A new material with low density and low thermal conductivity using post-consumer Tetra Pak packages

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Abstract. This paper shows the process for making a solid foam from post-consumer Tetra Pak packages at the laboratory level. We have found that it is relatively simple to include the gas phase using an endothermic foaming agent consisting of a mixture of sodium bicarbonate and sodium citrate. We performed the manufacturing by removing the entire paperboard from the container and using a 5% foaming agent through compression molding with hot plates. We achieved an expansion of twice the initial volume and a thermal conductivity of 0.2572 W/mK, which is lower than that of polyethylene 0.33 W/mK, a constituent of lower conductivity within the composite. Thus, we can use the resulting material in the construction industry and the automotive industry that requires low density and low thermal conductivity materials. The developed material is low cost and generates new applications for Tetra Pak waste, which could become an essential point in the packaging recycling chain, thus minimizing its environmental impact.

1. Introduction

Tetra Pak is the world leader in aseptic packaging. Tetra Pak packages allow products considered perishable to be distributed and stored without refrigeration for long periods. Tetra Pak packages consist of 75% paperboard, 20% polyethylene and 5% aluminum. In a year, Tetra Pak produces approximately 190 billion packages that generate a large amount of non-biodegradable waste due to polyethylene [1–3]. As a result, the company promotes annual initiatives to improve waste management, with which it has been able to recover approximately 50 billion packages per year, equivalent to only 26% [1]. The low recycling rate is partly due to the cost of separating the constituents of the Tetra Pak package, especially the polyethylene and the aluminum, which require high-cost technologies [4,5].

From a general perspective, research related to the recycling of Tetra Pak packages has been focused on the production of agglomerates for the construction of furniture and roofing [5–8]. The manufacture of agglomerates consists of shredding and hot compaction to make a composite, either with the three constituents of the post-consumer Tetra Pak packages or only with polyethylene and aluminum (LDPE-Al). Manufacturing methods include hot-platen press compression molding, extrusion molding or rotomolding. In addition, in [7], they show that LDPE-Al can be reinforced with vegetable fibers to improve mechanical properties [7,9].

According to our review, previous investigations have focused on improving the mechanical properties of Tetra Pak agglomerates. Still, the inclusion of a gas phase within the compound
has not yet been explored. These products are called solid foams and cover a range of physical properties that cannot be covered with continuous solids. Among the properties are low density, low thermal conductivity, low modulus of elasticity, low compressive strength, and good acoustic properties, resulting in a wide range of applications in automotive, construction, and marine sectors [10,11].

This paper aims to develop a rigid foam using post-consumer Tetra Pak containers to obtain a material with low density and low thermal conductivity. The solid phase of the foam developed in this research is a composite formed by a polyethylene matrix and a paperboard and aluminum reinforcement. The gas phase is obtained by the action of a foaming agent on the polyethylene, thus generating the cellular structure. This phase has three stages. The first stage consists of the formation of gas bubbles (produced at a certain pressure and temperature conditions), the second stage is the growth of the bubbles and the last step is the stabilization of the structure [12].

The manufacture of foams uses polymer processing techniques. In this case, we use compression molding as the most straightforward and most economical technique. Furthermore, incorporating the gas phase in the agglomerates manufactured with Tetra Pak packages allows us to study new properties [11]. In this case, we investigated the rigid foam’s relative density and thermal properties, resulting in a lightweight material with low heat conductivity that can be used in the construction or automotive industry to improve thermal comfort. Therefore, this manufacturing creates new applications that could become a critical development point for the Tetra Pak packaging recycling chain.

2. Materials
This section describes the proportions of the solid phase and the foaming agent for foam manufacture. In the solid phase, the proportions by weight change depending on the paperboard removed from the container. The initial proportions are 75% paperboard, 20% polyethylene and 5% aluminum. We selected a low-cost foaming agent for the gas phase and determined the percentage by weight based on the resulting material.

2.1. Weight proportions of the solid phase
Taking into account that the polyethylene of the Tetra Pak packages in the foam has a double function: to give cohesion to the paperboard and the aluminum and to generate the cellular structure, we consider different possibilities by removing part of the paperboard from the package as shown in Table 1. In case 1, we perform the experiment with the whole package; in case 2, we perform the separation of a fraction of paperboard, and in case 3, we obliterate the paperboard. In the following, we describe the process for each case. In case 1, we carry out a cleaning process of the Tetra Pak packages to prevent the waste from influencing foam formation dynamics; in case 2, we separate the paperboard by mechanical agitation in water using the hydro-pulping technique. This technique breaks the containers and dissolves part of the paperboard by density difference. Finally, in case 3, we submerged the material obtained by hydropulping (case 2) for 14 hours in an aqueous solution of sodium hydroxide (NaOH) at a concentration of 5% to degrade the lignin of the cellulose, which facilitates the total separation of the paperboard.

