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DEVELOPMENT OF AN IMPACT LIMITER FOR TYPE B PACKAGES – CHARACTERIZATION OF ITS POLYMERIC MATERIAL

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ABSTRACT

Impact limiters are sacrificial components widely used to protect radioactive waste packages against damage arising from falls, fires and collisions with protruding objects. Several materials have been used as impact limiter filling: wood, aluminum honeycomb, and metallic or polymeric foams. In addition, hollow structures are also used as impact limiters, either as a single shell or as a tube array. One of the most popular materials among package designers is the rigid polyurethane foam, owing to its toughness, workability, low specific weight, low costs and commercial availability. In Brazil, a foam developed using the polymer extracted from the castor-oil plant (*Ricinus communis)* is being studied as a potential impact limiter filling. For better performance of castor-oil foam, it is necessary to minimize the impact limiter dimensions without compromising the package safety. For this, a detailed knowledge of the foam physical and mechanical properties is essential. A relatively vast amount of data about regular polymeric foams can be found in the literature and in several manufacturers' brochures, but no data has been published about the properties of the castor-oil foam. This paper presents data gathered in an ongoing research program aimed developing a Brazilian Type-B packaging. Foam samples were submitted to study uniaxial static compression, hydrostatic, and impact tests. The results obtained reveal that the castor-oil foam has a mechanical behavior similar to that of regular foams, with good property reproducibility and homogeneity.

INTRODUCTION

Impact limiters have been extensively used to protect radioactive materials packages. The most severe requirement is the 9 m-drop test, which the prototype must pass with no leakage or significant increase (more than 20%) in surface radiation level.

Several materials with good toughness (volumetric energy absorption capacity), *U*, have been used as impact limiter fillings. Among them, wood – especially balsa and redwood – polymeric and metallic foams, expanded concrete, and hollow metallic structures (honeycombs and tubular arrays).

The material chosen in this study was the polyurethane foam developed using the polymer extracted from the castor-oil plant (*Ricinus communis*), a tropical bush. This material was chosen due to its favorable toughness, workability, low cost, and availability in the Brazilian market (Poly-Urethane, 2000).

To use this foam more efficiently in impact limiters, which means minimizing the transport and storage space available without lowering safety levels, the optimization of the impact limiter dimensions is essential. This optimization can only be attained through the detailed knowledge of the physical and mechanical material properties. Several studies have been carried out for traditional foams – obtained from the petrochemical industry – including data of their mechanical and thermal behaviors (Duffey 1992; Maju 1995 and 1996; Wenski 1997; Goods 1997; and General Plastics 1999), but little has been done concerning the castor-oil foam.

This paper presents the results of the test sequence carried out by the Brazilian nuclear institutes CDTN (Center for Development of Nuclear Technology) and IPEN (Energetic and Nuclear Research Institute) to obtain a database for this foam. In this research, prototypes were submitted for uniaxial and hydrostatic quasi-static compression tests and impact tests.

DESCRIPTION OF THE MATERIAL

Like the foams processed from petroleum, the castor-oil foam is produced by a chemical reaction between two components – an isocyanate and a polyol, triggered by catalysts. The difference between

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them lies in the origin of the polyurethane molecule, which, in the foam studied in this research, is synthesized from the castor oil.

Once the components are mixed together, a rapid exothermal reaction takes place and, due to the absorption of air from the environment, the mixture undergoes substantial volumetric expansion. If the expansion is restricted laterally – as normally occurs – the foam will "rise" vertically: this direction is frequently referred to as the *foam rising direction* or simply the *parallel direction*.

The product is manufactured by the Brazilian company POLY-URETHANE under the brand name ECOPOL, and is offered under the nominal foam densities of 40, 100 and 200 kg/m^3.

Its main uses in the local market are for thermal insulation in roofs, refrigerated trucks, freezers, and industrial storage tanks for the chemical and petrochemical industries. It has been used also as a structural element in recreation boats, where its resistance to gasoline makes it a good substitute for polystyrene.

