
Low Density Non-crosslinked Closed/Open Cell Polypropylene Foams with High Mechanical Properties

J. Escudero¹, A. Lopez-Gil², E. Laguna-Gutierrez¹, and M.A. Rodriguez-Perez¹

¹Cellular Materials Laboratory, (CellMat). Condensed Matter Physics Department, University of Valladolid, Paseo de Belén 7, 47011, Valladolid, Spain

²CellMat Technologies S.L. CTTA, Paseo de Belén 9A, 47011 Valladolid, Spain

Received: 21 April 2015, Accepted: 15 September 2015

SUMMARY

Low density polypropylene based foams with different cellular structures have been produced by the improved compression molding route using a high melt strength polypropylene as polymer matrix. In addition, different types of nanoparticles have been introduced in the formulation (multi-wall carbon nanotubes, organomodified nanoclays and natural nanoclays) to modify the structure and properties. The results have showed a clear correlation between the open cell content of the foams and the mechanical properties in compression. In the unfilled polypropylene high specific mechanical properties are only achievable with low values of open cell content. In comparison, for an equal value of the interconnectivity between cells, the samples containing nanoclays present much higher specific properties. This result is attributed to the reinforcement of these nanoparticles in the solid matrix, due to an improved exfoliation during the foaming process and the presence of a bimodal cellular structure. The produced foams have interesting properties with stiffness similar to those of commercial polymer foams used for the core of sandwich panels.

Keywords: PP foams, Nanocomposites, Nanoclays, Carbon nanotubes, Open cell content

Corresponding author: M.A. Rodriguez-Perez. Tel: +34 983184035.

Fax: +34 983423192. E-mail address: marrod@fmc.uva.es

©Smithers Information Ltd. 2016

INTRODUCTION

Polymeric foams can be defined as two-phase materials in which a gas is dispersed in a continuous macromolecular phase [1, 2]. These materials have wide applications in insulation and packaging as well as in the automotive and construction industries because of their excellent properties: they are lightweight and exhibit a high stiffness and strength to weight ratio, superior insulating qualities and excellent energy absorption. Polyethylene (PE) and polystyrene (PS) are two of the most commonly used materials for thermoplastic foam production [3] but, due to its outstanding functional characteristics, polypropylene (PP) has been considered industrially as substitute for these materials. PP has a low material cost like PE but on the contrary it presents a much better stiffness for static load bearing purposes. Since at room temperature PP is in rubbery state its impact resistance is higher than the one of PS. PE and PS foams are not suitable in applications that require high service temperatures, the heat deflection temperature of PP in comparison is higher. Finally PP foams have a comparable chemical resistance to PE but better than PS [1-4].

It is well known that for foams the loss of mechanical properties at low relative densities is very strong, with normally a square dependency with density [1, 2, 6]. The most common approaches followed to solve this problem consist on the one hand on reinforcing the polymer matrix trying to increase its stiffness and on the other hand on modifying the cellular structure of the foam somehow to improve the mechanical behavior [5, 6].

Dealing with the first approach, in the last years a lot of efforts have been focused in the production of polymer composite foams reinforced with particles in the nano-scale dimension. Several nanoparticles have been used for this purpose, namely carbon nanotubes, carbon nanofibers or silica particles but one of the most extended and promising ones is the reinforcement using nanoclays. The addition of these silicate layered nanoparticles imparts to the polymer good thermal stability, high heat distortion temperature and high specific stiffness at low concentrations of filler. Several works in the literature have studied nanoclays filled polypropylene foams using different foaming methods and diverse blowing agents. Chaudary et al. found that the addition of nanoclays to a linear PP promotes the strain hardening phenomenon. The foams were produced by extrusion foaming using a chemical blowing agent [7]. Due to the appearance of the strain hardening they obtained much better foams with the nanofilled samples than with the raw linear PP. A similar discussion is done by Zhai et al. in terms of cell nucleation and cell coalescence. The addition of nanoclays (5 wt.%) dramatically improves the cell morphology of extruded foams using CO₂ as physical blowing agent [8]. Antunes et al. compared the effect of different fillers in polypropylene based foams. Together with nanoclays the study includes the effect of other fillers such as cellulose fibers or carbon

nanofibers [9]. Although the semicrystalline character of polypropylene makes difficult its foaming using a batch gas dissolution foaming technique Velasco et al. accomplished a study using this procedure. The study compares the microcellular foamability of raw polypropylene with two filled polypropylenes, one reinforced with cellulosic fibers and the other one using organomodified nanoclays. The cellular structure found was finer in the case of the nanoclays-filled formulations. This fact together with the inherent reinforcement over the solid matrix led foams with improved stiffness [10].

Concerning the second approach the influence of the cellular structure and morphology on the mechanical properties of a foam is a broadly studied topic in the literature. Several parameters can be distinguished as the most influential ones, namely cell size, cellular homogeneity, anisotropy ratio and open cell content.

