Received: 28 May 2021 | Revised: 31 August 2021 | Accepted: 11 September 2021

DOI: 10.1002/app.51714

REVIEW

Journal of Applied Polymer Science WILEY

Polymer foams as advanced energy absorbing materials for sports applications—A review

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Funding information
Ministry for Innovation and Technology, Grant/Award Number: ÚNKP-20-5; National Research, Development and Innovation Office, Grant/Award Number: K 132462; NRDI Fund, Grant/Award Numbers: BME-IE-NAT, TKP2020; United World Wrestling; Hungarian Academy of Sciences, Grant/Award Number: János Bolyai Research Scholarship; NRDI Office

Abstract

The use of polymer foams is becoming increasingly important due to the attainable weight reduction and value-added properties. The development of foam structures is a popular research area as they have outstanding energy absorbing capability, which is related to the special deformation mechanisms of the cell structure (cell wall buckling and collapse of the cells). This property is exploited by the sports industry, where the main task of such products is to protect the health of the athlete and to ensure safe sports conditions. This review provides a comprehensive presentation of the advanced energy absorbing applications of polymeric foams in sports. The article presents in detail the processing technologies of polymer foams, as well as the sports-specific regulations which contain the requirements for sports products. The impact damping of polymeric foams is typically determined by falling weight impact tests, which were used in several previous studies. However, it is a great challenge to compare the published results, as the test parameters and the tested materials are different. Currently, an unexplored field of research is the detailed study of multilayer sandwich foam structures. Understanding the effect of layer order on mechanical properties would help researchers achieve a major improvement in this field.

KEYWORDS

energy absorption, engineering, impact testing, material science, polymer foam, sports application

1 | INTRODUCTION

A polymer foam is a two-phase system that contains statistically distributed gas bubbles in a polymer matrix.[1] Foamed polymer products have numerous advantageous properties, including low density, good heat and sound insulation, and excellent energy absorption (impact resistance). Due to these advantages, they are used in a wide variety of applications. The market of polymer foams is constantly growing, which is clearly indicated by the fact that, the worldwide annual consumption of polymer foams exceeds 26 million tons. These foams are extensively used by the vehicle industry, the building industry, the packaging industry, and they can be found in a lot of sports equipment. This results that the volume of the global foam market reached 113 billion dollars in 2019, and the yearly increase is about 4%.[1–5]

The excellent insulating and impact properties of polymer foams are due to their cellular structure. Thanks to the deformation mechanism of the cells, polymer foams can disperse the energy of impacts in such a way that the maximum forces are kept below a certain limit—in the case of an impact, the maximum force in a polymer foam is well below the maximum force in an identical, non-foamed material.[6]

This property is exploited in the engineering applications of polymer foams. Transportation industry is one of the biggest user segments, where the main function of the foamed vehicle cover parts is to provide the safety of the passengers. Likewise, impact-damping properties are utilized in the packaging industry, where foams need to protect the household appliances and technical products from the loads occurring during transportation.[7,8] Similarly, the safety of athletes, avoiding injury is also very important, that is why various foam structures are used in many areas in protective gear, or for a surface where sports activity can be safely done. Sports mats to dampen landing are mostly used in gymnastics, high jump, pole vault, and combat sports.[8] In combat sports, the requirements for polymer foam structures applied as sports mats are more complex (adequate impact damping, compression set, static stiffness, non-slippery surface). Here, the polymer foam products are used as the surface of the fights; hence, they need to be stiff enough to provide an optimal surface for the complex movements. In addition, high impact-damping capability is also required so that the load on the athlete does not reach the health-damaging risk limit.[8]

This review focuses primarily on demonstrating the sports applications of polymeric foams and their most commonly used testing methods. The importance of the topic is shown by the fact that the use of an unsuitable sports mat can even cause permanent sports injuries.[9–11] From this review, we can also learn about previous research results on the dynamic mechanical testing of polymer foams.

2 | POLYMER FOAMS—PROPERTIES AND PROCESSING TECHNOLOGIES

2.1 | Structural properties of polymer foams

Polymer foams have unique physical, mechanical and thermal properties, which are mostly influenced by the characteristics of the polymer matrix, the distributed gas bubbles, and their relationship. This relation affects the produced cell structure, which can be described by cell density, expansion rate, average cell size, and cell type. By using these properties, we can classify the polymer foam products in several ways based on their type of structure, average cell size, porosity or density.[12–14]

Porosity is widely used for the classification of different porous materials, which can be calculated as the ratio of the pore volume and the total volume of the foam material (see Equation (1)):

$$\emptyset = \frac{V_{\text{pore}}}{V_{\text{total}}}, \tag{1}$$

where $\emptyset$ (–) is the porosity, V_{pore} (m^3) is the pore volume in the foam, while V_{total} (m^3) is the total volume of the foam material. In addition to several other porous materials (such as ceramics and metals), porosity is also often used to characterize polymeric foam structures. It gives supplementary information about the homogeneity of the foaming process and can explain tendencies in the mechanical properties. If the exact volume of a foam sample is unknown, different two-dimension imaging techniques are used to determine the porosity and investigate the morphological properties (e.g, pore types).[15]

Generally, three main pore types are distinguished in the literature based on the accessibility to the surface of the porous material, closed pores, blind pores, and through pores (Figure 1). Closed pores are completely separated from the material surface; blind pores can be accessed from the surface, but they ends inside the materials, while through pores connect the inner and outer material surfaces.[16]

In the case of polymer foams, "pores" are most commonly called "cells". To the analogy of pore types, different types of cell structures can be distinguished, which greatly influences the application field of the final product. In the case of closed-cell foam structures, the foam cells are totally isolated from each other, and the gas-filled cavities are surrounded by closed cell walls. In general, closed-cell foams have lower permeability (e.g. sound), which results in better insulation. They are often characterized by their stiffness and strength, as well as their heat resistance capacity (*R*-value). As closed-cell foams generally have a higher relative density, their production requires a larger amount of polymeric raw material, which increases

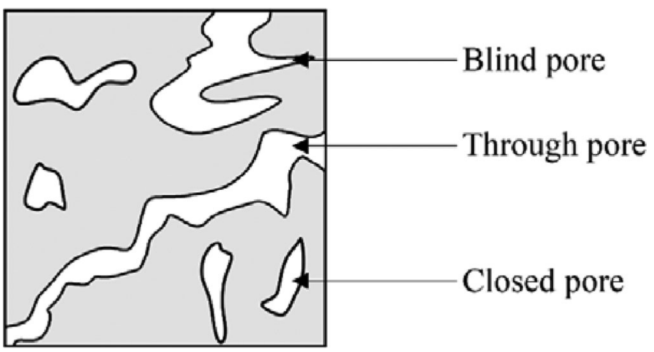

FIGURE 1 Different kinds of pore types (figure was created by the authors)

the commercial price of the products.[14,17] In the case of open-cell foams, the air can flow freely through the cells, which gives a softer and spongier appearance. These foams have higher water absorption capacity and can also be used for noise barriers.[8,14]

Figure 2 shows scanning electron images of closed and open-cell foam structures. In the case of open-cell polyurethane (PU) foam, air can flow freely between the cell walls. In contrast, this is not possible in case of the closed-cell polyethylene foam, as the cell walls isolate the cavities.[8]

Another grouping option is to divide the foams by their density. In general, we can distinguish low and high-density foams, which are separated by a density limit of 250 kg/m^3.[18] In many cases, the relative density of the material is more important, which can be defined as the ratio of the densities of the foam structure and the solid polymer matrix (see Equation (2)):

$$\rho_{rel} = \frac{\rho_{foam}}{\rho_{polymer}}, \quad (2)$$

where ρ_{rel} (–) is the relative density, ρ_{foam} (kg/m^3) is the density of the foamed structure, and $\rho_{polymer}$ (kg/m^3) is the density of the solid polymer matrix.[8]

Higher relative densities usually result in better mechanical properties, as the structure is closer to the properties of the starting solid polymer. This was confirmed by Avalle and Scattina,[19] who summarized the results of previous tensile tests[20–22] on microcellular acrylonitrile–butadiene–styrene (ABS) foams and microcellular polycarbonate (PC) foams. Based on these results, the effect of relative density on relative Young's modulus can be described by a quadratic formula. In this respect, relative Young's modulus is the quotient of the foam's Young modulus (E_h [Pa]) and the Young's modulus of the polymer matrix material (E_p [Pa]).[19]

This study summarized the characteristics of microcellular foams. It is important to define the cell size classes accurately. Based on average cell size, we can classify foams into the following groups[13,23]:

1. macrocellular structures: > 100 μm
2. microcellular structures: 1–100 μm
3. ultra-micro-cellular structures: 0.1–1 μm
4. nano-cellular structures: < 0.1 μm.

Furthermore, much research classifies porous structures into rigid and flexible foams. These types are different both in their mechanical properties and in application fields.[24] Rigid foams are used for insulating buildings, storing food and beverages, and in the packaging and furniture industries. The application of flexible foams covers the furniture industry, the shipping industry, seat inserts, sports applications (e.g. sports mats) and shock and noise reduction.[8,25]

2.2 | Foaming processes and their characteristics

In addition to the properties of the starting polymer raw material, the energy absorption and mechanical properties of polymer foams are mostly influenced by relative density and the cell structure (e.g. cell size, shape) formed during the foaming process. For this reason, the knowledge of polymer foaming technologies is extremely important.

