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DAMPING PROPERTIES AND DENSITY OF HELMET LINERS MADE OF EXPANDED POLYSTYRENE (EPS)

The purpose of the work was to determine the infuence of the bulk density ρ_z of granules, processing parameters and the density of ski inserts ρ_w made of expanded polystyrene (EPS) on their damping properties. For this aim liners for ski helmets with 3 different bulk densities were made. Sintering time and sintering pressure were also changed. The percentage damping factor η was determined on the basis of the results obtained in the rebound resilience test. Based on the analysis of the obtained data, it was found that increasing the density of EPS pads ρ_w increases their damping properties and at the same time contributes to a decrease in elasticity, increase in hardness and brittleness of EPS products.

Keywords: expanded PS, ski liners, PS foams, damping factor, bulk density

1. Introduction

In the era of more and more intensive care for the health, condition of the body and the associated security, it has become important to develop new solutions in this matter. Various types of protection, e.g. airbags in cars, inserts that dampen vibrations or relieve individual parts of the body against excessive overloads, have become a standard in our lives. Having this type of protection options, we increasingly decide on intense physical activity not only in spring and summer, but also in winter. A great example of activity can be sports such as skiing or snowboarding. It is necessary to properly protect the body, especially the head, exposed to traumas and injuries [1], because although head injuries constitute a small percentage of injuries associated with skiing and snowboarding, they are the main cause of death and disability associated with these sports [2]. Hence, it is often recommended to use helmets while skiing or snowboarding and many studies indicate a reduction in the risk of head injuries by up to 60% when using helmets during this activities [3-9].

The helmet components that protect the head are foam liner and helmet shell. Polymer foams, used for liners, are also often used as insulation, membranes, absorbents and for noise reduction and damping elements [10-17]. The task of the foam liner is to absorb energy during impact. The material often used for liners is, lightweight and cheap to produce, expanded polystyrene (EPS) [18-22]. Despite many years of using PS for liners, research is still being carried out on its expansion in various conditions. [23-24]. In turn, the authors of papers [25-29] analyzed, e.g. influence of polymer liner density on energy absorption during impact. In the works, it was noticed that helmet shells made of composites and dense EPS liners have better impact – absorbing properties. By controlling the thickness and density of the foam liners, it is possible to regulate the ability to absorb impacts [25]. However, the thickness of the liner is adjustable taking into account the shape and comfort of use. In contrast, the density is limited by the requirements for the weight and magnitude of the accelerations that can be transferred during an impact on the head [27]. Therefore, the thickness of the inserts in motorcycle helmets is between 30 to 40 mm, and the density from 40 to 50 kg/m^3. In turn, the thickness of the shells is from 1 to 2.5 mm if the shell is made of composite [29], or 4-5 mm if it is made of thermoplastics [30].

The properties of the base polymer, e.g. repeatability of units, terminal functional groups, crystal or amorphous structure, molecular weight and its distribution, as well as branched structure, have an impact on the cell structure, cell density and volume expansion factor (V.E.R) of polymer foams. For higher cell density in polymer foams with the same V.E.R. smaller cells, and therefore theoretically better mechanical and thermal properties, are obtained [31-33].

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Although in recent years both, the material and the geometry, of the shell and liners have changed many times to provide the best protection, tests are still being continued to obtain the increase in the absorbance of impact energy by motorcycle and bicycle helmets. At the same time, there is a lack of comprehensive studies on the impact of foam liners density on the damping factor of ski and snowboard helmets.

The purpose of the work was to determine the infuence of the bulk density ρ_z of granules, the density of inserts ρ_w and processing parameters of parts made of expanded polystyrene (EPS) on their damping properties. The percentage damping factor η was determined on the basis of the results obtained in the rebound resilience test.

2. Research material and methods

Firstly, using a device called a foaming machine, the beads of expandable polystyrene were subjected to initial growth.

A foaming machine is a device in which polystyrene (PS) is processed to expanded polystyrene (EPS) by activating blowing agents. The construction of the foaming machine for the continuous expanded process in steam is shown in Figure 1. This device continuously generates balls of foamed PS. The foaming machine consists of a container for non-expanded polystyrene, which is transported to the steam chamber by means of a motor-driven screw. The stirrer inside the chamber ensures even foaming of the granules and prevents the material from caking. As a result of expanding (supplying steam under pressure), the granules increase their volume. Pentane (blowing agent), included in PS, contributes to several dozen increases in the volume of each granule. In interior of granules, in the pores formed this way, accumulates air. The bulk density of a material per volume unit is reduced. This means that intensively expanded, large granules occupy greater space in a blowing chamber, but have less density. At different heights, the chamber wall has outlet opening, through which EPS is received. Depending on the height at which the outlet opening is located, different bulk density ρ_z is obtained from expanded polystyrene [25]. Bulk density ρ_z is the amount of EPS per volume unit. EPS with the lowest bulk density ρ_z is obtained by setting the outlet opening at the highest possible height level. Similarly, granules with the highest bulk density ρ_z are obtained by setting the outlet opening at the lowest level.

