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Investigation of the energy absorption properties of cross-linked polyethylene foams

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Abstract. We performed the dynamic mechanical investigation of cross-linked polyethylene (XL-PE) foams, which are the most commonly used polymer foams for damping purposes. Our experiments were primarily focused on analyzing the energy-absorbing capability of foams with different densities and studying the relationship between cell structure and shock absorption. The cell structure and energy absorption properties of the foams were determined by mechanical tests and microscopic examination. The samples were subjected to falling dart and falling weight impact tests using different weight geometries and impact energy. Our experiments showed that the impact damping properties of foams are significantly influenced by the deformation mechanisms in the cellular structure during dynamic loading since excessive deformation of the cell walls leads to the compaction of the foam, and therefore a significant reduction in impact damping capability.

1. Introduction

Today, the industrial use of polymeric foams is expanding due to their low density and weight, as well as their outstanding thermal and acoustic insulation, impact damping and energy absorption properties [1-4]. The leading industries are increasingly using foams, and the global polymer foam market is continuously growing. The most significant segments are the construction industry, where outstanding heat insulation is required, the car industry, which specially focuses on weight reduction, the packaging industry with high shock-absorption requirements, and the sports industry [5, 6]. Processing technologies are rapidly improving, and now foaming can be used even for upcycling to reduce the load on the environment [7].

The most important feature of polymer foam products used in sports is their outstanding impact damping and energy absorption capability. In many sports, several different mats are used for safety purposes or for providing an appropriate surface for sports activities. In these cases, the primary task is to protect the health of the athlete and prevent sports injuries [8]. Foams are suitable for this function because of their unique cellular structure. Under load, the cells undergo different types of deformation (bending of cell edges, cell wall buckling), so these materials can absorb a huge amount of energy while keeping the maximum stress below a certain value [9].

Current sports mats are produced from cross-linked polyethylene foams, rebonded polyurethane foams, ethylene-vinyl-acetate foams, and elastomeric foams, of which XL-PE foams are the most



commonly used [6]. Compared to conventional foams, they have better thermal stability and greater form stability due to the cross-links between the molecular chains. From the point of view of manufacturing technology, there are physical cross-linking by radiation or chemical cross-linking. In this case, peroxide compounds are used most commonly, which remove hydrogen atoms from the polymer chain and form free radicals. These radicals start combining, resulting in cross-linked bonds [10-12].

In recent years, increasing attention has been paid to the study of the energy-absorbing properties of polymer foams. In the case of sports mats, dynamic mechanical tests are the most popular, but the difference of falling weight geometries and impact energy in sports-specific standards make comparison with previous experimental results difficult [13, 14]. Dynamic mechanical tests can be low impact velocity tests, such as the falling dart [15, 16] and falling weight impact tests [17], while for high impact velocities the Hopkinson bar can be used [18]. However, the relationship between cellular structure, foam density, and energy absorption is not fully understood, and the previously mentioned testing methods are not compared, so the aim of our research is to investigate cross-linked polyethylene foams dynamically, analyze the effect of density on energy absorption properties and compare the two most commonly used testing methods for low-velocity impacts.

2. Materials and methods

This chapter presents the investigated materials, the investigating methods, and measuring devices used.

2.1. Materials

We performed the tests on two physically cross-linked polyethylene foams with different densities, supplied by UFM Bt. (Hungary, Mosonmagyaróvár). The main properties of these commercially available foams are summarized in Table 1 [19].

