International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:8, No:10, 2014

High Strain Rate Characteristics of the Advanced Blast Energy Absorbers

Martina Drdlová, Michal Frank, Jaroslav Buchar, Josef Krátký

***Abstract*—**The main aim of the presented experiments is to improve behaviour of sandwich structures under dynamic loading, such as crash or explosion. Several cellular materials are widely used as core of the sandwich structures and their properties influence the response of the entire element under impact load. To optimize their performance requires the characterisation of the core material behaviour at high strain rates and identification of the underlying mechanism. This work presents the study of high strain-rate characteristics of a specific porous lightweight blast energy absorbing foam using a Split Hopkinson Pressure Bar (SHPB) technique adapted to perform tests on low strength materials. Two different velocities, 15 and 30 $m.s^{-1}$ were used to determine the strain sensitivity of the material. Foams were designed using two types of porous lightweight spherical raw materials with diameters of 30-100 μm, combined with polymer matrix. Cylindrical specimens with diameter of 15 mm and length of 7 mm were prepared and loaded using a Split Hopkinson Pressure Bar apparatus to assess the relation between the composition of the material and its shock wave attenuation capacity.

***Keywords*—**Blast, foam, microsphere, resin.

I. Introduction

THE increase in terrorist bomb attacks around the world has reached to an alarming state since many lives were lost. Due to explosion, and insufficient energy absorbing capabilities of civil building structures, many structures collapsed, with catastrophic consequences, such as loss of life and property.

One of the solutions is the enhancement of the performance of the structural materials, in particular concrete, when subjected to the blast load. Different solution is to use sacrificial cladding structures. A cladding structure typically consists of thin outer layer usually made of metal or laminate. The function of this layer is to distribute the blast pressure more equally across the second part of the structure – the core.

The core is responsible for absorption of the blast energy in a controlled manner and is able to reduce the effect of the explosion load onto the civil structure. In general, the cladding structure should be formed by an efficient energy absorber which is lightweight to ease the installation, and not to load the construction excessively.

The function of the impact energy absorber is to absorb kinetic energy and convert it to a different kind of energy, preferably irreversibly. This can be realized by plastic deformation, viscous energy, friction or crushing of brittle materials. Foams based on lightweight hollow particles and resins are materials with high potential of impact energy absorption. Blast attenuation is provided by breaking the bonding between the particles. Also the particles themselves can be crushed or transformed otherwise, thereby changing their state and absorbing energy.

Several studies were performed in order to understand the polymer matrix foam behaviour at high strain-rates, e.g. [1]-[4]. To the best of the authors' knowledge, all of the available studies have characterized foams containing up to 70 vol.% of the hollow particle filler. Presented investigation covers the foams containing up to 97.5 vol.% of the filler.

II. Experimental Investigation

A. Materials and Procedures

Mixtures of foams for experimental test were prepared by mechanical stirring of hollow microspheres with polymer matrix. Two different types of hollow microspheres were used as the filler – 3M Glass Bubbles K1 and AkzoNobel Expancel DE40d42. Both types of microspheres were chosen because of their different nature to study the expected differences in mechanical parameters and behaviour under high strain rate load. Properties of the microspheres are listed in Table I.

Polyurethane resin Leeson 3149/20 was used as the binder. The mixtures were prepared by stirring different volume fraction of resins (2.5 to 30%) with the microspheres. Two sets of the specimens were prepared; mix proportions are listed in Table II.

The cylindrical specimens (see Fig. 4) with diameter of 15 mm and length of 7 mm were prepared by shaping the material to the silicone mould.

Split Hopkinson pressure bar (SHPB) apparatus was used to evaluate the high strain rate characteristics of the specimens. A typical SHPB setup is outlined in Fig. 1.

M. Drdlová is with the Research Institute for Building Materials, Hnevkovskeho 65, Brno, 617 00 Czech Republic (corresponding author to provide phone: 00420-730- 519- 707; fax: 00420-543-216-029; e-mail: drdlova@vustah.cz).

M. Frank is with the Research Institute for Building Materials, Hnevkovskeho 65, Brno, 617 00 Czech Republic (e-mail: frank@vustah.cz).