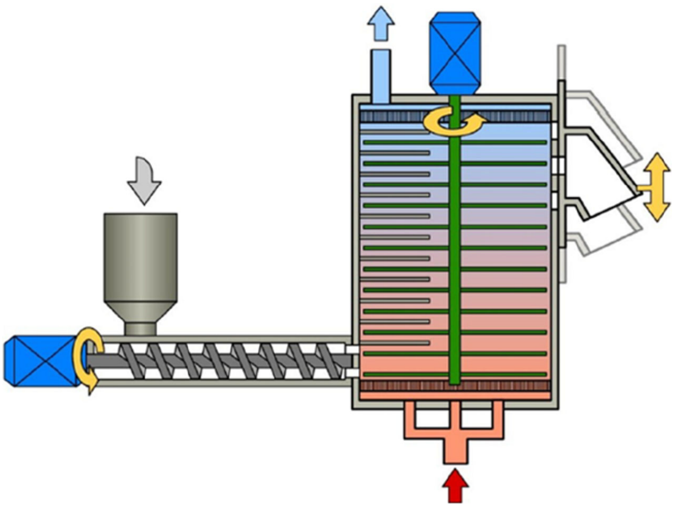

Fig. 1. Construction of a foaming machine [25]

By supplying steam at a pressure of about 0.4 MPa to the foaming chamber, pre-expanded PS granules were obtained. EPS was prepared in 3 different bulk densities ρ_z. In this way granules with low (A – 0.026 g/cm^3), medium (B – 0.043 g/cm^3) and high (C – 0.076 g/cm^3) bulk density ρ_z were prepared (Fig. 2) The foamed PS was dried and then seasoned for about 16 hours at room temperature. Seasoning in ventilated silos allows the removal of pentane residues and further air penetration inside the pores, providing them with necessary stability in further processing and operation.

Fig. 2. Pre-expanded polystyrene

The seasoned granules of pre-expanded PS were subjected to final sintering in an autoclave. The preparation of liners for helmets were as follows:

- pouring granules into the mould through the filling hole
- placing the mould in an autoclave
- selection and setting of process parameters, e.g. steam temperature and pressure etc.
- cooling the mould
- removing the mould from the autoclave
- opening the form and removing the finished liners for helmets

From the expanded PS, of three different granule sizes, 27 ski helmet liners have been prepared. Helmet liners number 1 to 9 were prepared from the EPS with the lowest bulk density ρ_z (A – 0.026 g/cm^3, large granules), details number 10 to 18 prepared form EPS with the medium bulk density ρ_z (B – 0.043 g/cm^3, medium granules), while those with numbers 19 to 27 were made of the material with the highest bulk density ρ_z (C – 0.076 g/cm^3, small granules) (Fig. 3). The sintering parameters are shown in Table 1. In the article, two densities are distinguished:

Fig. 3. Finished helmet liners made of EPS

- Bulk density ρ_z – determines the density of pre-expanded, non – sintered PS granules,
- Helmet liners ρ_w – determines the density of finished liners after the sintering process.

Three samples were cut from each helmet, by heated wire for thermal separation. The method of obtaining samples is shown in Figure 4. In this way 81 samples, produced with 3 variable parameters, were obtained:

- bulk density ρ_z – A, B and C,
- sintering time t_s – 15 s, 20 s, 25 s,
- sintering pressure p_s – 0.07 MPa, 0.09 MPa, 0.11 MPa.

2.1. Density of ski helmet liners

Helmet liners density ρ_w was determined using a laboratory hydrostatic balance by Radwag AS 220.3Y. The obtained results of the influence of time t_s and sintering pressure p_s on the density ρ_w of the helmet liners made of different bulk density ρ_z EPS are shown in Fig. 5÷7.

Analyzing the obtained results (Fig. 5) for the samples made of EPS with the low (series 1-3) and medium (series 10-12) bulk density ρ_z and sintering time t_s = 15 s, it was found that the sintering pressure p_s has no significant effect on the density of obtained helmet liners ρ_w. The slight effect of sintering pressure p_s is only noticeable for samples made of granules with the highest bulk density ρ_z (series 19-21) and is in the range from 0.54 to 0.57 g/cm^3.