Table 1 Main properties of the cross-linked polyethylene foams used [19]

Property	Unit	Measurement standard	XL-PE 45	XL-PE 60
Density	(kg/m ³)	ISO 845	45 ± 6	60 ± 8
Tensile strength	(kPa)	ISO 1798	> 215	> 380
Elongation at break	(%)	ISO 1798	> 210	> 300
Compressive strength	(kPa)	ISO 3386/1 (at 10 (%) comp.)	> 17	> 40
Compression set	(%)	ISO 1856 (22 (h), 23 (°C), 25 (%))	≤ 6	≤ 4
Thermal conductivity	(W/mK)	DIN 52612 (at 10 (°C))	0.039	0.051
Shore hardness	(-)	ISO 868	> 30	> 35

2.2. Methods

2.2.1. Density measurement. The densities given in the manufacturer's datasheet were verified by hydrostatic density tests with a Radwag analytical balance according to formula (1):

$$\rho_f = \frac{m_a}{m_a - m_l} \cdot \rho_l \quad (1)$$

where ρ_f (kg/m³) is the calculated density of the foam, m_a (kg) is the specimen's weight in air, m_l (kg) is the specimen's weight in liquid, and ρ_l (kg/m³) is the density of the measuring liquid at room temperature. We used distilled water as measuring liquid for the calculations. Prior to the mechanical tests, the thickness of the samples was also determined with a Mitutoyo digital micrometer.

2.2.2. Scanning electron microscopy. The microscopic images were taken with a JEOL JSM 6380LA scanning electron microscope. The samples were coated with a gold-palladium alloy for appropriate conductivity.

2.2.3. Falling dart impact tests. The falling dart impact tests were performed with a Ceast 9350 impact tester machine. The parameters for the tests are summarized in Table 2, while the layout of the test is shown in Figure 1. For the tests, samples with the size of 100 (mm) x 100 (mm) x 18 (mm) were cut out from the extruded foam sheets.

Table 2 Main parameters of the falling dart impact tests

Property	Unit	Value
Impactor geometry	(-)	cylinder, hemispherical end
Impactor diameter	(mm)	20
Applied mass	(kg)	5.41
Falling height	(mm)	942
Impact energy	(J)	50
Temperature	(°C)	23
Support type	(-)	hollow

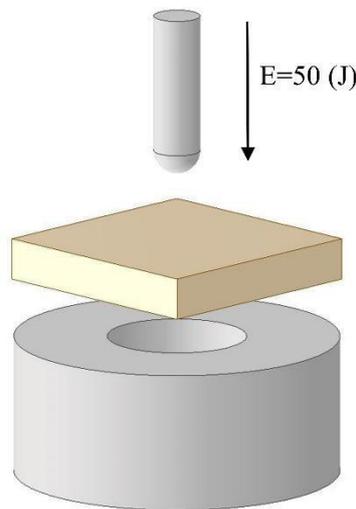


Figure 1 The layout of falling dart impact tests

The force-time diagrams were recorded during the tests, from which perforation energy (2) and ductility index (3) were calculated according to the following:

$$E_{perf} = \frac{E_{total}}{v} \quad (2)$$

where E_{perf} (J/mm) is the perforation energy, E_{total} (J) is the total absorbed energy during penetration, while v (mm) is the thickness of the sample.

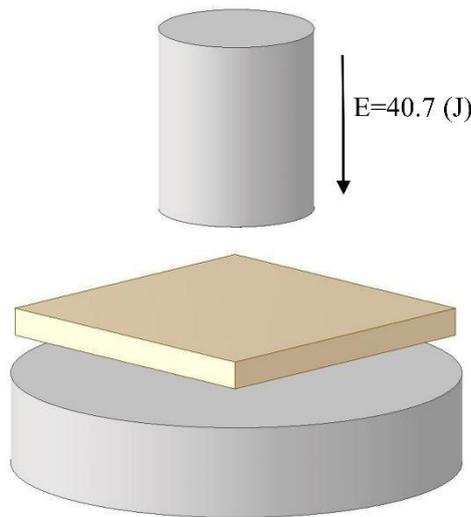
$$DI = \frac{E_{total} - E_{Fmax}}{E_{total}} \quad (3)$$

where DI (-) is the ductility index, E_{total} (J) is the total absorbed energy during penetration, while E_{Fmax} (J) is the energy absorbed until maximum load.

