
The Effect of Processing on the Structure and Properties of Crosslinked Closed Cell Polyethylene Foams

M.A. Rodríguez-Pérez^{1,*}, O. Almanza², J.L. Ruiz-Herrero¹ and J.A. de Saja¹

¹Cellular Materials Group (CellMat), Condensed Matter Physics Department, Faculty of Science, University of Valladolid, 47011, Valladolid, Spain

²Physics Department, National University of Colombia, Bogotá, Colombia

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ABSTRACT

This paper analyses the relationships between production, structure and properties of a collection of crosslinked closed cell polyethylene foams. Foams with similar densities produced from a similar base polymer and manufactured using three different technologies (high pressure nitrogen solution process, compression moulding and semicontinuous processing) have been characterised. On the one hand, several foam characteristics such as density, cell diameter, cell wall thickness, cell shape, fraction of mass in the edges, gel content, crystallinity and melting temperature have been measured and related to the way in which the foams were produced. On the other hand, three important physical properties such as thermal conductivity, Young's modulus and thermal expansion have been measured analysing the experimental results in terms of the previously cited foam characteristics. The results have shown that the production route used to manufacture the foam strongly influences the foam structure and as a consequence the main physical properties.

1. INTRODUCTION

Polymer foams are two-phase materials in which a gas is dispersed in a continuous macromolecular phase⁽¹⁻⁴⁾. These materials are important items in the economy, and because of technical, commercial and environmental issues, they represent an interesting dynamic in the twenty-first century society. The plastic foam industry is a major segment of the U.S. plastics industry, accounting for about 10% of total commodity resin consumption. This market⁽⁵⁾ is estimated at 3.83 billion kg by 2006 with an average annual growth rate of 2.8%. In terms of

*To whom correspondence should be addressed.
email:marrod@fmc.uva.es, Tel+ 34 983 184035, Fax +34 983423192

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sales, polyolefin foams are ranked at the fourth position, behind polyurethane, polystyrene and poly(vinyl chloride) foams, however polyolefinic materials have the highest average annual growth rate. A value of 3.8% was estimated in 2006, largely based on increasing demand for crosslinked polyolefin foams in market sectors such as: construction, packaging, buoyancy, automotive, medical, including the new and growing field of leisure and sports items.

From a technical point of view a variety of properties, such as light weight, buoyancy, chemical resistance, skin friendly, no water absorption, cushioning performance, sock absorption and thermal insulation have all ensured the success of crosslinked polyolefin foams.

Previous investigations on these materials have focused attention on the structure-property relationships for polyethylene and ethylene vinyl acetate foams⁽⁶⁻¹⁷⁾. These papers have demonstrated that the physical properties of polyolefin based foams depend on many factors, some of which are interdependent. Examples of these studied factors are the mean cell size, the cell wall thickness, the fraction of mass in the edges, the polymer morphology, the chemical composition of the material, the foam density and the gas entrapped. Several physical properties such as thermal expansion, thermal conductivity and mechanical properties have been experimentally and theoretically analysed in the last few years for this kind of materials. The physical mechanisms controlling these properties have also been discussed in the previous papers. However, in previous investigations the production route was not considered in detail.

There are several commercial technologies currently used to produce crosslinked polyethylene based foams. All these methods are characterized by three steps: sheet formation, crosslinking and foaming. Three of the most important technologies (described in section 2 of the paper) are the high pressure nitrogen solution process, the compression moulding process, and the semicontinuous process with crosslinking by irradiation^(3,18). These processing routes use a similar base polymer and are able to produce foams of similar relative densities, i.e. similar porosities. However, the method to produce the cellular structure is different and the cellular structure itself has different characteristics in each type of material. Therefore, different properties for all these materials should be expected.

Taking into account the previous ideas, the main aims of this paper are on the one hand to gain knowledge on the relationship processing-structure-properties for closed cell crosslinked polyethylene foams and on the other hand to find out the sources for the different properties of foams with similar densities and produced from similar polymers, but processed in a different way.

2. FOAMING TECHNOLOGIES AND MATERIALS UNDER STUDY

Low density crosslinked polyolefin foams are commercially produced by a variety of technologies. **Figure 1** shows three of the most important commercially available processes to manufacture these materials. Each technology is briefly discussed in the next paragraphs. More detailed information can be found in the literature^(3,18-21).

2.1 Gas-Solution Nitrogen Process (HP Foams)

In this process, low density polyethylene is compounded with a peroxide curing agent and extruded as a thick sheet which is passed through a hot oven to effect crosslinking. Slabs cut from the extruded sheet are placed in a first autoclave where they are subjected to high pressure (several hundred bars) of nitrogen gas at temperatures above the polymer softening point. Under these conditions, the nitrogen dissolves into the polymer. At the end of the solution stage, and after cooling, the pressure is reduced to zero gauge. Finally, the slabs are then placed under low pressure in a second autoclave and heated above the polymer melting point. Release of the pressure then results in full expansion. The slabs are taken out of the second autoclave and cooled to room temperature.