The influence of the cell size on the mechanical performance is not a well-established subject with different controversial studies. Gong et al. found an enhancement in mechanical properties of chemically foamed PP microcellular samples with the reduction of the cell size [11]. Similar results were found by Rachtanapun and co-workers in PP/PE blends. Smaller and more uniform cells resulted in improvements of the compressive properties [12, 13]. The beneficial effects of cell uniformity were studied also by Saiz-Arroyo et al. using either physical or chemical blowing agents in PP based foams. Each type of blowing agent produces better foams in a certain density range and it is found that the measured mechanical properties are deeply influenced by the cell size homogeneity achieved in each case [14]. Miller and co-workers found important improvements in the tensile and impact properties of polyetherimide foams when passing from the microcellular to the nanocellular range but no improvement was observed when passing from the conventional to the microcellular range [15,16]. No improvement was neither found with the reduction of cell size in the tensile properties of polycarbonate foams produced using sub-critical CO₂ by Weller et al. [17, 18].

The effect of anisotropy ratio of the cells has been deeply studied both from a theoretical [6, 19] and experimental [20-23] point of view in diverse polymer systems. Compression properties are the most benefited ones from the anisotropy when measured in a direction coinciding with the direction of higher elongation of the cells. Theoretically, the quotient between the elastic modulus measured in the anisotropy direction and the same property measured in a perpendicular direction can be modeled by the formula:

$$\frac{E_3}{E_1} = \frac{2R^2}{1 + \left(\frac{1}{R^3}\right)}$$

where E_3 and E_1 are the elastic modulus in the anisotropy direction and in a perpendicular one respectively and R represents the anisotropy ratio of the foam [19]. As can be observed, the dependency with R is very strong for the compressive properties. There are several industrial foam production processes that try to take advantage of this fact too [24-26]. The present work pays special attention to the open cell content of the produced foams. They are classified as open cell foams when open cell content (OC) is higher than 80% while on the contrary, they are classified as closed cell foams when OC is lower than 20%. This parameter is related with how the mass is distributed in the foam structure. The preferential distribution of mass in the cell walls yields closed cell morphologies and on the contrary, when the mass is preferentially distributed in the struts open cell structures are obtained. This mass distribution is directly connected with the observed mechanical properties of the foam [6].

In the particular case of PP obtaining closed cell structures is not a simple task and this fact has limited the applicability of PP foams. The low melt strength exhibited by the linear polypropylenes leads to rupture of the cell walls under the elongational forces occurring during cell growth; as a result final foam has a high amount of coalesced and open cells which harms mechanical properties. This low melt strength hinders also the production of low density PP based foams [14, 27]. Literature contains numerous and very different attempts to surmount these problems. Ahmadi and Hornsby tried to improve the foamability of PP just by modifying the foaming conditions during injection molding [28]. As it was mentioned in previous paragraphs, the addition of certain types of particles to linear polypropylenes increases the melt strength and imparts typical features of branched polymers [7, 8]. A less desirable solution goes through the crosslinking of the PP matrix. It turns the polymer non-recyclable and at the same time the crosslinking process can involve a certain degree of dangerousness [29-31]. A simple and extended solution consists on using special grades of PP known as high melt strength PPs in which the melt strength has been significantly increased by promoting a high degree of branching. Although the price of these branched grades can double the price of the normal ones the simplicity of the processing techniques makes the global production economically affordable [32-34].

The aim of this work is to present a procedure for the production of low density non-crosslinked closed/open cell polypropylene foams with high specific mechanical properties. These novel materials are based on a branched polymer and produced using the improved compression molding technique [35-38]. The variation of the processing conditions and polymer formulation yields a broad range of different cell openness which therefore permits an experimental study of the dependency between mechanical properties and open cell content. The almost unexplored possibility of combining high open

cell contents with high specific mechanical properties is also studied and achieved by the reinforcement of the polymer matrix with organomodified and natural nanoclays together with carbon nanotubes.

EXPERIMENTAL

Materials

A branched high melt strength homopolymer polypropylene (Daploy WB 130 HMS from Borealis) was used as main polymer matrix in all the cases. The density of this polymer is 910 kg/cm³ The melt flow index for this polymer is 2.4 g/10 min (230°C/2.16 kg) and the melting temperature is 163°C. Different kinds of nanoparticles were used as additives: montmorillonite-type nanoclays organomodified with quaternary ammonium salts Cloisite 20 A from Southern Clay Products, multiwall carbon nanotubes (MWCNT) in masterbatch form (Plasticyl PP2001 with 20 wt.% of carbon nanotubes Nanocyl NC7000 from Nanocyl, MFI=0.3 g/10 min) and natural nanoclays Cloisite Na⁺ from Southern Clay Products. In order to improve the dispersion and exfoliation of the organomodified nanoclays a coupling agent was also used. This coupling agent is a 1 wt.% maleic grafted polypropylene Polybond 3200 from Chemtura. The proportion between coupling agent and nanoclays was maintained constant based on previous experience in a value of 2:1 respectively.

The foaming was performed using a chemical blowing agent, azodicarbonamide Lanxess Porofor M-C1 with an average particle size of 3.9 ± 0.6 µm. The proportion of blowing agent was kept constant in a value of 2 wt.% both in the unfilled samples and in the samples filled with different kinds of nanoparticles. Antioxidants Irgafos 168 (from Ciba) in a proportion of 0.08 wt.% and Irganox 1010 in a proportion of 0.02 wt.% (from Ciba) were also used to avoid thermal degradation of the polymer.