2.2.4. Falling weight impact tests. The falling weight impact tests were performed on a custom-designed falling weight impact tester, which was built according to the wrestling mat regulation set up by United World Wrestling [20]. The applied parameters for the tests are summarized in Table 3, while the layout of the test is shown in Figure 2. For these tests, samples with the size of 200 x 200 x 18 (mm) were cut from the extruded foam sheets.

Table 3 Main parameters of the falling weight impact tests

Property	Unit	Value
Impactor geometry	(-)	cylinder, flat end
Impactor diameter	(mm)	100
Applied mass	(kg)	10.025
Falling height	(mm)	414 ± 0.4
Impact energy	(J)	40.7
Temperature	(°C)	23
Support type	(-)	solid

**Figure 2** The layout of falling weight impact tests

The falling weight impact tests consisted of eight drops on each sample to show the effect of repetitive impacts on damping properties. The time between impacts was one minute. In the evaluation of the results, we focused on four different parameters:

- The maximum deceleration during the impact: a ($g=9,81 \text{ m/s}^2$) – which refers to the gravitational acceleration.
- The amount of absorbed energy during the impact: E (%)
- The maximum deformation of the samples: p (mm)
- The duration of the collision: t (ms)

3. Results

This chapter contains the evaluation of the results of density, scanning electron microscope, falling dart and falling weight tests.

3.1. Density results

The results of the hydrostatic density tests and the measured thickness of the samples are shown in Table 4. The densities of the tested foams are almost the same as the density specified by the manufacturer. The XL-PE 45 and XL-PE 60 foams have the same thickness, so the different densities can be compared.

Table 4 Measured density and thickness

Property	Unit	XL-PE 45	XL-PE 60
Measured density	(kg/m^3)	43.82 ± 0.68	58.30 ± 0.27
Measured thickness	(mm)	17.87 ± 0.22	17.86 ± 0.27

3.2. Results of scanning electron microscopy

The scanning electron microscopic images (Figure 3) show that the tested foams have a closed-cell structure, that is, the foam cells are isolated from each other. The XL-PE 45 sample has an average cell diameter of 108 ± 42 (μm), whereas the XL-PE 60 foam has an average cell size of 87 ± 30 (μm), so the higher density foam has smaller cells. Another important difference is that the higher density foam has thicker cell walls, which effects a more rigid structure. It is likely that this type of difference has a significant effect on the shock absorption properties since the cells are more resistant to deformation.