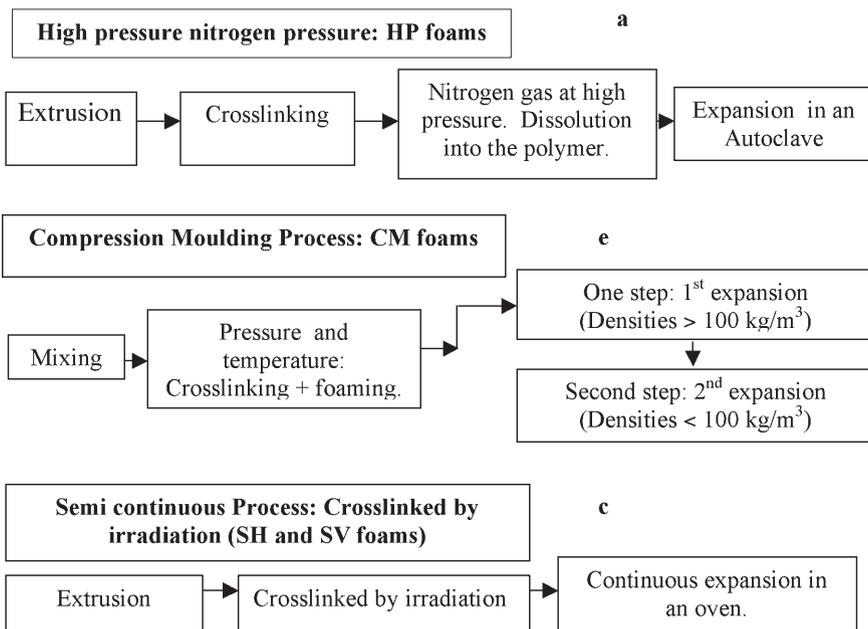


Figure 1. Schematic diagram showing the main steps of the technologies used to produce the crosslinked closed cell polyolefin foams of this paper

These foams are made as essentially rectangular blocks of various sizes (typical size is 1 m x 1 m x 0.035 m) having process skin surfaces. In this paper a 5 mm sheet was removed from the block surfaces before obtaining the samples for testing.

2.2 Compression Moulding Process (CM Foams)

A second process of foam production uses a chemical compound as blowing agent. This technology is used to manufacture foam blocks of high thickness. This foaming process starts with the production of a solid sheet with the following components: the base polymer (LDPE), the foaming agent (azodicarbonamide), the crosslinking agent (dicumyl peroxide) and several additives as processing aids, pigments, activators of the blowing agent decomposition, etc. A solid sheet is obtained from the previous mixture. In a first processing stage, the sheet is introduced into a mould which is closed under high-pressure (>200 bar). The mould is heated; as the temperature rises, the chemical crosslinking starts. Simultaneously, the foaming reaction (decomposition of the foaming agent) also begins generating the gas for expansion. After a period of time, pressure is released giving a first foam expansion. This method is used when high density foams ($\rho > 100 \text{ kg/m}^3$) has to be produced. For foams with densities below 100 kg/m^3 , a second foaming step is necessary. The material obtained in the first step is heated in a second mould to complete the expansion at atmospheric pressure. Then, the material is cooled and the final foam is obtained.

Typical thick blocks of 2 m x 1 m x 0.09 m can be produced (**Figure 2a**). The foams present a skin on the surfaces; this skin is usually removed by cutting two 5 mm thick sheets from the upper and lower surfaces (**Figure 2a**). Different post – processing techniques are used to transform the foam in a final product (machining, drilling, vacuum-forming, compression moulding, etc.). In general terms the first post – processing step includes cutting the block in sheets of a given thickness. In this work the foam blocks were cut into eight 10 mm thick sheets (**Figure 2a**). The tested foam samples were cut from the central part of each sheet.

2.3 Semi-Continuous Process. Crosslinking by Electrons Irradiation (SH and SV Foams)

In the first step of this process a sheet of low thickness (between 0.5 mm and 2 mm approximately) containing the blowing agent (azodicarbonamide) and several additional additives (activators of the foaming agent and processing aids) is produced by extrusion. In a second step this sheet is homogeneously crosslinked by irradiation with a high energy electron beam. Two different ways of foaming are used.

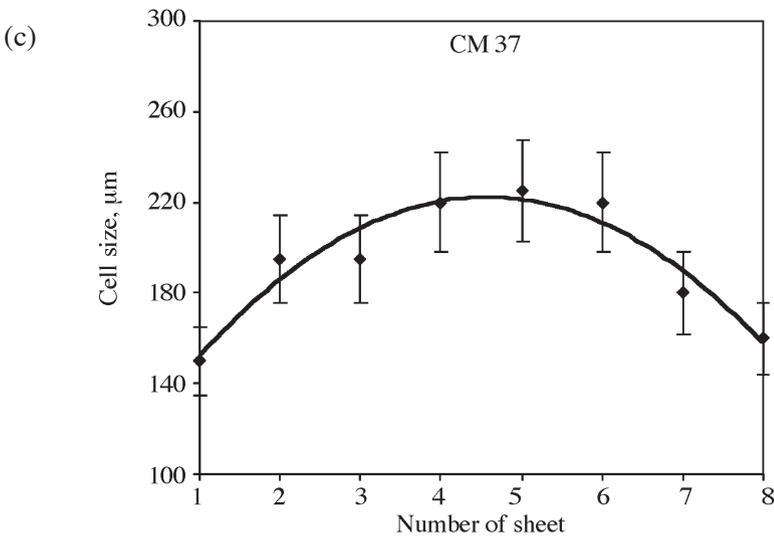
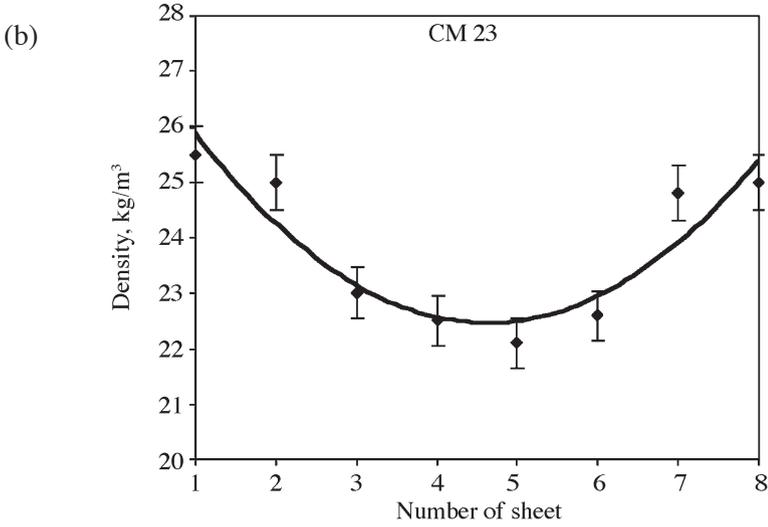
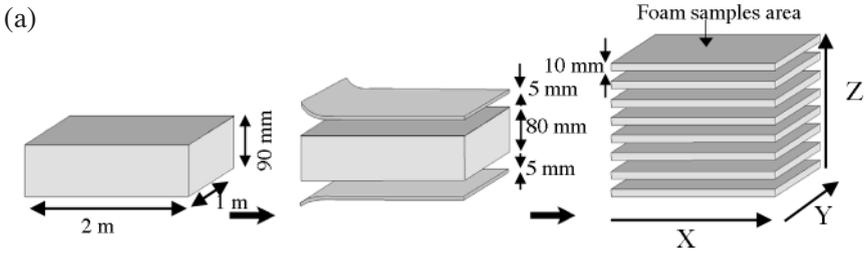