A general foaming process can be divided into four successive steps. After the distribution of the foaming agent in the polymer matrix, the formation of bubbles gradually begins, cells start to nucleate in the polymer, then the volume of bubbles starts to increase, and finally, the foam reaches its final structure and stabilizes by cooling. After cell nucleation, the volume increases continuously until a stable state is reached.[1,12,13,25]

In general, the raw materials of the process are the polymer and the so-called blowing agent, which is responsible for bubble nucleation and cell structure formation.[12,25]

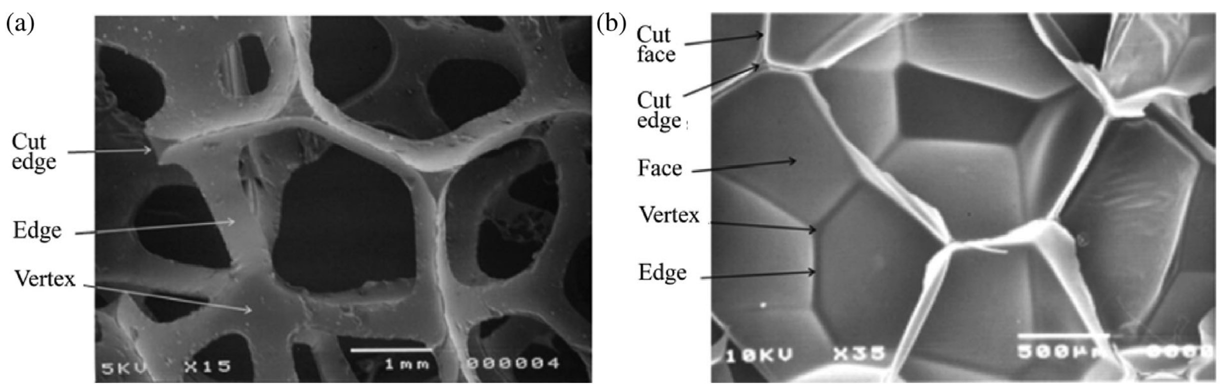

FIGURE 2 Scanning electron microscope images of open-cell polyurethane ($\rho = 28$ kg/m^3) and closed cell low-density polyethylene foam ($\rho = 24$ kg/m^3). Reproduced with permission.[8] Copyright 2021, Elsevier

If the blowing agent does not undergo a chemical transformation, it is called a physical foaming agent. In these cases, the formation of the polymer foam is ensured by a change of state of the material, caused by pressure and/or temperature difference. In the case of physical foaming, the blowing agent is typically introduced into the system at a stage of the process (e.g., extrusion) when the polymer is already in a melt state. Therefore, it is necessary to modify the processing line, since an additional injection unit must be formed, which introduces the gas (e.g. carbon dioxide) into the polymer melt typically in supercritical state.

The use of the so-called tandem extrusion line is also widespread in the industry, which can be achieved by connecting several extruders in a row. In the past, chlorofluorocarbons (CFCs) were the most widely used physical blowing agents, but their use was banned due to their ozone-depleting effect. Today, the most commonly used blowing agents are various hydrocarbons, hydrofluorocarbons, and especially inert gases (nitrogen, carbon dioxide). They have a common property that they do not react with the other components or with each other.[12,13,26,27]

If the foaming process takes place as a result of a chemical reaction or thermal decomposition, we can talk about the use of a chemical blowing agent. By using these agents (e.g. azodicarbonamide and sodium bicarbonate), a considerable cost reduction can be achieved during processing, as foaming can be performed on conventional processing equipment without significant modification. Because of this, the use of chemical blowing agents is widespread in the processing technologies of conventional thermoplastic polymers (e.g. injection molding and extrusion).[25,28]

In these cases, the polymeric raw material and the blowing agent are fed simultaneously through the feed hopper. An important factor is that the decomposition temperature of the blowing agent must be fitted to the processing temperature range of the polymeric matrix material.[29] Depending on the nature of the chemical reaction, a distinction can be made between endothermic and exothermic blowing agents. In the endothermic case, extra heat is required to start foaming, so the decomposition temperature range of these types is wider, usually, 130–230°C, while the exothermic types start to decompose around 200°C.[8,12,13]

3 | SPORTS APPLICATION OF POLYMERIC FOAMS

3.1 | Requirements in the sports industry

Foams used in the manufacturing of sports equipment mainly perform a safety function, as the main task of the various protective equipment, clothing, and different sports mats is to protect the health of athletes and avoid sports injuries. The worst-case scenario of sports injuries is when the athlete's head comes into contact with the sports mat first during a collision or landing, and the direction of the velocity vectors acting on the body and the head are the same. In this case, the total load is concentrated in the upper region of the body, which can lead to fatal neck injuries, craniofacial injuries and the development of focal brain injuries (such as focal vascular lesion). Based on this, regardless of the sport, it can be said that the outstanding energy absorption and impact damping capability is the most critical requirement for the foam structures used in the production of sports equipment.[8,11,30]

The most common modeling method for an athlete's collision or landing on a mat is the falling weight impact test. The principle of these tests is that a body with a given geometry and mass is dropped from a given height onto the test specimen., and the force on the body and the deceleration during the collision is measured, from which the desired parameters can be calculated.[10,31,32]

The geometry used in the falling weight impact tests and the exact test parameters differ from sport to sport and mat type (in some sports, mats are classified into subgroups based on the exact target area of the application) (Table 1).[33–36]

The classification is based on different mechanical parameters. In all cases where sports mats are used (e.g. judo, gymnastics, or jumping sports), the maximum deceleration acting on the body, the maximum deformation of the mattress, and the minimum absorbed kinetic energy are essential requirements. The regulation of United World Wrestling, which is the governing body of Olympic wrestling also covers an additional factor, a maximum limit for the duration of the collision.[33,35] As the continuous use of sports mats can cause a deterioration in their quality, the age of sports mats used in world competitions is also regulated in most sports.[35,36]

However, these sports-specific standards only define the mechanical parameters presented above, and there are no requirements for the raw material of the products, so the polymer material and structure of the mats sold by each manufacturer differ significantly. In general, it is true for all the products that they are composed of one or more polymer foam layers and an upper polyvinyl chloride (PVC) cover layer (Figure 3).[37–51]

Similar to sports mats, polymer foam products for winter sports also have a protective function. They appear in the barriers used at the borders of the ski slopes and in the various protective clothing worn by the athletes. The structure of these clothes is similar to protectors used in motorsport: sandwich structures built up

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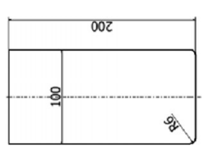
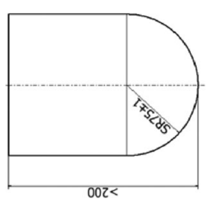
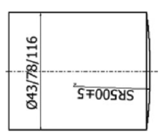
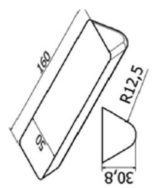
TABLE 1 Test parameters of different sport-specific standards[33–36]

Sport type	Wrestling	Gymnastics	Rod- and high-jumping	Judo	Motorsports, skiing (protective clothing)
Geometry					
Falling height (mm)	400	150–800	800 or 1200	200 or 600	~1000
Impactor mass (kg)	10.025	10 or 20 or 30	30	8	5
Standard	MSZ 20333:2015 United World Wrestling regulation	EN 12503	EN 12503	EN 12503 International Judo Federation regulation	EN 1621–2

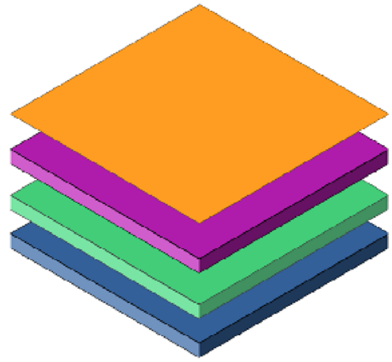


FIGURE 3 Typical structure of a martial art mat (figure was created by the authors) [Color figure can be viewed at wileyonlinelibrary.com]

from a harder thermoplastic polymer external layer and a softer polymer foam inner layer. The principle of operation of these products is that the harder thermoplastic polymer layer dissipates the force acting on the protective equipment. Hence, a larger volume of the soft foam layer plays a role in energy absorption, improving the impact damping efficiency of the product. The classification of the protective clothing of the two sports is the same. According to the EN1621 standard, a sample in which the maximum transmitted force does not exceed 12 kN receives a high protection rate (level 2). In comparison, a sample with a result between 12 and 24 kN is considered to have lower protection (level 1). When the transmitted force exceeds 24 kN, the protection level of the tested sample is inadequate, therefore not applicable.[34,52,53]

In addition to the requirement to reduce the load on the user in a collision, protective clothing also needs to be comfortable and should not restrict the wearer's movement. To maintain long-term high-level sports performance, adequate breathability (gas-permeability) is also a significant factor, which determines the ability of the clothing to allow moister vapor transmission by diffusion mechanism.[11,54] Structural properties greatly influence breathability, as closed-cell foams and blind pores reduce the ability of vapor transmission resulting in discomfort and increased body heart of the athlete.[55] Increased thickness is also a limiting factor for breathability, as water vapor needs to take a longer distance from the inside to the outside surface of the clothing. However, higher thickness results in better impact damping capability,[56] and both factors need to be considered in the designing process of protective equipment.

It is also important to emphasize that in martial arts, outstanding impact damping capability alone is not sufficient. Here, the mats need to be stiff enough; the athlete's foot must not sink into the mat to avoid ankle injuries. According to the EN12503 standard, this property can be measured by the so-called static stiffness. It is the difference between the deformation caused by a 50 kg cylinder with a diameter of 78 mm placed on the mat, and the deformation measured horizontally at a distance of 80 mm from the axis of the cylinder.[33]

The standard also specifies a separate procedure for measuring the coefficient of friction for the lower and upper surfaces of mats. It is important for safety, that the athlete must not slip on the mat and the mat must not move relative to the ground during sports.[33,57]

As in many cases, the space provided for storing sports mats is small, a typical storage method is to stack the mat elements on top of each other, even to the height of several meters. In this case, there is a constant load on the lower elements for longer periods, even for several days, which should not cause a deterioration in the quality of the product. The manufacturers check this by measuring the so-called compression set value.[58] Other important factors are the aging resistance and homogeneous structure of the products, as continuous use cannot impair mechanical properties, and each part of the sports mat must be equally safe.

Thus, the requirements for polymeric foams in the sports industry are complex. It is hard to meet all of them with the same type of foam material, therefore in this case, it is necessary to design sandwich structures consisting of different layers.

3.2 | Polymer foam materials in sports

The requirements presented above justify the use of materials that can provide adequate protection, dampen the forces acting on athletes in the event of a fall and absorb a significant part of the impact energy during the collision.[8] Figure 4 reveals that the density and thickness of the mats vary by the field of application based on the main function of the products. In high jump and pole vault, shock-absorbance is extremely important, so landing mats have the least density and highest thickness. On the other hand, striking combat sports require a secure stance for the movements, so mats used in these sport (e.g. karate and taekwondo) are much denser with lower thickness. The properties of sports mats used in gymnastics, wrestling, mixed martial arts (MMA) and judo are between the characteristics of landing and striking mats.[37–50]

However, regardless of sport, the foam material of the mats can be limited to four main raw material groups. The most common raw material is crosslinked polyethylene (XPE) foam. Still, there are also products made of polyurethane both in normal (PU) and recycled form (rPU), ethylene-vinyl acetate (EVA), and polyvinyl chloride/nitrile butadiene rubber (PVC/NBR) foams.[37–50]

3.2.1 | Crosslinked polyethylene foams

The most common raw material for sports mats is crosslinked polyethylene. Polyethylene (PE) has advantageous mechanical properties, but it is a thermoplastic polymer. Therefore, it cannot be used above its melting temperature (~ 110–130°C), and it softens under the influence of heat. A good solution for increasing heat-resistance is crosslinking, in which crosslinks are formed between the polyethylene molecular chains. This improves the mechanical properties of the material as well.[1,8,59]

Creating a crosslinked structure is possible by a physical or a chemical process. In the case of physical crosslinking, the material is exposed to high-energy radiation, which can be UV, electron, or gamma radiation. Upon radiation, free radicals are formed in the polymer chains, which start combining, resulting a weakly crosslinked structure. This process is more expensive compared to chemical crosslinking. However, it is faster and results in a more uniform crosslinked structure without the need for any added material. Chemical crosslinking uses chemicals, initiators (usually peroxide or silane), which are introduced into the polymer at low temperatures by compounding. As the temperature and pressure increase, the materials start to decompose and remove hydrogen atoms from the molecular chains. This results in free radicals, from which a crosslinked structure is formed.[59–61]

Crosslinked polyethylene foams are typically closed-cell structures. They have better heat resistance compared to non-cross-linked PE foams, and their recovery capability after static load is also better due to the modified structure, which is an essential requirement of sports mats. These properties are highly influenced by the foaming process and the crosslinking method used.

