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DOI 10.2478/ama-2018-0004 acta mechanica et automatica, vol.12 no.1 (2018)

CRUSHING BEHAVIOUR OF THE PVC FOAM LOADED WITH BEATERS OF VARIOUS SHAPES

Paweł BOGUSZ*, Roman GIELETA*, Marcin KONARZEWSKI*, Michał STANKIEWICZ*

*Department of Mechanics and Applied Computer Science Faculty of Mechanical Engineering, Military University of Technology
00-908 Warszawa 46, ul. Gen. Witolda Urbanowicza 2, Poland

pawel.bogusz@wat.edu.pl, roman.gieleta@wat.edu.pl, michal.stankiewicz@wat.edu.pl, marcin.konarzewski@wat.edu.pl

received 30 January 2017, revised 27 February 2018, accepted 3 March 2018

Abstract: Statistically, at least 50% of all injuries experienced by police officers in the line of duty are due to assaults with blunt objects. Therefore, vests used by the police should provide not only good ballistic resistance, but also good protection against such threats. Foamed materials are possible to be used for body protectors or inserts of protective clothes. The effects of dynamic impact with beaters of different shapes onto behaviour of polymeric foamed material were determined. There were used four types of beaters: flat, cylindrical, edgy and cornered. Strikes with blunt objects such as a flat board, baseball bat, edgy brick, pavement brick or a sharp stone, to which a protective ware can be subjected, were simulated. The impact load was applied to the rectangular specimens, made of polyvinyl chloride foam, with a usage of a drop hammer. Plots of force versus compression for all the tested samples were obtained and analysed. The effects of impacts with beaters of different shapes onto foamed material samples were presented. A shape of the blunt object significantly influences crushing behaviour of the foamed material. The impact energy of a flat beater is absorbed effectively on a short distance, since it is spread on a relatively large surface. The cylindrical and edgy beaters did not cause fragmentation of the samples, however, on the upper surfaces of the samples, permanent deformations mapping the beaters shapes as well as some cracks occurred. An impact with a sharp object, for example, a cornered beater is very difficult to be neutralized by the foam material, because it is cumulated on a small area.

Key words: Polymeric Foams, Polyvinyl Chloride Foam, Hitting With A Blunt Object, Energy Absorption, Impact Tests, Experimental Mechanics

1. INTRODUCTION

Bulletproof and knife-proof vests are manufactured for specific applications that determine their structure. Types of threats depend on the environment and a kind of service. Statistically, at least 50% of all injuries experienced by police officers in the line of duty is a consequence of attacks with blunt objects, such as a baseball bat, stone, bricks and a flat board. 35% of all injuries is due to attacks with a knife or other sharp objects, whereas only up to 15% of injuries occurs during attacks with firearms (Cook, 2008). Therefore, the vest should not only provide good ballistic resistance, but also good protection against the risks of injuries caused by attacks with a blunt object, knife or other sharp tools. The paper is focused on analysis of blunt objects impact hazards.

Typically, strong fibreglass/aramid, ultra-high-molecular-weight polyethylene (UHMWPE) and high strength-steel or ceramic-based materials are used in structures of protective clothing inserts.

Foamed materials are possible to be used materials for designing protective clothes as well as developing bulletproof and knife-proof vests. The cellular construction of the foam materials provides not only lightweight capability, but also a deformation mechanism that allows for efficient absorption of energy. Fig. 1 shows a typical curve of standard foamed aluminium obtained by compressing a cubic specimen quasi-statically along one direction. The curve exhibits three definite regions: linear elasticity, plateau and densification. At low strains, the behaviour is linear elastic, with a slope equal to the Young modulus of the foam.

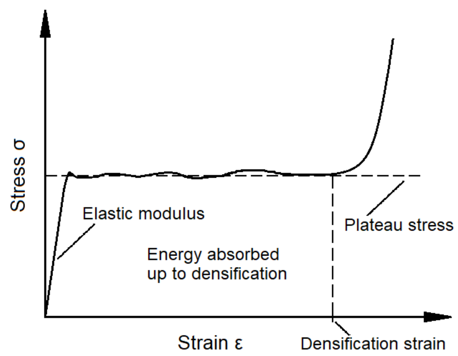

Fig. 1. The static compression curve for standard foamed material (Ashby et al., 2000; Avalle et al., 2001)

A small amount of energy is absorbed in this region. As the load increases, the foam cells begin to collapse by elastic buckling, plastic yielding or brittle crushing, depending on the mechanical properties of the cell walls (Ashby et al., 2000; Avalle et al., 2001). The most effective part of the curve is up to a so-called densification strain, for which pores of the foam are mostly closed. In this region, a stress value is approximately on a constant level or increases gradually. What allows for large energy absorption at

DOI 10.2478/ama-2018-0004

an almost constant load is a long plateau of the stress-strain curve. After closing the pores, force starts to increase rapidly, as in the case of the solid uniform material. During unloading the foam, the stress depends non-linearly on the strain (Avalle et al., 2001).

In Avalle et al. (2001), an efficiency diagram method is presented to obtain synthetic diagrams useful to characterize the material and to help design energy absorbing components for the three tested materials. The energy absorption characteristics have been examined for three polymeric foams (expanded polypropylene EPP, polyurethane foam PUR and a blend of polyamide reinforced with modified polyphenylene and polystyrene PS/PA foams). Also, the mechanical properties of the foams at room temperature have been experimentally evaluated in both static and impact loading conditions.