Figure 2. a) Schematic figure showing the post – processing of the CM foams b) density as a function of the number of sheet for CM foams c) average cell size as a function of the number of sheet for CM foams

For SV foams, the foamable sheet passes through a hot oven from top to bottom being the expanding sheet supported itself by gravity in the vertical direction. SH samples are manufactured in a similar way, although the foaming process is carried out in a horizontal plane being the sheet supported by a hot air flow.

After expansion, both types of foams are passed through cooling rolls and wound up. These foams are produced in sheets of width 2 m x L m long (L can be very high because the process is continuous), having variable thickness, depending on the type of foam (from 0.25 mm up to 9 mm). A range of densities from 25 kg/m³ to 330 kg/m³ can be produced by this technology.

In this investigation three series of closed-cell polyethylene-based foams corresponding to the three foaming processes previously described have been analysed. The foams have been kindly supplied by Zotefoams Plc (Croydon, UK), Microcel S.A. (Burgos, Spain) and Sekisui Alveo (Roermond, The Netherlands). The reference, chemical composition, density and thickness of the samples under study are summarised in **Table 1**. All the foams were produced from low-density polyethylene.

3. EXPERIMENTAL TECHNIQUES

Density measurements were carried out on the basis of Archimedes' principle, using the density determination kit designed for the AT261 Mettler balance. The gel content was determined in xylene at 120 °C during 24 h according to standard procedures for polyolefins. Characteristic thermal properties were studied by means of a Mettler DSC30 differential-scanning calorimeter, previously calibrated with indium. The weights of the samples were approximately 2.5 mg. To obtain the crystallinity and melting point experiments were performed between -40 °C and 200 °C at 10 °C/min. The melting point (T_m) was taken as the minimum of the melt peak in the enthalpy curve. The crystallinity (χ_c) was calculated from the DSC curve by dividing the measured heat of fusion by the heat of fusion of a 100% crystalline material (288 J/g for low density polyethylene)⁽²²⁾.

Scanning electron microscopy was used to assess the type of cellular structure the average cell diameter (ϕ), the mean cell wall thickness (ξ) and the mass fraction in the edges (f_s). A JEOL JSM-820 microscope was used for this purpose. Foams usually present anisotropic properties. In general the cells have a higher size in the parallel direction to the foaming direction. Therefore, it was necessary to measure the cell size for each one of the three principal directions of the materials. The average cell diameter was taken as the mean

Table 1. Reference and main characteristics of the materials under study. For CM foams the values in the tables are averages of the characteristics of the eight sheets in each foam block

Sample	Density (kg/m ³)	Sample thickness (mm)	Melting Temperature (°C)	Crystallinity (%)
HP17	17	11.2	108.8	38.3
HP25	25	10.2	109.6	38.8
HP31	31	11.1	110.3	40.0
HP32	32	11.0	108.1	40.2
HP59	59	10.2	111.1	39.2
CM23	24	9.4	108.8	38.3
CM25	25	9.9	111.5	39.3
CM37	37	10.2	109.6	38.8
CM61	61	10.6	110.3	40.0
SH29	29	6.5	108.7	36.9
SH48	48	6	108.6	36.2
SH49	49	12	110.0	42.6
SH65	65	4	111.7	39.1
SH85	85	6	111.5	42.5
SV29	29	3	106.7	36.0
SV30	30	4	106.2	38.4
SV50	50	5	107.6	37.6
SV58	58	4	106.6	38.9
SV62	62	5	107.6	38.9
SV67	67	4.5	108.0	38.7

value of the cell size measured in the three directions of a given material. The degree of anisotropy was characterised by the ratio between the larger and the smaller cell size (anisotropy ratio (AC))⁽¹⁶⁾.

A Rapid K Heat Flow Meter from Holometrix was used for thermal conductivity measurements. Measurements were made under steady state heat flow conditions through the sample, in accordance with ASTM C518 method. The measurements were performed at 24 °C.

Stress (σ) strain (ϵ) curves were measured with an Instron machine (model 5500R6025) at room temperature and at a strain rate of 0.1 s⁻¹. These curves were used to determine the Young's modulus as the slope of the initial part of

the stress-strain curve. The diameter of the samples was 10 centimetres and each type of material was tested three times in order to obtain the average response.

The linear thermal expansion coefficient (α) was measured using a Perkin-Elmer TMA7 thermomechanical analyser. To obtain the thermal expansion coefficient out of the temperature range where thermal transitions were present, the foam was cooled from room temperature to 5 °C, where it was kept for 15 minutes. Heating from 5 °C to 25 °C was performed at 1 °C/min, then the sample was kept at 25 °C for 15 minutes. Each material was scanned three times. The applied compressive stress of 130 Pa is really low (for a low density foam this stress results in a 0.06% strain at room temperature) and was sufficient to keep the probe in contact with the sample and small enough to neglect the compressive strain.

A detailed description of the experimental methods used to characterise the foams has been given elsewhere⁽⁶⁻¹²⁾.

4. RESULTS

4.1 Density

Table 1 shows the values of the density for five HP foams with densities between 17 and 60 kg/m³, for four CM blocks with a range of densities between 24 and 61 kg/m³, for five SH foams with densities between 29 and 85 kg/m³ and six SV foams with a range of densities between 29 and 67 kg/m³. It is interesting to note that the three foaming technologies under study can be used to produce foams of similar densities, i.e. with a similar gas content. Porosities are in the range between 90.6% and 98.1%.

