World Academy of Science, Engineering and Technology
International Journal of Materials and Metallurgical Engineering
Vol:9, No:4, 2015

Advanced Energy Absorbers Used in Blast Resistant Systems

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Open Science Index, Materials and Metallurgical Engineering Vol:9, No:4, 2015 publications.waset.org/10001002.pdf

Abstract**—**The main aim of the presented experiments is to improve behaviour of sandwich structures under dynamic loading, such as crash or explosion. This paper describes experimental investigation on the response of new advanced materials to low and high velocity load. Blast wave energy absorbers were designed using two types of porous lightweight raw particle materials based on expanded glass and ceramics with dimensions of 0.5-1 mm, combined with polymeric binder. The effect of binder amount on the static and dynamic properties of designed materials was observed. Prism shaped specimens were prepared and loaded to obtain physico-mechanical parameters – bulk density, compressive and flexural strength under quasistatic load, the dynamic response was determined using Split Hopkinson Pressure bar apparatus. Numerical investigation of the material behaviour in sandwich structure was performed using implicit/explicit solver LS-Dyna. As the last step, the developed material was used as the interlayer of blast resistant litter bin, and it´s functionality was verified by real field blast tests.

Keywords**—**Blast energy absorber, SHPB, expanded glass, expanded ceramics.

I. INTRODUCTION

BLAST absorbing capabilities of structures and structural elements is insufficient. Bomb attacks are unfortunately the part of nowadays life and many lives are lost every year due to catastrophic consequences of the explosions. Especially the places with high concentration of people are threatened, such as subway, bus or railway stations, airports or shopping centres. Impact energy absorption materials represent a significant safety element for mitigating the consequences of a sudden impact loading.

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. Materials based on porous 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. The void structure creates optimal environment for blast wave decomposition which increases the damping characteristics of the material.

Several studies were performed in order to understand the polymer matrix porous materials behaviour at high velocity load, e.g. [1], [2]. To the best of the authors' knowledge, all of the available studies have characterized smaller filler particles with different properties.

II. EXPERIMENTAL INVESTIGATION

A. Materials and Procedures

Mixtures of materials for experimental tests were prepared by mechanical stirring of particles with polymeric binder. Two different types of particles were used as the filler –Expanded glass and Expanded ceramics. Properties of the particles are listed in Table I. Polyurethane resin Leeson 3149/20 was used as the binder. Different volume fraction of resins (8 to 14% by volume, with 2% step) was mixed with the filler. Two sets of specimens were manufactured; mix proportions are listed in Table II. To obtain the physico-mechanical properties, the prism specimens of dimensions 40x40x160 mm were prepared (see Fig. 2). The bulk density and flexural and compressive strength under quasi-static load was determined 72 hours after finishing the manufacture. The average values of at least 5 specimens of the same mixture are listed in Table III. The cylindrical specimens with diameter of 15 mm and length of 7 mm were prepared by shaping the material to the silicone mould. These specimens were subjected to the compressive high strain rate loading provided by Split Hopkinson pressure bar (SHPB) apparatus. 4 different strain rates were used to evaluate the dynamic response of the specimens. SHPB consists of two long slender bars. The short cylindrical specimen is placed between them. By striking the end of the incident bar, a compressive stress wave is generated that immediately starts traversing towards the specimen. Upon arrival at the specimen, the wave partially reflects back towards the impact end. The remainder of the wave transmits through the specimen and into the second bar with strain gauge sensors. By monitoring the strains in the two bars, the energy absorbed by the specimen can be calculated. The detailed description of the device, measurement technique and calculation of the absorbed energy was given in previous study [3]. The view on the equipment is shown in Fig. 1. At least three specimens were tested for each strain rate, allowing evaluation of the test reproducibility. The average values of calculated absorbed energy are summarized in Table III.