Batista Dias et al.[62] tested 70–90 kg/m^3 PE foams crosslinked by an electron beam and foamed with 2–4 m% azodicarbonamide as a blowing agent. They showed that increasing the radiation dose causes an increase in tensile strength and a decrease in elongation at break. Based on their results, the radiation level for the best mechanical properties and cell structure is between 20–60 kGy. A higher dose leads to a decrease in the decomposition temperature, thereby an increase in the tendency to degrade.

The effect of radiation dose was also investigated by Xing et al.,[60] who produced a microcellular foam structure using supercritical carbon dioxide. When the material was irradiated before processing (extrusion, pressing), it showed higher expansion during foaming, and the foam structure had larger cell size and lower cell density. They also showed that the average cell size

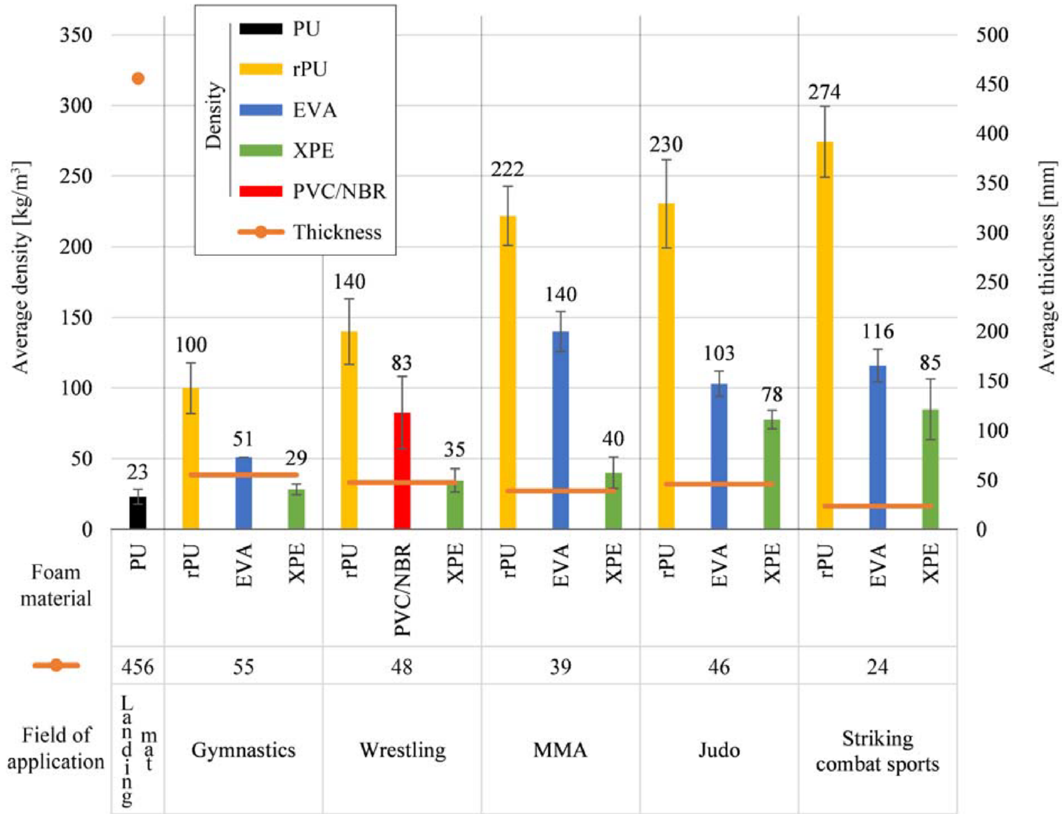


FIGURE 4 Characteristics of sports mats from different fields of application (figure was created by the authors) [Color figure can be viewed at wileyonlinelibrary.com]

increased as radiation was increased up to 50 kGy, but decreased above it, while cell density changed inversely.

In addition to the radiation dose, the amount of crosslinking agent is also important in the case of chemical crosslinking, which is also used in industry—understanding the effect of the amount of blowing agent is required in both cases. Cardoso et al.[63] showed on 60 kg/m^3 density XPE foams that increasing the weight percentage of the azodicarbonamide blowing agent (5%–15%) reduces the degree of crosslinking regardless of the radiation dose and thus mechanical properties, such as tensile strength. In the case of chemical crosslinking, dicumyl peroxide is the most often used crosslinking agent. Increasing its amount results in an increase in the Young's modulus, and thereby a decrease in the rate of expansion.[64]

3.2.2 | Ethylene–vinyl acetate foams

Ethylene-vinyl acetate is a copolymer of ethylene and vinyl acetate materials, in which the vinyl acetate content typically ranges from 10 to 40 m%. More and more of it is used (e.g., in the packaging and pharmaceutical industries), due to its transparency, flexibility, and low production cost.[65,66]

Its foamed form is mainly used in applications which require high energy absorption capacity, such as the automotive and the sports equipment industries.[66] For example, shoe soles, which are subjected to constantly repetitive dynamic loads, are mostly made from 150–250 kg/m^3 density closed-cell EVA foam with a modulus of 200 kPa.[67] The core layer of the protective equipment used in cricket is also made from EVA foam, which is surrounded on both sides by a polycarbonate shell layer. This sandwich structure has to provide protection against impacts up to 45 m/s impact velocity.[68]

Shimazaki et al.[69] also studied sandwich structures produced from EVA foam layers in order to develop the shock-absorbing performance of footwear subjected to cyclic dynamic loads. By varying the concentration of azodicarbonamide (8, 12, and 16 phr), three different density foams were produced (23, 17, and 11 kg/m^3) in 5 mm thickness, from which sandwich structures containing three foam layers were laminated. Their tests on the different density foams showed that increasing the amount of blowing agent causes an increase in expansion and tangent δ (loss factor) and a decrease in density, hardness, and Young's modulus.[69]

They investigated the shock absorption efficiency (see Equation (3)) of the multilayer laminates by applying cyclic load with a maximum of 1000 N and a period of 1 s. The input and output loads were detected with pressure sensor sheets placed in the upper and lower interlayers.

$$\eta_{\text{imp}} = 1 - \frac{\int_{\text{cycle}} f_{\text{trans}} dt}{\int_{\text{cycle}} f_{\text{input}} dt} \quad (3)$$

where η_{imp} (%) is the shock absorption efficiency, while f_{input} (N) and f_{trans} (N) are the detected input and output loads.

The results of the tests performed on the multilayer samples showed that the shock absorption efficiency of the foams could be successfully improved by modifying the order of the layers. By decreasing the density from top to bottom, the higher density upper layer absorbed less, so more load was transmitted to the lower layers. If the layer order was reversed, the shock absorption efficiency increased from 60% to 65%.[69]

In the last 10 years, many researchers focused on the foaming of EVA-rubber blends in order to soften the material and increase its flexibility. Kim et al.[70] successfully improved flexibility by foaming EVA–natural rubber (NR) blends with an azodicarbonamide blowing agent. Maiti et al.[71] combined EVA with NR, and butadiene rubber (BR) using dinitropentamethylene tetramine as blowing agent and produced a closed-cell foam structure with favorable mechanical properties (tensile strength~9 MPa, elongation at break ~500%, compression set~4%). The blends were prepared with a Brabender internal mixer, and the BR particles were homogeneously distributed in the continuous EVA matrix.

3.2.3 | Polyurethane foams

The family of polyurethanes includes materials containing the urethane linking group —NH—C (═O) —O—. In the production of polyurethane, polyaddition takes place between di- and polyisocyanate and di- and polyol units. PU foams give the largest segment of the total urethane market with a market share of 68%. By varying the amount of the components of the raw materials, the properties of the foam can be changed on a wide scale from soft foams through integral foams to hard foams. The processing technology can be batch foaming (e.g. reactive injection molding) or a continuous operation.[1,26,72,73]

As previously described, PU foams can be produced with the use of both physical and chemical blowing agents. The most commonly used physical blowing agents are hydrochlorofluorocarbons (HCFCs) and pentane, while carboxylic acid and water are the most typical examples of chemical blowing agents. They react with the isocyanate to form carbon dioxide, which ensures the production of a typically open-cell structure.[26] In addition to the foams produced this way, recycled/rebonded PU foams is of great importance, as shown by a large number of relevant patents. These foams have a density range of 100–250 kg/m^3 and an elastic modulus range of 10–300 kPa.[8,74–77]

Landing mats are mostly produced from polyurethane foam, while rebonded polyurethane foam is the preferred raw material of martial arts mats. The widespread use of polyurethane foams in processing technology leads to a large amount of waste material. Most of this is the material cut down during the production of polyurethane blocks.[78] As proper waste management is of paramount importance for both social and economic reasons, several technologies have become widespread for the recycling of polyurethane foam waste. It can be recycled either physically or chemically,[78,79] but as sports mats are typically produced from physically recycled PU foams (see above in Figure 4), we will focus on this group.