As it has been mentioned in the previous section, each CM foam block was cut in eight 10 mm thick sheets. Data obtained from each sheet of the CM23 foam block are shown in **Figure 2b**. The density values as a function of the sheet number presented a parabolic shape, being the values lower in the inner part of the foam block.

This is due to the expansion of the material at atmospheric pressure in a closed mould during the last stage of the foaming process (see section 2). The areas of the foam block that take contact with the mould walls (sheets 1 and 8) due to this physical constrain (expansion is limited by the mould wall) expand in a lesser extent giving sheets of higher density.

This density evolution was not observed in the foams produced by the other techniques. For SH and SV foams the thickness of the samples was very small and due to this reason a density profile along the sample could not be detected. HP foams, without the skins, were found to be homogeneous; the density was almost constant along the 30 mm thick blocks.

4.2 Polymer Morphology

The measured values of gel content were almost constant for all the materials of a the same family being the values, $45\pm 3\%$ for the foams produced by a high pressure nitrogen solution process, $52\pm 4\%$ for the foams produced by compression moulding, and $37\pm 4\%$ for the foams produced by the semicontinuous process. Foams produced with different methods were crosslinked in a different extend. It is known that the degree of crosslinking is connected with the cell size of the produced material⁽³⁾. This point will be discussed in the next section.

The values of the crystallinity and melting point for each material are summarised in **Table 1**. From these data it can be deduced that the LDPE resin used to produce the different foams had similar characteristics. Melting temperature ranged between 106 and 110 °C and crystallinity between 36% and 43%.

4.3 Cellular Structure

4.3.1 Average Cell Size and Isotropy

Values of the average cell size were determined as a representative parameter of the foam microstructure (**Table 2**). In addition **Figure 3** shows characteristics micrographs of the foams under study. From this figure and the data of the cited tables, several interesting results can be inferred about the cellular structure of each type of material:

Foams produced from the gas solution process are isotropic ($AC\approx 1$) and they have polyhedral-shaped cells (**Figure 3a**). High magnification micrographs (not shown) also proved that no residues of foaming agent were present in these materials.

This kind of structure is expected taking into account that no chemical blowing agents are used in these materials and that foaming is carried out in an “isotropic way”, without any preferential direction of processing (bath process) or physical constraints (i.e. moulds are not used).

Foams produced from compression moulding also showed a cellular structure in with polyhedral-shaped cell (**Figure 3b** and **c**) are detected. As expected,

Table 2. Characteristic of the cellular structure of the different materials. For CM foams the values in the tables are averages of the characteristics of the eight sheets in each foam block

Sample	Average cell diameter (μm)	Anisotropy coefficient (AC)	Cell wall thickness (δ)	Fraction of mass in the edges (f_s)
HP17	313.5	1.00	1.4	0.22
HP25	311.9	1.01	1.9	0.16
HP31	528.1	1.02	4.2	0.24
HP32	424.4	1.00	3.6	0.28
HP59	773.4	1.02	10.3	0.24
CM23	263.4	1.05	1.1	0.30
CM25	255.2	1.02	1.2	0.31
CM37	213.5	0.98	1.5	0.33
CM61	162.0	1.02	2.0	0.33
SH29	614	1.17	2.7	0.54
SH48	463	1.21	4.8	0.59
SH49	509	1.08	4.9	0.59
SH65	400	1.10	6.7	0.50
SH85	418	1.18	8.9	0.52
SV29	300	1.2	2.5	0.54
SV30	288	1.3	2.6	0.54
SV50	235	1.16	3.5	0.39
SV58	215	1.35	3.9	0.39
SV62	288	1.13	4.3	0.37
SV67	259	1.26	4.0	0.37

in high magnification micrographs (not showed) foaming agent residues were observed. The content of foaming agent residues was estimated to be between 8 and 13% depending of the foam density⁽²³⁾. Due to the foaming route a non-homogeneous cellular structure along foam block thickness has been observed (**Figure 3b** and **3c**). Cells are, in average, smaller close to the surface, where present an ellipsoidal shape (**Figure 3b** and **3c**), with the mayor axis-oriented parallel to foam block surface. The typical value of the anisotropic coefficient for these materials was 1.2. In the inert part the cells are also oriented, but with the major axis oriented perpendicular to foam block surface (**Figure 3c**) The anisotropy coefficient was typically 0.8 in this area. In addition it has been observed that the average cell size was higher for the sheets of the inert