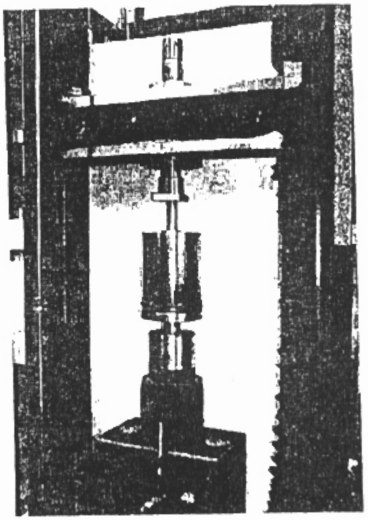
The castor-oil foam has notable environmental advantages compared to the petrochemical foam: it is manufactured from a renewable material, is biodegradable, and does not use the notorious greenhouse gas CFC as a blowing agent. Because of this, the United Nations Programme for Development (UNDP) in Brazil and the foam manufacturer signed a contract to manufacture and deliver – cost free to end users – foam dispenser machines. This machine mixes the foam components automatically and applies the resulting foam as required.

Testing program

The uniaxial compression tests were performed in a universal INSTRON testing machine, at the Mechanical Testing Laboratory of CDTN. These tests were carried out according to the specifications of the standard ASTM-D-1621, *Compressive strength of rigid cellular plastics* (ASTM 1990). Six foam densities were tested – 41, 60, 87, 147, 253 and 361 kg/m^3 according to three different strain rates $\dot{\varepsilon} = 1.4\times10^{-3}$, 5.6×10^{-3} and 1.4×10^{-2} s^{-1}. In order to access the anisotropy of the material, prototypes were extracted from both parallel and perpendicular foam rising directions. The specimen dimensions are 50×50×60 mm.

The hydrostatic tests were carried out using a pressure chamber provided with a piston with a seal, which is directly compressed by the INSTRON testing machine (Fig. 1). The specimens, which measured 100 × 100 × 25.4 mm, were made watertight by sealing them inside a double latex pouch. Three volumetric deformation rates were applied, $\dot{\varepsilon}_{vol} = 1.8\times10^{-3}$, 4.5×10^{-3} and 9.0×10^{-3} s^{-1}.

(a) Pressure chamber



(b) Pressure chamber mounted in the INSTRON standard machine

Figure 1. Set-up for the hydrostatic test

Finally, a series of impact tests is presently being conducted to investigate the dynamic response of the castor oil foam to short duration loads. A flat surface drop weight is released from variable heights onto 100 × 100 × 25.4 mm specimens. The lower part of the falling weight consists of a strain-gage type load cell, whose electronic signal is measured by an oscilloscope and processed on a portable computer using appropriate software. Figure 2 shows the signal conditioning unit and the load cell used in the tests.

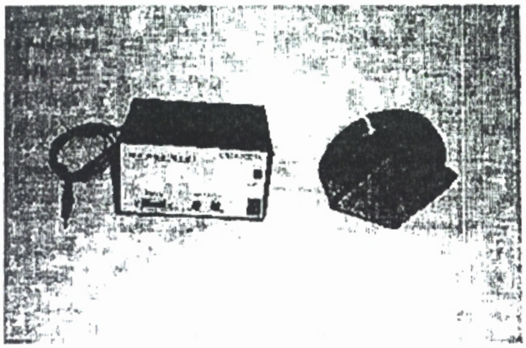


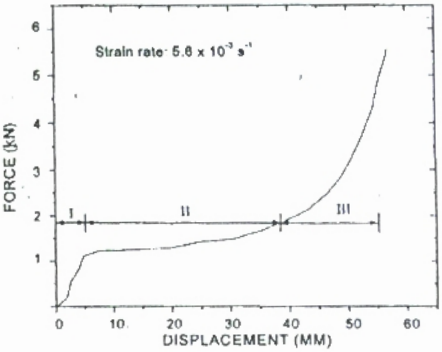
Figure 2. Impact test setup.
Left: signal conditioning unit. Right: load cell