TABLE 1

Sintering process parameters

Sample number	Bulk density ρ_z [g/cm^3]	Sintering time t_s [s]	Sintering pressure p_s [MPa]
1	A	15	0.11
2	A	15	0.09
3	A	15	0.07
4	A	20	0.11
5	A	20	0.09
6	A	20	0.07
7	A	25	0.11
8	A	25	0.09
9	A	25	0.07
10	B	15	0.11
11	B	15	0.09
12	B	15	0.07
13	B	20	0.11
14	B	20	0.09
15	B	20	0.07
16	B	25	0.11
17	B	25	0.09
18	B	25	0.07
19	C	15	0.11
20	C	15	0.09
21	C	15	0.07
22	C	20	0.11
23	C	20	0.09
24	C	20	0.7
25	C	25	0.11
26	C	25	0.09
27	C	25	0.07

On the other hand, for samples produced at t_s = 20 s, it was noted that the highest density ρ_w was found for the helmet liners produced at the sintering pressure p_s equal to 0.09 MPa (samples 5, 14 and 23, Fig. 6), regardless of the bulk density. Changing (both increasing and decreasing) the sintering pressure, causes reduction of the helmet liners density ρ_w. This trend is most visible for helmet liners made of granules with a maximum bulk density ρ_z. In addition, it was found that increasing the bulk density ρ_z (A → C, tab. 1) causes increasing the helmet liners density ρ_w. For example, samples made of granules with a minimum bulk density ρ_z (A) have a density ρ_w of approximately

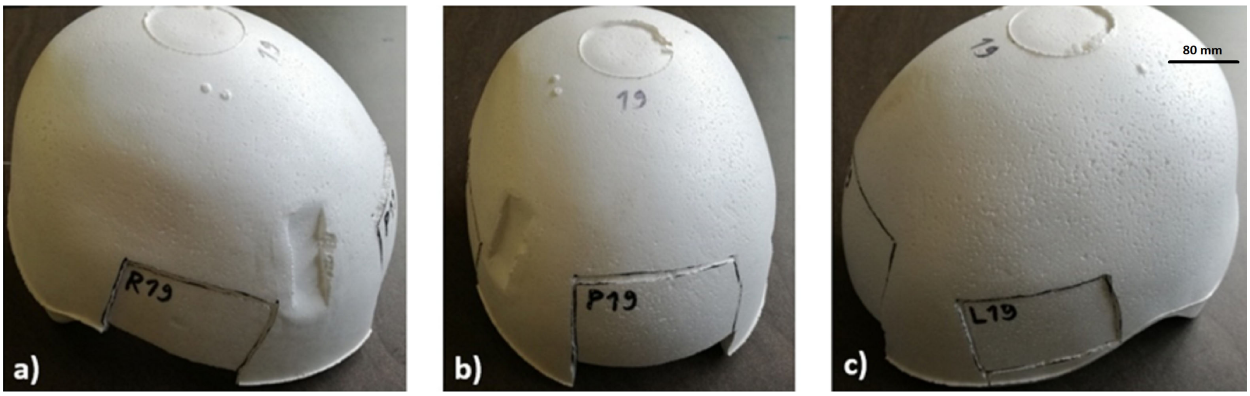

Fig. 4. Helmet liners with marked sampling locations: a) right side b) front c) left side

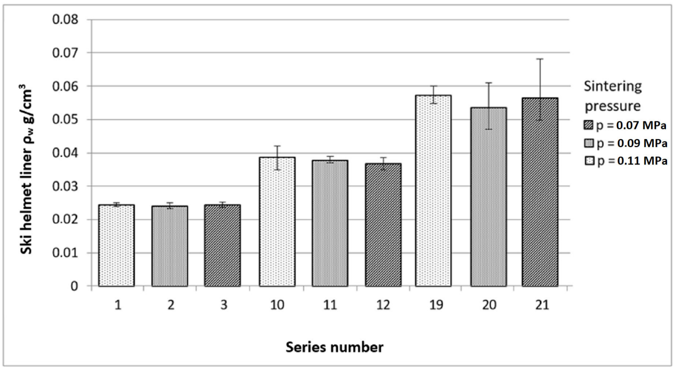

Fig. 5. Influence of sintering pressure p_s on the helmet liners density ρ_w produced atsintering time 15 s

