With increasing stringent noise standards, stochastic foams are increasingly used in several engineering fields as effective absorbing materials. These materials offer broadband absorption capabilities. However, the frequency range of maximum absorption is still fairly high. One interesting way to overcome this limitation is the use of multilayered materials with each layer tailored to absorb noise at different frequency range. Another challenge is related to the development of a manufacturing process capable of producing multilayered materials with consistent and repeatable properties. The main objective of this work is to develop a manufacturing process to produce multilayer thermoset foams combining both acoustic and mechanical capabilities. The process is based on the particulate leaching process where both the porosity and the material can be changed through the thickness. Microscopic and X-ray microtomographic analyses were used to assess the efficiency of the process. The acoustical properties by means were investigated of a 30mm-diameter impedance tube and the mechanical properties using a standard compression tests. The properties of the multilayered materials were analysed with respect to the number and the order of the layers through the thickness of the material. It is shown that depending on the layer facing the sound wave, multilayer foams can provide either broadband absorption better than the one-layer foams, or resonance-like absorption at low frequencies. The values of the compressive modulus of multilayers are ranged between 5MPa and 20MPa and are generally controlled by the weakest layer.

Keywords: sound absorption, porous material, open-cell polymer foam, multilayers, foaming process

1. Introduction

As noise regulations are becoming more stringent and noise reduction has become a major challenge in engineering fields such as aeronautics, construction and transportation. Passive and/or active techniques are generally used to reduce unwanted noise. Among passive techniques, absorbing materials, like stochastic foams, exhibit broadband absorption capacities. However, for most foams, the absorption capabilities remain in a high frequency range. Studies have shown that the use of multilayer
foams instead of one-layer foams can lead to a higher absorption at low frequencies if each layer is tailored made for specific frequency range. Even though multilayer foams exhibit better acoustical properties, processes to produce them remain difficult to control, leading to multilayers with inconsistent properties [5]. The aim of the present work is to develop a foaming process that produces multilayer foams with good absorption capabilities in a wide frequency range, including low frequencies. The mechanical properties of the multilayer foams will be discussed with respect to the processing parameters.

2. Experimental procedure

2.1 Materials

The epoxy vinyl ester 411-350 from Derakane and the epoxy D.E.R.383 from Dow Chemical were used for the experiments. Table 1 gives the details of their physical and mechanical properties. Compared to the D.E.R., the Derakane cures at room temperature which makes it easier to process.

<table>
<thead>
<tr>
<th>Type of resin</th>
<th>Density at 25°C (g/cm³)</th>
<th>Viscosity at 25°C (mPa.s)</th>
<th>Curing temperature (°C)</th>
<th>Tensile strength (MPa)</th>
<th>Tensile modulus (MPa)</th>
<th>Flexural strength (MPa)</th>
<th>Flexural modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derakane 411-350</td>
<td>1.08</td>
<td>370</td>
<td>Room</td>
<td>86</td>
<td>3200</td>
<td>150</td>
<td>3400</td>
</tr>
<tr>
<td>D.E.R.383</td>
<td>1.16</td>
<td>9000 to 10 500</td>
<td>100°C</td>
<td>71</td>
<td>2500</td>
<td>108</td>
<td>2641</td>
</tr>
</tbody>
</table>

Salt particles (NaCl) were sieved and classified in two categories depending on their size: from 710 µm to 850 µm diameter (particles T2) and from 450 µm to 500 µm (particles T3).

2.2 Process

The foaming process is based on the particulate leaching technique. A polymer solution is mixed with particles that will be further leached out to produce a porous material. The full process is illustrated in Figure 1.

First, the resin is formulated and mixed with the particles with the proper proportions. The mixture is introduced into a cylindrical mold, constituted of a piston and of four vents at its top, to form the first layer of the foam. Another mixture made of a different type of resin or another size of particles is prepared in a similar way, and introduced into the mold on the top of the first mixture. Then, the mold is placed between two compression plates of a Material Testing System (MTS Insight 050-820-EL) where a specific pressure is applied on the two mixtures through the piston of the mold. The pressure is chosen to bring the salt particles into contact and is maintained until full polymerization of the resin. This compaction pressure is the most important processing parameter as it ensures the interconnectivity of the resulting porosity. A previous study of the process proved that to obtain a porous material, compaction pressures must remain between 35MPa and 50MPa. It must be noted that, during the compaction, only the resin is expelled from the mold through the vents machined on the top of the mold. Indeed, no salt particles get out of the mold during the compaction because the size of the vents is smaller than the diameter of the particles. After the compaction, the intermediate material, full of particles, is weighted and then placed into a container full of water for 3 to 10 days in order to leach out the salt particles. Once the material is floating, it is good evidence that all particles are leached out. Finally, the specimen is dried into an oven for about 5 hours at 70°C. The final dried porous material is weighted and measured again. An optic microscope is used for the first microstructure analysis of the specimen.
2.3 Measurements

Acoustic absorption coefficient and acoustic impedance of the materials are obtained by an impedance tube in absorption configuration with hard backing (Fig. 2).

