Mechanical Characterization of a PUR Foam by Means of DMA – Statically and Dynamically, No Problem!

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Intorduction

Due to their low density, foams have a wide range of applications. Soft foams are used, for example, as cushioning material, for acoustic damping or as rattle protection. Rigid foams in particular are employed as insulating materials, in shoe soles, or for such applications as filling layers in composite structures. When the focus is on the thermal insulation effect or material resistance under various environmental conditions, closed-cell foams are usually used. Soft foams especially, on the other hand, are usually open-cell, enabling the gas to escape from the individual cells and thus allowing the foam to undergo greater elastic compression.

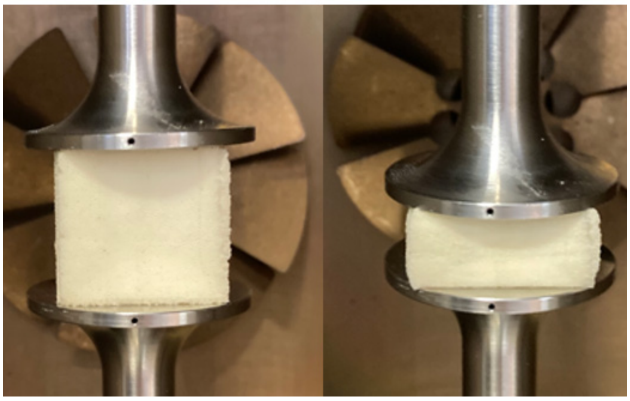
Generally, many polymers are suitable as starting materials for foams. Expanded polystyrene or polyurethane- (PUR-)based foams are particularly widely used. Depending on their manufacture, various PUR foams can exhibit very different properties. The density and degree of crosslinking of the foams vary greatly depending on the amount of blowing agent (water), the addition of further additives and also the chain length of the starting materials, thus allowing for a wide range from soft to very stiff foams.

For the determination of mechanical properties, testing with classic universal tensile testers is well established. Along with the static deformation behavior, also damping of the foam is frequently of central importance for the application. Here, DMA can make a valuable contribution by recording the entire visco-elastic behavior of the foams. In this contribution, a soft, open-pored PUR foam is investigated as an example.

Static Testing

During static (quasi-static) testing with the High Force DMA GABO EPLEXOR® 500 N, a slowly varying load is applied as in a universal tester and the resulting forces and deformations are measured. According to common installation situations for foams, the measurement is usually carried out in compression mode.

Figure 1 shows the unloaded sample on the left and the compressed sample on the right, in the EPLEXOR®. It can be noticed that only a relatively small transverse strain occurs and one can assume here an entirely compressible material in an initial approximation.



1 PUR foam sample with dimensions of 18 x 18 x 20 mm.
Left: in unloaded state; right: in compressed state

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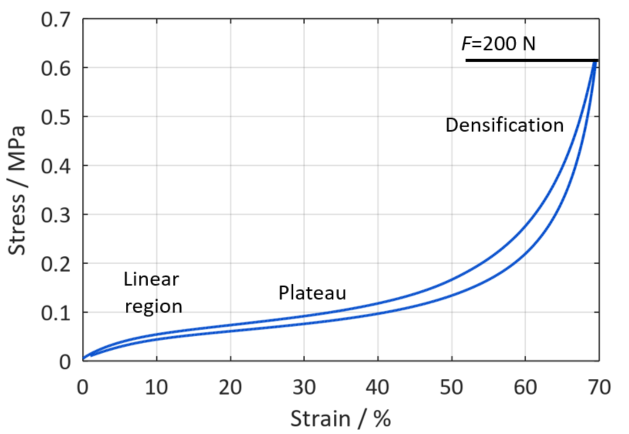
First, the static stress-strain curves are recorded. To exclude one-off effects, the foam sample is typically loaded and unloaded twice, whereby only the second loading cycle is shown in figure 2.



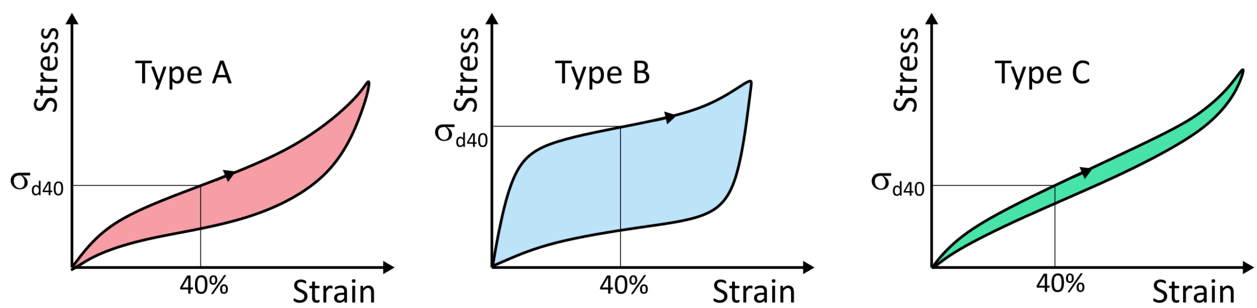
2 Stress-strain diagram of the PUR foam sample in the second load cycle, v=2 mm/s