The mixing was always done using a twin screw extruder Collin ZK 25T with an L/D of 24. In the case of the organomodified nanoclays the clays as received were first melt blended with the coupling agent in the mentioned proportion (2 parts coupling agent per 1 part nanoclays) at an average speed of 50 rpm and a die temperature of 195°C. Afterwards the masterbatch coupling agent-nanoclays was diluted with the high melt strength polypropylene using the same extrusion conditions in order to finally get 5 wt.% of nanoclays. The MWCNT masterbatch was melt blended also in the same extrusion conditions with the branched polypropylene seeking a final proportion of 1 wt.% of carbon nanotubes. 5 wt.% of the natural nanoclays were directly blended with the

branched polymer using the same temperature profile in the extruder and the same processing speed. **Table 1** summarizes the different samples studied.

Table 1. Different nanocomposites produced with the different proportions of each component

Sample	Branched PP wt. %	Coupling Agent wt. %	Masterbatch MWCNT wt. %	Organomodified Nanoclays wt. %	Natural Nanoclays wt. %
Pure PP	100	0	0	0	0
PP+MWCNT	95	0	5	0	0
PP+NC	85	10	0	5	0
PP+NNC	95	0	0	0	5

The previously mentioned composites together with the unfilled polypropylene are afterwards blended with the azodicarbonamide (2 wt. %) and the antioxidants (0.08 wt. % Irgafos 168 and 0.02 wt. % Irganox 1010). The same extruder is used for this purpose at a speed of 120 rpm and a die temperature of 155°C to avoid the premature decomposition of the blowing agent.

Samples Foaming

These foams are intended for lightweight industrial applications so the densities of these materials should be lower than 200 kg/m³. Achieving such low density foams with a non-crosslinked polypropylene matrix is not a simple task. For this reason, a branched high melt strength polypropylene was selected as base material. In addition the foaming method selected, improved compression molding (ICM), plays also a fundamental role in the achievement of such low densities. The ICM foaming route comprises three different steps:

1. Mold filling: pellets of the previous formulations already containing the blowing agent and the rest of the additives are introduced inside a disc-shape stainless steel mold. Once the mold is correctly filled it is closed using a piston and placed inside a pre-heated hot plates press.
2. Temperature and pressure: the temperature of the press plates is always higher than the decomposition temperature of the chemical blowing agent used. In our case a temperature of 200°C was used for the pure PP and for the formulation containing nanotubes. In the case of the formulations containing clays a temperature of 190°C was used instead. The decomposition of the blowing agent generates a certain gas pressure

(P_{ADC}) inside the mold. The mechanical pressure (P_0) applied externally is always higher than the gas pressure inside the mold. In the working conditions used the gas generated is dissolved into the polymer and no foaming occurs while this external pressure is applied. In our case pressures of 35 bar for the pure and MWCNT formulations and of 7 bar for the clay-containing formulations were applied during 15 minutes. These processing parameters were optimized through experimental testing and we selected the ones giving the best properties for each material.

3. Pressure release and cooling: once the blowing agent is totally decomposed and completely dissolved in the polymer the pressure is released at a controlled rate. The whole foaming occurs inside the mold and the foam growing is constrained in the direction coinciding with the pressure release one. The density is controlled by retaining the piston displacement (d) at a certain point (ER Control Part in **Figure 1**) and afterwards the mold with the foam inside can be freely extracted from the hot press and cooled, in our case immersing it in cool water.

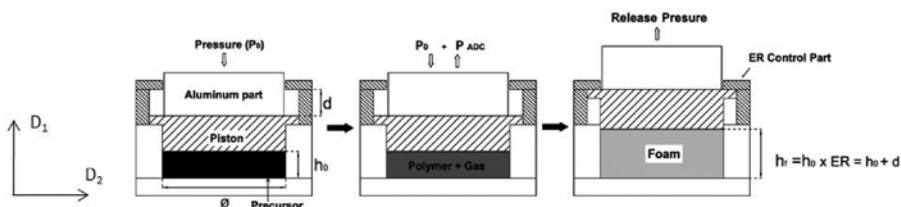


Figure 1. Schematic in the expansion plane ($D1/D2$) showing the different steps followed in the Improve Compression Molding Route

The ICM foaming route has several advantages in comparison to other conventional routes. On the one hand the possibility of achieving an accurate control of foam density and on the other hand the possibility of modifying the microstructure of the foamed part, (in terms of cell size, cell type and cell shape) by acting on both foaming parameters and chemical composition. Further details of the ICM foaming route can be found elsewhere [35-39].

The foams produced in this paper had densities of 150 kg/m^3 and 180 kg/m^3 . The samples were disks with 150 mm in diameter and 12 mm and 10 mm in thickness (h_f) respectively.

Samples Characterization

The density of the samples was measured by the geometric method, that is, dividing the mass of the samples between their corresponding volume (ASTM Standard D1622-08).