A polyvinyl chloride (PVC) foam is extensively used in sandwich structures as a lightweight core and is combined with different face layers, e.g. aluminium, fibre glass composite, polypropylene, plywood or others. Several studies have been undertaken to experimentally characterize the impact properties of PVC foams.

Objectives studied in Mahfuz et al. (2006) included, among others, investigation of behaviour of PVC foam materials at strain rates ranging from quasi-static to around 2000 s^{-1}. Room temperature response, strain rate sensitivities and failure characteristics have been determined for various density foams. The performed investigation showed that with the increase in the strain rate, a moderate increase in the compressive strength of the foams occurs. At quasi-static and high strain rate regimes, the increased temperature led to degradation of strength and stiffness. This degradation, however, increased with the density of the core (Mahfuz et al., 2006).

In paper Zhang et al. (2012), a methodology for characterising the elastic properties of Divinycell PVC H100 foam at elevated temperatures is proposed. The focus is on determination of reliable values of the tensile and compressive moduli and Poisson's ratio based on the strain data obtained using digital image correlation (DIC). The design of the specimens and loading jigs are developed and assessed in terms of introduction of the uniform strain. The tests conducted at elevated temperatures ranging from 20°C to 90°C showed that the material is highly anisotropic with stiffness of 50% less in the plane of the foam sheet compared to the through thickness direction. A nonlinear reduction in Young's modulus is obtained with a significant degradation occurring above 70°C, losing more than half of the room temperature stiffness – 130 to 55 MPa at 90°C. The Poisson's ratio remains stable at different temperatures – 0.43 on average (Zhang, 2012).

The uniaxial compressive responses of two PVC foams (Divinycell H100 and H250) and balsa wood ProBalsa LD7 have been measured within strain rates ranging from 10^{-4} s^{-1} to $4x10^{3}$ s^{-1}. These materials are extensively used as cores for composite light-weight structures capable of providing impact and blast protection. The high strain rate compression tests were performed using a Split Hopkinson Pressure Bar. The compressive yield strength of the H250 PVC foam and balsa wood doubles when the strain rate is increased from quasi-static rates to rates in the order of $10^{3}s^{-1}$. In contrast, the H100 PVC foam displays only a small elevation in uniaxial compressive strength (about 30%) for the same increase in the strain rate (Tagarvielli et al., 2008).

Divinycell PVC H100 foam was also the subject of the research in papers (Chen and Hoo Fatt, 2013; Hoo Fatt and Chen, 2015; Hoo Fatt et al., 2017). In Chen and Hoo Fatt (2013), cyclic material tests were done to obtain both out-of-plane and in-plane compression and shear material properties after foam yielding. The ratio of out-of-plane to in-plane stiffness and yield strength for the PVC H100 was found to be approximately 3/2 in both the compression and shear modes. After viscoplastic yielding, the foam underwent permanent damage and exhibited hysteresis, mainly in the form of viscoelasticity.

A phenomenological constitutive model for Divinycell PVC H100 foam undergoing crushing and hysteresis under cyclic compression loading was developed in Hoo Fatt and Chen (2015). The PVC H100 foam exhibited strain-rate dependency of a damage mode and hysteresis. The damage that occurred in the foam after yielding was fixed at a given strain amplitude and progressed with increasing the strain amplitude (the pattern of Mullins). A damage initiation criterion based on critical compressive strain was proposed. A standard model, an elastic spring in parallel with Maxwell element, was used to describe viscoelastic behaviour before and after damage.

In Hoo Fatt et al. (2017), a precise constitutive foam model, which can be used to predict crushing behaviour, energy absorption and damping properties of structural polymeric foams, was developed. To determine the multi-axial, elastic-plastic and hysteresis characteristics of Divinycell PVC H100 foam, several experiments was carried out. The foam exhibited elastic-plastic response followed by viscoelastic hysteresis in compression, shear and combined compression and shear. A Tsai-Wu plasticity model, including combined kinematic and isotropic hardening, was developed to accurately describe multiaxial yielding of the foam.

Plasticized PPVC is widely utilized, for example, in automotive industry, as part of an energy absorbing structure of a car body. In Bernard et al. (2015), an influence of a wide range of strain rate on the mechanical response and mechanical properties of PPVC composed of 50% of PVC, 40% of plasticizers and 10% of additives was investigated using normalized thicknesses of different samples: 1.0, 1.25 and 1.5. The experimental results indicate that the mechanical properties, especially at high strain rates, are different for the various thicknesses. Considering all the investigations, the elastic modulus and yield stress are greater for the higher thickness (Bernard et al., 2015).

In Loung et al. (2013), a set of closed-cell polyvinyl chloride (PVC) foams with different densities is studied for compressive response. The results show that the mechanical properties depend on the foam density and are strain rate sensitive. The compressive strength and modulus increase with the foam density. Similarly to other publications, it has been found that within the quasi-static strain rate regime, compressive strength of PVC foams at $10^{-1}s^{-1}$ can be up to 50% higher than at $10^{-4}s^{-1}$. At strain rates of 2000 s^{-1}, the strength can be 200% higher than the quasi-static values noted at $10^{-4}s^{-1}$. The peak and plateau strengths are dependent on the foam density. Foams with higher density provide better properties. The absence of experimentally measured mechanical properties in the intermediate strain rate range of 1–500 s^{-1} is observed for PVC foams. The main failure mechanisms are buckling and plastic deformation of cell walls leading to foam compaction. Cell wall buckling is clearly observed in high density foams, whereas low density foams demonstrate wrinkling and stretching of cell faces (Loung et al., 2013).