This shows a tripartite stress-strain curve, typical for soft-elastic foams; e.g., compare to (Keller, 2019). Under relatively small strains, the cells are only slightly deformed and the material behaves in an approximately linear-elastic manner. With increasing strain, the cells of the open-cell foam collapse. Since air has to escape from the cells in this process, the results are a function of the deformation rate. In this plateau region, the stress required for deformation increases only slowly. At very high levels of strain (here beginning at approx. 50%), the cells that have already collapsed are then further compressed and the stress increases again more starkly. During subsequent unloading, the required stresses are only somewhat lower due to the energy dissipation that occurred in the meantime, and a typical hysteresis occurs.

According to ISO 3386, the compression hardness is determined as the necessary stress under an increasing strain of 40%; here, the compression hardness amounts to $\sigma_{d\ 40}$ = 0.12 MPa. The area of hysteresis allows for rough estimation of the material damping. The damping capacity of the PUR foams varies considerably.

Figure 3 shows schematically different hysteresis curves. According to their damping behavior, the PUR foams can be classified into medium damping (type A), strongly damping (type B) or weakly damping (type C). Accordingly, the sample investigated can be categorized as more type C.

As an alternative to the full-surface loading used here, penetration tests are frequently carried out on foams. In this case, a smaller body is pressed into the sample instead of the upper rod. The force required for this is called indentation hardness.



3 Schematic compressive stress-strain diagram of soft-elastic PUR foams (www.wiki.polymerservice-merseburg.de, 2022)

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Dynamic Testing

In a static sweep of the DMA, a static load is applied in each step and then a dynamic oscillation experiment is carried out in this condition. This way, the Young's modulus can be measured directly at this point and thus, damping can also be locally determined.

The foam sample is again statically stretched in steps up to 70%. In figure 4, the same behavior can be seen as in the static tests: For small strains, the sample behaves approximately linearly, but then develops a degressive spring characteristic with increasing strain. The final compression is then again characterized by a spring stiffness that increases with static strain and can therefor be characterized as progressive spring stiffness.

By means of DMA, a Young's modulus can be measured at each point due to dynamic oscillation. As expected, the modulus initially drops in the region of small strains, is then relatively constant and finally increases again with increasing compression. The modulus measured by means of DMA thus behaves exactly the same as the tangent modulus after evaluation of a static test.

With mechanical testing equipment, the Young's modulus of a sample is not directly measured, but a stiffness is first determined based on the measurable forces and deformations. Depending on the sample's geometry and the material model, the Young's modulus is then calculated. Since the foam behaves as largely compressible, the cross-sectional area does not appreciably change during deformation. Accordingly, the stress acting on the sample can be calculated; this is always expressed as:

$$\sigma = F/A_0$$

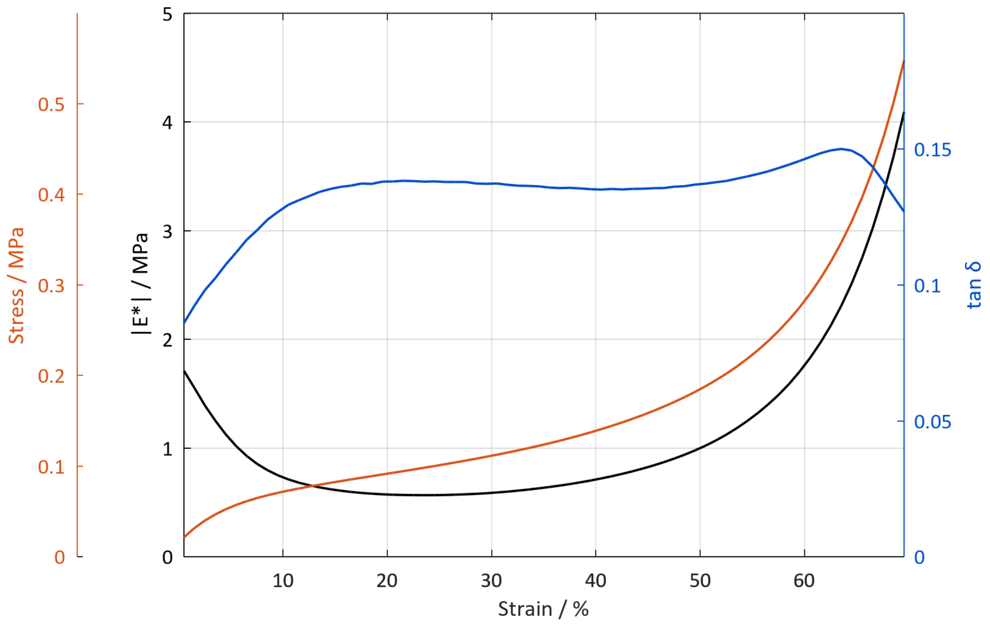
Here, F ist the force and A_0 the nominal initial cross section.