The production of rebonded PU foams uses the waste cut during the production of open-cell polyurethane foam blocks. Pieces of different hardness and color cut to a diameter of 5–10 mm are mixed and then bonded together under uniaxial compression with the addition of extra polyol and isocyanate as an adhesive. Due to the pre-bent edges, this structure provides a more linear stress–strain response for compression than normal PU foams. The individual scrap parts in the structure are bonded together by the closed-cell adhesive added in a smaller proportion to the material. Figure 5 shows scanning electron and optical microscope images of the structure produced this way.[8,80]

Mills and Lyn[81] performed dynamic mechanical tests on rebonded PU foams with a falling weight impact testing machine. The three investigated mats had a thickness of 100, 200, and 400 mm with a density range from 63.3 to 82.2 kg/m^3. All samples were produced with the same recycling technology as presented above. To model the impact of a human head, a weight which conforms to the BS EN 960:1995 standard with a circumference of 58 cm and a mass of 4.1 kg was dropped from different heights (between 0.125 and 1 m).[81]

Their results showed that the load phase of the force-deformation curves was linear for all cases except the 100 mm thick sample, where the relationship became nonlinear above 70% deformation. This was probably due to the compression of the cells, as the opposite cell edges met, which led to an increase in the force.[81] Their research also included the study of the effect of repetitive impacts. They performed impacts from a height of 1 m on the 0.4 m sample every 10 min and showed that the repetitive impacts did not affect the maximum deceleration (18 ± 1 g), or the

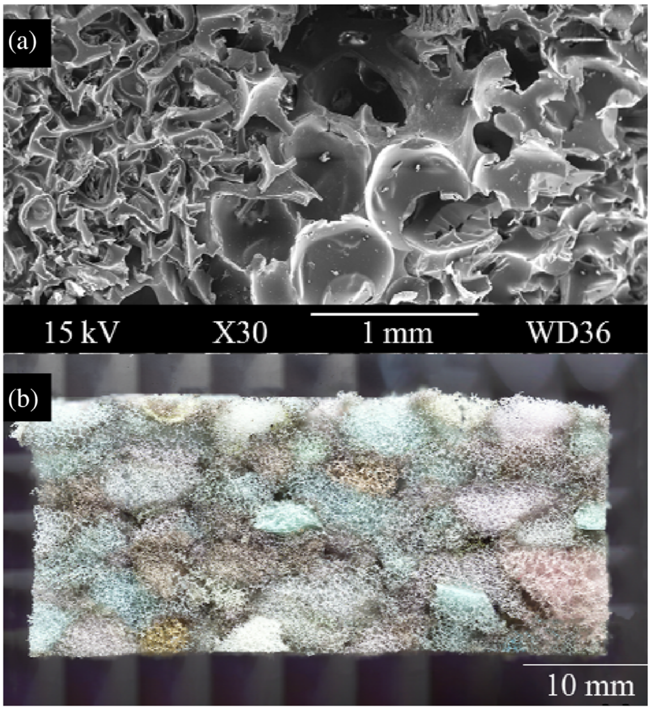


FIGURE 5 Scanning electron (a) and optical microscope (b) images of rebonded PU foams. Reproduced with permission.[8] Copyright 2021, Elsevier [Color figure can be viewed at wileyonlinelibrary.com]

maximum deformation (96 ± 2 mm). They concluded that, in contrast to closed-cell polyethylene foams, the mechanical properties of recycled polyurethane foams do not deteriorate under repeated loads.[81]

3.2.4 | Polyvinylchloride/nitrile butadiene rubber foams

PVC/NBR materials belong to the family of thermoplastic elastomers. They can be reversibly melted and processed by conventional thermoplastic technologies and have the advantageous properties of elastomers, such as the capability of large irreversible deformation.[82,83]

These materials are mostly linear block copolymers (-AAAA-BBBB-AAAA- structure), in which each block forms soft and hard segments resulting in a physically crosslinked structure (Figure 6).[84,85]

The mechanical properties of such structured materials can be easily modified by varying the ratio of the hard and soft segments.[86] This was studied by Thomas and Harvey,[82] who investigated the hardness, tensile strength, and elongation at break of PVC/NBR materials. They proved that increasing the ratio of NBR segment makes the material softer—the hardness and tensile strength decreases, while elongation at break increases.[82]

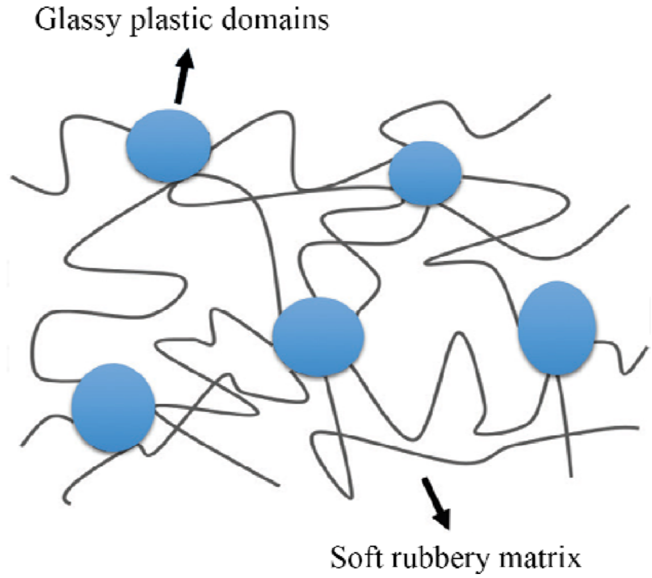


FIGURE 6 The structure of thermoplastic elastomers. Reproduced under terms of the CC-BY license.[85] Copyright 2021,IntechOpen [Color figure can be viewed at wileyonlinelibrary.com]

This kind of PVC/NBR foam sports mats are supplied by many US manufacturers in the density range of 56–100 kg/m^3 with ~500 kPa tensile strength.[87–89] Interestingly, one manufacturer promises a lifetime twice as long as the lifetime of XPE mats, which are also sold by the company.[88] However, despite the widespread use of PVC/NBR foams in the industry, they are little researched. Shakarami et al.[90] produced microcellular PVC/NBR foams and studied the effect of the NBR ratio and the foaming parameters on the properties of the final product. In their research, foams containing 5 and 15 m% NBR were produced by batch foaming, with carbon dioxide as blowing agent. They showed that increasing the temperature and time in the foaming process causes an increase in average cell size and a decrease in relative density. Expansion was higher in the case of samples containing less NBR, and the lowest relative density was achieved with a PVC/NBR ratio of 9:1, at the foaming temperature of 110°C and a foaming time of 15 s. The tensile test results of the foams with different NBR contents did not differ significantly. The foams had a tensile strength between 4 and 6 MPa, while their elastic modulus ranged between 25 and 30 MPa.[90]

4 | INVESTIGATING METHODS OF POLYMER FOAMS

As polymer foams are widely used in the sports industry, accurate knowledge of their mechanical properties is essential. As we demonstrated, foam products have to fulfill several requirements to reduce the risk of sports injuries to the minimum.

4.1 | Compression testing

The appropriate stiffness of sports mats is essential regardless of sports type.[33] A too soft mat can cause ankle sprains or dislocations in sports with more dynamic movements (e.g., martial art mats) and can decrease the comfort in sports with slower motions and static positions (e.g., yoga, fitness). Therefore, the material answer to compression is essential to design appropriate sports mats. In the case of compressive loads, the deformation of polymer foams can be divided into three well-distinguishable regions (see below in Figure 7). In a small strain range (usually up to about 5-10%), the nature of deformation is almost linearly elastic, and the slope of the curve gives the elastic modulus of the foam. This small region can be related to cell edge bending and cell wall buckling. As a result of the increasing load, the cells start to collapse, which typically occurs in a narrow stress range, and that causes the appearance of the so-called stress plateau. Once the opposite cell walls meet, the so-called densification zone starts, where the stress level starts to increase steeply. In this case, the foam behaves as a solid polymer material.[14,56,91–93]

The increased energy absorption capability of polymer foams is provided by the second region (plateau stage). In this stage, foam products (e.g. helmets, martial art mats) can absorb a large amount of energy without a significant increase in the stress level.

If the deformation during the load is too high and the densification zone is reached, the foam product will not perform its function properly, and the risk of health damage increases. Therefore, it is important to optimize the thickness of the foam: a too-thin foam is dangerous due to the compaction zone, while a too-thick foam increases the production cost due to the amount of matrix material required.[6,8,56]

As higher density foams have higher elastic moduli, the slope of the first part of the curves increases, and the plateau will appear at a higher stress level. In a closed-cell foam, the compression of the cells compresses the air in the cells, which generates an additional force. This can be calculated with Boyle's law. Boyle's law states that the volume and the pressure of a gas at a given temperature are inversely proportional (Equation (4)).

$$pV = k, \tag{4}$$

where V (m^3) is the volume of the gas, p (Pa) is the pressure of the gas, and k (J) is a constant. The deformation mechanism of an open cell structure is slightly different, as in this case, the air can freely flow between the cells.[14,92]

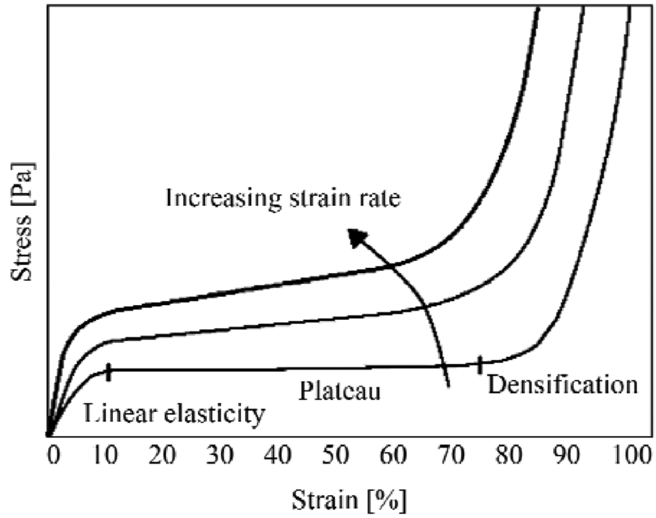


FIGURE 7 Strain rate dependence of the stress–strain response of polymer foams. Reproduced with permission.[98] Copyright 2021, Elsevier

In the case of foams, standard compression tests are not performed until failure, and compression strength is calculated with the maximum force at a given deformation (Equation (5)):

$$C_m = \frac{F_m}{S_0}, \tag{5}$$

where C_m (MPa) is the compression strength, F_m (N) the maximum force detected at a given deformation, while S_0 (mm^2) is the cross-section area of the sample perpendicular to the axis of compression.