To support development of sandwich composite failure models, a series of PVC material tests were performed in Loup et al. (2005) to characterize foam core material response under quasi-static and dynamic tension loading. Material stress-strain response was found to be highly nonlinear and dependent on the

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loading orientation relative to the axis of the foam sheet. At low to moderate strain rates, less than 150 s^{-1}, tension strength and modulus increased, whereas ultimate strain at failure decreased (Loup et al., 2005).

The failure behaviour of a PVC closed-cell cellular foam under a multiaxial state of stress was investigated in Gtoutos et al. (2001). The uniaxial compressive, tensile, and shear stress-strain curves along the in-plane and through-the-thickness directions were obtained. A series of multiaxial tests including strip, thin-wall ring and thin-wall tube specimens under combined tension/compression, torsion, and internal pressure was performed. As a result of these tests, biaxial strength in the in-plane and through-the-thickness directions was obtained. The results were in good agreement with the Tsai-Wu failure criterion (Gtoutos et al., 2001).

The aim of the paper is to determine the crushing resistance of rectangular samples of HEREX C70.130, made of polyvinyl chloride closed-cell foam, to the effects of impact with blunt objects of different shapes. This core material is intended to be used for many lightweight sandwich structures subjected to dynamic or static loads. The material may be used for rotor blades and turbine generator housings in wind turbines, in the structure of skis, snowboards or surfboards, fuselage, wing and interiors of aircrafts, and others (Alan Composites, 2016). Closed-cell foams are used in marine vessels and ground transportation applications due to their compressive energy absorption capabilities, especially, as a core material in sandwich composites (Luong et al., 2013).

Tab. 1. Material properties for HEREX C70.130 foamed material (Alan Composites, 2016)

Average properties	Norm	Units	Value
Tensile strength in the plane	DIN 53455	MPa	3.8
Tensile modulus in the plane	DIN 53457	MPa	115
Compressive strength perpendicular to the plane	ISO 844	MPa	2.6
Compressive modulus perpendicular to the plane	DIN 53421	MPa	155
Shear strength	ISO 1922	MPa	2.3
Shear modulus	ASTM C393	MPa	50

The detailed material strength properties for the HEREX C70.130 foamed material are presented in Tab. 1. The material is described as a rigid, closed-cell foam. It is characterised with a high stiffness and a strength to weight ratio. The foam is used as a core material for lightweight sandwich structures (Alan Composites, 2016) and provides great resistance to chemicals. It does not absorb water and it's purchasing cost is relatively low.

The tactical and technical assumptions of the protective clothes are based on the adequate standards. There are many standards for the classification of soft and hard ballistic performance. The primary task of ballistic inserts is to stop the projectile. The second issue is to limit deflection of the body armour, which can cause non-penetrating injuries to internal organs, referred to as a blunt trauma. The vests, especially for uniformed services, should also protect from knife blades, needle-shaped objects, shrapnel, and blunt heavy objects.

Typical standards present tests for verification of ballistic performance. The most popular is the US National Bureau of Justice's NIJ standard 0101.06 (2008) and NIJ standard 0101.04 (2000). The NIJ standard has been developed primarily for users of uniformed services, not military ones and, therefore, it is specific to pistol-type hazards. It divides the ballistic protection into five classes of resistance - Level IIA, II, IIIA, III, IV. The latest version of 2008 is NIJ 0101.06 standard (2008) and is very restrictive, especially in terms of a test run and an expensive certification procedure, therefore, most manufacturers make their ballistic protection products in compliance with the earlier NIJ 0101.04 standard (2000). According to level IIIA, for the new soft ballistic test, resistance to 9 mm is performed using Parabellum bullet with a lead core weighted 8 g and a impact speed of 436 m/s or with 0.44-inch Magnum bullet with a mass of 15.6 g and impact speed of 436 m/s. The maximum deflection arrow can be up to 44 mm.

In the MIL-STD-622F (1997) standard, the FQ/PD 07-05 specification, the ballistic resistance of the soft panels was set to withstand impact of three 9 mm Parabellum FMJ bullets with a mass of 8.0 g fired at 464.2 m/s. Maximal deflection of the material after the impact is allowed to be 44 mm.

The Polish Ballistic Standard PN-V-87000:2011 (2011) was developed based on STANAG 2920 adopted by NATO. According to K2 level, bulletproof performance can be verified by measuring resistance to a 7.62x25 mm lead core bullet fired from TT gun. The maximum deflection arrow may be 40 mm, which is more restrictive than the American standards.

The second parameter, according to which the vests are tested, is the shrapnel resistance verifying whether the cover stops a so-called "standard shrapnel" with a mass of 1.10 g at different speeds. For example, according to PN-V-87000, the O3 class of shrapnel resistance, defines a standard shrapnel as a 1.1 g fragment with speed from 600 to 675 m/s. This also conforms to the NATO standard STANAG 2920.