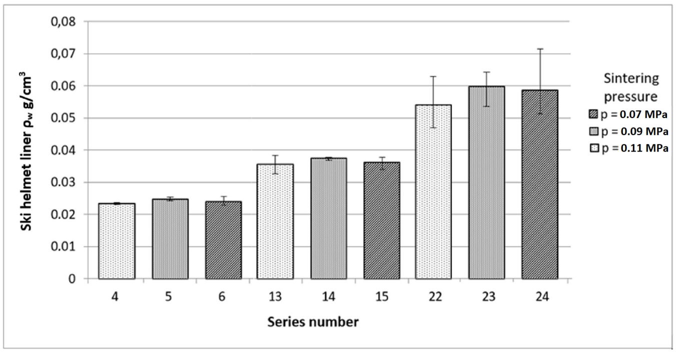

Fig. 6. Influence of sintering pressure p_s on the helmet liners density ρ_w produced atsintering time 20 s

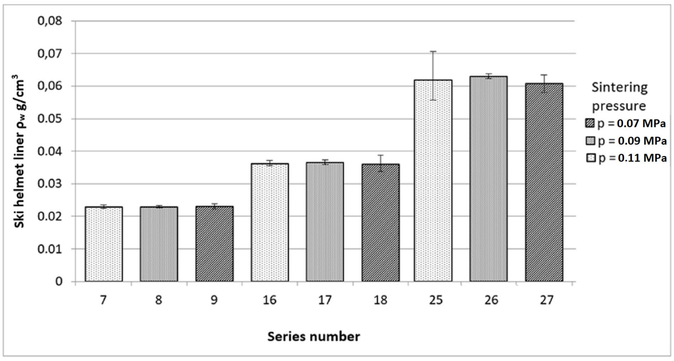

Fig. 7. Influence of sintering pressure p_s on the helmet liners density ρ_w produced atsintering time 25

0.023 g/cm^3 at a sintering time of 20 s (regardless of pressure p_s). As a result of the bulk density ρ_z increase, the helmet liners density ρ_w increased by 57% (series 4 and 22) and 61% (series 5 and 23 and 6 and 24).

In the case of further extension of the sintering time to 25 s, the tendencies observed earlier, persist (Fig. 7). However, in this case it was observed that the sintering pressure ρ_s has no significant effect on the obtained helmet liners density ρ_w. Samples density is similar, regardless of the sintering pressure.

Comparing the obtained results (Figs. 5-7), it was found that for samples (series 19-27) made of granules with the highest bulk density ρ_z the extension of sintering time causes the increase in the helmet liners density ρ_w. It may be due to tight filling of the space between the granules during their further growth and shrinkage of some granules overheated with steam.

2.2. Rebound resilience test

The study was conducted on a self-designed and built test stand. The construction of the stand was designed on the basis of the standard PN-EN ISO 4651: 2000, where a steel ball with a mass of $m_n = 28$ g and a diameter of $D_n = 16$ mm dropped from a height of $H_n = 0.4$ m is used to calculate the damping factor [34].

In order to determine the height from which a steel ball with a mass $m_k = 12.62$ g and a diameter of $D_{kl} = 14.5$ mm should be dropped, appropriate calculations were made. Using formula (1) for gravity potential energy [35]:

$$E_{p_c} = m \cdot g \cdot h \tag{1}$$

where: m – object mass [g], g – gravity [m/s^2], h – height, at which the object is located relative to the adopted reference system [mm], and formula (2) on sphere-cross section:

$$P = \frac{\pi \cdot D^2}{4} \tag{2}$$

where: D – ball diameter, obtained (3):

$$\frac{m_n \cdot g \cdot H_n}{\frac{\pi \cdot D_n{}^2}{4}} = \frac{m_k \cdot g \cdot H}{\frac{\pi \cdot D_{kl}{}^2}{4}} \tag{3}$$

where: m_k – ball mass, H – height, from which the ball will be dropped, D_{kl} – ball diameter

After conversion was received (4):

$$H = \frac{\frac{\pi \cdot D_{kl}{}^2}{4} \cdot \frac{m_n \cdot g \cdot H_n}{\frac{\pi \cdot D_n{}^2}{4}}}{m_k \cdot g} \tag{4}$$

After substitution (5):

$$H = \frac{\frac{3{,}14 \cdot (0{,}0145)^2}{4} \cdot \frac{0{,}028 \cdot 9{,}81 \cdot 0{,}4}{\frac{3{,}14 \cdot (0{,}016)^2}{4}}}{0{,}012624 \cdot 9{,}81} \tag{5}$$

$$H = 73 \text{ [cm]}$$

On the basis of calculations, it was specified that the steel ball should be dropped from a height H = 730 mm.

The previously prepared samples were successively placed under a vertically attached transparent tube made of polycarbonate (PC) with the following dimensions:

- 16 mm internal diameter,
- wall thickness 2 mm,
- length 1000 mm.