The magnitude of the strain and the geometrical dimensions of the test specimen vary by standard. Rigid foams are usually measured up to 10% deformation, while flexible foams up to 25%–50%.[18,94–97]

The applied strain rate significantly influences the compression stress–strain response of polymer foams. Ouellett et al.[98] investigated the strain rate dependence of expanded polystyrene (EPS), and high-density polyethylene (HDPE) foams in the strain rate range of 0.0087–2500 1/s by using a conventional tensile machine, a falling weight impact tester, and a Hopkinson bar. Their results showed (Figure 7) that increasing the deformation rate resulted in a larger stress plateau and a smaller starting deformation of the densification zone. This effect became more dominant at higher velocities, and for higher density foams.[98]

This kind of dependence on the rate of deformation is often defined in the literature with the dimensionless strain rate sensitivity (m_s) (Equation (6)):

$$m_s = \log\left(\frac{\sigma}{\sigma_0}\right) - \log\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right), \quad (6)$$

where σ (Pa) and σ_0 (Pa) are the currently applied and initial reference stresses, while ε (1/s) and ε_0 (1/s) are the current and initial reference strain rates.[99,100]

Deshpande and Fleck[100] also investigated the strain rate sensitivity on 100–200 kg/m^3 density flexible PVC foams and showed that an increase of the deformation rate from 10^{-3} 1/s to 1/s increased the stress plateau of the compression tests by 25%. The strain rate sensitivity of the foams they tested was 0.04, which is less significant than the previous results in the literature.

The results of the compression tests are influenced by the amount of blowing agent and other additives. Zakaria et al.[101] performed compression tests on polyethylene foams according to ASTM D3575 to determine their compression strength at 80% strain. They used azodicarbonamide as blowing agent and a dicumyl peroxide initiator to achieve a crosslinked structure. They found that increasing the amount of peroxide caused an increase in foam strength while increasing the concentration of azodicarbonamide impaired the strength of the foams.[101]

Another possible method for the evaluation of quasi-static and dynamic mechanical compression tests is the use of the so-called energy absorption diagram and efficiency parameter described by Avalle et al.[6] The method can be used to determine the optimal density of the polymer foam structure for a given load level (Figure 8). The amount of absorbed energy can be obtained by integrating the stress by the deformation, which is equal to the area under the curves. The areas marked in the figure show the same amount of absorbed energy. When a lower density foam is used—marked with index 1, the densification zone is reached sooner, which results in an increase in the maximum force value. Similarly, the higher density foam—marked with 3—is not favorable either, as higher initial stress and lower deformation appears.[6]

It can be seen that the use of the foam marked with 2 is optimal, because the lower density foam can only absorb the same amount of energy with much higher deformation, while the initial stress of the denser foam is too high. Based on this, the impact damping capacity of the foam can be maximized for a given energy absorption target value by varying the density. This ideal density can be determined with the energy absorption diagram, which plots the amount of energy absorbed as a function of stress. By plotting the diagram for different foams, it is possible to determine the foam with the best damping capability at the given energy level and the best energy-absorbing foam for a given maximum stress.[6]

The comparison based on the so-called efficiency parameter uses a similar principle. Efficiency parameter (E) is the ratio of the absorbed energy and the actual stress (σ) (see Equation (7)):

$$E = \frac{\int_0^e \sigma(\varepsilon) d\varepsilon}{\sigma}, \quad (7)$$

By plotting the efficiency as a function of stress, the optimal density for a predetermined stress level can be determined, as well as the energy-absorbing capacity at a given density. Hence the method is suitable for selecting the optimal foams for a particular application.[6,14,102]

4.2 | Investigation of the impact damping capability of polymer foams

The use of polymer foams is significant in applications where the main task is to protect the user and prevent health damage. In these cases, the foam product must absorb the energy during the impact while keeping the generated maximum force below a certain value.[6,67] The dynamic mechanical characterization of foam products is essential to define how well polymer foam shoe soles reduce the loads acting on the knee joints,[103] sports mats reduce the reaction force of landing,[104] or protective clothing reduces the reaction force of a collision.[92] These kinds of impact loads can be modeled with various dynamic tests, of which the falling weight impact test is the most commonly used. Figure 9 shows the general layout of such a measuring device.[8,94,105]

Regardless of the investigated specimen type, all falling weight impact tests have the same principle: dropping a weight with a given mass and geometry from a given height onto the specimen. Impact energy can be increased with the use of a bigger mass or a greater falling height. If the specimen is fixed with a clamping ring, the noise is lower, and the amount of energy required to perforate the samples can be determined. Another commonly used layout is when the foam is placed on a solid support, mostly concrete, so the foam is not perforated. In this case, the evaluation is based on the maximum force or acceleration exerted on the weight.[31,32,105] This method is used by the sport-specific standards presented earlier, and the material of packaging products is also selected on a similar principle.

Nasim et al.[53] investigated back protectors used in motorsport with similar falling weight impact tests. They attached 1 and 2 mm thick polyethylene layers to the top of the 16 mm thick nitrile butadiene rubber foam layer to

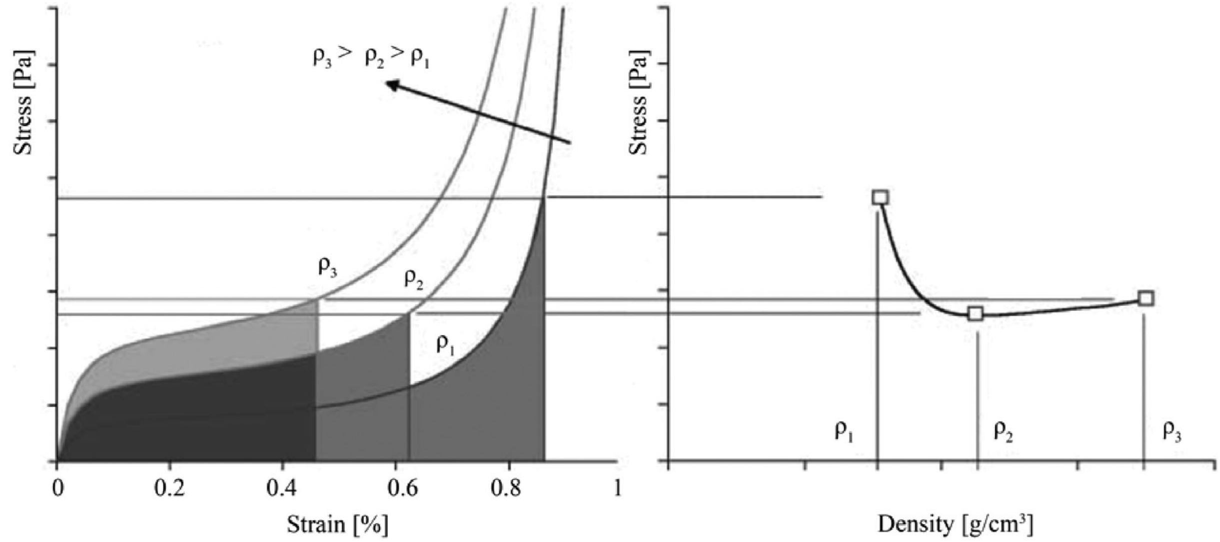


FIGURE 8 Compression diagrams of the same type polymer foams in three different densities. Reproduced with permission.[6] Copyright 2021, Elsevier

investigate the effect of the cover layer on stress distribution. They performed three tests on each sample with a 5 kg falling weight and 50 J impact energy. In the case of the plain NBR foam, the maximum force was approximately 8 kN, which was reduced to 6.5 kN by the addition of the 2 mm PE layer. Increasing the thickness of the PE layer resulted in a more homogeneous load distribution in the foam structure, which resulted in higher energy absorption capacity.[53]

4.2.1 | Packaging applications—cushion curves

In packaging, polymer foams have a similar function as landing mats or protective equipment. They need to protect the product the same way as mats protect the athlete: keeping the maximum reaction force during the impact under a specific limit. Therefore, foams in packaging applications must fulfill very similar requirements to the foams used in sports. So, research results and testing methods in this area can be used in the sporting goods industry as well.[106]

In packaging technology, foams for cushioning the product are selected with the use of so-called cushion curves, which are attached to the material data sheet of the foam. These diagrams summarize the results of several falling weight impact tests as a function of the static load and are available for several drop heights. During the impact tests, the thickness of the test specimen and the mass dropped are varied. The method is excellent for selecting the foam type for the given application and for designing the dimensions of the packaging material. The

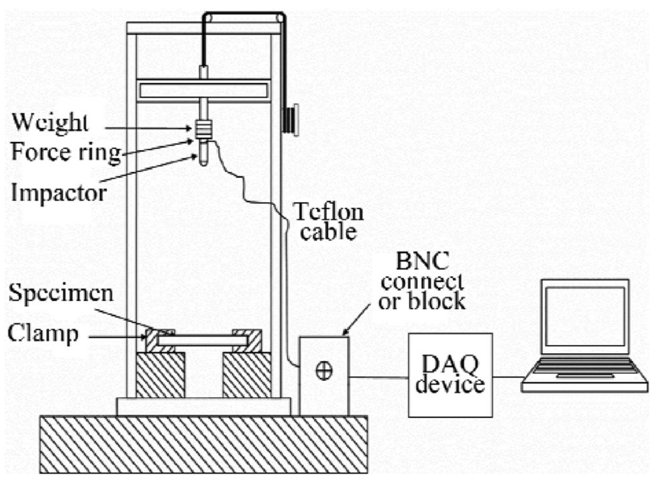


FIGURE 9 General layout of a falling weight impact tester. Reproduced under terms of the CC-BY license.[105] Copyright 2021, Scientific Research Publishing

curves are obtained by plotting the maximum deceleration values acting on the product during the impact as a function of static stress, which is equal to the compressive stress acting on the foam during the storage of the products (Equation (8)).

$$\sigma_s = \frac{mg}{A}, \tag{8}$$

where σ_s (Pa) is the static load, m (kg) is the mass of the product, $g = 9.81$ (ms^{-2}) is the gravitational acceleration and A (m^2) is the contact surface area.[8,13,107]

In the packaging industry, the failure rate of different products is characterized by the fragility factor, which estimates the linear acceleration limit beyond which mechanical damage occurs on the product. This limit depends on the type of the product: e.g., gyroscopic devices have a fragility factor of 15–25 g. In comparison, the maximum limit for audio and television devices ranges between 60 and 80 g. When selecting the packaging material for a given product, the required drop height of the impact tests is determined based on the total mass of the product and the typical way of transportation. For example, products carried by one person require a different drop height (90 mm) from products transported by hand trolley (60 mm).[8]

With the knowledge of the product-specific drop height and fragility factor, the appropriate thickness, and type of foam material can be selected. Therefore, the use of cushion curves is an efficient way to design the appropriate protective packaging for a product with known requirements (Figure 10).[8,108]

The exact test conditions for determining the curves are described in ASTM D-1596, which defines five drops for each sample with 1-min intervals and treats the result of the first drop separately from the results of falls 2–5.[109] The applicability of the method is well illustrated by the fact that many large packaging companies use it, and some manufacturers even detail the method on their websites.[110,111] In addition, several articles on the method can be found in the literature, with the main purpose of reducing the number of tests required to determine the data set.[112–115]

Sek and Kirkpatrick[113] developed a model for determining the cushion curves using measurement results from static compression tests, while Sek et al.[112] successfully improved the accuracy of the model by completing the results of the compression tests with a few falling weight impact tests.