In standard MIL-STD-622F (1997), restrictions were set to stop fragments of weight from 0.12 g to 1.01 g moving at a speed of 563.8 to 826 m/s.

The basis for the resistance against knife and/or spike piercing is the NIJ Standard-0115.00 (2000), Stab Resistance of Personal Body Armor (2000), which describes a research method for the stab resistance of ballistic packages. According to this standard, a free-falling sabot system, with a knife blade or spike attached, strikes the ballistic package lying motionless on a deformable surface. The protection level 2 defines the sabot kinetic energy to be 33 J with maximum penetration of 7 mm or 50 J with maximum penetration of 20 mm, in both cases for striking angles of 90° or 45°. Piercing-by-needle resistance is evaluated with a needle-shaped arrow blown at a speed of more than 50 m/s, from a distance of 5 m.

Blunt and/or heavy objects resistance, which is the scope of this article, is the subject of the British Standard BS 7971-8 (2003). The standard presents guidelines for protective clothing and equipment performance to be used in violent situations. It adopts a value of 20 J for impact energy as a basis for the research. An average value of the transferred force should not exceed 4 kN and none of the individual forces should exceed 6 kN.

The next standards presented are not directly related to the military or even non-military uniformed services, however, they contain guidelines for protection of body parts from different injuries.

The Polish PN-EN 1621-2: 2014-03 (2014): Motorcyclists' protective clothing against mechanical impact – Part 2: Motorcyclists' back protectors – Requirements and test methods is based on the EU standard EN 1621-2: 2014. The document sets the loading energy at the level of 50 J with accuracy of ±1.5 J. The beater

DOI 10.2478/ama-2018-0004

mass is set to 5000±50 g. Therefore, the impact energy is greater than in the case of BS 7971-8 standard. The standard proposes two protection levels. Protection level 1: the average value of transmitted force not greater than 18 kN, single impact force not greater than 24 kN. Protection level 2: the average value of transmitted force not greater than 9 kN, single impact force not greater than 12 kN.

Requirements and test methods for protective clothing for hockey on the grass goalkeepers and players in the field are described in PN-EN 13546:2008 (2008). It sets standards for protection of the most vulnerable and exposed parts of a body, e.g. arms, chest, foot, genitals. The area of the heart has five levels of protection: level 1 – energy 5 J, level 2 – energy 20 J, level 3 – energy 30 J, level 4 – energy 40 J, level 5 – energy 50 J, similar as in the case of the PN-EN 13546 (2008).

Standard PN-EN 13277-1 (2002) introduces requirements for protective equipment for martial arts. In this case, impact energy of a beater is limited to 12 J. The maximum weight of the loading beam is 2.5 ±0.025 kg. The maximum transferred energy cannot exceed 3 kN.

PN-EN 13158 (2010) presents requirements and evaluation methods for protective clothing for horse riders and those working with horses. According to the standard, a flat beater should have energy levels of 25 to 35 J. An average value of the transmitted force should be less than 25 kN, none of the individual values should exceed 30 kN.

As presented in the literature review, the highest value of the impact energy from blunt objects and different injuries for the protective equipment to withstand is 50 J.

2. RESEARCH METHODOLOGY

The paper presents an investigation of PVC foam crushing behaviour tests. The tests were performed on a drop hammer presented in Fig. 2. The testing bed design allows setting an appropriate impact energy through control of a dropping height or a dropping beam weight. It allows measuring the impact force, displacement, and dropping height automatically. The force is measured with a piezoelectric sensor Piezotronics PCB M200C50 operating within the range of 222.4 kN. The sensor is mounted under the support plate of the hammer. A beam movement, corresponding to a specimen compression, is measured by a laser triangular sensor. Beaters with different shapes can be mounted to the beam.

Prior to the proper tests with a drop hammer, the impact energy parameter for the foamed material tests was determined during an additional experimental research. The research was based on throwing or hitting with various blunt objects by a few adult people. The different types of blunt objects used in the evaluations are presented in Fig. 3. There were used: pavement stones, small and big bricks, small and big rocks. Also, striking with a baseball bat was covered in the tests. Five people performed each type of test. The experiment was recorded with a high-speed camera to measure velocity of thrown objects or striking with a baseball bat. Special marks were placed on the objects to evaluate velocity using Digital Image Correlation method (DIC) – Fig. 4. Afterwards, a kinetic energy for each blunt object was calculated. All results were averaged and the statistical averaged kinetic energy of throwing/striking with blunt objects was measured It was determined to be 195 J.

