maximum compression pressure supported by the briquettes without undergoing a permanent deformation. A pressure of 70 MPa (double that of the selected working pressure) was set at the expected compression pressure supported by the briquettes, and the briquettes that passed the gravitational fall test also supported 70 MPa with no change in their shape.

In conclusion, the conditions proposed to produce briquettes of flexible polyurethane foam were 180°C and 35 MPa.

The European Committee for Standardization established a series of standards for wastes to employ them as fuels in the cement industry. A mean net calorific value of 22 MJ/kg is one of the characteristics that the waste should meet. Flexible polyurethane foam presents combustion properties of 24 MJ/kg (475 MJ/m³) high calorific value. However, the compaction of the material improved the volumetric calorific value considerably [22] (**Table 3**), which is of great benefit for the cost of transport and storage of this waste. At 180°C and 35 MPa of compacting conditions, the volumetric net calorific value increased 28 times its initial value.

Table 3

3.2. Heterogeneous Briquettes

As mentioned previously, heterogeneous briquettes made of FPUF mixed with VMF and LATEX were also tested. Before performing the study of briquetting mixtures, we attempted to compact the materials separately, but no acceptable briquettes were obtained. The VMF foam, due to its property of recovering its shape after a deformation, could not maintain the form, whereas the LATEX foam was converted into granules when it was compacted. Therefore, we considered carrying out the compaction of different blends of these wastes with FPUF because it

is more abundant than the other two wastes and to know the maximum amount of secondary foam that FPUF could accept.

Figure 4 shows the briquettes obtained from the different blends of FPUF with VMF and LATEX foams at 180°C and 24 and 35 MPa of compacting conditions. It is deduced that with 25% of secondary foam, 24 MPa of pressure was not high enough to achieve a correct compaction of blends, whereas at 35 MPa acceptable briquettes were obtained from both mixtures.

The gaps present in heterogeneous briquettes for the blends with 10 and 25% of VMF and at 24 and 35 MPa, respectively, did not affect the resistance of the final product and they were considered a valid final product.

Figure 4

The apparent density of heterogeneous briquettes is shown in **Table 4**. General behaviour is shown; the briquettes of FPUF and VMF were those that presented the highest densities. Bearing in mind that the composition of FPUF and VMF foam is similar, an expected type of behaviour was obtained because when both foams were heated and they became more flexible, the cohesion between two flexible materials allowed briquettes with high quality to be obtained. The presence of FPUF prevented the recovery of the shape of the VMF foam and played the role of adhesive in the briquettes. However, when the content of VMF was 25%, the briquettes presented some gaps whereas the briquettes obtained from the mixture of FPUF and 25% of LATEX in the same condition did not show these imperfections. This means that in spite of VMF having a similar composition to FPUF, when the content of VMF is 25% or higher, the viscoelasticity of this type of foam, became so important that it avoided the correct cohesion of the briquette.

On the other hand, the briquettes obtained with LATEX as secondary foam, presented worse quality in general due to the decomposition of the LATEX foam to granules in the compaction process. Only briquette carried out at 35 MPa with the lowest proportion of LATEX seemed to present the best quality and had the highest apparent density.

Table 4

In order to more clearly analyse the effect of secondary foam content in the densification of the mixtures, the compaction ratio has been calculated considering the amount of each type of foam in the sample, the corresponding density of each of them and the final volume of the briquette obtained. The results are shown in **Figure 5**

Figure 5

As can be seen, the effect of pressure was higher in the FPUF+VMF mixture than in the FPUF+LATEX samples, increasing by around 41% and 45% the compaction ratio for the FPUF+10% VMF and FPUF+18% VMF samples, respectively, when the pressure increased from 24 MPa to 35 MPa. For the mixtures of FPUF+LATEX in the same proportions, the compaction ratio also rose when the working pressure increased, but lower values were obtained, 24% for FPUF+10% LATEX and 11% for FPUF+18% LATEX.

The increase in the secondary foam content from 10% to 18% involved a reduction of around 16% of the compaction ratio in all cases except for the FPUF+LATEX blend at 35 MPa where the contraction achieved was 30% (from 25 to 18 compaction ratio).

In conclusion, for the heterogeneous briquettes and bearing in mind the quality of the final products and the working conditions employed, the selected briquettes would be: FPUF+18%VMF at 35 MPa and FPUF+10%LATEX at the same pressure.

The volumetric high net calorific values have been calculated for the heterogeneous briquettes considering the content of each foam and the volume of the briquette. **Table 5** shows the values obtained.

Table 5

Comparing the high calorific value of the briquette with 18% of VMF foam made at 35 MPa, it can be observed that this value increased 5 times with respect to the calorific value of VMF foam (¡Error! No se encuentra el origen de la referencia.), whereas for the FPUF+10% LATEX blend at 35 MPa, the value obtained was 11 times higher than NCV of LATEX foam.