A steel ball pre-positioned at height H = 730 mm was dropped onto each of the 81 samples. The obtained results are shown in the table 2. Each attempt was recorded with a digital camera. From the recordings played back in slow motion, the height at which the steel ball bounced was determined.

The average height of bounced ball was calculated using the formula (6) for the percentage damping factor [36]:

$$\eta = \frac{h_{o_{sr}}}{H} \cdot 100\% \tag{6}$$

where: $h_{o_{sr}}$ – average height of bounced ball [mm], H – height, from which the ball will be dropped [mm]

TABLE 2

Damping factor related to the average bounce height

No.	Bulk density ρ_z	Average rebound height [mm]	Damping factor η [%]	Sintering time t_s [s]	Sintering pressure p_s [MPa]
1	A	186	25,53	15	0.11
2	A	176	24,05	15	0.09
3	A	173	23,74	15	0.07
4	A	189	25,87	20	0.11
5	A	185	25,40	20	0.09
6	A	181	24,75	20	0.07
7	A	190	26,00	25	0.11
8	A	184	25,18	25	0.09
9	A	187	25,62	25	0.07
10	B	148	20,33	15	0.11
11	B	145	19,92	15	0.09
12	B	146	20,00	15	0.07
13	B	159	21,84	20	0.11
14	B	153	20,99	20	0.09
15	B	159	21,83	20	0.07
16	B	156	21,37	25	0.11
17	B	161	22,01	25	0.09
18	B	153	20,98	25	0.07
19	C	119	16,30	15	0.11
20	C	120	16,39	15	0.09
21	C	118	16,12	15	0.07
22	C	126	17,28	20	0.11
23	C	119	16,36	20	0.09
24	C	121	16,58	20	0.07
25	C	132	18,06	25	0.11
26	C	124	16,95	25	0.09
27	C	122	16,76	25	0.07

Based on the obtained results (Table 2) for samples produced during 15s (series 1-3, 10-12 and 19-21), it was found that the sintering pressure p_s does not significantly affect changes in the damping properties. Only for series 1-3 the damping factor η of samples produced at sintering pressure p_s equal 0.11 MPa is slightly higher than the others. It was also noted that the helmet liners made of EPS with the highest bulk density ρ_z have the highest damping factor η approx. 25% (for samples from series 1). The lowest value of the damping factor η was observed for samples made of EPS with the lowest density ρ_z (about 16% for details number 19-21).

The extension of sintering time t_s to 20s (series 4-6, 13-15 and 22-24) did not significantly affect the damping factor of the helmet liners obtained from the lowest density ρ_z EPS. However, in the case of helmet liners made of medium density ρ_z EPS, a slight increase in the damping factor η (approx. 2-9%) can be seen. It was also found that at sintering pressure p_s = 0.11 MPa, the damping factor is slightly higher for all tested samples.

For samples made at sintering time t_s 25s, a reduction of the damping factor η by as much as 15-35% (series 7-9, 16-18 and 25-27) in comparison to samples from series 1-3, was found. However, it cannot be clearly determined whether this is the effect of sintering time or the bulk density of the granulate. There was no significant effect of sintering pressure p_s on the damping factor. It is noteworthy that in most cases, the largest value of the damping factor η was found in samples produced at sintering pressure p_s of 0.11 MPa. The pressure reduction to 0.07 MPa caused a slight decrease in the value of the damping factor η.

Based on the obtained results, it was found that the worst damping properties characterized helmet liners made of EPS with the highest bulk density ρ_z. The best properties have samples whose density ρ_w is between 0.054 to 0.06 g/cm^3.

3. Conclusions

Based on the carried out tests, it has been noticed that it is possible to prepare helmet liners with different bulk density. Depending on the mentioned density, the helmet liners may have a different damping factor. Samples were prepared according to a test plan containing three variables, i.e. bulk density ρ_z, sintering pressure p_s and sintering time t_s. From the obtained results in the rebound resilience tests, used to determine the percentage damping factor, it can be concluded that the bulk density ρ_z has the greatest influence on changes in the damping properties of elements made of EPS.

The described results clearly indicate the relationship between the helmet liners density ρ_w and the damping factor η. Increasing the helmet liners density increases the damping properties of the ski helmet. However, it also contributes to increasing the hardness and brittleness of EPS products [25-28].

The best properties have samples whose density ρ_w is between 0.054 to 0.06 g/cm^3 and were made in the low bulk density ρ_z regardless of sintering time and pressure (1-9 series).

The tests allowed to obtain important information that can be used for further research, and as a consequence improve safety, including a better development of the construction of ski helmet liners.

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