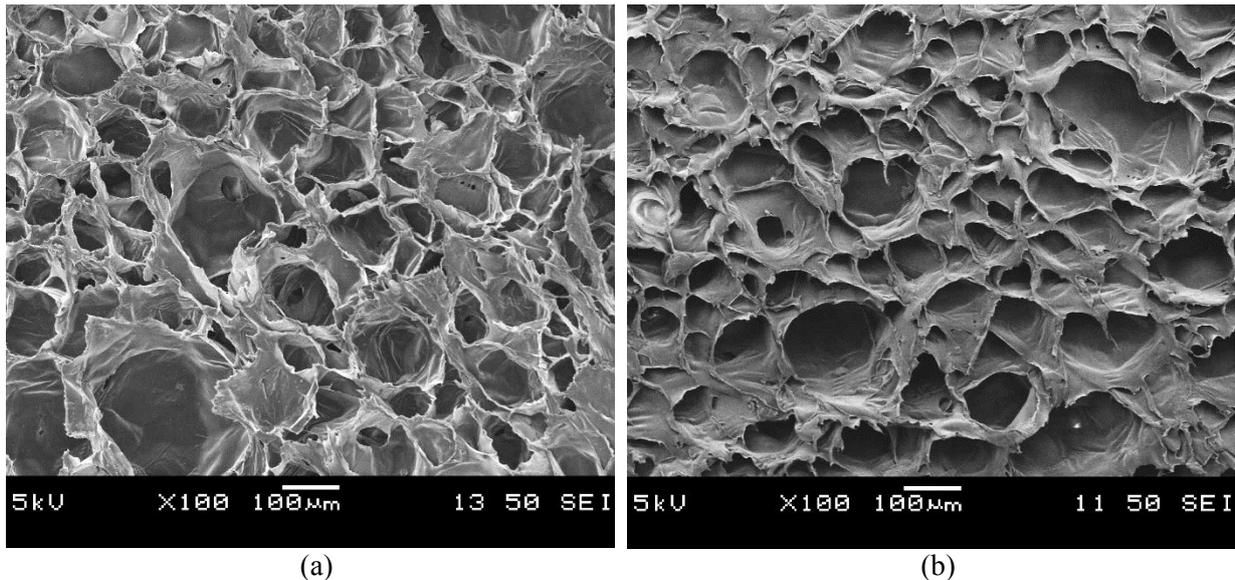


Figure 3 SEM images of XL-PE 45 (a) and XL-PE-60 (b) samples

3.3. Falling dart impact tests

During the falling dart impact tests, the samples were completely punctured, hence we compared the dynamic mechanical properties of the two foams by calculating perforation energy and the ductility index. The recorded force-time diagrams (Figure 4) show that during the penetration of the dart, small vibrations and harmonics appeared, but they did not significantly influence the test, so the results are valid. The noise during the test was caused by the measurement layout, which did not consist of any clamping; if a clamping ring had been used, the cellular structure of the foams would have been deformed, and it would have affected the results.

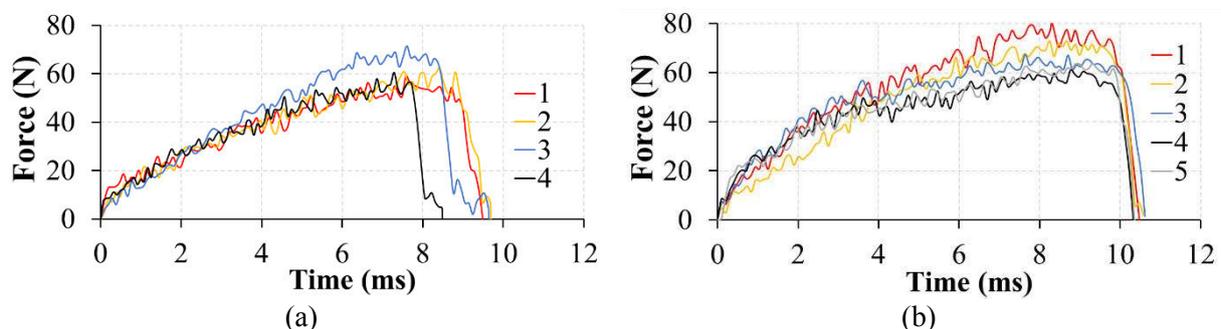


Figure 4 Force-time curves of the falling dart tests in case of XL-PE 45 (a) and XL-PE 60 (b)

In the case of XL-PE 60 samples, total rupture time exceeded 10 (ms), while in the case of XL-PE 45 type foam it was 9 (ms). The reason for this difference is that the foam with thicker cell walls was more resistant, therefore the maximum force during the test was also higher. These properties also

influenced the ductility of the fractured material and the amount of energy absorbed. The stiffer cell structure resulted in higher perforation energy and a higher ductility index (Table 5).

Table 5 Results of the falling dart impact tests

Property	Unit	XL-PE 45	XL-PE 60
E_{nerf}	(J/mm)	0.09 ± 0.01	0.12 ± 0.01
DI	(-)	0.13 ± 0.08	0.22 ± 0.09

The fact that the specimens were fully ruptured suggests that the impact damping properties of foams cannot be tested with this method. Using solid support can resolve this issue.

3.4. Falling weight impact tests

The results of the falling weight impact tests show that the higher density foam effected a lower maximum deceleration on the falling weight and was also able to absorb more energy (Table 6). This can be explained by the stiffer cell structure.

The XL-PE 45 sample showed approximately 1 (mm) larger deformation, which explains the higher maximum deceleration, since due to the higher compression, the cells became more compact and were likely to approach the behavior of the solid material.