The mechanical resistance test was more important for these types of briquettes than for homogeneous briquettes due to the different behaviour in the compaction conditions of the different foams. The acceptable heterogeneous briquettes achieved in these runs (all runs except that carried out with 25% of secondary foam) did not undergo any deformation after falling from three metres three times in a row. These briquettes were also submitted to 70 MPa of compression pressure without undergoing any deformation. Therefore, all the briquettes obtained showed good mechanical resistance in spite of small gaps observed in some of them.

In addition, in order to analyse the expansion of the final products, the briquettes were stored for 12 months in a normal environment without any special conditions. Afterwards, all the briquettes were measured again and no change was observed. This means that flexible foams can be compacted and their compressed shape remains for a long time, in contrast to that postulated by some authors previously [16, 30] about the compaction of this type of foam. These authors argue that due to the resilient nature of polymer, during the compaction, the flexible cell walls from the closed cell structure are not crushed maintaining the initial shape, which makes it necessary to bale the compacted material immediately after compression. However, the combination of moderate temperature and moderate pressure makes the baling process unnecessary.

3.3. Bonding mechanism

As mentioned previously, firstly, the briquetting of the VMF and LATEX was attempted individually but no acceptable briquettes were obtained. It was therefore decided to perform the compaction of different blends of these foams with FPUF, which presented good compacting properties. The best heterogeneous briquettes were obtained from the mixture of FPUF with 18% and 10% of VMF and LATEX, respectively, working at 180°C and 35 MPa. From these results, it could be said that the FPUF acted as a binder in the heterogeneous briquettes and therefore some transformation should have occurred in the chemical structure of FPUF in the compacting condition.

In order to investigate this transformation during the briquetting processes, the molecular structure study of the FPUF (raw material) and of the homogeneous briquette of only FPUF

(named Briquette from now on) obtained in the same operating conditions as the heterogeneous briquettes (180°C and 35 MPa) were studied, employing a FTIR spectrometer. FTIR is a useful technology to investigate the chemical structure of the surface of the material that has been employed in the past to characterise the compacted materials [33-35].

The analysis was performed five times for each material obtaining really good reproducibility of results. The results obtained in the characterisation of the FPUF and the Briquette are shown in **Figure 6**. As can be observed, during the briquetting processes there was no significant change in the chemical structure of the FPUF, which means that the polymer managed to compact without undergoing any partial degradation avoiding the loss of combustion properties. The same chemical bonds were detected in the FPUF and the Briquette, but small changes in the intensity of some of these peaks were detected, e. g. the peaks located at 1013, 1086, 1720 and 3286 cm^{-1} , reducing their intensity in the Briquette with respect to the FPUF. These wave numbers correspond to the absorption bands of symmetric stretching vibration of the C-O-C group (1013 and 1086 cm^{-1}), the carbonyl group (C=O) at 1720 cm^{-1} and the N-H group (3286 cm^{-1}) [36].

Figure 6

At this point, it is important to remember that polyurethanes are polymers made from the reaction between diisocyanates and at least two reactive hydrogen atoms of the polymer precursor diol or polyols, obtaining the urethane bond that has the chemical structure shown in **Figure 7**.

Figure 7

The groups present in the urethane bond are C-O-C (C-O-R), C=O and N-H, so the reduction in the intensity of the peaks for these groups in the Briquette (**Figure 6**) could mean that during the briquetting process some of these urethane bonds were destroyed improving the mobility of long polymeric chains. This allowed the FPUF to start flow filling the gaps between neighbouring layers of FPUF and/or the pieces of secondary foam (VMF or LATEX). After cooling of the briquette, the urethane bonds remaining in the foam contributed to the stability of the briquette.

In order to confirm the partial destruction of the urethane bond in the briquetting process, a study of the gases evolved during the thermal degradation of both the FPUF and the Briquette,

was carried out by TG-IR analysis. Also, in this case, the studies were repeated five times to ensure the results.

Nitrogen was selected as the carrier gas to avoid oxidation or other undesired reactions and the samples were heated from 30 to 950°C at 10°C/min. The TG and the derivative (DTG) curves from the thermogravimetric analysis are shown in **Figure 8**.

Figure 8

The FPUF and the Briquette decomposed in two main steps; the last weight loss (around 700°C) was that corresponding to the presence of CaCO_3 as part of the dirt in the foam [36]. In **Figure 8B**, the beginning of the first step has been expanded to see how the Briquette started to decompose around 140°C, and FPUF did so at 180°C, just the temperature selected to make homogeneous and heterogeneous briquettes. It is known that the first degradation step in polyurethanes is related to the rupture of hard segments by the breaking of the urethane bond [37, 38]. The effect of pressure at 180°C could favour the breaking of the urethane bond. Apart from this fact, it is also important to remark that the compacted material presented more resistance to degradation obtaining at the end of the first step 29% of Briquette degraded vs. 32% of the FPUF. This difference was more visible in the second step where the FPUF presented its maximum degradation around 380°C whereas for the Briquette the value was 395°C.