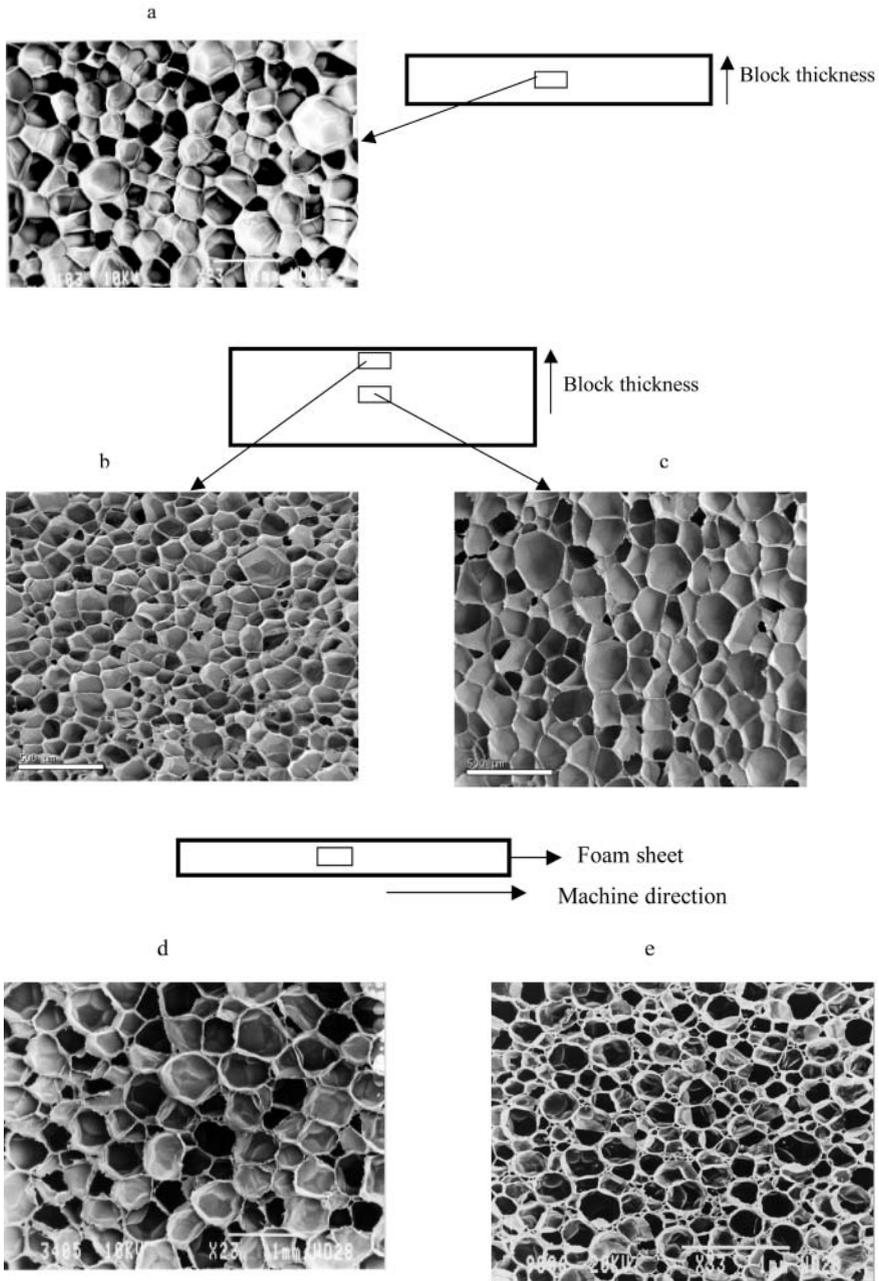


Figure 3. Micrographs of foams produced from different technologies. a) High pressure solution process, b) compression moulding near the block surface (sheet 1, left) and c) compression moulding in the inner area (right), d) semi-continuous process with foaming in the horizontal direction, and e) foaming in the vertical direction

part, in fact a parabolic trend of cell size as a function of sheet number was observed (**Figure 2c**). Therefore, it should be expected that foam sheets cut from different positions could show different physical properties. The average values for the blocks are included in **Table 2**. In these data it can be observed that the whole block could be considered as isotropic. This means that the anisotropy showed by the cells close to the surface is compensated by that of the sheets on the inert part of the block.

SH and SV foams showed cells clearly elongated in the machine direction (**Figures 3d** and **3e**). In general these foams do not show the typical polyhedral-shaped cells observed in the other processes. For these materials the amount of residues of foaming agents was similar to those found in CM foams. The average value of the anisotropy coefficient for SH foams was 1.14 and for SV foams was 1.23, which seems to indicate that the degree of stretching during the continuous production, which is the main cause of elongated cells, was higher for SV materials.

Figure 4 shows the cell size of the foams as a function of density. It can be observed that in general terms the average cell diameter of HP samples

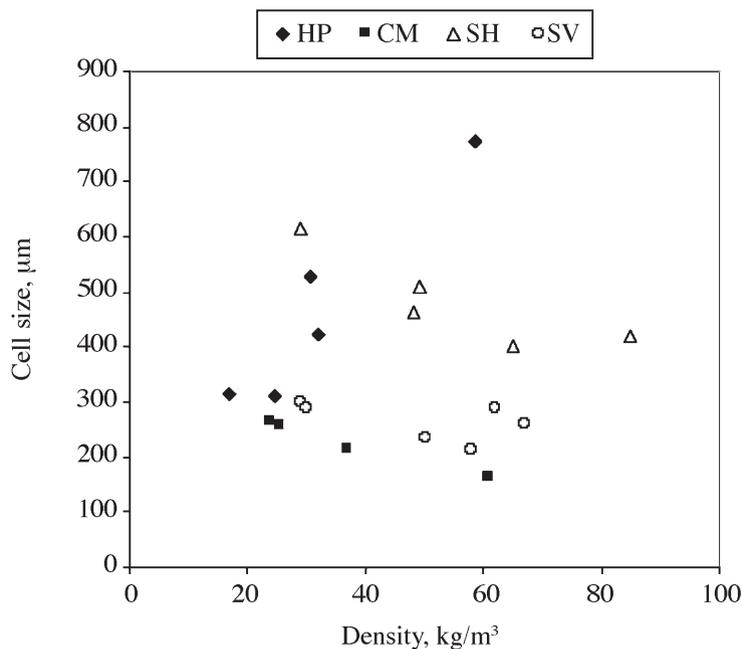


Figure 4. Average cell diameter as a function of foam density for all the foaming processes

increases when density increases, whereas the trend found in CM, SH and SV foams is the opposite, the cell size decreases slightly as density does. As a result, microstructural differences between both series of foams become more accused for higher density samples.

The clear differences between HP and SH, SV and CM foams is due to the different physical mechanisms involved in foaming. In SH, SV and CM foams a chemical blowing agent was used. Therefore, the cells are generated in a process dominated by an heterogeneous nucleation. In HP foams, in which neither residues of foaming agent, nor nucleating agents are used cells are generated in a process in which homogeneous nucleation dominates. In addition, the gas nitrogen solution process allows controlling cell size and density independently by modifying physical processing conditions such as the pressure drop rate at the end of the solution stage in a similar way to the method used to produce microcellular foams^(24,25).