Cellular structure of the whole collection of foams was analyzed using scanning electron microscopy, (SEM). In order not to distort their microstructure, samples were frozen in liquid nitrogen and afterwards fractured. Surface fracture was made conductive by sputtering deposition of a thin layer of gold and observed using a Jeol JSM-820 scanning electron microscope.

Cell size as well as anisotropy ratio, were measured using an image processing tool based on the software ImageJ [39]. At least 75 cells per image and at least three different images were analyzed.

Open cell content of foamed materials was determined according with ASTM Standard D6226-10 using a gas pycnometer Accupyc II 1340 from Micromeritics.

Compression tests were carried out in a universal testing machine, (Instron model 5500R6025). Samples of 20x20 mm² cut from the 150 mm diameter discs were tested at were tested at a strain rate of $h/10$ mm/min where h is the height of the specimen. The maximum static strain was 75% for all the experiments. The maximum standard deviation (in percentage) obtained for the foams measured in compression was $\pm 5\%$. Tensile tests for the solids were performed according to ASTM D638 using a strain rate of 1 mm/min. The solids were produced by compression molding. In this particular case, the maximum standard deviation obtained for the solid samples was $\pm 2\%$.

RESULTS

Cellular Structure of the Foams

Micrographs taken along the plane parallel to the expansion direction (D1/D2) corresponding to the different foams are presented in **Figure 2**. Morphological parameters in terms of cell size and anisotropy ratio are collected in **Table 2**.

The mean cell size presents comparable values between samples with no large differences. The solid residues left after the decomposition of the azodicarbonamide is a competing nucleation mechanism that is present both in the samples with and without nanoclays. The presence of a bi-modal cell distribution is characteristic of the foams containing clays. This bi-modal

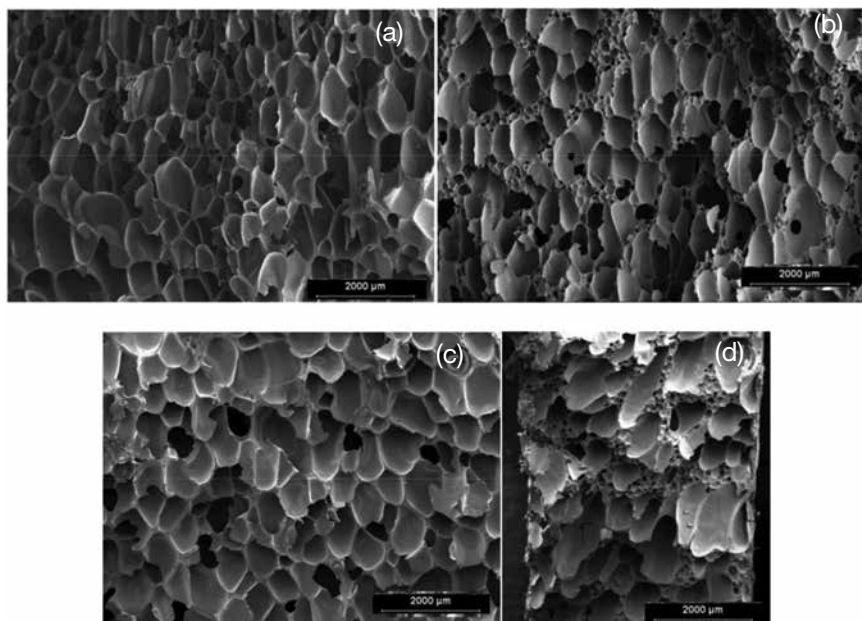


Figure 2. Micrographs corresponding to a) pure PP b) PP+5 wt. nanoclays c) PP+1 wt.% MWCNT and d) PP+5 wt.% natural nanoclays

Table 2. Quantification of morphological parameters corresponding to the cellular structure of the different samples

Sample	Density /(kg/m^3)	Mean Cell Size/ μm	Standard Deviation/ μm	Cell Density /(cells/cm^3)	Anisotropy Ratio	OC (%)
Pure PP	179	300	105	$1.4 \cdot 10^4$	2.2	18
PP+MWCNT	181	315	96	$1.1 \cdot 10^4$	1.6	52
PP+NC	180	321	262	$8.3 \cdot 10^4$	2.6	94
PP+NNC	182	343	203	$8.6 \cdot 10^4$	2.5	78

distribution, that can be visually observed in micrographs of **Figure 2**, doubles the standard deviation value calculated for the different samples. On the contrary the samples containing multi wall carbon nanotubes present the more homogeneous cellular structure with the lowest standard deviation. Due to the bi-modal distribution, the cell density is also strongly increased in the samples containing clays, with values almost eight times higher than in the

rest of the samples (**Table 2**). The appearance of two different populations of cells is the only fact that can be attributed to a nucleation role played by the nanoclays. Although the mean cell size is bigger for the samples containing clays and the open cell content is also remarkably higher, denoting coalescence and cell coarsening phenomenon, the presence of a significant population of cells, placed preferentially on the cell walls of the bigger cells and with cell sizes below 100 μm can be connected to the nucleation of the exfoliated/intercalated nanoclays.

The preferential growth of the cells in the pressure release direction gives as result anisotropy values higher than 1. All the samples have anisotropy ratios near 2.5 except the one containing carbon nanotubes.