Fig. 2. A specimen placed on the support plate of the drop hammer with a flat beater installed on the beam

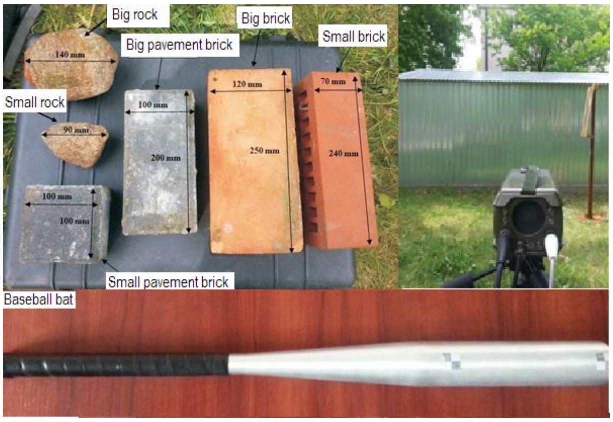

Fig. 3. Blunt objects and baseball bat used in the kinetic energy evaluation test with high-speed camera

The adopted averaged value of the kinetic energy–obtained from the additional tests is more than ten times greater than the potential energy set in the testing standards considering loading with blunt instruments. The British Standard BS 7971-8 (2003) adopts a value of 20 J as a basis for the research, whereas Polish PN-EN 1621-2 (2014) sets the loading energy at the level of 50 J. Those values appear to be low when compared to possible treats experienced by police officers in the line of duty.

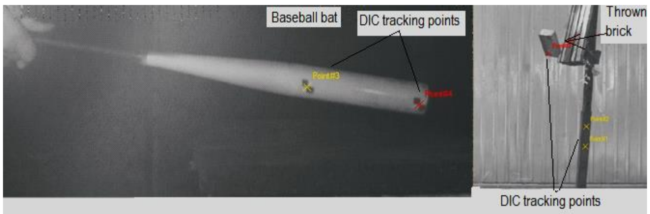

Fig. 4. Evaluation of velocity and kinetic energy of blunt objects thrown and baseball bat strike, using tracking points of Digital Image Correlation method

A dynamic impact load was applied using beaters with different shapes. Four types of beaters were prepared: flat, cylindrical, edgy and cornered. A flat beater, presented in Fig. 5a), has dimensions of 70x70 mm and simulates an attack with flat objects

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such as boards. A baseball bat is modelled using a cylinder with a diameter of 55.2 mm and length of 70 mm – Fig. 5b). An edgy beater (Fig. 5c) has the following dimensions: height – 40 mm, the base – 45x80 mm. The fourth one, presented in Fig. 5d), is a cornered beater. Its base is an equilateral triangle with side length of 68.7 mm and height of 40 mm. The last two beaters are to simulate attacks with edged bricks, crushed pavement stones or sharp stones.

The dropping height of the hammer beam for each sample was determined in such a manner that the potential energy was equal to 195 J. The total mass of the beam of the drop hammer with a beater installed was equal to 15 kg. To achieve the desired impact energy, the dropping height was set to 1325 mm. The impact speed was equal to about 5 m/s. The experimental conditions correspond to the strain rate of about 10^2 s^{-1}. According to majority of the literature, i.e. (Mahfuz et al., 2006; Zhang et al., 2012; Luong et al., 2013; Loup et al., 2005), PVC foam crushing force is sensitive to a strain rate increase compared to the static tests.

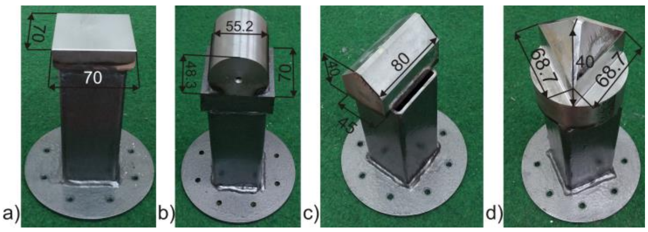

Fig. 5. The beaters used in the study of the PVC foam crushing resistance: a) flat; b) cylindrical; c) edgy; d) cornered

Rectangular samples of HEREX C70.130 with dimensions of 70x70x40 mm and density of 130 kg/m^3 were prepared. The actual average density was equal to 139 kg/m^3. The samples were cut, using a water jet machine, from a raw factory-prepared PVC foam sheet of 40 mm height. The samples were loaded in through-thickness direction, wherein the material has the best properties (Zhang et al., 2012). A sample placed on the testing bed equipped with a flat beater is shown in Fig. 2.

In the case of flat, cylindrical and cornered beaters, five samples were tested. However, in the case of the edgy beater, six samples were evaluated.

In the initial tests, load of 100% was applied, which means that the beam with an appropriate beater was dropped from the maximum height (1325 mm). In the cases where the impact energy was too high, and an impact caused sample fragmentation, the drooping height was gradually reduced for another samples by 20%, and if it did not prevent fragmentation, it was reduced by 50% of the initial height.

It should be noted that the test does not reflect real conditions of the human body protection against strikes with blunt objects. This is due to firmly stiff steel backplate of the testing bed, on which the samples were set during the tests. However, the paper presents the most disadvantageous condition in which crushing behaviour under impact of objects of various shapes can be observed.

Based on the obtained data, the graphs of force versus compression for all tested samples were evaluated, analysed and compared. The presented force curves were determined until the maximum compression of the samples was reached. The area under the curves represents the absorbed energy which was also calculated for each sample.

3. RESULTS OF THE RESERCH

The crushing behaviour and energy absorption performance of the tested PVC foam are very dependent on the shape of the striking object. The samples of foam material after the tests with a flat beater are shown in Fig. 6. None of the tested samples underwent fragmentation. On the top surfaces of the samples, permanent and evenly distributed deformations occurred. The impact energy of a flat beater is absorbed effectively on a relatively short distance, compared to the tests of other beaters, since the impact is spread on a relatively large surface.

