Effect of Density on the Fatigue Behaviour of EPP and ETPU Bead Foams

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Abstract. Previous research has shown that the static mechanical properties of bead foams are highly dependent on the base material, the materials the foam is made of. Knowledge on the mechanical behaviour is used to produce resource-efficient components tailored to the application. However, components made from bead foams are often subjected to cyclic dynamic loads during their lifetime. The extent to which this changes the mechanical response over time is still unclear. To close that gap in knowledge, foam blocks were made from commercially available expanded thermoplastic polyurethane (ETPU) and expanded polypropylene (EPP) of the same density. The elastic stress of the two materials was determined in quasi-static mechanical tests. To compare the fatigue behaviour, long-term hysteresis measurements were performed in stepwise increasing strain tests (deformation-controlled) and single-stage (stress-controlled) compression tests.

The results of the mechanical tests show excellent fatigue behaviour of ETPU as the material maintains its progressive stress-strain behaviour in the stepwise increasing strain test up to 80 % deformation. Dynamic creep is significantly lower compared to EPP. The one-step test illustrates the different fatigue behaviour at a load of 150 % of the respective elastic stress. EPP shows a compaction of 27 % after 1,000 load cycles and ETPU a compaction of 7.4 % after 500,000 load cycles. The stiffness of EPP increases significantly due to densification, while the stiffness of ETPU remains constant over the entire test duration after settling at the beginning.

INTRODUCTION

Bead foams allow the combination of relatively low densities and complex shapes. Therefore, they are very popular for lightweight construction applications [1]. In the last 20 years, much research and development work has been done in the field of bead foams [2]. In general, foam properties can be categorized by the relative density, the foam structure, and the properties of the base material [3]. EPP is widely used as material for energy absorbing components in the automotive industry, as protective components in the sports industry, or in reusable packaging for high-priced products [4–6].The quasi-static and short-term dynamic mechanical properties of EPP show a strong dependence on the process parameters, density, ambient temperature, and microstructure[5, 7–10] Bead foams made of ETPU are used as midsole material in sports shoes and as a cushioning layer for running tracks. The material exhibits high energy return and exceptional recovery characteristics [11, 12].

Although bead foams are often subjected to long-term dynamic loads in their applications, very little scientific literature was dedicated to this topic. To the best of our knowledge, fatigue behaviour was only studied for EPS [13, 14], while EPP and ETPU were not addressed yet, although these materials are frequently used in applications exposed to cyclic loads.

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MATERIALS AND METHODS

Materials

In this study, expanded polypropylene beads Neopolen® P92HD 180 and expanded thermoplastic polyurethane beads Infinergy® 32-100 U10 (both BASF SE, Ludwigshafen) were used. The beads were fused to plates with similar densities ranging between 230 and 265 kg/m^3. The crack fill steam chest molding was performed using an ENERGY FOAMER 5.0 from Kurz Ersa, Würzburg, according to the technical data sheet. The specimens were prepared by waterjet cutting according to DIN EN ISO 844.

Methods

The density (ρ) of each tested sample was analyzed. The geometric volume (V) and the mass (m) of the samples were measured. The density was calculated with equation $\rho = \frac{m}{V}$.

Tests were performed to analyze the quasi-static compression behaviour according to DIN EN ISO 844. A 10 kN load cell was used on a universal testing machine Z050 from Zwick Roell GmbH. A pre-load of 3 N was applied before the compression step. The specimens were deformed to a total compaction of 60 %. The elastic stress σ_{el} was determined as the intersection of the tangents of the linear elastic and plateau surfaces according to Gibson et al.[3].

Dynamic tests were performed on a Schenck servo-hydraulic testing machine PL16N. The deflection was measured with the position sensor of the piston. A 2 kN load cell U3 from the HBM company was used. The performance of the materials was continuously recorded using the DynMat software (BASF SE, Ludwigshafen).

To obtain an overview of the mechanical dynamic response of EPP and ETPU, load increase tests were first performed according to Fray et al.[15]. While, the lower load level is chosen to be 0.1 of the elastic stress, the upper load level is approached in a strain-controlled manner and is stepwise increased. The steps were selected at 3 %, 10 %, 20 %, 40 %, 60 %, and 80 % of compression. At each step, 10,000 cycles are performed. Between the cycles, a recovery period of 1,000 cycles at a load level of 0.1* σ_{el} was applied.