Burgess[114] developed a procedure which accurately estimates the data for any height and thickness with the knowledge of only one single cushion curve. In his research, neglecting the dependence of the dynamic stress on the deformation rate, he found the following general relationship (Equation (9)):

$$(G+1)\sigma_s \sim \frac{\sigma_s h}{t}, \tag{9}$$

where G is the maximum deceleration value ($g = 9.81$ m/s^2), σ_s (Pa) is the static load, h (m) is the drop height, while t (m) is the thickness of the sample. By using the equation, the generalized dynamic stress–strain relationship of the material and the cushioning curve for any thickness and drop height can be determined. The accuracy of the method was verified on closed-cell polyethylene foam with a density of 32 kg/m^3 and expanded polystyrene foam with a density of 24 kg/m^3. The estimated values deviated from the measurement results obtained by high-speed camera recording only by ±5%, which fell within the standard deviation of the test results.

With the method presented above, one cushion curve is enough to determine the impact damping property of the given material, which requires about 10–20 drops when a falling weight impact tester is used. Burgess[115] continued this research and developed a new method that is capable of determining cushion curves even from one single drop. The method uses the deceleration change in time acting on the body; however, the accuracy is greatly influenced by the proper filtering of measurement noise, so it is very difficult to apply.[115]

4.2.2 | The application of the head injury criterion

A common feature of the testing methods of sports mats is that a certain limit is set for the maximum deceleration value (G_{max}) acting on the weight during the impact of the falling weight with the foam material.[8,35,107]

These methods are excellent for evaluating the packaging of technical devices, as the appropriate packaging material can be selected if the maximum deceleration value detected during the impact tests is known.[8] However, in cases where the primary function of the foam is to protect the health of the user/athlete, in addition to the magnitude of the load, the duration of the impact is also an important factor to consider in grading of the foam.[10,30]

This is the purpose of the so-called head injury criterion (HIC), which was first introduced in 1972 by the American National Highway Traffic Safety Administration (NHTSA). HIC was originally designed to evaluate crash tests in the automotive industry, but nowadays, its use to assess the shock absorbance of sports surfaces is also widespread. The HIC takes into account both the deceleration of the head and the duration of the critical part of the impact (Equation (10)):

$$\mathrm{HIC} = \max\left((t_1 - t_0)\left[\frac{1}{(t_1 - t_0)}\int_{t_0}^{t_1} a(t)dt\right]^{2,5}\right), \tag{10}$$

where t_0 (s) and t_1 (s) the start and end points of the time interval considered in calculating the HIC value, while $a(t)$ (g = 9.81 m/s^2) indicates the acceleration acting on the body as a function of time.[10] Therefore, the process of determining the HIC of sports surfaces begins with the performance of a conventional falling weight impact test but also takes into account the duration of the collision in the evaluation (Figure 11).[10,116]

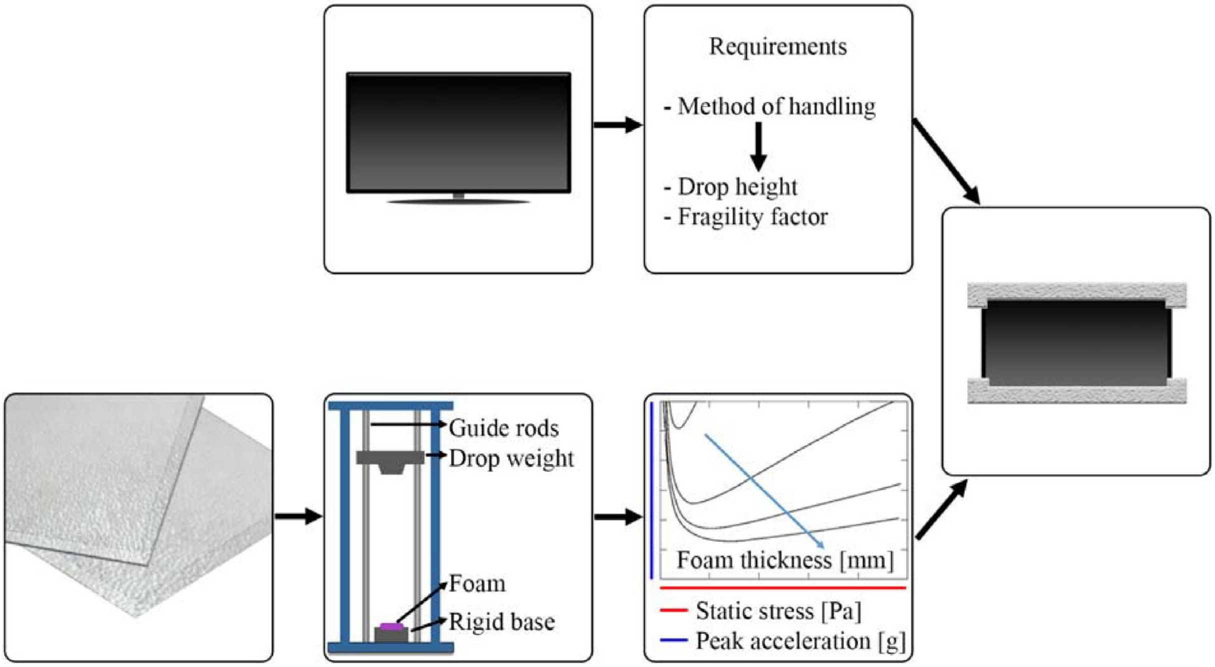


FIGURE 10 Designing process of a protective packaging for TV with the use of cushion curves. Reproduced with permission.[8] Copyright 2021, Elsevier [Color figure can be viewed at wileyonlinelibrary.com]

Establishing the relationship between the HIC value and the probability of head injury can also be linked to the NHTSA. The relationship is shown by the so-called Prasad–Mertz curves, named after the researchers (Figure 12).[10,116–118]

By using the diagram, which is based on the results of several biomechanical measurements, the probability of different severity head injuries can be determined for a given HIC value. According to the NHTSA, a simulated automotive collision must not result in severe head injury, so the HIC result for passengers 6 years old or older should not exceed 700. This boundary line is indicated by a dashed line in the figure. It can be seen that for the HIC of 700, the probability of a critical and fatal injury is zero, while a severe injury is 5%, a serious injury is 20%, a moderate injury is 60%, and a minor injury is 90% likely to occur.

To accurately define the severity of an injury, it is important to know the symptoms that occur in each case, which are also available in the literature. For example, minor head injuries cause only headaches and dizziness; while moderate injuries can result in loss of consciousness. For critical injuries, skull fracture, neurological damage, and hemorrhage are also possible.[10,116–118]

In addition, several biomechanical studies related to HIC measurements are available in the literature, which can be used to determine the severity of potential health damage for a given HIC value.[10,30,116,119]

Mosleh et al. used the HIC to determine the dynamic mechanical properties of polymer foams. Their research compared the impact damping properties of expanded polystyrene foam with a density of 80 kg/m^3 and a hybrid foam structure produced from EPS foams with a density of 40 and 120 kg/m^3. In the case of the hybrid foam, the weight ratio of the 120 kg/m^3 density cylindrical phases and the 40 kg/m^3 density enclosing phase was 50%–50%. The measurements were performed using a Hybrid Type III head dummy, and the parameters were set according to the EN1079 standard for the classification of bicycle helmets (falling height = 1.5 m; impact velocity = 5.4 m/s). The 80x80x25 mm nominal size samples were put on an anvil in at an angle of 45°, and at least three drop tests were performed on each sample. The deceleration acting on the body was detected with an accelerometer built in the head dummy and was plotted in the function of time. The structure of the investigated samples, the measurement arrangement and the results of the impact tests are summarized in Figure 13.[120]

It can be seen that the use of the hybrid foam structure reduced the maximum deceleration during the collision, but did not change the duration of the collision. This is also shown by the calculated HIC values, which were 324 ± 20 for the hybrid foam and 402 ± 18 for the plain EPS foam. Based on the results of the research, it is likely that the impact damping capability of a product

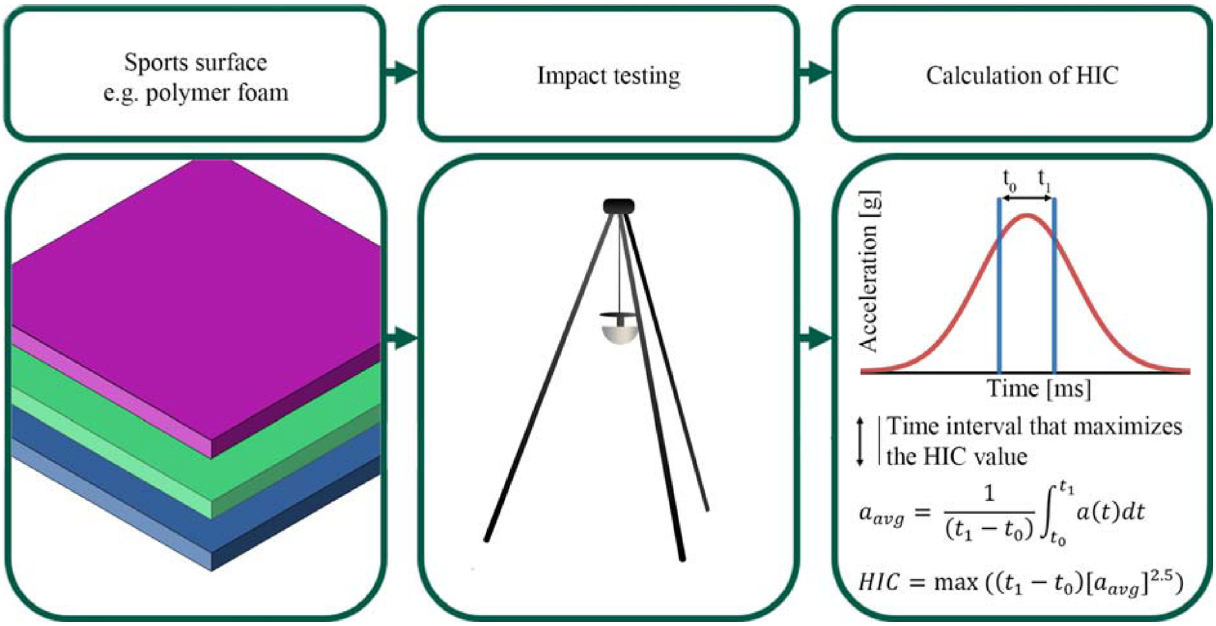


FIGURE 11 Determination process of head injury criterion (figure was created by the authors) [Color figure can be viewed at wileyonlinelibrary.com]