Although the production conditions are the same as those used with the pure PP, this last sample has an anisotropy patently lower, with a value of 1.6.

These high anisotropy values could benefit several properties of the foams. For example, theoretically, for an anisotropy of 2.5, the elastic modulus in compression measured in the direction of maximum elongation of the cells would be 11.75 times higher than the one measured in a perpendicular direction [19].

Mechanical Properties of Unfilled Polypropylene Foams

One key morphological parameter of major importance influencing the mechanical properties of foams is the open cell content. The open cell content is mainly connected with how the mass is distributed in the foam. When the mass is mainly placed in the cell walls we are dealing with closed cell foams. And, on the contrary, open cell foams are obtained when the mass is mainly placed in the edges. This mass distribution is strongly connected with how the foam withstands the external stresses applied, therefore it strongly influences the mechanical properties. Homogenous mass distributions (mass placed in the cell walls) yield stiffer foams so in general, for structural applications, closed cell foams are required [6, 19]. A study of the dependency of the elastic modulus in compression with the open cell content has been also performed. The study was carried out using exclusively the pure HMS PP. Varying the azodicarbonamide content between 2 wt.% and 5 wt.% and fixing the rest of the foaming conditions, different open cell contents were achieved maintaining constant the anisotropy ratio, cell size and homogeneity [14]. Seven different specimens were produced with seven different open cell contents. The specific elastic modulus and collapse strength (property divided by the foam density) in compression were measured for all samples and correlated with the corresponding open cell contents in **Figure 3**.

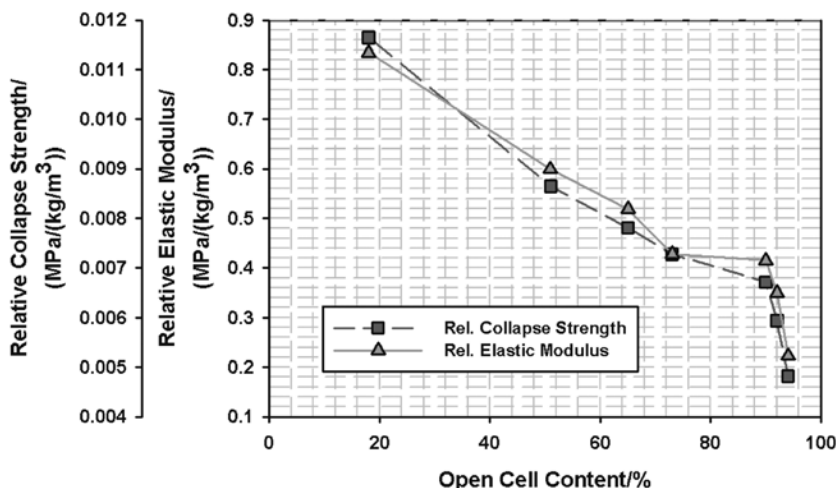


Figure 3. Correlation between open cell content, compressive modulus and collapse strength for the pure PP foams

The mechanical properties are drastically reduced when the cells in the foam are interconnected. At high open cell contents slight variations in the interconnectivity produce important differences in the mechanical performance. Both the elastic modulus in compression and the collapse strength follow the same tendency. With this unreinforced polymer matrix, good specific mechanical properties are only reached with closed cell cellular structures.

Mechanical Properties of Filled Polypropylene Foams

The tensile modulus of the solid specimens was also measured in order to quantify the improvements produced by the addition of the nanofillers. The pure HMS PP presents a 1.98 GPa modulus that is increased to a value of 2.20 GPa for the samples containing nanoclays. Surprisingly the addition of 1 wt.% of carbon nanotubes negligibly improves the elastic modulus (**Table 3**). A poor coupling between the polymer matrix and the carbon nanotubes

Table 3. Elastic Modulus of the solid samples filled with different kinds of nanoparticles

Solid Sample	Elastic Modulus/GPa
Pure PP HMS	1.98
PP + MWCNT	2.02
PP + NC	2.21
PP + NNC	2.18

and/or the presence of bundles of nanotubes could justify the negligible reinforcement found.

At equal open cell contents, the elastic modulus of the foams produced from the nanocomposites containing clays are remarkably higher than the unfilled ones. The same behavior is found for the collapse strength. These interesting results are depicted in **Figure 4**.