Finally, the long-term fatigue behaviour was investigated. For this purpose, single load tests were performed with an upper load limit of 1.5 of elastic stress and a constant stress ratio of 0.1. Each specimen was tested for 500,000 load cycles at a frequency of 1 Hz. The stiffness is calculated as the slope of the mid curve of the hysteresis. The minimum stiffness is the slope at the beginning of the load cycle and the maximum stiffness is at the end of the load cycle.

FIGURE 1 gives an overview of the mechanical tests carried out in this work. All tests were performed at 23 °C and 50 % humidity.

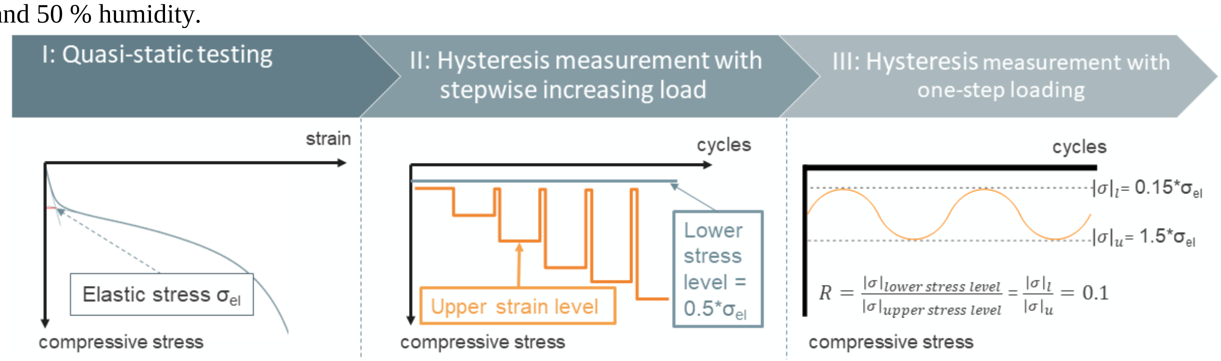
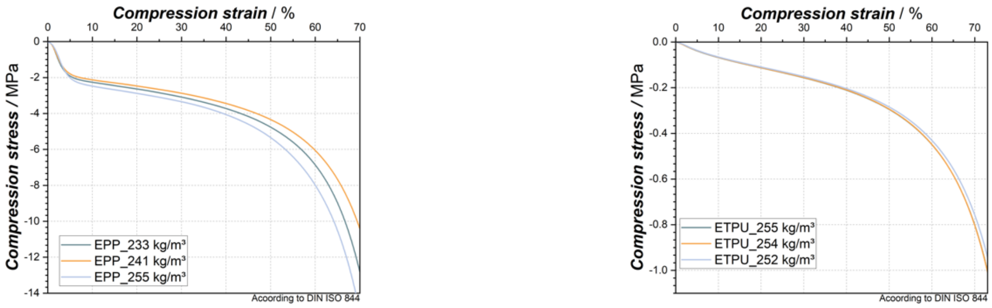


FIGURE 1: Steps of the mechanical testing of the materials starting with the quasi-static evaluation (I) of the elastic stress, continuing with the stepwise increasing load test (II) and finally the one-step loading (III) test to evaluate the long-term fatigue behaviour.

RESULTS AND DISCUSSION

The compressive stress-strain curves of the quasi-static tests are illustrated in **FIGURE 2**.

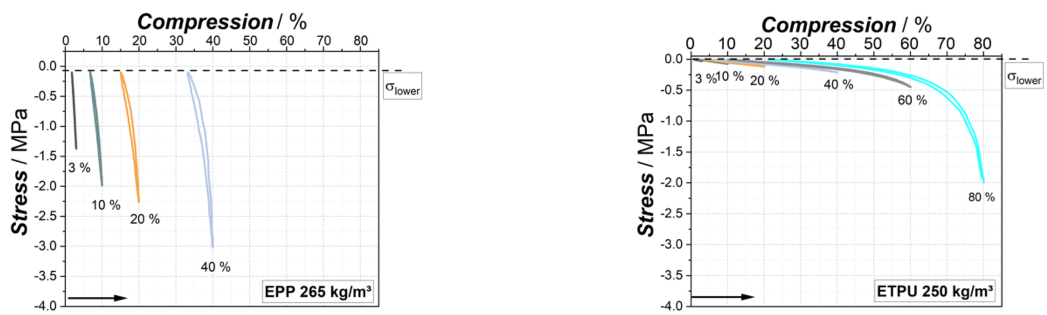


(a) (b)