The detailed results of the impact tests are covered in Tab. 2, which presents impact speed of the hammer beam, displacement covering sample compression, maximum crushing force, average crushing force and energy absorbed by the specimens. The absorbed energy was calculated as an area below the force-displacement curves. The averaged values were calculated and are presented in the last row of Tab. 2.

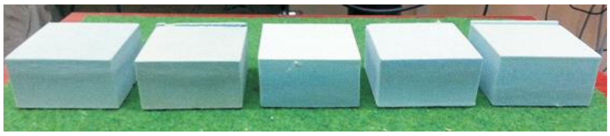

Fig. 6. Samples after the tests with a flat stamp

Tab. 2. Results of the impact tests for flat beater impact

Dropping height [%]	Impact speed [m/s]	Displace place-ment [mm]	Maxi-mum force [kN]	Aver-aged force [kN]	Ab-sorbed energy [kJ]
100	5.1	8.8	25.7	20.8	182.9
100	5.1	9.3	26.0	20.5	190.3
100	5.1	9.3	25.2	20.4	189.9
100	5.1	9.5	24.8	20.0	189.7
100	5.1	9.8	24.3	19.3	189.6
Average:	**5.1**	**9.4**	**25.2**	**20.2**	**188.5**

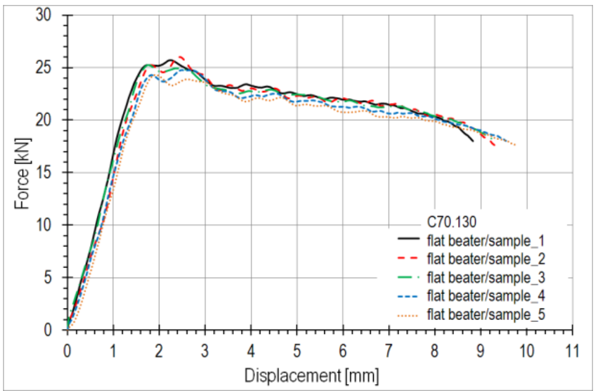

Fig. 7. Force-displacement curves obtained in the flat beater tests

In Fig. 7, the force-displacement curves obtained in the flat beater tests for all five specimens are presented. The compression curves are presented to the moment of the maximum specimen compression. The results are repeatable as shapes of the curves are very similar to each other. After a linear force increases and reaches its maximal value, which is equal to about 25 kN,

DOI 10.2478/ama-2018-0004

a gradual decrease occurs when the beater decelerates. Both the maximum and the average transferred crushing force exceed the values proposed in most standards regarding blunt object impacts or injury resistance. This is due to a relatively high initial energy and a stiff steel backplate of the testing bed. The averaged absorbed energy for all tests is equal to 188.5 J. Most energy of the impact was absorbed by the foam.

The samples crushed with a cylindrical beater are presented in Fig. 8. As it can be observed in the photo, samples did not undergo any fragmentation. However, on the top surfaces of the foamed materials, some semi-circular deformations and small cracks were formed.

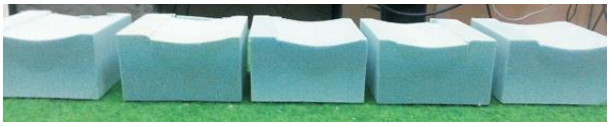

Fig. 8. Samples crushed with a cylindrical beater

Tab. 3 presents quantities of the energy absorbed obtained for the cylindrical beater. The maximum transferred force was equal to 16 kN and averaged force – 12.2 kN. The averaged absorbed energy is equal to 185.8 J, which means that almost 96% of the impact energy was absorbed by the specimens. PVC foam is slightly less effective in counteracting the rounded-shaped object strike compared to a flat object impact. Only a small amount of energy would be transferred to the protected object.

In the crushing plots obtained during the cylindrical beater impacts, presented in Fig. 9, the crushing force increases smoothly along with deflection, which is due to a gradual increase of the contact area of the beater with the sample in the crushing zone. The maximum force is significantly less than for a flat beater and it occurs at the end of the impact; however, displacement is almost twice as high. The impact energy is absorbed in a longer distance, due to a smaller cross section area of the beater. The 40 mm-thick foam is capable resisting this kind of threat without being fragmented.

Tab. 3. Results of impact tests for cylindrical beater impact

Dropping height [%]	Impact speed [m/s]	Dis-place-ment [mm]	Maxi-mum force [kN]	Aver-aged force [kN]	Ab-sorbed energy [kJ]
100	4.9	15.1	16.5	12.4	187.2
100	4.9	15.3	15.8	12.3	188.4
100	4.8	15.3	15.9	11.9	182.2
100	4.9	15.1	15.8	12.4	187.3
100	4.9	15.2	15.9	12.1	183.9
Average:	**4.9**	**15.2**	**16.0**	**12.2**	**185.8**

For samples loaded with an edgy beater, presented in Fig. 10, different degrees of destruction for various samples were observed. Therefore, in this case, the tests for six samples were made. Samples no. 2 and no. 4-6 (last four samples shown in Fig. 10) did not undergo fragmentation. There were permanent deformations shaped in the form of the beater and cracks present along the specimens; however, the samples resisted the test without any fragmentation. In the case of the first two specimens presented in Fig. 10 (samples no. 1 and 3), the load of the dropping hammer caused some significantly large cracks clearly visible in the picture. Parts of the samples, separated with the cracks through the whole height, were stuck to the rest of the sample parts only on small fragments. Permanent deformations of the surfaces in the shape of the cylindrical beater are also clearly visible. Despite the occurrence of large cracks, piercing through the thickness was not observed.