| Material       | Case 1 | Case 2 | Case 3 |
|----------------|--------|--------|--------|
| Paperboard (%) | 75     | 31.0   | 0      |
| Aluminum (%)   | 5      | 13.8   | 20     |
| Polyethylene (%)| 20   | 55.2   | 80     |
2.2. Weight proportions of the foaming agent

For the generation of the gas phase, we use a foaming agent consisting of a mixture of sodium bicarbonate (75% in weight) and sodium citrate (5% in weight), according to research [13]. Generally, in the manufacture of polymeric foams, the percentage by weight of foaming agent can vary between 0.5% and 2%. Outside this range, the relative density remains constant. However, the polymer of the foam developed in this work is mixed with paperboard and aluminum, thus increasing the volume of the material to be foamed, so we propose to increase the concentration from 2%, adding in one unit until a uniform bubble dispersion is obtained throughout the composite.

3. Methods

This section establishes the parameters for the manufacture and methods to determine the density and thermal conductivity of the foam. Initially, we perform a thermogravimetric analysis of the foaming agent to determine the temperature range in which there is a higher gas release and relate it to the melting point of the polyethylene. Subsequently, we describe the manufacturing process based on compression molding, and finally, we describe the methods used in the characterization.

3.1. Thermogravimetric analysis of sodium bicarbonate and sodium citrate

Thermogravimetric analysis (TGA) records the weight loss of a sample as the temperature is increased. The temperature range we used was between 30°C and 350°C, the heating rate was 20°C per minute and we used a nitrogen atmosphere. With these conditions, we obtained the curves (TG) corresponding to the solid line in Figure 1 and the differential thermogravimetric analysis (DTG) curves, dashed line in Figure 1. We performed the TGA on the foaming agent to determine the temperature at which there is greater gas release and also to be able to choose a suitable range so that there is no gas loss before crosslinking or expansion of the polyethylene of the Tetra Pak packages.

![Figure 1. TGA curve for the foaming agent sodium bicarbonate and sodium citrate.](image-url)
The equipment used was the NETZSCH TG 209 F1 from the University of Quindío, Colombia; in Figure 1 we observe that at 100°C there is a slight mass change that can be attributed to moisture in the sample. The most significant mass loss of the foaming agent is between 119.6°C and 15.3°C, as shown in the continuous line in Figure 1. In particular, the temperature where the highest mass loss occurs was at 63°C, as shown in the DTG, piecewise line in Figure 1.

Now, considering that the melting point of low-density polyethylene is 114°C [14], the wide temperature range and can influence the dynamics of the bubbles. Consequently, for foam manufacturing, we decided to reduce the temperature range as follows: 130°C for the melting of the polyethylene and 180°C for the decomposition of the foaming agent. The range corresponds to a vicinity of the TG inflection point where there is the highest gas release.

3.2. Compression molding
We used a circular mold with a diameter of 7 cm, which increases the temperature at a rate of 4°C per second. The mold used, see Figure 2, consists of the following parts: two caps located on each of the hot plates for changing the heating elements in case of damage (Figure 2(a)), a lower hot plate to melt the polyethylene of the Tetra Pak (Figure 2(b)), a cylinder for depositing the material (Figure 2(c)), a hot upper plate that allows pressure to be applied while heating the composite (Figure 2(d)), and bolts for complete disassembly of the mold (Figure 2(e)).

We proceeded to grind the material for each of the cases in Table 1. With this procedure, we got particles smaller than 5 millimeters. Then we passed the particles through a sieve to select only those smaller than 0.5 millimeters, this is done to obtain particles similar to those of the foaming agent and guarantee a homogeneous mixture. Then we mix the Tetra Pak particles with the foaming agent. Initially, we use 2% concerning polyethylene and increase it by one unit depending on the resulting material.

To make the foams, we used 12 grams of the mixture, applied pressure of 750 psi, and a temperature of 130°C for 30 minutes to melt the polyethylene and give cohesion to the constituents. Then, we removed the pressure and increased the temperature to 180°C for decomposition of the blowing agent. This process was obtained by trial and error, starting with 8 minutes and increasing it by one minute until the appropriate time was obtained. It is also necessary to provide a space inside the mold for the formation of the bubbles, for which we proposed an initial expansion of 1/5 concerning the initial thickness and adjusted it up to a maximum expansion in which the desired material is obtained (impermeable and without pores on the surfaces). Finally, we suspended the heating system and cooled the mold with air currents to preserve the foam’s cellular structure.

Figure 2. Compaction mold.
3.3. Determination of relative density
An essential characteristic of solid foams is the relative density $\rho$, which can be expressed by the equation $\rho = V_s/V_c$, where $V_s$ is the volume of the solid and $V_c$ is the volume of the foam. The relative density allows us to classify foams into three classes: when it is less than 0.3, we call them low-density foams. When it is greater than 0.6, they are high-density foams, and when their relative density is between 0.3 and 0.6, they are medium-density foams [13].