J. Buchar is with the SVS FEM s.r.o., Skrochova 48, Brno, Czech Republic (e-mail: buchar@node.mendelu.cz).

J. Krátký is with the BOGGES, spol. s r.o., Rudice 1, Rudice, Czech Republic (e-mail: josef.kratky@bogges.cz).

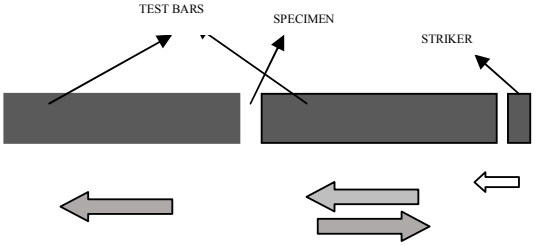

Fig. 1 The Split Hopkinson Pressure Bar Technique

SHPB is composed of long input and output bars with a short specimen placed between them. The impact of the projectile at the free end of the input bar develops a compressive longitudinal incident wave σ_I. Once this wave reaches the bar specimen interface, a part of it, σ_R, is reflected, whereas another part goes through the specimen and develops in the output bar the transmitted wave σ_T. Those three basic waves recorded by the gauges on the input and output bars allow for the measurement of forces and velocities at the two faces of the specimen. This measurement technique is based on the wave propagation theory and on the superposition principle. According to the wave propagation theory, the stress and the particle velocity associated with a single wave can be calculated from the associated strain measured by the strain gauges. Using the superposition principle in an elastic bar, the stress and the particle velocity in one section are calculated from the two waves propagating in opposite directions in this section. The view on the equipment is shown in Fig. 2.

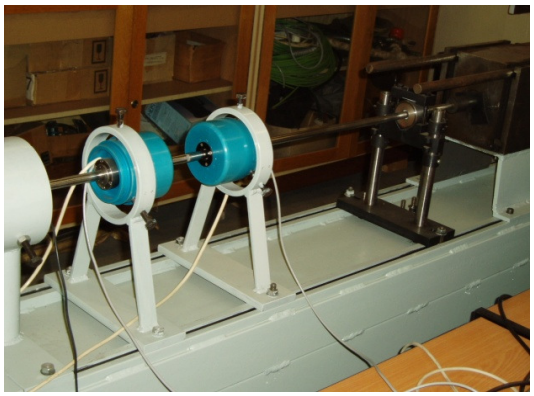

Fig. 2 The Split Hopkinson Pressure Bar

The loading stress pulse is characterized by the following parameters:

Maximum of the stress (amplitude):

$$\sigma_{\mathrm{Im}}$$

Impulse:

$$I_I = \int_0^{\pi_I} \sigma_I(t)dt \tag{1}$$

where π_I is the time of the stress pulse duration

Energy of the stress pulse:

$$w_I = \frac{1}{Z}\int_0^{\lambda_I} \sigma_I^2[t]dt \tag{2}$$

where Z is the acoustic impedance of the test bar.

In our experiment the incident bar is 1000 mm long and is made of Dural (Z =13.95 MPas/m). The length of the transmission bar is 1000 mm and it is made of PMMA (Z = 2.153 MPas/m).

These parameters are defined for the remaining stress pulses. The following symbols are used:

Amplitudes:

$$\sigma_{Rm}, \sigma_{Tm}$$

Impulses:

$$I_R, I_T$$

Energies:

$$w_R, w_T$$

It has been found that the capability of the specimen to attenuate of the stress pulse is described by the next dependences:

$$\sigma_{Tm} = f(\sigma_{\mathrm{Im}}) \tag{3}$$

$$\frac{I_T}{I_I} = f(\sigma_{\mathrm{Im}}) \tag{4}$$

$$w_s = f(\sigma_{\mathrm{Im}}) \tag{5}$$

where

$$w_s = w_I - w_R - w_T \tag{6}$$

is the energy absorbed by the specimen. Instead of the absolute value of this energy its dimensionless form is also used:

$$\eta = \frac{w_s}{w_I - w_R} \quad resp. \quad \frac{w_s}{w_I - w_R} x100 \quad (\%) \tag{7}$$

The course of the incident (σ_I), reflected (σ_R) and transmitted (σ_T) stress pulses were captured and the maximum peak values – amplitudes (σ_{Im}, σ_{Rm}, σ_{Tm}) were evaluated. The relative attenuation of the stress pulse connected with energy absorption potential of the material was subsequently calculated using equation:

$$\varsigma = (\sigma_{Im} - \sigma_{Rm} - \sigma_{Tm})/(\sigma_{Im} - \sigma_{Rm}) \tag{8}$$

The higher the value of relative attenuation, the higher the shock wave energy absorption potential of the material can be expected.

Scanning electron microscope (SEM) photomicrographs were used to confirm the homogeneity of the designed materials. The microstructure of the specimen G-PU20 is presented as an example in Fig. 3.