RESULTS AND DISCUSSIONS

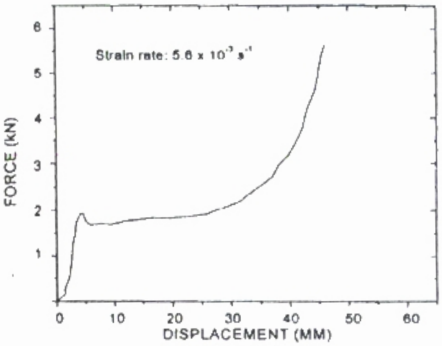
The stress-strain curves obtained in the uniaxial compression tests describe the typical behavior of the rigid polyurethane foams obtained from the petrochemical industry. Figures 3a and b show the force-displacement typical curves obtained in the INSTRON machine. These curves are converted into stress-strain curves by simply dividing the axis values by the specimens area or height, as applicable. Three well-defined regions can be observed during the deformation process. In the initial region I, the foam presents an elastic behavior and the stress varies linearly with the strain. This is followed by a plastification plateau (region II), where, due to the successive and rapid collapse of the cells (mainly by the cell struts buckling), the material undergoes a vast volumetric deformation with none or little increase of the compression stress. Two important parameters are defined in this region: the plateau stress σ_{pl}, as the mean stress value and the tangential (or plastic) hardening modulus (E_t), as the average slope of the curve. Finally, there is region III – sometimes known as the densification region – that is characterized by a rapid increase of stress with no significant strain increase. This behavior reflects the almost complete collapse of the cells, with the vanishing of almost all void spaces inside the material structure.

It is worth noting that the transition from region I to region II is well defined, which is not the case between regions II and III. It was therefore established in this study that this transition occurs when the stress value increases 50% from the initial value at the beginning of region II.

The stress peak between regions I and II, as shown in Fig. 3b, was observed when foams of intermediate densities (60 and 87 kg/m^3) were compressed in the parallel direction. This sort of phenomenon is dictated by the foam microstructure instability, but it remains unclear why it was observed only in the parallel direction and only for certain densities.



(a) Perpendicular direction



(b) Parallel direction

Figure 3. Typical curves obtained in the uniaxial quasi-static compression tests

The results of the uniaxial compression tests are summarized in Figs. 4 to 8. With the exception of Fig. 8, the results refer to tests in the foam rising direction. Figure 4 shows the stress-strain curves for all densities tested, each curve representing the average results of prototypes produced from a single foam block. The response of the properties of interest – Young's modulus (*E*), toughness (*U*) and plateau stress (σ_{pl}) – to the foam density is presented in Figs. 5 to 7. It can be seen that all parameters vary exponentially with the density, the exponent been 1.3, 1.7, and 1.9 for *E*, *U*, and σ_{pl}, respectively. These results are in good agreement with the experiments conducted by Goods (Goods 1997), who found a dependency order of 1.6 and 2.1 for *E* and σ_{pl}, respectively.

The Poisson's ratio ν was evaluated by measuring the transversal dimensions of the prototype before and after the test. This parameter is relevant in applications where the foam is constrained laterally, as is the case of impact limiters, when normally the foam filling is surrounded by a metallic shell. It was observed that foams of low and intermediate densities (typically up to 147 kg/m^3) presented an average ν of 0.07, whereas for the high-density foams (253 and 326 kg/m^3) this value was 0.13.

Also, the contribution of the elastic (ε_{el}) and plastic (ε_{pl}) strain fractions to the total strain (ε_t) was investigated. For this, the specimen volume was measured immediately after the test and a week afterwards. As expected, the lighter foams – more flexible – exhibited a smaller fraction of plastic deformation. The proportion $\varepsilon_{pl}/\varepsilon_t$ varied from 0.36 for the 41 kg/m^3 foam to 0.52 for the 253 kg/m^3 one.