3.4. Thermal conductivity test
We performed the thermal conductivity test in the characterization laboratory of the Composite Materials Group of the Universidad del Valle Colombia. We used the TPS 500S equipment whose method is standardized in ISO 22007-2 [15] to determine the thermal conductivity, thermal diffusivity and volumetric heat capacity of homogeneous and isotropic materials, as well as anisotropic materials.

4. Results and discussion
This section shows the foams obtained considering Table 1 for the solid phase and the assumptions of section 2.2 for the blowing agent.

4.1. Manufacturing
The fabrication process with the proportions of case 1 in Table 1 resulted in a brittle material, as can be seen in Figure 3(a). This is due to the low concentration of polyethylene, which cannot cover the entire reinforcement and generate the cellular structure. In addition, the material does not show expansion in volume since the contact surface of the foaming agent is greater in the paperboard than in the polymer. With the proportions of case 2 of Table 1, we obtained a fragile material but more stable than the previous one due to the high concentration of the reinforcement; however, it should be noted that in this process, an expansion of 7% concerning the original thickness is achieved (see Figure 3(b)).

![Figure 3](image-url)

Figure 3. Foams manufactured using 2% of the mixture of sodium bicarbonate and sodium citrate.

Figure 4 shows the material we obtained with the concentrations of polyethylene and aluminum of case 3 of Table 1. In this case, the polyethylene covers the entire reinforcement generating a stable material with a dispersion of bubbles in its interior. However, the manufacturing conditions proposed in [13] with 2% foaming agent generate material with areas that present expansion and others that do not, as shown in Figure 4(a). This phenomenon occurs because the foaming agent is not uniformly distributed throughout the composite, so we increase the foaming agent concentration.
Figure 4(b) and Figure 4(c) result from using a 5% concentration of foaming agent concerning the weight of polyethylene. As a result, we obtained a porous face corresponding to the lower plate (Figure 4(b)) and a totally smooth one corresponding to the upper plate, as shown in Figure 4(c). To obtain a foam with pore-free surfaces, we took advantage of the segregation phenomenon and gravitational drainage in the bubbles by increasing the stabilization time, achieving a foam with a pore-free surface and cellular structure inside in a time of 17 minutes.

![Figure 4](image)

**Figure 4.** Polyethylene and aluminum foams; (a) foam manufactured with 2% foaming agent, (b) and (c) bottom and top of foam manufactured with 5% foaming agent.

In addition, we determined an expansion limit by adjusting the height of the foam inside the mold. Figure 5 shows the result of such expansion, which is two times the initial thickness. Therefore, the relative density is 0.5, which classifies it as a medium-density foam. The material obtained from polyethylene and aluminum presented a rigid structure provided by the aluminum and impermeable due to the hydrophobic nature of the polyethylene.

![Figure 5](image)

**Figure 5.** Polyethylene and aluminum foams with twice the expansion of the solid material and pore-free walls.

4.2. Thermal conductivity
We performed thermal conductivity tests on the foam with a relative density of 0.5 since we are interested in the material having high porosity so that the thermal conductivity is low and it is also stable so that it can be handled. According to the characterization performed in the TPS 500S equipment, we obtained that the thermal conductivity is $0.2572 \text{ W/mK}$ and that the thermal diffusivity is $0.1427 \text{ mm}^2/\text{s}$. On the other hand, the polyethylene matrix of the foam has a thermal conductivity of $0.33 \text{ W/mK}$ and a thermal diffusivity of $0.1887 \text{ mm}^2/\text{s}$, which are higher than those of the rigid foam, indicating that the porosity of material significantly reduces these properties even though it is reinforced with aluminum.
5. Conclusion

This paper indicates that rigid foams manufactured from Tetra Pak paperboards could become an essential point of development for the recycling chain to reduce the environmental impact. We show that paperboard can be optimally separated by mechanical agitation and sodium hydroxide. The foaming agent used is non-toxic, easy to process and low cost, resulting in a competitive material in the industry. To obtain a solid foam, we need to remove all the paperboard from the post-consumer packaging and use 5% foaming agent concerning polyethylene to ensure dispersion throughout the material. For manufacturing, we used a pressure of 750 psi to compact the mixture, a temperature of 130 °C for 30 minutes to melt the polyethylene and a temperature of 180 °C for 17 minutes for the decomposition of the foaming agent and the stabilization of the bubbles.

The resulting material was characterized by having a rigid cellular structure provided by aluminum and impermeable due to the hydrophobic nature of polyethylene. The relative density of the foam was 0.5, classifying it as a medium density foam and the thermal conductivity was 0.2572 W/mK, which is lower than that of the constituents. The above makes the foam favorable for developing different products, particularly for construction where robust and low-density materials with low thermal conductivity are needed.

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