Compressive tests are performed on the materials to obtain their compressive modulus. According to standards D695 [6] and D6226-10 [7], specimens are placed between the plates of the same MTS used to produce the specimens and a load is applied at a head speed of 1.8mm/min.

Moreover, an X-ray microtomograph was used to assess the quality of the leaching process by detecting the residual salt particles within the final multilayer material.

2.4 Multilayers’ configurations

Two series of multilayers were fabricated. One serie (P) with different porosities (different particles size) and same material, and a second serie (M) with two different materials (Derakane and D.E.R.) but with the same particles size:

- multilayers with 2 and 3 layers from particles T2 and T3, and the Derakane.
- multilayers with 2 and 3 layers from particles T3 and both with Derakane and D.E.R.

Figure 3 explains the configuration of the multilayers with respect to the layer receiving the sound wave into the impedance tube.

Figure 1: Process to produce multilayer foams.

Figure 2: Schematics of impedance tube apparatus.
3. Multilayer foams characterization

3.1 Microscopic observations

Figure 4 shows images from a binocular microscope of multilayers specimens fabricated at a compaction pressure of 42MPa. Images of specimens P2 and P3 clearly show the difference of porosity between the layers. As for M2 and M3 specimens, the colour evidences the presence of different layers given the use of particles T3 only. Contrary to specimens P2 and P3, the interface between layers in specimens M2 and M3 are not straight. The parabolic interface is the consequence of the resin flowing towards the mold vents during compression.
3.2 Validation of the process

The leaching process was validated by X-ray microtomographic analysis. This investigation enables the verification of the interconnection between pores and the detection of residual salt particles in the material. Figure 5(a) gives the 3D and 2D images of P2 specimen where the porosity interconnection can be clearly seen. Figure 5(b) gives a 3D image of the same specimen pointing out salt residues (coloured areas). Except for a salt particle at the center of the specimen that seems to have not been completely leached out, only salt residues are detected which confirms the completeness of the leaching process, therefore the entire process. In fact, the salt residues represent less than 1% of the total sample volume which corresponds to a degree of purity over 98% for the samples produced by this method.

![Figure 5](image)

Figure 5: (a) 3D and 2D images of a P2 specimen. (b) 3D image of salt residues (same P2 specimen).

3.3 Acoustical properties

3.3.1 Influence of the layer receiving the sound wave

Depending on which layer is first impinged by the sound wave in the impedance tube, the acoustical behaviour of the multilayer is different. Figure 6 gives the absorption coefficient as a function of the frequency for multilayers P2 - layer T2 (red curves) and multilayers P2 - layer T3 (blue curves). A peak of absorption is observed for specimen P2 - layer T3 which is characteristic of a resonance phenomenon. It can be explained by the difference of impedance between layer T2 and layer T3. The sound wave hardly penetrates into the material through pores T3 and then reaches large pores T2 which act as resonance cavities for the travelling sound wave. Also, it can be observed that the maximum absorption peak decreases with increasing the compaction pressure. As for specimen P2 - layer T2, the sound wave penetrates through pores T2 more easily than through pores T3 leading to the broadband absorption observed. Similar behaviours were observed for multilayers P3.

As for multilayers M2 and M3, since the same particles were used to fabricate the layers, the absorption is quite similar for both layers facing the sound wave.

3.3.2 Influence of P2 and P3 multilayers compared to one-layer foams

The acoustic absorption of multilayers P2 and P3 is compared to the absorption of one-layer foams T2 and T3 fabricated with the Derakane. All specimens have the same thickness (17mm).

Figure 7 gives the absorption coefficient as a function of the frequency for multilayers P2, P3\(^1\) and one-layer foams T2 and T3, all fabricated at a compaction pressure of 35MPa.

\(^1\)On each Figure, the layer facing the sound wave is specified: (a) Layer T2 (b) Layer T3.
Figure 6: Absorption curves of multilayers P2 for both configurations in the tube. Compaction pressures: (—) 35MPa, (− −) 42MPa, (· · ·) 50MPa.