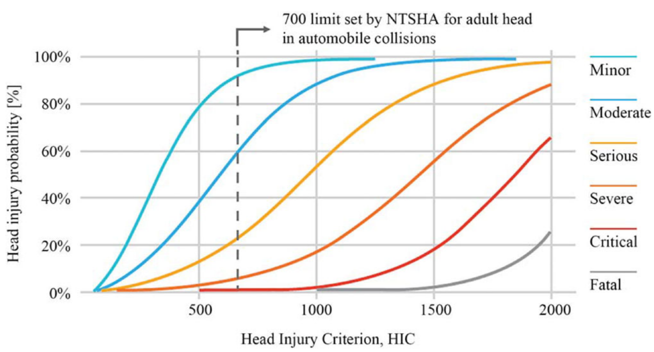


FIGURE 12 Expanded Prasad–Mertz curves. Reproduced with permission.[116] Copyright 2021, Brock USA [Color figure can be viewed at wileyonlinelibrary.com]

can be effectively increased by combining different density foams.[120]

4.2.3 | Comparison based on critical fall height

Thanks to the benefits of the Head Injury Criterion presented in the previous subsection, several sports have integrated the evaluation method into their own sport-specific standard. The value of the HIC is influenced not only by the deceleration and its duration but also by the geometry of the dropped weight. The conventional older standards (see above in Table 1) study the impact of a flat-faced cylindrical body, but this geometry differs significantly from the geometry of the human head. Newer standards attempt to use drop weights, which are similar to the human head (mass and shape).[10] The ASTM F355 standard is a good example, which rates different sports surfaces.[121] The standard's E missile with a hemispherical shape and a mass of 4.58 kg is considered equivalent to the human head, so its application gives more relevant test results compared to flat drop weights.[10,116]

This missile is used by the ASTM F1292 standard to determine the so-called Critical Fall Height (CFH). During the tests, the F355-E missile is dropped onto the surface from increasing heights until the Head Injury Criterion reaches the value of 1000. This height is called the critical fall height of the tested sample. As it is shown by the extended Prazad–Mertz diagram (Figure 12), in the case of a HIC value of 1000, the probability of a fatal head injury is greater than zero. The advantage of this method is that the introduction of the well-understandable CFH value simplifies the comparison of different sports surfaces, and it can be clearly decided whether the examined sports surface is suitable for use in the given sport. If the critical fall height of the specimen tested is less than the height of the desired application activity, the material shall not be used as a sports surface.[10,122]

This method was used by Shields and Smith to compare the different sports surfaces used by cheerleaders. They calculated the HIC and CFH values of the most commonly used surfaces in the sports to compare their

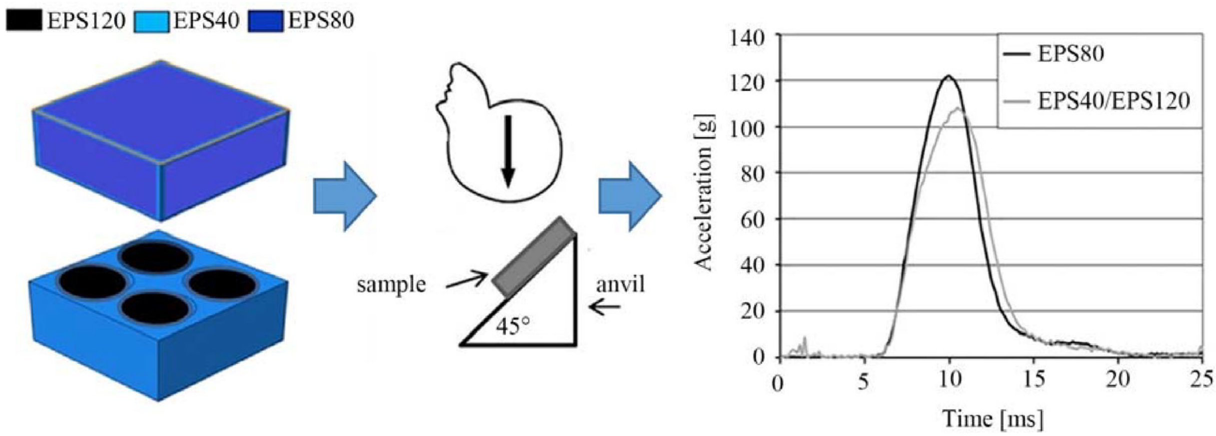


FIGURE 13 Measurement process of impact testing hybrid foam structures. Reproduced with permission.[120] Copyright 2021, John Wiley and Sons [Color figure can be viewed at wileyonlinelibrary.com]

impact damping capability with other floor types (artificial turf, asphalt, carpet, concrete, grass, polyurethane foam mattress, rubberized track, wood gym floor, spring floor). Their study also included the investigation of the effect of soil moisture content and average grass length on CFH in the case of grass-covered sports fields. The fall height, maximum deceleration (Gmax), and HIC were also recorded for each floor type. Table 2 summarizes the results of the study.[123]

The obtained measurement results provide excellent data for each sport to reduce the number of head injuries, as the most suitable sports surface can be selected. Based on the results, the landing mats and the spring floor clearly have the highest critical fall heights, so their use is the most recommended.[123]

Another important conclusion is that the classification based only on Gmax values is not sufficient, as surfaces with higher HIC values, which means higher risk to human health, do not always have higher G_{max} values. The comparison of results of 10 cm high grass and a wooden gym floor is a good example of this, as the gym floor had higher Gmax value, but the grass showed higher HIC for the same drop height.[123]

4.3 | Frictional and adhesion properties of polymer foam structures

In addition to the high energy absorption capability presented in the previous chapters, adequate frictional properties are also important requirements for different sports mats. If the athlete slips on the mat or if the mat moves on the ground, the risk of sports injuries increases significantly. This is well illustrated by the fact that a significant proportion of knee and ankle sprains, which gives 30% of all injuries in wrestling and 17.2% in judo, are caused by the poor friction between shoes or foot and sports mats.[57,124,125]

Due to these reasons, most sports have their own regulation for measuring the friction properties, which are included in the EN 12503 standard for polymer foam sports mats. The bottom surface of the mat, which provides contact with the ground, is classified by the so-called pendulum skid resistance (SRT) tester. The measuring equipment was originally used to certify roads and floor coverings. Its basic principle is that the pendulum, which has a rubber slider, is released from a horizontal position to strike the surface. From the initial position and the distance covered by the pendulum after the contact with the surface, the frictional resistance of the surface can be calculated. The coefficient of friction of top surface of the sports mat, which gets in contact with the athlete, are determined with a different testing method, which is based on the measurement of torque. During the test, a disc loaded with a given mass is placed on the test surface and the torque required to rotate the disc is recorded, from which the coefficient of friction is calculated.[33,36]

In addition to these standards, several studies proved the importance of the proper relationship between athlete and surface. Research in the literature focuses primarily on American football[126–128]; however, the coefficient of friction of top surface of wrestling mats were also investigated. Newton et al.[57] studied the change in the static coefficient of friction between shoes and mats in dry and wet conditions using new and used sports shoes and mats. The wet condition was provided with a saline solution containing 0.9% sodium chloride in order to simulate the influence of sweating. During the tests, a shoe with a total weight of 100 N, was subjected to an increasing force in parallel to the ground until the shoe began to slip, and the static coefficient of friction

TABLE 2 Critical fall height, Gmax and HIC values of different sports floors[123]

Surface	Critical fall height (m)	G_{max} (g)	HIC value
Concrete	0.15	392	976
Asphalt	0.30	370.5	1254
Carpet	0.30	380	1228
Rubberized track	0.46	284.5	1082.5
Artificial grass	1.22	217	1090
Grass (5 cm height)	1.07	201.5	960.5
Grass (10 cm height)	1.37	229	1177
Wood gym floor	1.37	239.5	1168
PU landing mat	3.20	278.5	1010.5
Spring floor	3.35	127	653.5

was determined. Their studies showed that the wet interface reduced the coefficient of friction by 14% compared to dry conditions, and the use of new mats and new shoes resulted in a 36% and 28% increase in the coefficient of friction, respectively. However, it is important to emphasize that neither the material of the sports mat nor the material of the sports shoe was indicated in the research, so it is not possible to show further correlations by investigating the effect of material properties.[57]

In addition to the surface of sports mats in contact with the ground and the athlete, another important requirement is the sufficient connection between the foam layers that make up the mat. Currently used sports mats typically consist of several layers, which are joined together by welding or gluing. Due to its simplicity, high productivity and cheap cost, the most commonly used welding technique is flame lamination, in which polymer foam sheets are melted by passing over a flame and then laminated together using rollers.[129]

In this technology, it is important to adjust the flame well to ensure proper melting without burning the polymer foam or reducing the thickness of the foam layers. The interlayer formed is mainly influenced by the type of gas used and the height and propagation of the flame. The other welding technologies used for joining together polymeric foam layers are the same as the method presented here; they only differ in the type of the heat source.[129] Another possible method is gluing the layers together; however, this is not common in the sports mat industry due to medical reasons.[11]

4.4 | Recovery capability of polymer foams after a static load

An important factor in sports applications of polymer foams is the behavior of a given product under long-term static load, the recovery capability after unloading and the extent of permanent deformation. As it was presented earlier, a long-term constant load can occur on martial art mats in case of improper storage, which should not deteriorate the quality of the product. Recovery capability of sports mats used for rehabilitation exercises and yoga is also critical, as prolonged exercises (e.g., stretching) should not shorten product lifetime.[8,25,80] For these reasons, it is essential to understand the time-dependent mechanical behavior of polymer foams, i.e. creep and stress relaxation. In foams, larger deformations occur compared to solid materials due to the bending of cell edges and the collapse of cell walls, which makes it difficult to model their mechanical behavior. The most commonly used structural models for solid materials give an adequate response only in the linearly viscoelastic range, where there are no irreversible deformations. Nevertheless, several studies tried to develop models that adequately describe the creep of polymer foams.[8,130,131]

Mills and Gilcrist[132] showed on crosslinked polyethylene foams that the creep compliance of the foam is directly proportional to the creep compliance of the solid polymer up to 5% deformation, but for larger deformations, the behavior of the foams differs significantly. This was also proved by creep study of Zhu and Mills,[133] who investigated the applicability of a structural model, which was no longer able to properly handle the deformations occurring in the cells for load levels higher than 2 kPa and deformations more than 10%.[133]

Despite the difficult modeling of time-dependent mechanical properties, it is essential for manufacturers to rate and quantify the recovery capability of their products after long-term static loads. The international ISO 1856 and American ASTM 3575 standards are used for this purpose. Both standards have the same principle: the test specimen is subjected to constant deformation under well-defined conditions, at a given temperature, for a given time interval. Then the change in the thickness of the test specimen from its initial state is determined at a given time after unloading. The tests are performed at room temperature (23°C) or at 70°C, depending on the standard, with a nominal sample size of 50 × 50 × 25 mm. The samples are subjected to a deformation of 50% or 75% for 22 h.[58,134]

The classification of the samples in each case is based on the so-called compression set value, which is calculated from the initial thickness measured before the test and the recovered thickness measured 30 minutes/24 hours after the static load ends (Equation (11)):

$$CS = \frac{h_0 - h_r}{h_0} \times 100, \quad (11)$$

where CS (%) is the compression set of the sample, h_0 (mm) is the initial thickness, while h_r (mm) is the recovered thickness of the foam.[58,135]

The use of these standards can be found in the literature, as many researchers focused on the investigation of the compression set of polymer foams.[136,137] However, most of them investigated only a few material types and the number of articles dealing with sports applications or multilayer structures is negligible.