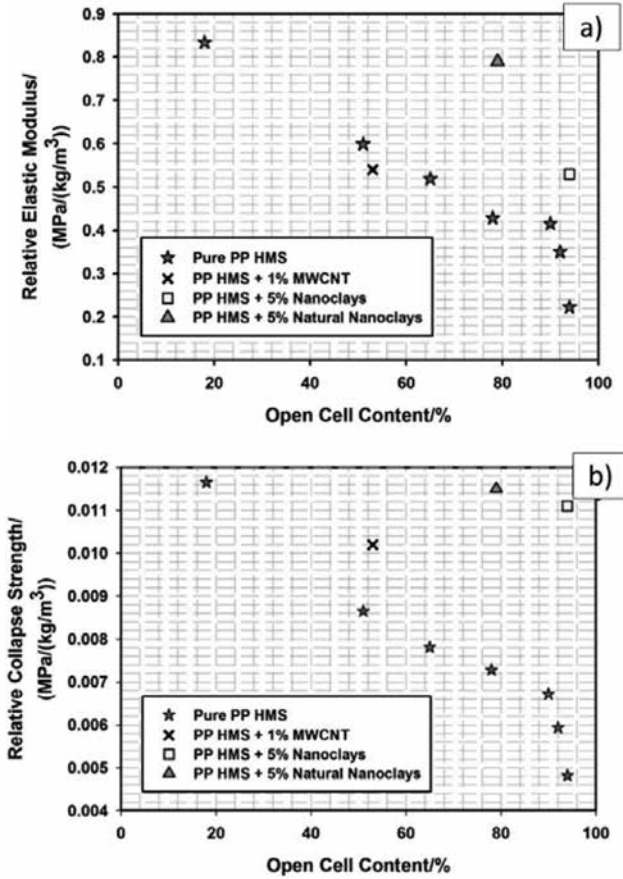


Figure 4. Comparison between the elastic modulus and collapse strength of filled and unfilled polypropylene at certain open cell contents

At equal open cell contents the specific elastic modulus of the samples containing natural nanoclays almost doubles the value of the unfilled one and the addition of organomodified nanoclays multiplies by 2.5 the specific elastic modulus in compression of the unfilled samples at a open cell content higher than 90%. The anisotropy ratio of unfilled and of nanoclays-filled samples

is practically the same so the improvements found in elastic properties at fixed open cell values could be attributed, partly, to the reinforcement of the nanoparticles over the solid matrix. When the interconnectivity of the cells is high, the solid matrix acquires a more relevant role withstanding the external applied stresses. But this is not the only reason behind. The reinforcements over the solid matrix showed in **Table 3** do not justify the improvements found on the foams. Two other reasons are proposed to support these results. In the case of the nanoclays it has been demonstrated in previous works that the foaming by itself promotes the exfoliation of the nanoparticles yielding higher mechanical properties [40]. Besides this, the presence of nanoclays gives rise to a bimodal cell size distribution, with two main different populations of cells, some bigger ones and some smaller ones. The small cells, only present in the samples with clays, can be acting as reinforcement points conferring the foams an improved compressive behavior. In the case of the MWCNT the specific mechanical properties are slightly lower. As previously mentioned the reinforcement over the solid matrix is negligible. This fact, together with the low anisotropy values achieved in these foams, diminish the mechanical performance of these samples.

Collapse strength of the foams depends more strongly on the properties of the solid matrix than on other structural parameters as the anisotropy ratio. This result can be inferred from **Figure 4b**. At comparable open cell contents the filled samples present improvements in collapse strength in all the cases (18% improvement for MWCNT, 58% improvement for natural nanoclays and 130% improvement for organomodified nanoclays). Even for the samples containing carbon nanotubes, that present a smaller anisotropy ratio, the collapse strength is increased. The case of the organomodified clays is interesting. At a higher open cell content than the natural nanoclays (94% to 78%) they present a similar collapse strength due to the higher reinforcement of the organomodified nanoclays on the solid matrix.

GENERAL OVERVIEW AND COMPARISSON WITH OTHER STIFF FOAMS USED IN STRUCTURAL APPLICATIONS

For the sake of comparison the elastic modulus in compression was measured also in two commercial materials, one based in a PVC solid matrix and the other one based on a SAN solid matrix. The PVC based foams are crosslinked, losing any recyclability. Both the PVC and the SAN based materials are used as cores and structural panels for applications such as yachts, wind power blades, automotive sector or aircraft construction. All these applications seek a high stiffness-to-weight ratio in their core materials. The PVC foams (produced by DIAB) are closed cell with an homogeneous and

isotropic cellular structure. The SAN foams, commercially named Corecell, are produced by Gurit and share properties with their counterparts: closed cell structure, homogeneity in the cell size distribution and isotropy.

Although the solid PVC or SAN are stiffer matrices than the polypropylene (typical elastic modulus are 3 GPa for PVC, 3.75GPa for SAN and 2 GPa for PP) the compressive modulus of the PP-based foams are comparable or higher in the two studied densities of 150 kg/m³ and 180 kg/m³. The high anisotropy ratios achieved compensate for the low stiffness of the polypropylene matrix, yielding high specific mechanical properties for the developed foams. Even the foams filled with organomodified nanoclays with open cell contents higher than 90% have acceptable properties compared to the commercial materials. The theoretical estimation with $n=1.5$ included in **Figure 5a** is made using an elastic modulus of 2 GPa for the solid according to the formula:

$$E_f = E_s \left(\frac{\rho_f}{\rho_s} \right)^n$$

where E_f and E_s represent the elastic modulus of the foam and of the solid respectively, ρ_f and ρ_s represent the density of the foam and of the solid and n is a variable exponent between 1 and 2 [6]. Conventional foams have a value of n near 2 so the value of $n=1.5$ found in our samples gives an idea of the improved mechanical behavior achieved in our samples.