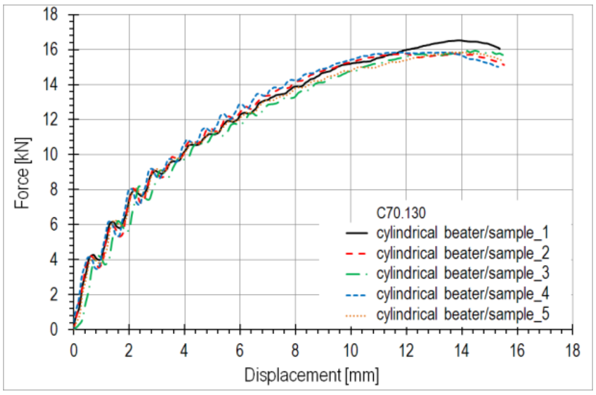

Fig. 9. Force-displacement curves obtained in the cylindrical beater tests

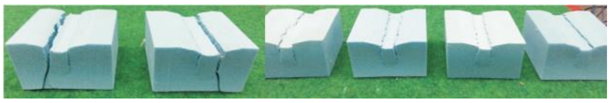

Fig. 10. Samples crushed with an edgy beater

The results of the crushing tests for an edgy beater impact are presented in Tab. 4. The maximum crushing force was equal to 14.2 kN and the averaged crushing force – 9.2 kN. Both values are even less than in the case of the cylindrical beater and the resulting displacement of the specimens is greater. On average, almost 89% of the impact energy of the edgy beater was absorbed by the foam, which means that the rest of the energy would be transferred to the protected object causing injuries. A smaller amount of the impact energy of the hammer beam was absorbed on the longer distance.

Tab. 4. Results of impact tests for edgy beater impact

Dropping height [%]	Impact speed [m/s]	Dis-place-ment [mm]	Maxi-mum force [kN]	Aver-aged force [kN]	Ab-sorbed energy [kJ]
100	5.0	18.5	14.3	9.2	170.4
100	5.0	19.1	14.1	9.3	177.6
100	5.0	18.1	13.9	8.9	160.2
100	5.0	19.6	14.3	9.4	184.4
100	5.0	18.4	14.5	9.4	172.2
100	5.0	18.9	14.2	9.2	173.8
Average:	**5.0**	**18.8**	**14.2**	**9.2**	**173.1**

Fig. 11 shows a graph of the impact compression with an edgy beater for six samples. In this scenario, a cross section of the beater hitting the specimen gradually increases during the impact, which results in a linear force increase and crushing distance extension. Elongation of the crushing displacement is an adverse phenomenon, due to limited thickness of the protective

DOI 10.2478/ama-2018-0004

material. The 40 mm-thick PVC foam is not sufficient to withstand the threat caused by a sharp object.

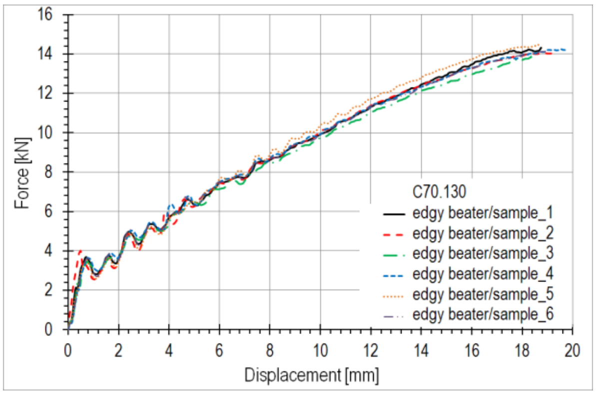

Fig. 11. Force-displacement curves obtained in the edgy beater tests

Based on the experience obtained in previous investigations, in the case of the cornered beater strike, the level of the initial dropping height of the hammer beam was reduced by 20% of the basic value (to 1060 mm). It corresponds to dropping energy of 156 J. After the first two tests, it was found that the samples were pierced through by the cornered beater and completely defragmented (first two samples presented in Fig. 12). For the remaining samples, the dropping height was limited to 50% of the maximum height (97.5 J). These samples were not torn apart. Permanent and deep deformation mapping the shape of the cornered beater is observed on the surfaces of these samples. Fig. 12 presents all samples after the tests.

Fig. 12. Samples crushed with a cornered beater

Tab. 5. Results of impact tests for cornered beater impact

Dropping height [%]	Impact speed [m/s]	Displaceplacement [mm]	Maximum force [kN]	Averaged force [kN]	Absorbed energy [kJ]
80	4.3	24.7	10.6	5.1	124.8
80	4.3	26.0	10.9	5.3	138.5
50	3.4	21.7	8.7	4.1	88.7
50	3.4	22.1	8.7	4.1	91.2
50	3.4	22.0	8.7	4.1	89.7
Average:	**3.4**	**21.9**	**8.7**	**4.1**	**89.9**

In Tab. 5, the results of the crushing tests with a cornered beater are shown. The averaged values were calculated based only on the last three specimens, which were hit from the level of 50% of the total height and these rows are marked grey. Comparing the absorbed energy from the impact tests with a flat beater and the last scenario, only a small amount of the energy was absorbed by the foamed material hit with a cornered beater. This is due to a strongly sharp shape of the beater. A load is cumulated on a small area, which leads to a considerably low crushing force observed during the tests.

