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Abstract. In this work, the viscoelastic behavior of open cell polyurethane foams used in noise control applications is investigated through dynamic mechanical analysis in compression. Several levels of static strains superimposed on a small dynamic one were considered in order to assess the effect of material non-linearity on the mechanical response. Further, a wide range of frequencies and temperatures was explored. For each static strain a different master curve for conservative component of complex modulus, E', could be determined. Interestingly, the loss factor was the same at all static strains, indicating that the relative contribution of energy dissipation and conservation is unaffected by the static strain. Moreover, shift factors (and thus the bulk material relaxation times) turned out to be independent on static strain level. These results suggest that the non- linearity of the foam is linked to the change in foam structure with strain rather than to a non-linear behavior of the viscoelastic constituent material. The acoustic performance of the considered materials was modelled for a case study with two approaches: i) standard simulations performed taking a single valued complex modulus, measured at 50Hz and room temperature or ii) simulations taking into account the complex modulus frequency dependence obtained from the master curves. The transmission loss prediction obtained in the second case is in better agreement with experiments, especially at high frequencies.

INTRODUCTION

Among the variety of damping materials and absorbers, lightweight polyurethane foams have proven to be indispensable, particularly in motor vehicle acoustics for which maximum noise control along with minimum weight is required [1]. The automotive industry requirements for more efficient and lighter components call for the optimization of mass distribution and material properties. The design of light and efficient components for noise control is aided by FEM (Finite Element Method) and SEA (Statistic Energy Analysis) routines which, based on the component geometry and on the material mechanical properties, can give a prediction of the acoustic performances. Determining the correct material properties is thus of fundamental importance for the success of the entire design procedure.

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Even though the possibility of obtaining material properties characterization over a wide range of frequency has been explored [2], the current methodology for the measurement of elastic modulus of acoustic foams to be used in acoustical simulations consists in measuring the complex dynamic modulus only at the frequency of 50 Hz. The use of the modulus determined at just this particular frequency for the prediction of the acoustical response (which indeed involves frequencies ranging from 20 to 20 kHz) can however result in severe mis-estimation of the acoustic performance of a given device.

Dynamic mechanical analysis coupled with time-temperature equivalence [3] can be exploited to measure bulk polymer properties in a wide range of frequencies, but the use of this method in the case of polymeric foams may present some problems. In fact, if on one hand polymeric foam mechanical properties are frequency dependent because of its constituent materials' viscoelasticity [4], on the other their microstructure and its change during deformation can influence the response. Few authors have investigated the influence of a superimposed static deformation on the dynamic-mechanical response of foams [5-8], but their studies were limited to room temperature or to a limited range of frequencies and static strains. In this work we demonstrate the applicability of time-temperature equivalence to obtain the master curves of two polyurethane foams and discuss the effect of a superimposed static strain on the response to a small periodic strain. Finally, the good agreement of transmission loss measurements and simulations performed considering the complex modulus dependence on frequency confirms the validity of a time-temperature reduction scheme to extend the range of available frequencies also for the case of polymeric foams.

MATERIALS AND METHODS

Two flexible polyurethane foams with nominal density of 31.2 kg/m^3 (PU1) and 94.6 kg/m^3 (PU2), supplied by Adler Group (Villastellone Torino, Italia) were investigated. Both materials present an open cell structure and are actually employed in noise control applications.

Foams were supplied as slabs from which cubic samples of nominal dimensions 15x15x15 mm^3 were cut using a sharp razor blade. This geometry allowed the sample to be completely contained within the 25 mm diameter compression plates available, ensuring that at the same time a significant number of cells (at least 20x20x20) were tested.

A TA Instrument Rheometric Series RSA III dynamic mechanical analyzer was employed to investigate the dependence of the conservative, E', and dissipative, E'', components of the dynamic modulus and of the loss factor, $\tan(\delta)$, on frequency and temperature. All tests were carried out in uniaxial compression, applying a sinusoidal strain with 0.01% amplitude and frequency, f, ranging between 0.1Hz and 10Hz. The frequency sweep tests were performed at temperatures spanning from -80°C to 20°C, as detailed in table 1. In order to avoid the detachment of the compressive plates from the sample surface, a static compressive strain had to be superimposed to the periodic one. For PU1 several levels of static strain were applied, as reported in table 1. In the case of PU2 only a static strain of 40% was considered due to lack of samples.

The static strain was applied at room temperature, and then the sample was cooled to the lowest testing temperature and after a proper conditioning time a frequency sweep was performed without making any correction in plates relative position in order to compensate for the thermal shrinkage. After the sweep, the temperature was risen to the following value and the frequency sweep was repeated. This procedure was repeated to cover all the temperatures of interest. A fresh sample was used for each static strain.