In general terms, the process using chemical blowing agents give rise to cellular structures in which an increase in density is connected with a reduction in cell size⁽³⁾. In these processes controlling independently cell size and density is a more difficult task, and the extent of this control is much smaller than for the gas nitrogen solution process. The cells of CM foams are smaller than that of SH and SV foams due to two main reasons, the first one is the higher degree of crosslinking reached in these materials as it was explained in previous sections. The second one is that cells are created by a pressure drop release during the first foaming stage, therefore cells are produced all at the same time reducing coalescence and then reducing the final cell size.

4.3.2 Cell Wall Thickness, Fraction of Mass in the Edges and Average Cell Shape

The data for the mean cell wall thickness (ξ) and mass fraction in the edges (f_s) are summarised in **Table 2**. All the foams have a non-negligible mass in the edges. This is a typical result for closed cell polymeric foams. The materials with a lower proportion of mass in the edges f_s are HP foams and this is probably due to a foaming process in which no external forces are applied to the materials (SH and SV foams are stretched and CM foams are compressed during processing). From **Table 2** is concluded that $f_{s,HP} \leq f_{s,CM} \leq f_{s,SH} \leq f_{s,SV}$.

The following equation was used to establish the relationships between the parameters that characterise the cellular structure⁽¹⁵⁾.

$$\phi(1 - f_s) \frac{\rho}{\rho_f} = C\xi \quad (1)$$

where ϕ is the average cell diameter, f_s is the mass fraction in the edges, ρ is the foam density, ρ_s is the base polymer density (0.91 gr/cm³), ξ is the mean cell wall thickness and C is a constant that depends on the cell shape, and that, for instance, takes a value of 3.46 for pentagonal dodecahedrons and a value of 3.35 for tetrakaidecahedral cells.

The experimental data for all the foams fits the previous equation with a C value showed in **Table 3**, which suggests that HP and CM foams have cells with a polyhedral shape, (values are of the same order than the theoretical ones), which is in agreement with the observed micrographs (**Figure 3**). However, the previous fit gives a different C value for the SH and SV foams, which in average, seems to have a non polyhedral cell shape, probably due to the stretching produced during foaming.

Table 3. C constant for the different foaming processes

Foams	C	R ²
SH	1.44	0.99
SV	-0.54	0.21
HP	3.65	0.98
CM	2.79	0.99

4.4 Thermal Conductivity

The experimental thermal conductivity (λ) for all the foams under study, at room temperature (24 °C) is presented in **Figure 5** as a function of foam density. Previous investigations have proved that for low density closed cell polymer foams an increase of conductivity when the density and/or the cell size are increased is the general trend^(26,27).

For SH, SV and CM* foams, thermal conductivity clearly increase when density does, therefore the effect of the reduction in cell size is not detected probably because the difference between the cell sizes for low density and high density foams was not very significant for all these materials. For instance for T foams cell size ranged between 215 and 300 μm .

*Data for CM foams in **Figure 5** correspond to the average value for the eight sheets in a block

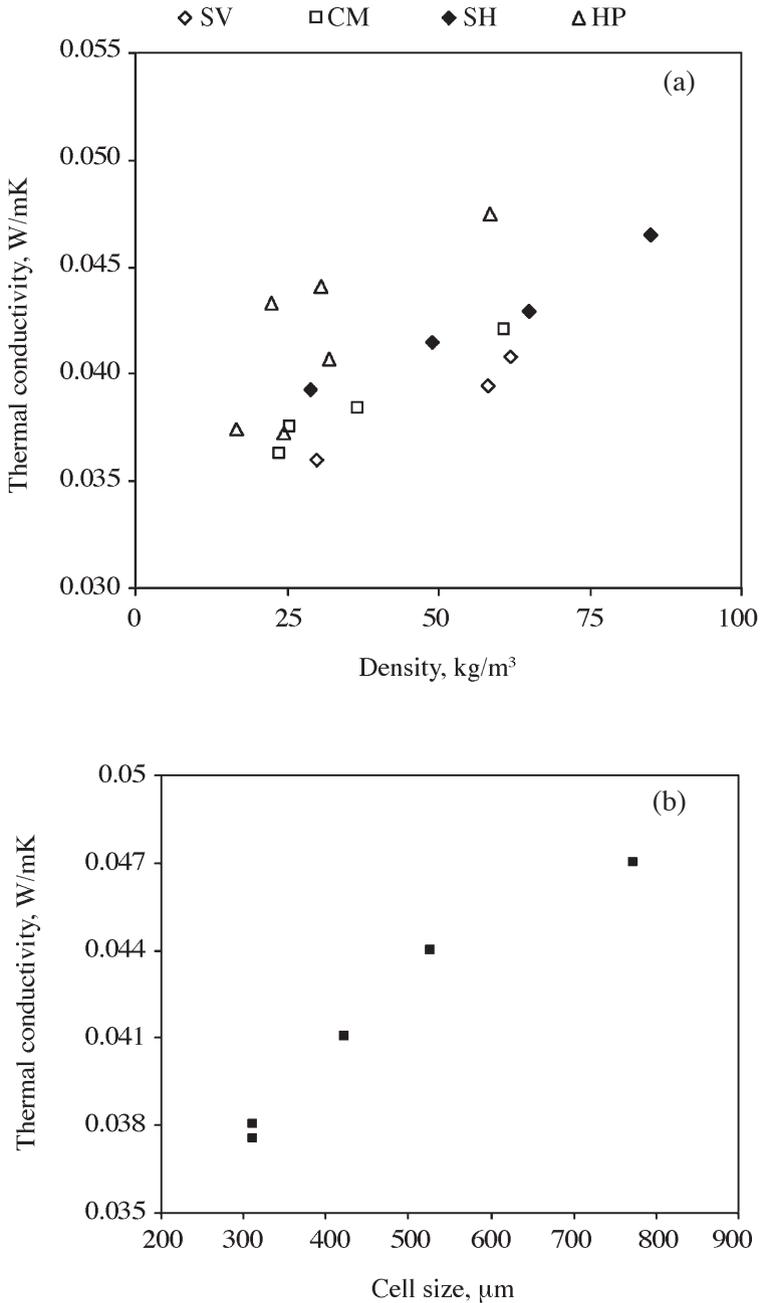


Figure 5. a) Experimental thermal conductivity as a function of the foam density. Values for the CM foams correspond to the average value for each foam block. b) Thermal conductivity as a function of the cell size for HP foams

For HP foams, the thermal conductivity does not show a clear trend as a function of density in the density range between 17 and 59 kg/m³ (**Table 1**), but it follows a linear trend with cell size (**Figure 5b**). The variation in cell sizes for these materials was much higher, between 313 μm and 773 μm, which justify the much higher influence of cell size for these materials.