The graphs illustrating the force progress are presented in Fig. 13. The maximum force is reached at the end of the trials. A low level of crushing force at the beginning means that the crushing distance necessary to absorb all of impact energy can potentially be greater than the thickness of the protective layer. The last scenario of impact with cornered blunt elements (corners of brick or stones) is the most difficult for the foamed material to withstand and effectively protect against the threat.

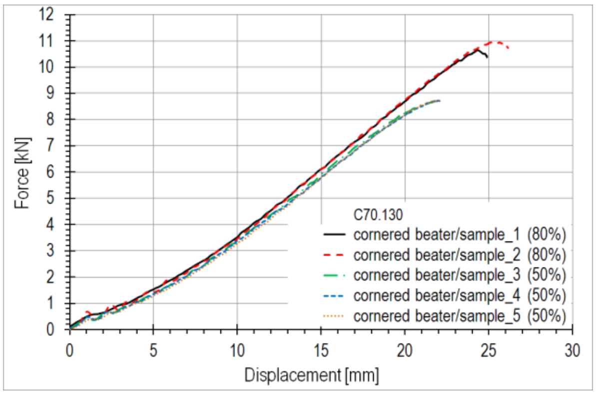

Fig. 13. Force-displacement curves obtained in the cornered beater tests

The selected specimens of scenarios evaluated in the impact tests with beaters of different shapes are compared on the graph in Fig. 14. The area under the curves represents the energy absorbed by the samples. It is clearly illustrated how significantly the shape of the blunt object influences the behaviour of the foamed material. The PVC foam materials can easier withstand flat object strikes and absorb more impact energy, while sharp objects impacts are very difficult to resist. The average crushing force is low; therefore, impact energy cannot be neutralized sufficiently by the foam. The average force of the flat beater impact (20 kN) is 5 times greater than the corresponding average force of the cornered beater impact (4.1 kN). The impact energy is cumulated on a very small area of the impact zone.

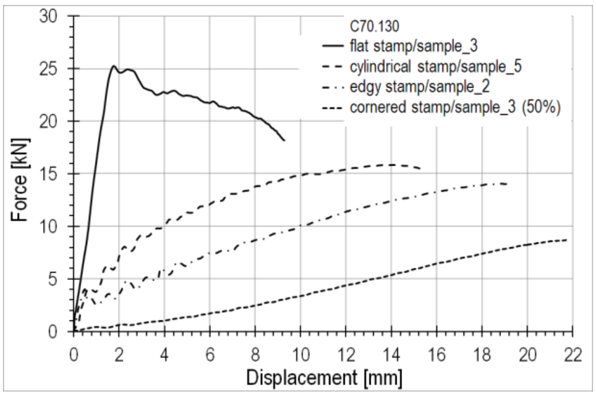

Fig. 14. Comparison of force-displacement curves for all types of crushing tests

4. CONCLUSIONS

The following conclusions of the study of the PVC foam material behaviour under load simulating the impact of a blunt object have been drawn:

1) The results for crushing tests of impact with different beaters

DOI 10.2478/ama-2018-0004

cannot be directly compared because a cross section area and a shape were different for each beater shape; however, general conclusions can be derived;
2) The impact energy of a flat beater is absorbed very effectively. For this case, a path of compression was considerably short. There were permanent but uniform deformations over the entire surfaces of the samples. The foam protects from flat blunt object strikes effectively;
3) The cylindrical and edgy beaters did not cause fragmentation of samples; however, the impact energy was absorbed in a considerable longer distance, compared with a flat beater. On the upper surfaces of the samples, permanent deformations mapping the beaters shapes as well as some cracks occurred;
4) The foamed material was able to absorb only a small amount of the impact energy of the cornered beater. To avoid fragmentation of the samples, the dropping height was reduced by 50%. On the top surfaces of the specimens, some deep cavities and cracks appeared. Those kinds of threats are very dangerous and difficult to be neutralized by the foam;
5) A shape of the blunt object significantly influences the behaviour of the foamed material. Flat objects cause the foamed material to absorb more energy and, thus, to be more effective, while sharp objects impacts are very difficult to be neutralized;
6) In the case of stiff foamed material like PVC foam investigated in the paper, edgy and cornered objects can cause cracks and defragmentation of the material during an impact;
7) It is shown that an averaged value of the kinetic energy obtained from the additional tests is more than ten times greater than the potential dropping energy set in the testing standards considering loading with blunt objects;
8) The test of throwing the blunt objects of different shapes and striking with a baseball bat allowed establishing an impact energy value for the test using beaters with different shapes. The potential energy for the main tests was equal to 195 J.

The paper covers the study of the crushing effects of impact load of the foamed material with beaters of different geometry, simulating an attack with blunt objects, such as: flat board, baseball bat, edgy bricks, pavement stones or stones.

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Acknowledgement: The work has been accomplished under the research project: INNOTECH-K2/IN2/56/182840/NCBR/13 financed by the National Centre of Research and Development (NCBiR).