TABLE 1. Frequency sweep tests experimental conditions.

Material	Static deformation [%]	Temperature [°C]
PU1	1%, 2%, 8%, 40%	-65, -60, -55, -50, -45, -40, -30, -20, -10, 0, 10, 20
PU2	40%	-80, -70, -50, -40, -30, -20, -10, 0, 10, 20

RESULTS

Dynamic Mechanical Characterization

As an example of the experimental data, Figure 1 shows the results of DMA tests performed at a static strain of 40% for PU1. From the $\tan(\delta)$ data, a master curve was built by shifting the curves along the frequency logarithmic axis, adopting the glass transition temperature, Tg=-45°C as reference temperature. The shift along the frequency logarithmic axis is referred to as shift factor, a_T^{Tg} .

The result of the application of this data reduction scheme is reported in Figure 2, from which it is possible to notice that the master-curve of tan(δ) is the same at all static strains, indicating that static deformation level does not change the relative contribution of the conservative and dissipative components of the material's dynamic modulus. In addition, the shift factors are the same for all static deformations, suggesting that the level of static deformation does not affect the mobility of the polymeric chains in the material. Shift factor dependence on temperature could be fitted with the Arrhenius equation (below Tg) and WLF equation (above Tg).

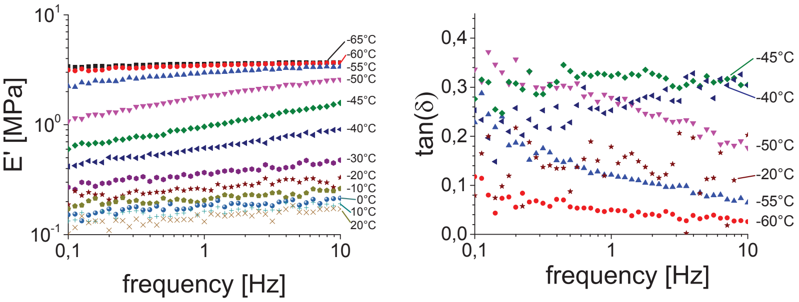

FIGURE 1. PU1: E′ and tan(δ) dependence on frequency and temperature. Applied static strain 40%; strain amplitude 0.01%

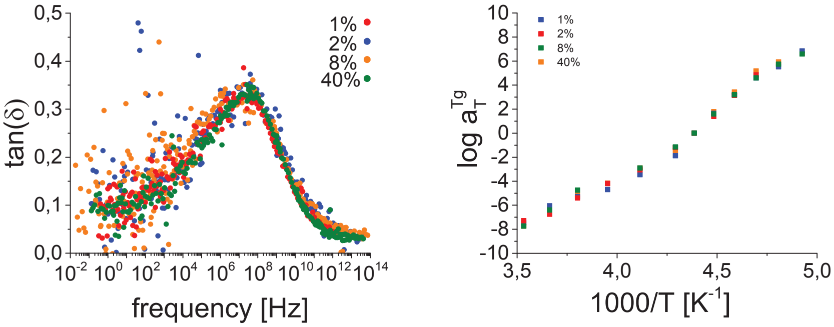

FIGURE 2. PU1: Master curve for tan(δ) at the reference temperature, Tg=-45°C, and relevant shift factors.

Figure 3 reports master curves of the conservative component, E′(*f*), at the investigated strains, obtained adopting the shift factors of figure 2. It can be observed the static strain shifts the E′(*f*) curves vertically, without changing their shape. The trend is in agreement with the tangent modulus dependence on applied strain in constant strain rate compressions reported in literature [4-5], which is related to the changes occurring in the foam structure and subsequent mechanical response. All these observations suggest that the effect of constituent material viscoelasticity is completely decoupled – at least up to 40% static strain– from that of the change in foam structure.

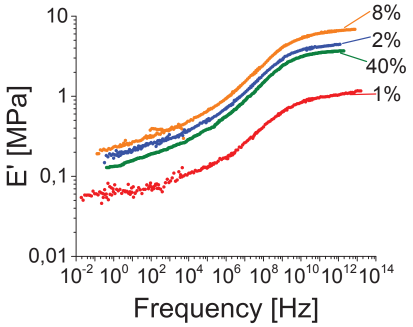

FIGURE 3. PU1: Master curve for E′ at room temperature obtained using the shift factors of Figure 2.

Time-temperature equivalence could also be applied to the case of PU2 at 40% strain, as shown in figure 4, reporting the trend of E′, E″ (Figure 4a) and tan(δ) (Figure 4b) with frequency at Tg=-55°C and shift factor dependence on temperature (Figure 4c).