FIGURE 2: Quasi-static Compression behaviour of EPP (a) and ETPU (b)

The graphs highlight the different compressive behaviour of EPP and ETPU. EPP shows a clear separation between the linear elastic and plateau regions. The results of ETPU, on the other hand, show a less pronounced transition between the two characteristic deformation zones, indicating a more elastomeric behaviour. The main reason for this difference is the base material the foam is made of [3]. Therefore, the elastic stress σ_{el} of EPP, 1.97 ± 0.15 MPa, is higher than the elastic stress of ETPU, 0.04 ± 0.002 MPa.

In the test with stepwise increase of strain, 10 % of σ_{el} was used as a load. Representative hysteresis curves at these different strain steps are shown in **FIGURE 3**.

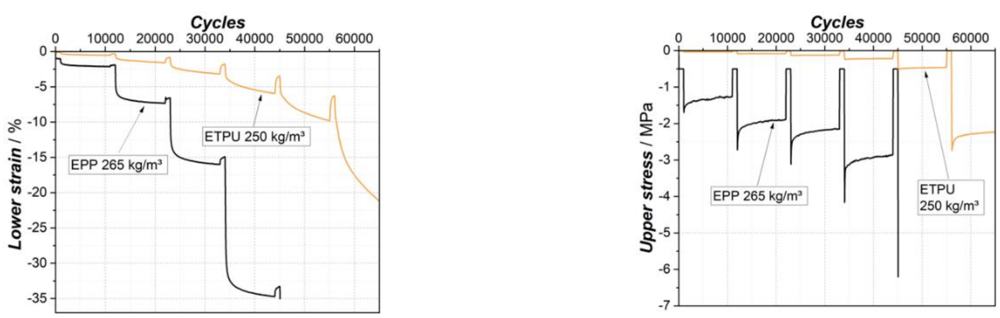


(a) (b)

FIGURE 3: Hysteresis of the individual strain increase steps 3 %, 10 %, 20 %, 40 %, 60 % and 80 % of EPP (a) and ETPU (b)

The difference between the two materials is striking. Firstly, the stress which is needed to achieve the controlled strain is much higher for EPP than ETPU at each step. Secondly, the change of the starting point of the hysteresis is stronger shifted in the direction of compression with EPP compared to ETPU. This indicates a higher dynamic creep of the EPP. For ETPU, a dynamic creep is observed. However, even with a compression of 80 %, this material maintains its progressive stress-strain behaviour.

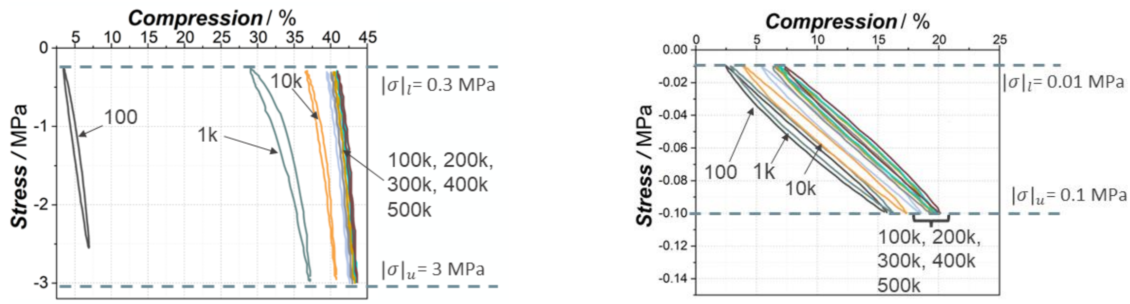
FIGURE 4 provides a more detailed view on the progression at the lower strain and at the upper stress level of both materials.