A higher amount of residue was obtained in the Briquette pyrolysis (7.1%) than in the FPUF pyrolysis (5.9%) (**Figure 8A**), which also involved a lower production of volatile compounds. This behaviour was observed previously by Jiang et al. [34] in their study of mixed pellets from sewage sludge (SS) and Chinese fir. In this case, the increase of residue was a consequence of the higher sludge ratio in the final product. However, in the present study, the Briquette was made from only FPUF, so the changes in the molecular structure of the FPUF during the briquetting process should be responsible for the increase in the residue production.

The oxidation of the final product obtained by the pyrolysis of the Briquette and the FPUF produced the same amount of ash. This can be seen in **Figure 9** where a final combustion stage was added at the end of the pyrolytic degradation study exchanging air for nitrogen as the carrier gas and maintaining a temperature of 950°C for 10 minutes. Auaprakul et al. [25] also found a

similar ash content in pellets produced with only corn stover at different compacting conditions such as moisture and preheat temperature.

Figure 9

From the results obtained in the IR analysis during the pyrolytic degradation, the spectra acquired in the first and second step for both materials can be found in **Figure 10A** and **Figure 10B**, respectively. As can be seen, similar spectra were obtained from both materials but once again, changes in the peaks intensity were detected.

Figure 10

In the first step (**Figure 10A**) the peak located at 2276 cm^{-1} experienced an important decrease from the FPUF to the Briquette. This peak is characteristic of the isocyanate group (-NCO) which releases directly from the urethane bond. Similar behaviour was detected for the peak of stretching vibration of the -NH group (3367 cm^{-1}) which also came from the urethane bond.

In the second step (**Figure 10B**) the highest peak intensity variations were observed for the stretching vibration of the C-O-C bond (1107 cm^{-1}) and the bend vibration of the -NH group (1531 cm^{-1}), both of them present in the urethane bond.

From the results obtained in the FTIR and TG-IR analyses, it can be concluded that the briquetting process for homogeneous and heterogeneous briquettes occurred by the breaking or weakening of part of the urethane bonds contained in the FPUF. The fracture of the hard segments allowed better mobility of the polymeric chains to fill the gaps present and form new bonds.

4. Conclusions

Good mattress briquettes have been obtained in the laboratory. 35 MPa compacting pressure and 180°C temperature were selected as the conditions to produce FPUF briquettes of great quality. Under these conditions, the volumetric net calorific value of FPUF increased 28 times, from 475 to 13279 MJ/m^3 , which meant a considerable improvement in the management of this waste.

On the other hand, mixtures of FPUF with up to 18% of VMF could be produced whereas, for heterogeneous briquettes with LATEX foam, only 10% of this secondary foam presented a good aspect working also at 35 MPa and 180°C. An increase of 5 and 11 times the volumetric net calorific value for the 18% of VMF and 10% of LATEX blends, respectively, was achieved with this densification of the mixture of materials.

The results of the FTIR measurements showed that Briquette made from only FPUF at 35 MPa and 180°C had a lower intensity of urethane bonds than the FPUF. This fact was confirmed by the TG-IR analysis from both materials where a lower residue formation was also obtained during the pyrolysis of the Briquette with respect to the FPUF as a consequence of the structural change of the foam during the briquetting process. The partial loss of the urethane bond and the changes in the molecular structure of FPUF during the briquetting process could be responsible for the bonding in the heterogeneous briquettes.

Neither the pressure (35 MPa) nor the temperature (180°C) selected to achieve good quality briquettes are really high, so this technology can be introduced in a system taking advantage of residual vapour to heat the cylinder. Finally, the briquettes could be employed as fuel in rotary kiln combustion, reducing the dependence on fossil fuels which can lead to the conservation of natural resources.

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Tables

Table 1. Apparent density and high net calorific value of flexible polyurethane, viscoelastic memory and latex foams.

Table 2. Properties of FPUF briquettes

Table 3. Volumetric high net calorific value of the FPUF briquettes.

Table 4. Apparent density (kg/m^3) of heterogenic briquettes obtained from the mixtures of FPUF with VMF and LATEX foams.

Table 5. Volumetric high net calorific value obtained in the heterogeneous briquettes.

Figures

Figure 1. Briquettes obtained from the compaction of FPUF at different temperatures and pressures.

Figure 2. Effects of pressure and temperature in compaction ratio of FPUF briquettes.

Figure 3. Effects of pressure and temperature in curvature ratio of FPUF briquettes.

Figure 4. Briquettes obtained in the experiments performed with FPUF and different contents of VMF and LATEX foams at 180°C .

Figure 5. Evolution of compaction ratio in heterogeneous briquettes with secondary foam content at 24 and 35 MPa.

Figure 6. FTIR spectra of FPUF and Briquette of FPUF made at 180°C and 35 MPa.

Figure 7. Chemical structure of urethane bond.

Figure 8. TG (A) and DTG (B) curves from the thermal degradation under N_2 atmosphere of FPUF and Briquette.

Figure 9. Thermogravimetric analysis of ash production from the Briquette and the FPUF. Expanded the moment when the carrier gas changed from N_2 to Air.

Figure 10. IR spectra registered in the first (A) and second (B) degradation step of the FPUF and the Briquette