Finally, an investigation was conducted into the anisotropy of the foam. Samples were tested in both parallel and perpendicular planes related to the foam rising direction. Figure 8 shows *E*-ρ curves for both directions and it can be observed that the less dense foams are more compliant when compressed in the perpendicular direction. This situation is inverted for the heavy foams, which are stiffer in the perpendicular direction. Foams of density between 250 and 300 kg/m^3 can be considered to have the same Young's modulus in all directions. A similar behavior has been reported for the commercial LAST-A-FOAM® foam by General Plastics Co. (General Plastics 1999).

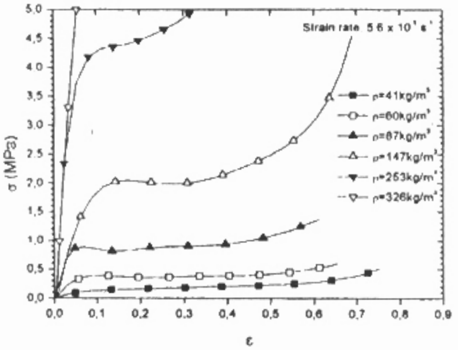


Figure 4. Stress-strain curves for the quasi-static compression tests

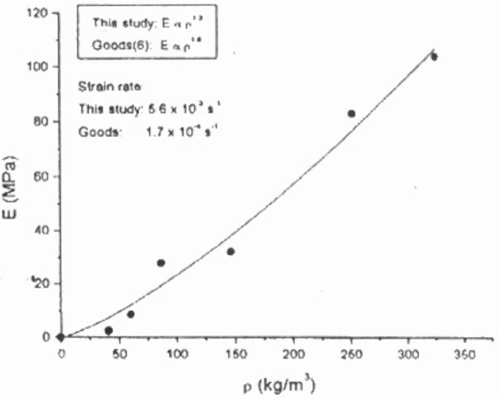


Figure 5. Response of the Young's modulus to foam density – static compression test

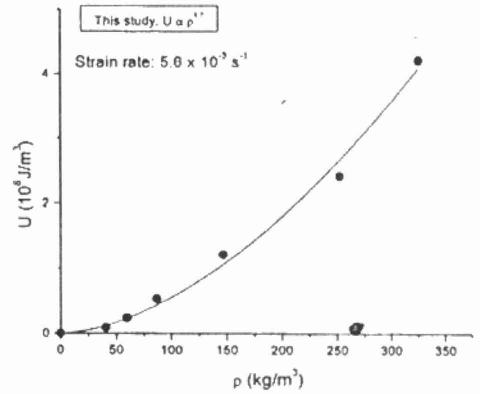


Figure 6. Response of toughness to foam density – static compression test

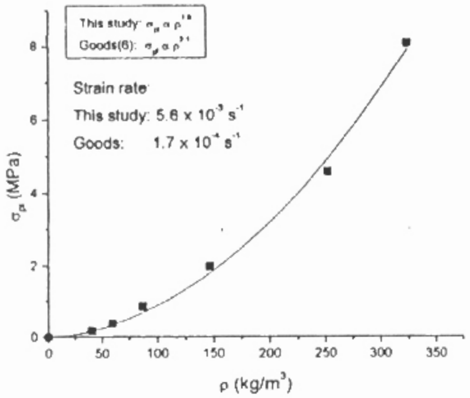


Figure 7. Response of the plateau stress to foam density – static compression test

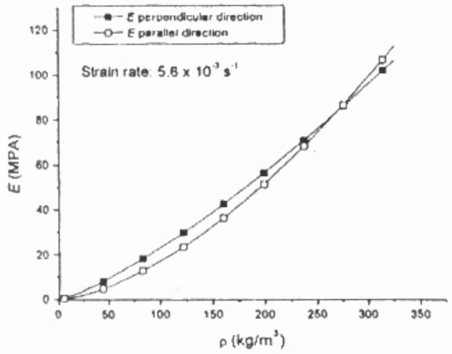


Figure 8. Anisotropy of the foam – response of the Young's modulus to the rising direction

The results of the hydrostatic tests are shown in Fig. 9. The volumetric strain is defined as $\varepsilon_v = V/V_o$, where V_o is the initial volume and V the deformed volume.