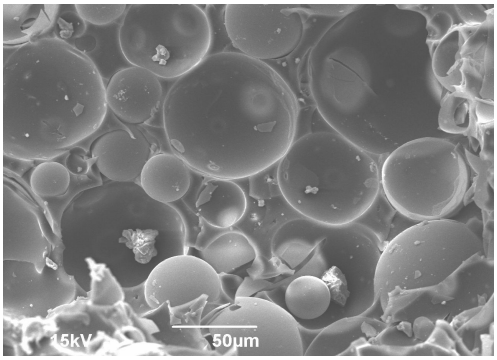

Fig. 3 General microstructure of designed materials

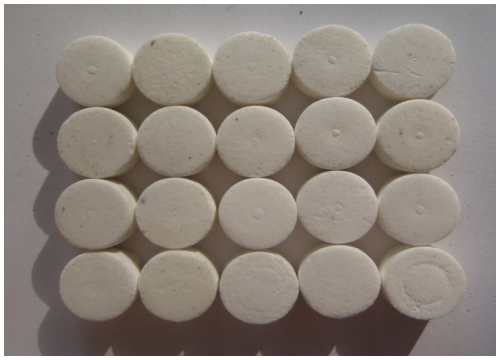

Fig. 4 Test specimens

TABLE I
PROPERTIES OF THE MICROSPHERES

Microsphere	Type	Colour	Density (kg.m^{-2})	Particle size (µm)
K1	*Glass*	white	125	50-100
DE40d42	Polymer	white	40	30-50

TABLE II
MIX PROPORTIONS

Specimen	Binder type	Microsphere type	Volume fraction of binder (%)
G-PU2.5	Polyurethane	Glass	2.5
G-PU10	Polyurethane	Glass	10
G-PU20	Polyurethane	Glass	20
G-PU30	Polyurethane	Glass	30
P-PU10	Polyurethane	Polymer	10
P-PU20	Polyurethane	Polymer	20
P-PU30	Polyurethane	Polymer	30

III. RESULTS AND DISCUSSION

Dynamic tests were performed at two different strain rates using the Split Hopkinson pressure bar apparatus adjusted (as described above) for successful testing of the designed material. The compressive pulse was generated by axial impact on the incident pressure bar by the striker bar at the velocity of 15 m.s^{-1} and 30 m.s^{-1} respectively, to assess the strain rate sensitivity of the specimens. The maximum values captured for incident, reflected and transmitted stress wave are summarized in Table III. The calculated relative attenuation of the stress wave presents Table IV. Fig. 5 depicts the dependence of the amplitude of the transmitted pulse on the amplitude of the incident pulse.

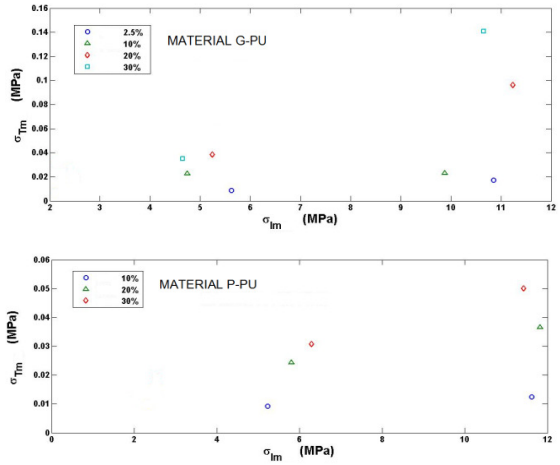

Fig. 5 Dependence of the transmitted pulse amplitude on incident pulse amplitude

The composition of the material influences the behaviour of the material under dynamic loading strongly. The amount of the filler, as well as the filler material, affects the relative attenuation and thus absorption potential when tested at the same strain rate. Specimens containing polymeric microspheres attenuated higher proportion of the stress wave compared to those with glass microspheres, this statement can be applied to both load velocities (see Table IV).

The relative attenuation of the stress wave increases by 4 to 84% (materials with glass microspheres) and 2 to 4% (in case of materials with polymeric microspheres) with increasing strain rate throughout the strain rate range investigated in this study.

Experimental results indicate that the material based on glass microspheres is more strain rate sensitive compared to the polymeric microsphere based one. The strain rate sensitivity of foams is connected to the properties of the filler material. The observed difference arises from the different nature and interfacial adhesion between filler and binder.