Miller Tate et al.[136] compared the recovery capability of 100 kg/m^3 nominal density polyethylene, polyurethane, and polyimide foams by applying different deformation levels (2.5%–35%) and temperatures (20, 40 and 70°C). Their results showed that polyethylene foam clearly has the best recovery capability at room temperature and that the increasing temperature resulted in an increase in the compression set, and a decrease in recovery capability for all three foam types.[136]

Multilayer sandwich foam structures were tested according to the ISO 1856 standard by Boldis et al.[135] The aim of their research was to investigate the effect of different joint types between the layers on the compression set, and to compare the applicability of different self-clamping joints to that of gluing. All the investigated foam structures consisted of three polyurethane foam layers with different properties. In the first three samples (A, B and C), the fixing of the foam layers was provided by self-clamping joints, while in the reference sample (D), the foam layers were glued together. In the case of sample A, the connection between the layers was provided by an extra foam layer, which was also made from PU (see below in Figure 14).[135]

Prior to the tests, the samples were conditioned at 23°C and 50% humidity. During the tests, 50% deformation was applied on the foams for 72 h, and several times (after 2, 4, and 24 h) the load was temporarily interrupted and the thickness of the specimens was measured. The thickness of the specimens was also measured 30 min and 10 days after the end of the 72-h load, and the recovery capability of the foams was compared. The measurement results are shown in Figure 14.[135]

Sample A showed much higher compression set values compared to the others, so it was not advantageous to ensure the connection between the individual layers with another foam material. However, the compression set values of the Samples B and D were similar, so such self-clamping joints can be a good alternative to gluing.[135] However, it is important to note that in many cases, foam layers are fixed together by welding, but this joining method was not examined in the article.

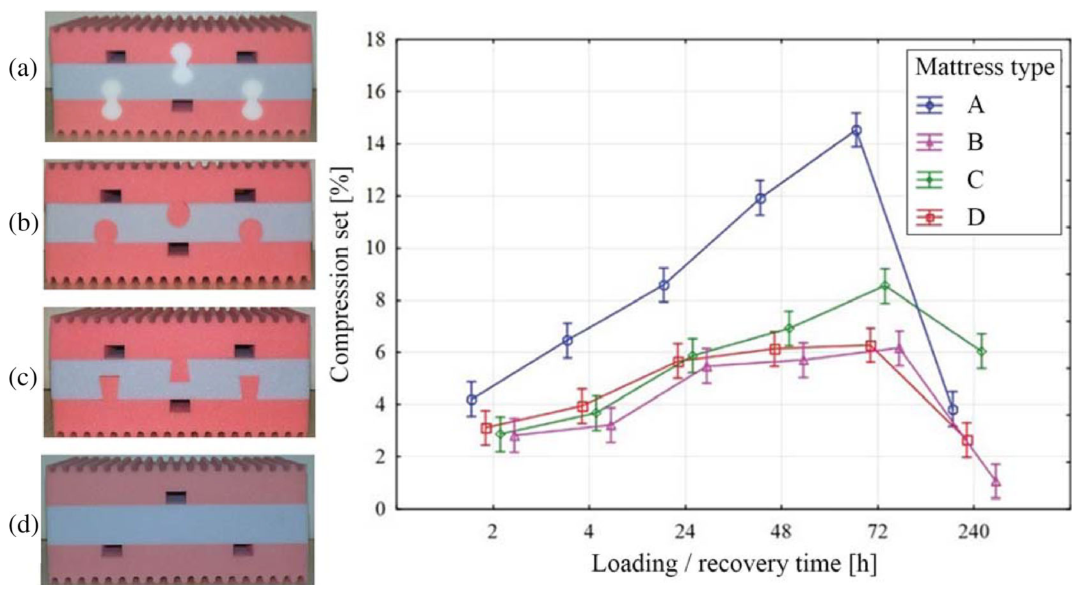


FIGURE 14 Compression set values of the investigated foam structures as a function of time. Reproduced with permission.[135] Copyright 2021, Woodresearch [Color figure can be viewed at wileyonlinelibrary.com]

4.5 | Fatigue characteristics and lifetime

In the case of sports mats and protective equipment, it is important to know the rate of mechanical deterioration as a result of continuous use because it determines the lifetime of the product. This is why mats are tested with a repetitive falling weight impact test procedure in many sports, and the duration of the industrial applicability of new products is also determined.[33,35,36]

However, few scientific publications on cyclic testing examine foams with properties that can be exploited in the sports industry. The type of foams tested and the measurement parameters used in the literature are widely varied. Yousaf et al.[138] performed cyclic compression test according to the ISO 7743-2011 standard on high-density polyurethane foams produced by syntactic foaming. Cylindrical specimens with a diameter of 29 mm and a height of 12.5 mm were compressed with 10 mm/min to 25%, 50%, and 75% deformation for five cycles repetitively. Due to the cyclic load, the foams softened, so the compressive stress decreased as the number of loading cycles progressed. Due to the viscoelastic nature of the tested materials, hysteresis was observed between the up and unloading curves, which was more significant for foams with a larger cell wall thickness to cell diameter ratio.[138]

Di Prima et al.[139] performed cyclic compression tests on epoxy foams of different relative densities (0.14–0.4 [–]) at elevated temperature (110°C). They applied a strain rate of 0.0025 1/s for 100 loading cycles with different maximum strains (40%, 60%, 80%, and 85%). Their results showed that the difference between the compressive stress of two consecutive cycles and the degree of residual deformation increase with increasing maximum compressive strain.[139]

In addition, there are also measurement results for high deformation rates. Shen et al.[140] performed a cyclic compression test on open-cell polyurethane foams with a density of 65 kg/m^3 to evaluate the vibration-damping capability. Specimens with a dimension of 100x100x50 mm were cyclically loaded to 75% deformation with 700 mm/min test speed, and they were kept unloaded for 10 min between each cycle to regain their original size. The foams were permanently deformed, which was explained by the irreversible deformations in the cell structure.[140]

However, for sports mats and protective equipment, the most important investigating method is the falling weight impact test, in which the effect of repetitive load can also be examined. In this regard, Lyn and Mills showed that a relaxation time of 10 min between two drops is sufficient for a rebonded polyurethane foam to recover without residual deformation.[81] In contrast, in our previous study[56] on weakly crosslinked polyethylene foams, we found an opposing phenomenon. The impact tests repeated every minute resulted in a deterioration in the energy absorption and impact damping capability. The repetitive drops caused irreversible deformations on the foam walls during the impact, thus permanently reducing the mechanical properties of the foam.[56]

This also shows the complexity of the relationship between repetitive load, cellular structure, and mechanical properties. In order to fully understand the topic, further research is required in the field of studying the fatigue characteristics and lifetime of polymer foams.

5 | CONCLUSIONS

This review summarizes the properties, requirements, and processing technologies of polymeric foams used in the sports industry as well as previous results in the field of the mechanical testing of polymer foams.

Overall, the mechanical testing of polymeric foams has been the subject of numerous studies. As deformation mechanisms of polymer foams during compression have been investigated by several researchers in the last decades, the reason for the outstanding energy absorption capacity of foams (deformation of the cell structure: cell wall buckling, cell edge bending) is well known. In addition, the effect of the increasing strain rate on the stress–strain response of foams during compression was also analyzed in detail.

Even though the impact damping capability of polymer foams was also investigated by several studies, it is not possible to compare polymer foam types most commonly used for sports applications in this respect. These studies used falling weight impact testing but they differ significantly in the applied test parameters, the impactor shape used, and the raw materials tested.

Most sports-specific standards rate sports surfaces according to the maximum deceleration affected on the body during the impact tests and do not examine the duration of the impacts. Although the evaluation of energy-absorbing materials in the automotive industry and sports surfaces in the sports industry based on the head injury criterion is popular, polymer foams are little researched. Multilayer polymer foam structures are even less researched; however, understanding the exact effect of layer order would enable engineers to design value-added foam products for many industrial fields.

Several studies determined the compression strength of foams, and the effect of the amount of blowing agent and other additives on cell structure. Mechanical properties are also deeply investigated. As the compression set of few polymers were investigated, it is not possible to form a comprehensive picture of the recovery capability of different foam types. Developing an appropriate model to simulate the time-dependent behavior (creep and stress relaxation) of polymer foams at higher load levels is a great challenge for researches to solve. The other future trends in the field of polymer foams can be the development of multilayer sandwich structures and the deeper investigation of the effect of repetitive loads.

ACKNOWLEDGMENTS

The research reported in this paper and carried out at BME has been supported by the NRDI Fund (TKP2020 IES, Grant No. BME-IE-NAT) based on the charter of bolster issued by the NRDI Office under the auspices of the Ministry for Innovation and Technology. This work was also supported by the National Research, Development and Innovation Office – NKFIH, K 132462; by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences; by the ÚNKP-20-5 New National Excellence Program of the Ministry for Innovation and Technology from the source of the National Research, Development and Innovation Fund; and by United World Wrestling.

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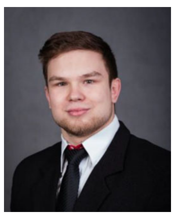

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How to cite this article: M. Tomin, Á. Kmetty, *J. Appl. Polym. Sci.* **2022**, *139*(9), e51714. https://doi.org/10.1002/app.51714