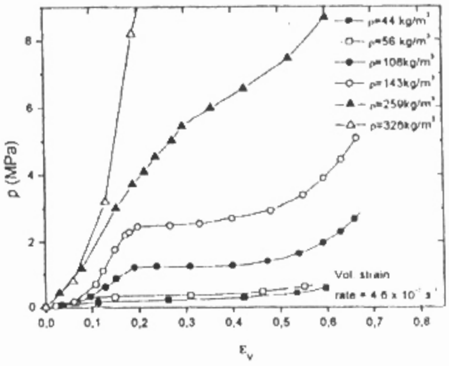


Figure 9. Hydrostatic test results

The overall behavior of the foams under hydrostatic compression is similar to that under uniaxial load (compare with Fig. 4). In both situations the foams undergo three deformation phases; toughness increases with density, and the denser the foam, the more plastic hardening it exhibits (measured by the curve slope in the plateau). The data from the hydrostatic tests – pressure against either linear or logarithmic strain – are directly mapped into many finite element-based software applications as input for numerical simulation of the foam behavior.

The results obtained so far in the ongoing impact test sequence are depicted in Fig. 10 for the parallel direction. Only foam densities up to 165 kg/m^3 were tested due to limitations of the testing setup (improvements are currently being introduced to enhance the testing capability). Drop heights – and, consequently, strain rates – were chosen as follows:

Table 1. Drop height and strain rate for impact tests

Foam density (kg/m^3)	Drop weight (kg)	Drop height (mm)	Strain rate (s^{-1})
43	19.4	560	130
60	19.4	570	132
108	48.5	1,200	191
165	48.5	1,940	243

It can be observed that, as in the quasi-static compression tests, the foams undergo three distinct phases when deformed dynamically. Likewise, the same observations made previously concerning the behavior of the main properties – Young's modulus (E), toughness (U) and plateau stress (σ_{pl}) – apply to the impact tests.

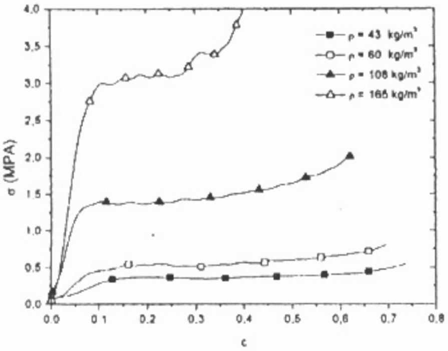


Figure 10. Impact tests partial results

CONCLUSIONS

Two main conclusions can be drawn from the test sequence conducted so far.

First, the behavior of the polyurethane foam obtained from castor oil under static and dynamic uniaxial compression and under hydrostatic compression is similar to that of the traditional foam. The typical curves obtained present the three characteristic phases (linear elastic, plastification plateau, and densification) and the main material parameters have values of the same order. Moreover, it can be stated that the castor-oil foam also presents anisotropy regarding the foam rise direction, although this still has to be confirmed for the dynamic tests.

This similitude of behavior is very important, because it allows the castor-oil foam to be numerically simulated by finite element software applications, which have foam in their material library (HKS 1998; Livermore Software 2001).

The second conclusion has to do with the influence of the strain rate in the material response. Although the prototypes were tested according to three different strain rates in the static compression test ($\dot{\varepsilon} = 1.4\times10^{-3}$, 5.6×10^{-3} and 1.4×10^{-2} s^{-1}) and the hydrostatic test ($\dot{\varepsilon}_{vol} = 1.8\times10^{-3}$, 4.5×10^{-3} and 9.0×10^{-3} s^{-1}), no detectable variation in the response was observed. Yet it has been reported in the literature that the regular foam responds more rigidly when compressed at higher speeds.

This aspect will be closely examined during the last phase of the impact test sequence.

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