A different trend is found for the collapse strength. This property is more influenced by the modulus of the solid matrix than the compressive modulus and this fact is reflected in **Figure 5b**. The commercial foams based in PVC or in SAN present, at any density, much higher collapse strength values since they are based in stiffer matrices. The reinforcement produced by the nanoclays over the solid matrix yield comparable or higher collapse strength values even when these foams have open cells. The lowest values are found for the MWCNT foams according to their low reinforcement and low anisotropy ratios.

As a final conclusion low density foams have been produced based on a non crosslinked polypropylene matrix with high specific compressive properties in two different versions: open and closed cell. It is not so common finding open cell foams with good mechanical behavior so these are novel materials. The openness of the cells confers these foams improved properties as sound absorbers and filtration capabilities.

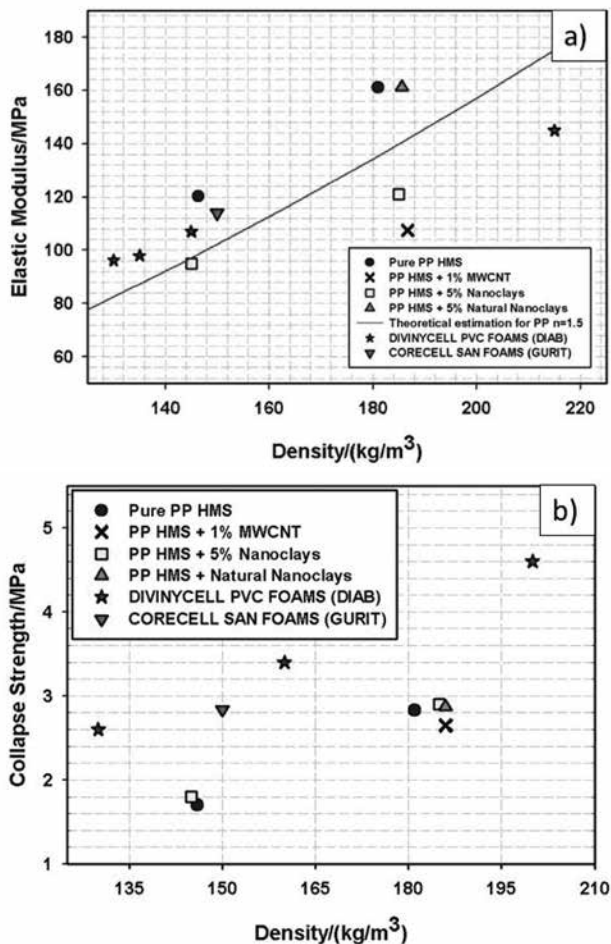


Figure 5. General map of compressive modulus (a) and collapse strength (b) for the different nanocomposites. Two commercial materials have been included for comparison

CONCLUSIONS

A direct correlation has been established between the cellular morphologies obtained in terms of open cell content and the mechanical properties in compression for several pure and nanoreinforced PP based foams. Slight variations in the interconnectivity (at high interconnectivities) of the cells have a high impact on the measured mechanical properties. In the unfilled polypropylene high specific mechanical properties are only achievable with low values of open cell content. In comparison, for an equal value of interconnection between cells, the samples containing nanoclays present

much higher specific properties. This result is attributed to the reinforcement of these nanoparticles on the solid matrix, due to an improved exfoliation during the foaming process and the presence of a bimodal cellular structure.

The combination of a branched high melt strength polypropylene with the improved compression molding foaming route allows obtaining non-crosslinked polypropylene foams with densities as low as 150 kg/m³. Because of the inherent anisotropy ratio obtained due to the foaming route these foams present also high specific mechanical properties, comparable to commercial foams produced from crosslinked stiffer solid matrices. Two different types of materials can be distinguished, both with high specific properties. The first one based on unfilled polypropylene can be considered as closed cell (values <20%). The second one corresponds to foams that combine good mechanical performance with high open cell contents (>80%). These later foams are obtained with the addition of nanoparticles, mainly nanoclays, to the branched polypropylene.

ACKNOWLEDGEMENTS

Financial assistance from MINECO and FEDER Program (MAT 2012-34901), the Junta of Castile and Leon (VA035U13), the FPU grant Ref: AP2007-03319 (J. Escudero), the FPI grant Ref: BES-2010-038746 (A. Lopez-Gil) and PIRTU contract of E. Laguna-Gutierrez by Junta of Castilla and Leon (EDU/289/2011) and co-financed by the European Social Fund is gratefully acknowledged.

REFERENCES

1. Klemptner D., Sendjarevic V. handbook of polymeric foams and foam technology. 2ndedn. Hanser Publisher. Munich (2004).
2. Eaves D. Handbook of polymeric foams. Rapra Technology, Shawbury (2004).
3. Leaversuch R. D. *Mod. Plast.*, **73**, 52 (1996).
4. Park C. B., Cheung L. K. *Polym. Eng. Sci.*, **37** (1) 1-10 (1997).
5. Lee S. T., Foam Extrusion Principles and Practice. CRC Lancaster (2000).
6. L. J. Gibson, m. F. Ashby. Cellular Solids. Cambridge University Press, United Kingdom (1999).
7. Chaudhary A. K., Jayaraman. *Polym. Eng. Sci.*, **51** (9) 1749-1756 (2011)
8. Zhai W., Kuboki T., Wang L., Park C.B. *Ind. Eng. Chem. Res.*, **49** (20) 9834-9845 (2010).