The phenolic polymer has the Young modulus of about 6,8 GPa whereas soda lime glass about 77 GPa. The difference in Young modulus and properties connected with it (resilience, toughness and reversible compressibility) is believed to be an important factor to the difference in the behaviour trends of both systems. Also the relationship between the material of the binder and the filler can influence the final properties [2]. It was found that the higher the Young modulus of the inclusion compared to the binder, the higher the stresses developed in the material. The particles–matrix compatibility significance theory was confirmed also by [5].

The higher amount of the filler the lower sensitivity to strain rate was observed in the case of the specimens with glass microspheres. This trend was not observed in case of specimens with polymer microspheres.

In general, with increasing amount of filler, the relative attenuation of the stress wave is increasing as well, which could be stated for both glass-resin and polymer-resin systems with steeper trend in case of first mentioned.

TABLE III
MAXIMUM OF THE INCIDENT σ_{IM} , REFLECTED σ_{RM} AND TRANSMITTED STRESS σ_{TM}

Specimen	Approximate velocity of the striker 15.0 m.s^{-1}			Approximate velocity of the striker 30.0 m.s^{-1}		
	σ_{Im} [MPa]	σ_{Rm} [MPa]	σ_{Tm} [MPa]	σ_{Im} [MPa]	σ_{Rm} [MPa]	σ_{Tm} [MPa]
G-PU2.5	5.61875	5.53900	0.008667	10.85000	10.4625	0.017333
G-PU10	4.74875	4.60000	0.022750	9.88125	9.68750	0.023021
G-PU20	5.42500	5.30100	0.055521	11.23750	10.6563	0.096146
G-PU30	4.65000	4.59000	0.035208	10.65625	10.0750	0.140833
P-PU10	5.23125	5.13438	0.009208	11.62500	11.4313	0.012458
P-PU20	5.81250	5.61875	0.024375	11.81875	11.4313	0.036563
P-PU30	6.29688	6.06790	0.030875	11.43125	10.9900	0.050104

TABLE IV
RELATIVE ATTENUATION OF THE STRESS WAVE

Specimen	Attenuation of the stress wave [%]	
	Approximate velocity of the striker 15.0 m.s^{-1}	Approximate velocity of the striker 30.0 m.s^{-1}
G-PU2.5	89.1	95.5
G-PU10	84.7	88.1
G-PU20	55.2	83.5
G-PU30	41.3	75.8
P-PU10	90.5	93.6
P-PU20	87.4	90.6
P-PU30	86.5	88.6

The overall damping characteristics of the designed materials are satisfactory; the relative attenuation reached the value of 95.5% (Specimen G-PU2.5), which predetermined this class of materials suitable for several shock wave absorbing applications.

IV. SUMMARY

This paper presents the results of the experimental works dealing with the behaviour of foams containing two different types of microspheres tested under high strain rate. The experimental characterization was performed by means of compression tests at two strain-rate levels using Split Hopkinson pressure bar apparatus.

The shock stress wave attenuation potential of designed materials was examined to assess the influence of the filler type and content on the material behaviour when subjected to dynamic load.

From the results presented in this paper can be concluded that for the dynamic response of designed materials the composition is of crucial importance. The systems with polymer filler showed higher attenuation potential and lower strain rate sensitivity compared to glass filler systems.

For both systems could be stated, that as the strain rate is increased, the relative attenuation increases throughout the strain rate range investigated in this study. More tests with different strain rates (both higher and lower) are planned to confirm the high strain rate sensitivity of the glass-resin systems.

This work demonstrates the usefulness of the designed absorbers as a core material in blast attenuation structures, which can be used as part of any structure and protective element.

ACKNOWLEDGMENT

The authors wish to express their gratitude and sincere appreciation to the authority of The Grant Agency of the Czech Republic, project No. GA13-22945S for financial support.

REFERENCES

[1] N. Gupta. and V. C. Shunmugasamy, *Mater. Sci. Eng. A*, vol. 528, pp. 7596–7605, 2011.
[2] N. Gupta. V. C. Shunmugasamy, Q. Nguyen and P. G. Coelho, *Mater. Sci. Eng. A*, vol. 527, pp. 6166–6177, 2010.
[3] P. H. Viot, K. Shankar and D. Bernard, *Compos. Struct.*, vol. 86, pp. 314–327, 2008.
[4] E. Woldesenbet, N. Gupta. and A. Jadhav, *Journal of Materials Science*, vol. 40, pp. 4009–4017, 2005.
[5] H. Guohe, Y. Demei, *Materials Science and Engineering,* vol. 528, pp. 5177-5183, 2011