If the thermal conductivity of foams with a similar density, but produced from different routes is compared the following trend is observed:

$$\lambda(\text{SV}) \leq \lambda(\text{CM}) < \lambda(\text{SH}) < \lambda(\text{HP})$$

For example, a difference of 8.2% is observed between SH65 and SV58 foams. This is mainly due to the smaller average cell diameter (ϕ) of the SV58 foam ($\phi(\text{SV58}) = 215 \mu\text{m}$; $\phi(\text{SH65}) = 400 \mu\text{m}$). HP59 foam has a cell size of 773 μm and CM61 of 162 μm. The difference in thermal conductivity between these materials was 17%. The same explanation is valid for the difference observed between HP and CM foams. This difference increases if the difference in average cell diameter increases.

Two more important factors contribute to the reduced thermal conductivity of SV foams. On the one hand the presence of elongated cells in the perpendicular direction to the heat flow, which increases the number of cell walls in the heat flow path, reduces the heat transfer by radiation^(26,28). On the other hand the low thickness (below 10 mm) of these materials. It has been proved that the thermal conductivity decreases when the thickness is reduced for thickness below 10 mm approximately^(26,29).

On other hand, the evolution of the thermal conductivity along the thickness of a foam block produced from the compression moulding process has also been considered. The results are shown in **Figure 6**. It is evident that the heat transfer is higher for foams in the middle of the foam block. This is due to the variation of cellular structure along the block. An increase in the cell size and an orientation of the cells in the parallel direction of the heat flow increases the thermal conductivity.

4.5 Mechanical Properties

The values of the elastic modulus obtained for all the foams under study, are showed in **Figure 7**. From this figure and for foams with approximately the same density the following trend is deduced:

$$E_f(\text{CM}) > E_f(\text{HP}) > E_f(\text{SH}) > E_f(\text{SV})$$

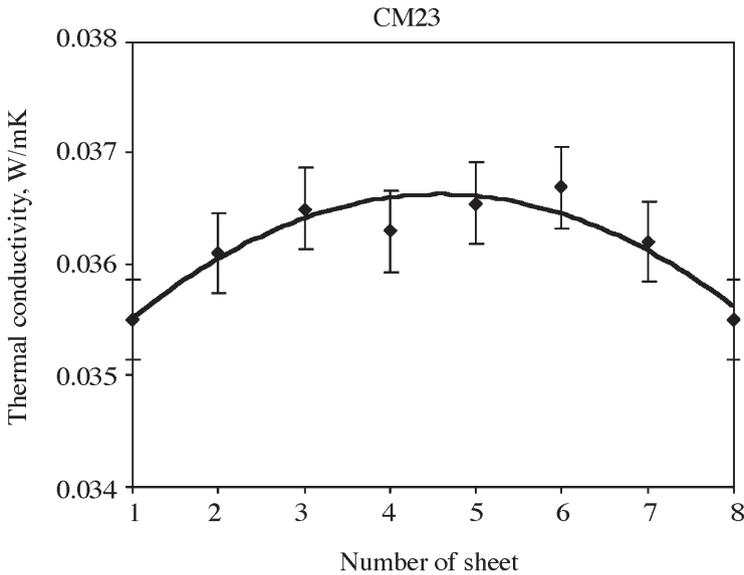


Figure 6. Thermal conductivity as a function of the number of sheet for a foam block (CM23) produced by compression moulding

For CM foams, the E values in this figure were obtained from a central sheet of the foams block.

For foams of 25 kg/m^3 density, the differences are 52% between CM23 and HP25 and 61% between CM23 and SH29. These differences have its origin in the different cell shape observed in each type of material (**Figure 7**). The stiffer material is the one with cells elongated in the parallel direction to the applied stress; the most flexible materials have the cells elongated in the perpendicular direction to the applied stress. As expected, the isotropic materials have an intermediate stiffness.

4.6 Thermal Expansion

The thermal expansion coefficient for all foams obtained in the experiments carried out between 5 and 25 °C can be observed in **Figure 8** as a function of the density. The measurements were performed in the same direction than the mechanical tests.

First, it can be seen that the thermal expansion coefficient decreases when the density of the foamed material increases, being this decrease slower for the higher densities. This result can be explained in terms of the physical mechanisms