Since the sample's length changes considerably, the dynamic strain should always be related to the current sample length, i.e.,

$$\varepsilon = \Delta L/L_m$$

with deformation ΔL and the current sample length L_m. This yields the geometry factor for calculation of the modulus as L_m / A_0.

This factor is generally valid for compressible materials and can be directly selected in the EPLEXOR®9 software.



4 Static sweep from 0.5% to 70% strain, dynamic 0.5% strain at 10 Hz

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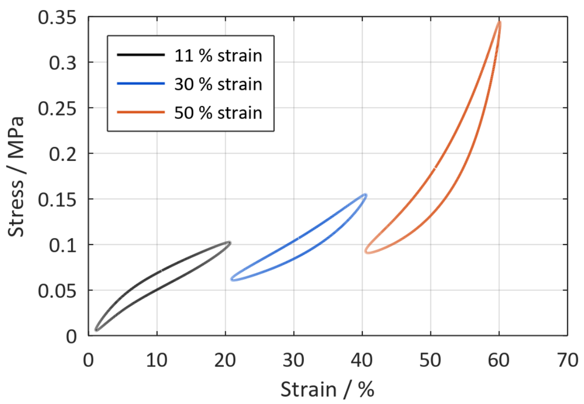
In static testing, it is possible to characterize the damping behavior of the foam based on the hysteresis of the entire deformation. DMA allows for more accurate characterization since local damping can be determined for each static load. It becomes clear that the foam has only low damping capacity in the range of small deformations. Damping (here tan δ) remains relatively constant in the plateau region and then increases again in the compression region. Thus, DMA allows for correct determination of the damping capacity in loaded state.

The non-linear material behavior is completely analogous when increasing the dynamic vibration oscillation amplitude. Figure 5 shows the corresponding hysteresis of a dynamic oscillation cycle (with 10% dynamic strain amplitude) at different static strain levels. The Young's modulus results again from the slope in the stress-strain diagram. It can be seen that the stiffness initially decreases in the range of small static strains (degressive stiffness) and then increases again under large strains (progressive stiffness). At large dynamic amplitudes, this behavior is also evident in the deformation of the hysteresis. The increase in damping with static preload can also be noticed in the large area of the hysteresis.

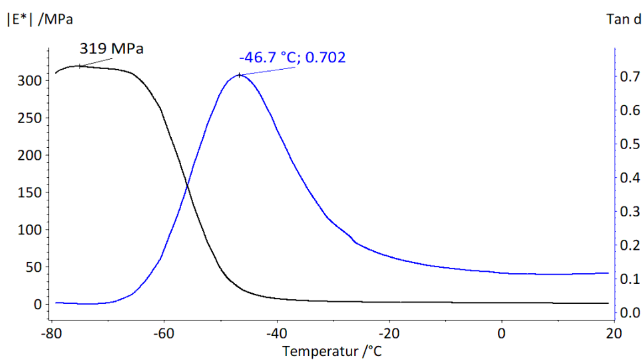
Temperature Behavior

Along with the measurement of the mechanical non-linear material behavior, the DMA GABO EPLEXOR® in particular also allows thermomechanical analysis to be carried out. Thus, the analyses carried out previously are also possible at elevated temperatures or temperatures below the freezing point. Thermal characterization is mostly performed in the linear range of small amplitudes. Due to the strong insulating effect of the foam, a low heating rate of 2 K/min was chosen.

Along with the direct temperature behavior, material properties at frequencies that are not directly accessible by measurement are often of interest. This applies, for example, to using foams for acoustic damping. Here, the time-temperature superposition method can be employed for the generation of master curves. This also allows for conclusions to be drawn on the material behavior at much higher frequencies.



5 Static sweep from 0.5% to 50% strain, dynamic 10% strain at 10 Hz



6 Temperature sweep with a dynamic amplitude of 0.2% at 1 Hz, a staticical proportional factor of 1.5 and a heating rate of 2 K/min

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Summary

The DMA GABO EPLEXOR® 500 N offers sufficient force reserves to measure foams in meaningful sizes so that the non-linear and time-dependent mechanical behavior can be characterized. In addition to information yielded by the stress-strain diagram, the DMA can also be employed to determine stiffness and damping in the compressed state. Furthermore, with the DMA the temperature behavior and, by means of the master curve technique, also the Young's modulus at high frequencies can be determined with just one instrument. This enables the characterization of foams for a variety of application scenarios.

References

Keller, J.-H., 2019. Hysteresismessungen an Partikelschäumen: Erstellung eines Modells zur Simulation der Mitteldehnung bei dynamischer Ermüdung. Bayreuth

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