9. Antunes M., Realinho V., Ardanuy M., MasPOCH M. Ll., Velasco J. I. *Cell. Polym.*, **30** (4) 187-200 (2011).
10. Velasco J. I., Antunes M., Realinho V., Ardanuy M. *Polym. Eng. And Sci.*, **51** 2120-2128 (2011).
11. Gong W., Gao J., Jiang M., He L., Yu J., Zhu J. *Polymer*, **122**, 2907-2914 (2011).
12. Rachtanapun P., Matuana L. M., Selke S. E. M. *Soc. Plast. Eng. Annu. Tech. Conf.*, 2003, **61**, 1762.
13. Rachtanapun P., Selke S. E. M., Matuana I. M. *Polym. Eng. Sci.*, **44**, 1551-1565 (2004).
14. Saiz-Arroyo C., de Saja J. A., Velasco J. I., Rodriguez-Perez M. A. *J. Matter. Sci.*, **47** (15) 5680-5692 (2012).
15. Miller D., Chatchaisucha P., Kumar V. *Polymer*, **50** (23) 5576-5584 (2009).
16. Miller D., Kumar V. *Polymer*, **52** (13) 2910-2919 (2011).
17. Weller J., Kumar V. *Polym. Eng. Sci.*, **50** (11) 2160-2169 (2010).
18. Weller J., Kumar V. *Polym. Eng. Sci.*, **50** (11) 2170-2175 (2010).
19. A. T. Huber, L. J. Gibson. *J. Mat. Sci.*, **23**. 3031-3040 (1988).
20. Jang W. Y., Kraynik A. M., Kyriakides S. *Int. J. Solid. Struct.*, **45** (7-8) 1845-1875 (2008).
21. Rodriguez-Perez M. A. *Adv. Polym Sci.*, **185** 55-56 (2005).
22. Rodriguez-Perez M. A., Velasco J. I., Arencon O., de Saja J. A. *J. Appl. Polym. Sci.*, **75** (1) 156-166 (2000).
23. Lee T., Lakes R. S. *J. Mat. Sci.*, **32** (9) 2397-2401 (1997).
24. Simard Y., Lalancette E., Jones D. T. U. S. patent 0104478 (2011).
25. Alderson A., Alderson K. L., Davies P. J., Smart G. M. U. S. patent 0029796 (2010).
26. Duwenhorst J., Ruellmann M., Prissok F., Lasai S., Mayer S., Harms M., Gabriel C. U. S. patent 0038579 (2010).
27. Zheng W. G., Lee Y. H., Park C. B. *J. Appl. Polym. Sci.*, **117** 2972-2979 (2010).
28. Ahmadi A. A., Hornsby P. R: *Plas. Rubber Proc. Appl.*, **5** (35) (1985).
29. Nojiri A., Sawasaki T., Koreeda T. U.S. Patent 4424293 (1984).

30. Nojiri A., Sawazaki T., Konishi T., Kudo S., Onobori S. *Furukawa Rev.*, **2** (34) (1982).
31. Lee Y.D. Wang L. F. *J. Appl. Polym. Sci.*, **32** 4639-4647 (1986).
32. Naguib He., Park C. B., Panzer U. *Polym. Eng. Sci.*, **42** 1481-1492 (2002).
33. Zhai W., Kuboki T., Wang I., Park C. B., Lee E. K., Naguib H. E. *Ind. Eng. Chem. Res.*, **49** 9834-9845 (2010).
34. Bhattacharya S., Gupta R. K., Jollands M., Bhattacharya S. N. *Polym. Eng. Sci.*, **49** 2070-2084 (2009).
35. Rodriguez-Perez M. A., Lobos J., Perez-Muñoz C. A., de Saja J. A. *Cell. Polym.*, **27** 327-342 (2008).
36. Rodriguez-Perez M. A., Lobos J., Perez-Muñoz C. A., de Saja J. A. *J. Cell. Plast.*, **45** 389-403 (2009).
37. Rodriguez-Perez M. A., Simoes R. D., Roman-Lorza S., Alvarez-Lainez M., Montoya-Mesa C., Constantino C.J.L., de Saja J. A. *Polym. Eng. Sci.*, **52** 62-70 (2011).
38. Y. Ma, Pyrz R., Rodriguez-Perez M. A., Escudero J., Rauhe J. Ch., Su X. *Cell. Polym.*, **30** (3) 95-109 (2011).
39. Pinto J., Rodriguez-Perez MA., de Saja JA in *XI Reunión del Grupo Especializado de Polímeros (GEP)* 10-14 September 2009, Valladolid. Spain.
40. J. I. Velasco, M. Antunes, O. Ayyad, C. Saiz-Arroyo, M. A. Rodríguez-Pérez. F. Hidalgo, J. A. de Saja. *J App. Polym. Sci.*, **105**, 1658-1667 (2007).