In both Figures, at frequencies lower than 1500Hz, multilayer P3 - layer T2 exhibit higher absorption capabilities than the other foams. Also, below 1500Hz-2000Hz, absorption of multilayers P2 - layer T2 (Fig. (a)) is almost similar than the absorption of one-layer foams T2 and T3, and even higher for frequencies higher than 3500Hz. Multilayer P2 - layer T2 seems to combine the low-frequency absorption of the one-layer T3 and the high-frequency absorption of the one-layer T2.

For multilayers P2 - layer T3 and P3 - layer T3 (Fig. (b)), the trend is inverted. The absorption coefficients of multilayers are higher than those of one-layer foams at frequencies lower than 1500Hz. At higher frequencies, the absorption of one-layer foams remain higher.

According to these observations, the choice of a layer facing the sound wave and the number of layers of a multilayer foam will depend on whether the application require high absorption capabilities at low or high frequencies.

Similar behaviours were observed for every compaction pressure. Also, for all cases, increasing the number of layers does not enhance the absorption capability of the multilayers.

Figure 7: Absorption curves of (a) multilayers P2 - layer T2, multilayers P3 - layer T2, one-layer foams T2 and T3. (b) Multilayers P2 - layer T3, mulitlayers P3 - layer T3, one-layer foams T2 and T3. Compaction pressure: 35MPa.
3.3.3 Influence of M2 and M3 multilayers compared to one-layer foams

The absorption of multilayers M2 and M3 is compared to the absorption of one-layer foams fabricated with particles T3 and both the Derakane and the D.E.R. Again, all specimens are 17mm-thick.

Figure 8 gives the absorption coefficient as a function of the frequency for multilayers M2, M3\(^2\) and one-layer foams Derakane and D.E.R. fabricated with particles T3. In those Figures, measurements are made on specimens fabricated at a compaction pressure of 35MPa.

Similar behaviours were observed for every compaction pressure. In both cases, multilayers M2 and M3 exhibit a better broadband absorption than the one-layer foams. Also, as for the multilayers P2 and P3, the number of layers does not seem to enhance the absorption capability of the multilayers.

![Figure 8](image)

Figure 8: Absorption curves of (a) multilayers M3 - layer D.E.R., one-layer foams fabricated from T3 particles and from Derakane and D.E.R. (b) Multilayers M2 - layer Derakane, multilayers M3 - layer Derakane, one-layer foams fabricated from T3 particles and from Derakane and D.E.R. Compaction pressure: 35MPa.

3.4 Mechanical properties

Compression tests were performed on each specimen of multilayers. Figure 9 gives the compressive modulus of (a) multilayers P2, P3 and one-layer foams T2 and T3, and (b) multilayers M2, M3 and one-layer foams Derakane and D.E.R. fabricated with particles T3. For multilayers P3 and M3, the compressive modulus of both configurations (depending on the layer at the top and the bottom of the foam) were measured.

Compressive modulus of multilayers P2 and P3 are similar to the compressive modulus of the one-layer foam T2, meaning that the weakest layer is controlling the mechanical behaviour of the multilayer foam. The same phenomenon was observed with multilayers M2 and M3 with their compressive modulus matching the compressive modulus of the D.E.R. foam which is the weakest layer. Also, the compaction pressure has little effect on the compressive modulus of the multilayers.

4. Conclusion

The main purpose of multilayers is to combine interesting acoustic properties of each constitutive layer. Therefore, multilayers may exhibit absorption capabilities useful for some specific applications. The particulate leaching process was used to manufacture open-cell thermoset foams and the following main results were obtained:

\(^2\)On each Figure, the layer facing the sound wave is specified: (a) Layer D.E.R. (b) Layer Derakane.
Figure 9: Compressive modulus depending on the pressure of (a) multilayers P2, multilayers P3 (both configurations) and one-layer foams T2 and T3 - (b) multilayers M2, multilayers M3 (both configurations) and one-layer foams fabricated from particles T3 and from the Derakane and the D.E.R.

- The foaming process is versatile enough to allow the fabrication of multilayer foams.
- Multilayer foam improved the acoustical properties of one layer material both at low and high frequencies.
- The compaction pressure has little effect on the acoustical and mechanical properties of the multilayers.
- Increasing the number of the layers did not enhance the properties of the multilayers. Each layer must be well-optimized to have an effect on the global properties of the multilayer foam.
- A compromise has to be reached between the acoustical and mechanical properties of the multilayer foams. The mechanical properties is always controlled by the weakest layer.

REFERENCES