(a) (b)

FIGURE 4: Comparison of the response signals of EPP and ETPU to the stress regulated lower load: the lower strain (a) and the strain regulated upper load: the upper stress (b)

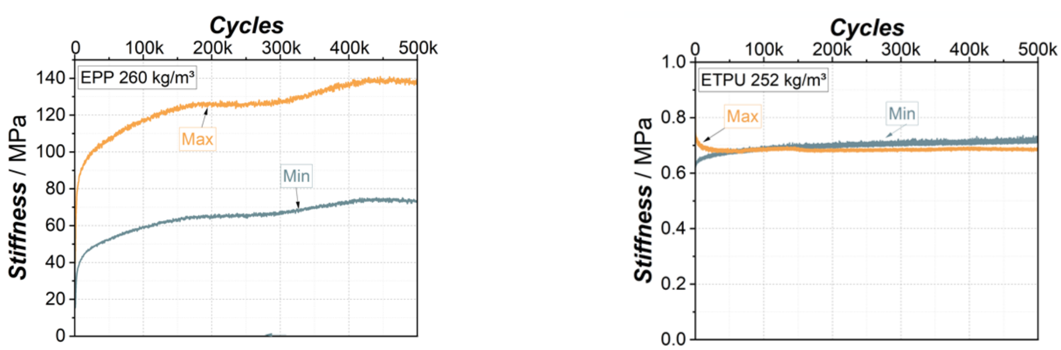
The figure on the left shows the increasing lower strain, which indicates a permanent compression of the samples caused by the dynamic load. At the end of the fourth step, the density of the EPP increased to 400 kg/m³. The density of ETPU increased after the same step to 268 kg/m³. The changes of ETPU are relatively small, even at the end of the test. After 65,000 cycles and compressions up to 80 %, the sample height after unloading is reduced to around 27 %. The figure on the right shows that the stress required to achieve the specified strain-controlled compression increases at each step for both EPP and ETPU. The permanent densification increased the resistance to the further deformation, as the relative density of the foam significantly influences the stiffness of a foam [3].
To analyse the behaviour of the foam subjected at a constant stress level, one step load tests were performed. As an upper load level, $1.5{*}\sigma_{el}$ is chosen for both foams. This approach ensures that both foams are permanently dynamically loaded in the respective plateau region. In **FIGURE 5**, selected hysteresis curves of the fatigue tests are shown.



(a) (b)

FIGURE 5: Development of the hysteresis after 100, 1k, 100k, 200k, 300k, 400k, and 500k of EPP (a) and ETPU (b) due to dynamical fatigue stress

As observed in the previous tests, the two foams show very different behaviour. While the shape of the hysteresis of EPP changes after only a few cycles, the behaviour of ETPU remains constant up to 500,000 cycles. The dynamic creep of EPP after 1,000 cycles is at 27 % and significantly higher than ETPU with 7.4 % after 500,000 load cycles. **FIGURE 6** illustrates the change in stiffness calculated as the slope of the mid-curve of the hysteresis.



(a) (b)

FIGURE 6: Comparison of the development of the stiffness at the beginning of a single load cycle (min) and at the end of a single load cycle (max) of EPP (a) and ETPU (b)

The stiffness of EPP increases rapidly at the very beginning of dynamic loading. After 500,000 loading cycles, the stiffness minimum differs from the stiffness maximum by 65 MPa. It can be concluded that the material is stiffer at the end of the loading cycle than at the beginning. The figure on the right shows the stiffness evolution of ETPU. At the beginning, the maximum stiffness is higher than the minimum stiffness. Both stiffnesses converge after 50,000 cycles and subsequently remain almost identical until the end of the test. In summary, ETPU maintains similar stiffness regardless of loading and unloading over the complete duration of the test.

CONCLUSION

In this study, the mechanical behaviour of EPP and ETPU was compared under quasi-static and dynamic long-term loading. The difference between the foams is striking. EPP shows a plastic-elastic behaviour and ETPU a more elastomeric behaviour. The base material also has a strong on the results of the fatigue tests. While EPP shows strong dynamic creep during the first stages of the stepwise strain increase tests, ETPU maintains its progressive stress-strain behaviour up to a compaction of 80 %. ETPU's excellent fatigue behaviour was also demonstrated in the single-step fatigue test. ETPU shows compression of only 7.4 % after 500,000 cycles. In comparison, EPP loses 27 % of its height during the first 1,000 cycles.

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