Table 6 Results of the falling weight impact tests

Property	Unit	XL-PE 45	XL-PE 60
p	(mm)	15.88 ± 0.16	14.81 ± 0.47
a	(g)	130.03 ± 12.96	113.24 ± 26.87
E	(%)	45.09 ± 3.50	55.76 ± 7.41
t	(ms)	16.85 ± 0.72	16.76 ± 1.23

We also examined the effect of repetitive impacts. As the tests progressed, the maximum deceleration in both samples during impact increased continuously while the absorbed energy decreased continuously (Figure 5). This indicates that the impact damping property of the foams decreases in the case of repetitive impacts, as the material gradually hardens.

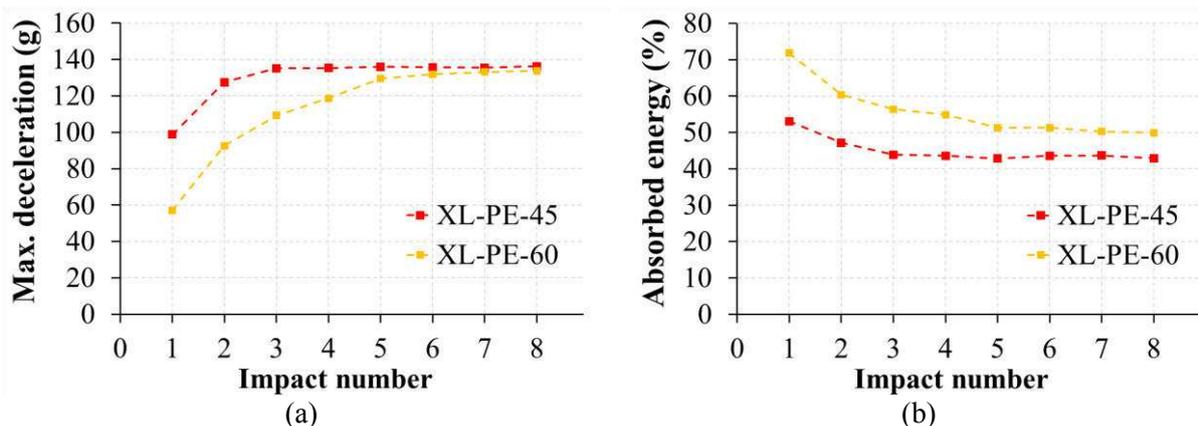


Figure 5 The effect of repetitive impacts on maximum deceleration (a) and energy absorption (b)

The reason for this phenomenon is that during the collision, the cells were deformed and compressed, as a result of which opposite cell walls probably met, and the one minute between the impacts is probably not enough for the cells to return to their original condition. This results in a reduction of the impact damping and energy-absorbing properties of the foams during repetitive impacts.

This method was more suitable for investigating the impact damping properties of foams. The solid support represents a model closer to the real-life use of sports mats, where they are laid down on the floor to reduce the force on the athletes.

4. Conclusions

We performed the dynamic mechanical investigation of two cross-linked closed-cell polyethylene foams with different densities, by falling dart and falling weight impact tests. Based on the results, the following conclusions can be drawn:

- The cross-linked polyethylene foam with a density of 60 (kg/m³) has higher perforation energy, ductility index, and better impact damping and energy-absorbing properties compared to the foam with the lower, 45 (kg/m³) density.
- The impact damping properties of polymer foams are significantly influenced by the deformation mechanisms in the cellular structure during dynamic loads, since excessive deformation of the cell walls leads to the compaction of the foam structure. This significantly reduces impact damping capability.
- In falling dart impact tests with a hollow support, the foams are fully ruptured, therefore this method is inappropriate for investigating the impact damping properties of foams. The use of a solid support similar to the support in the falling weight impact tester can resolve this issue.

As the use of cross-linked polyethylene foams in the sports industry is increasing and falling weight impact tests are also used in the packaging industry, our research results can be utilized in many industries to select the appropriate density and cell structure of the foam.

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