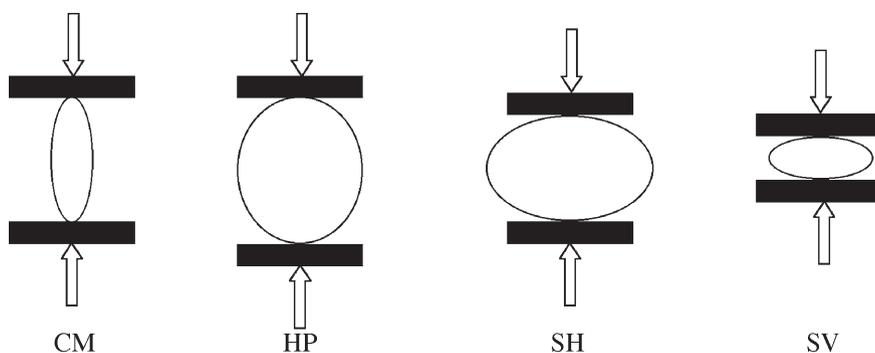
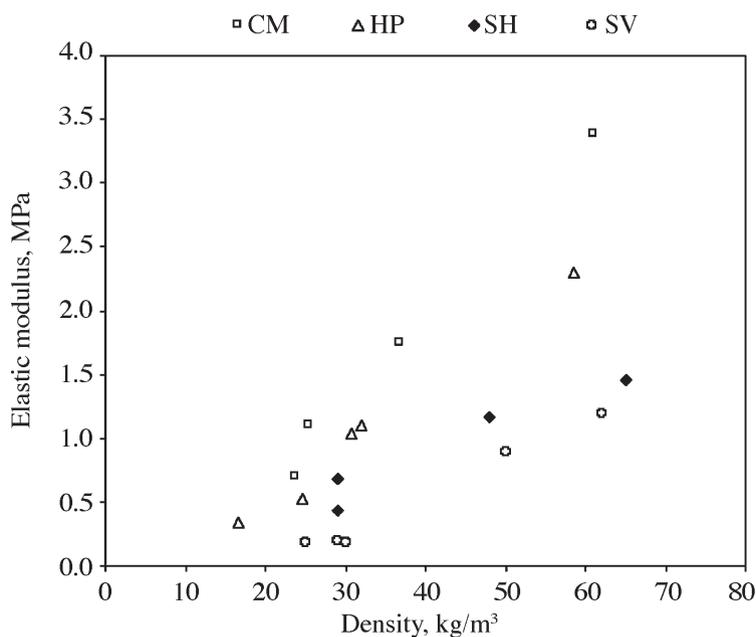


Figure 7. Young's modulus as a function of the density for foams produced using different processes. Schematic diagram showing the cell shape and the direction of the applied stress.

controlling the thermal expansion of these materials^(30,31). At low densities the expansion of the gas phase plays an important role, increasing the thermal expansion coefficient. At higher relative densities (higher than approximately 0.06) the gas expansion is negligible and the expansion approaches that of the solid polymer from which the foams are produced.

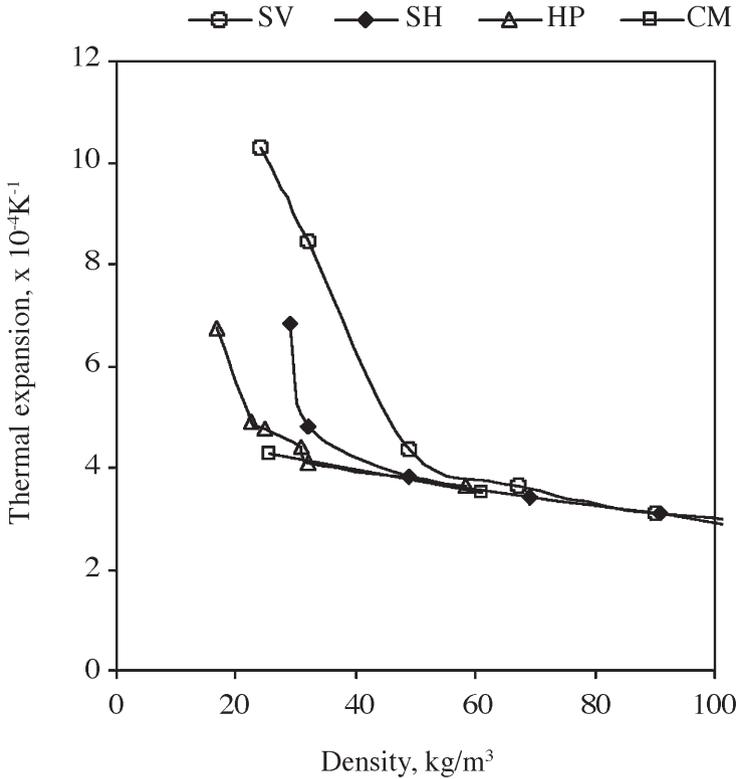


Figure 8. Thermal expansion coefficient, in the perpendicular direction to the foam sheet, versus density

Second, for densities below 60 kg/m³, the thermal expansion coefficient depends on the foaming method. In fact the following trend can be deduced for foams with a similar density, but produced from different routes:

$$\alpha(\text{SV}) > \alpha(\text{SH}) > \alpha(\text{HP}) \geq \alpha(\text{CM})$$

The differences are 58.5% between SV29 and CM23 foams, and 37.5% between SH29 and CM23 foams.

Thermal expansion in closed cell foams is a competitive process between the pressure exerted by the gas inside the cells when the temperature increases and the resistance of the cell walls and struts to be deformed. Therefore, the expansion coefficient is related to the cells walls stiffness, which as it has been showed in the previous section, modifies the foam Young's modulus. Due to this reason foams with higher modulus (CM) in the measurement direction

has the lower expansion, and on the contrary foams with a low stiffness (SH, SV) present a higher expansion.

5. CONCLUSIONS

Closed cell polyolefin foams of similar densities produced from a similar LDPE resin using different technologies present significant differences in their cellular structures and as a consequence in their physical properties. Very high differences in the properties (up to a 70%) for a constant density have been measured.

Foams produced from a semi-continuous process have elongated cells in the machine direction with small cell sizes than foams produced from gas dissolution. These materials present a significant amount of foaming agent residues. The materials have a low mechanical stiffness and a high thermal expansion in the perpendicular direction to the machine direction due to the anisotropic cells. When the foams are produced with fine cells (SV foams) they have a very good behaviour as thermal insulators.

Blocks produced from compression moulding are non-homogeneous. Density, cell size, cell shape, thermal and mechanical properties show an evolution along the block thickness. The materials due to its low cell size are good thermal insulators, and they have good mechanical properties, especially the sheets taken from the central part of the block, this is due to an anisotropic cellular structure in which the cells are oriented perpendicularly to the applied stress for sheets in this area.

Foams produced from the high-pressure solution process present isotropic cells, without foaming agent residues. Due to its high cell size these materials are poor foams for thermal insulation, however due to its isotropic cellular structure they have mechanical properties intermediate between those of CM foams and those of SH and SV foams.

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