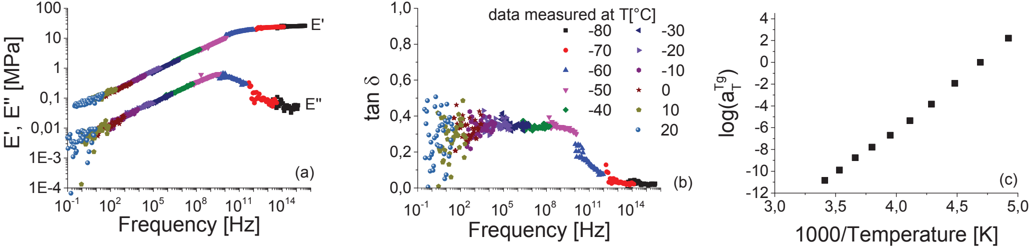

FIGURE 4. PU2: Master curve for E′, E″ (a), and tan(δ) (b) with the relevant shift factor (c).

Prediction of Transmission Loss Performance

The frequency dependence of E′ and E″ for PU2, reported in Figure 4, was used to predict the acoustic behavior of a multilayer panel made of 1.8 mm thick steel plate , PU2 and 1.8 mm thick rubber layer. Experimental tests have been carried out according to ISO 15186-1:2003 Standard [9] in a laboratory for automotive applications. Rectangular panels (size equal to 1.21 x 0.95 m^2) are mounted on a frame between two rooms and sound transmission loss was determined by measuring the average sound pressure level in emitting room and the average sound intensity outgoing from the panel in the receiving room.

The transfer matrix method [10] has been used for the numerical simulations. Such method has been developed for the study of plane wave propagation within multilayer systems (made of elastic solids, rigid and elastic framed porous materials, membranes, resonators, porous and impervious sheets, etc.). The method can be used for simulating normal and oblique incidence as well as diffuse field sound absorption and transmission loss. In the case of sound transmission loss the diffuse field has been calculated by integration of the transmission coefficient between 0° and 78°, and a correction has been applied to take into account the finite size of the panel. In the simulations, the material PU2 has been considered as poro-elastic medium. Regarding the fluid phase experimental measurements of airflow resistivity, open porosity, and tortuosity have been carried out. Viscous and thermal characteristic lengths have been determined by using an inverse procedure starting from minimization of surface impedance with respect to the Johnson-Champoux-Allard's model [11].

In Figure 5 the experimental data are compared with the predictions given by the model using in one case the modulus of the foam as a constant value over the whole range of frequencies, and in the other the frequency-dependent properties. Figure 5 clearly shows that the prediction obtained by using frequency-dependent properties is significantly more accurate. However, some error is still present in the result of the model: in particular it underestimates the real value of about 5 dB around 600Hz and overestimates of 2dB around 3000Hz. These discrepancies may arise from the fact that the panel tested in the reverberant room is sandwiched between the steel plate and the rubber layer with an (unknown) applied static strain different from that used for dynamic mechanical characterization. Nonetheless, the reduction scheme employed for obtaining frequency dependent data was efficient and the use of frequency dependent data is without any doubt an effective way to improve the accuracy of the prediction of the acoustical behaviour.

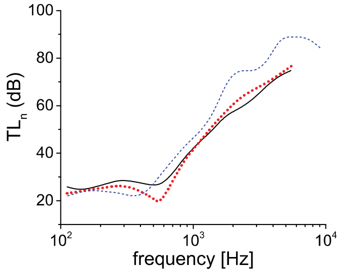

FIGURE 5. Experimental data and numerical prediction of transmission loss of a PU2 panel. Black line: experimental data; blue line, prediction with E*=E*(50Hz); red line: prediction with E*=E*(*f*).

CONCLUSIONS

In this study the effects of static deformation, temperature and frequency on the dynamic mechanical response of two polyurethane foams for acoustic application were investigated.

Dynamic mechanical tests performed by superimposing the same small cyclical strain to different levels of static strain showed results consistent with those reported in the literature. The change in the conservative component of the dynamic modulus may be related to the deformation mechanism of the foam microstructure. Conservative and dissipative components of the complex moduli show the same variation with the applied static strain and thus an almost constant value of tan(δ) irrespective of static deformations is observed. This indicates that in these foams no additional dissipative phenomena arises from the interaction between parts of the structure that may occur at increasing strain level during small strain cyclical tests.

Master-curves of dynamic mechanical properties for PU1 and PU2 could be built by using the time-temperature equivalence. In the case of PU1 the same shift factor could be used all the investigated static deformation, indicating that the static deformation superimposed to the cyclical one has the effect of changing the deformation regime of the foam microstructure, without affecting the constituent material viscoelastic response.

Finally, the adoption of frequency dependent properties of PU2 foam determined applying time-temperature equivalence in acoustic simulations provided a significantly better prediction of experiments than these provided by the standard procedure in which data measured at the frequency of 50 Hz are considered.

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