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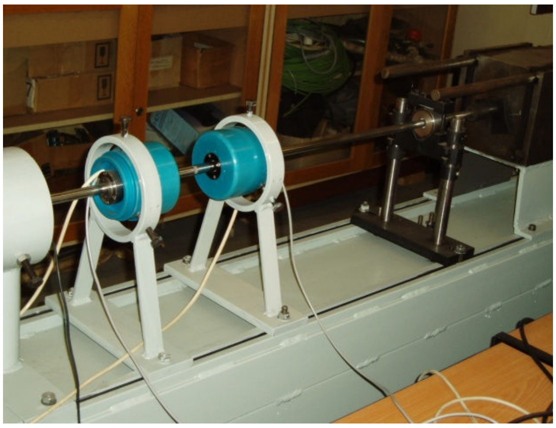

Fig. 1 Split Hopkinson Pressure Bar

Numerical investigation of the material behaviour in sandwich structure and in the next step in the real element was performed using implicit/explicit solver LS-Dyna. LS-DYNA offers a variety of material models, each with capabilities designed to capture the unique behaviour of a different types of porous materials. Material Type 63 [4] – which is dedicated to modeling crushable foam with optional damping and tension cutoff was selected for numerical investigation of the designed materials. Tension is treated as elastic perfectly-plastic at the tension cut-off value. This material model requires the input of six parameters: density of material, modulus of elasticity, Poisson's ratio, stress strain curve, tensile stress cutoff, and damping coefficient. The first four parameters were found experimentally. However, tensile cutoff and viscous damping coefficient were obtained from the literature [5].

Fig. 2 Test specimens of absorption materials

As the last step, the developed material was used as the middle absorbing layer of blast resistant litter bin, and it´s functionality was verified by real field blast tests. The blast tests were run according to the certified methodology M-VTÚO 11/11. This methodology is intended for the verification of blast resistance of real elements. The test object is placed on a 25 mm concrete block. Around at least half of the perimeter (180 degrees) of the test sample check panels are placed on the compacted sand ground and fixed with clinches, opposite to the expected weakest point, at a distance of 1500 mm from the axis of the test object. The test layout is depicted in Fig. 8. A check panel consists of a steel frame with the dimensions of 1x2 m, holding a hardboard-polystyrene-aluminium plate sandwich. Spheres of Semtex C4 plastic explosive weighting 1540 g, which is equivalent of 2000 g TNT, were used as a testing charge. Observed and evaluated parameters were the integrity of the tested object, its displacement, formation of secondary fragments and condition of the check panels. To assess the test result as satisfactory, the displacement of the sample must not exceed 1 m with preservation of the integrity of the object, and the check panels must not be penetrated by secondary fragments.

III. RESULTS AND DISCUSSION

The results of measuring physico-mechanical properties of materials with different amount of the binder show that both flexural and compressive strength increase with decreasing amount of filler with steeper trend and higher absolute values in the case of materials with ceramic particle filler. The higher strength of expanded-ceramics based material can be explained by better bonding between filler and binder caused by higher absorptivity of the ceramics particles and also by their higher initial strength. 8 and 14 vol. % of binder were the limit values to obtain material with suitable properties from technological point of view – less binder caused insufficient coherence of the specimens, the binder dosage higher than 14 vol. % led to creation of inhomogeneity in specimen cross-section due to flowing down of the binder to the bottom of the mould.

Dynamic tests were performed at four different strain rates using the Split Hopkinson pressure bar apparatus adjusted for successful testing of the designed material [3]. The compressive pulse was generated by axial impact on the incident pressure bar by the striker bar at the velocity of 26, 22, 14 and 7 m.s^{-1},to assess the strain rate sensitivity of the specimens. The course of the incident (σ_I), reflected (σ_R) and transmitted (σ_T) stress pulses were captured and relative energy absorbed by the specimens was calculated according to the methodology described in previous study [3]. The obtained values are shown in Table III. The composition of the material influences the behaviour of the material under dynamic loading. Both sets of materials showed good attenuating properties, slightly better results were achieved in case of ceramic based specimens. 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. In general, with increasing amount of binder the relative absorbed energy decreases. The specimens with lower amount of binder contain more voids - which in connection with a lot of interfaces creates good environment for decomposition of the blast wave and thus good absorbing potential. Both sets of materials showed strain rate sensitivity - the relative absorbed energy increases with increasing strain rate throughout the strain rate range investigated in this study.

TABLE I
PROPERTIES OF THE FILLER

Particle	Colour	Bulk density (kg.m^{-3})	Density (kg.m^{-3})	Particle size (mm)
Expanded glass	grey	250	450	0.5-1
Expanded ceramics	brown	575	850	0.5-1

Two selected materials (G10 and C10) were subjected to the numerical investigation as a part of the sandwich structure consisting of 40 mm layer of designed materials placed between two 4 mm steel plates. The sandwich was supported around the whole perimeter and loaded by the shockwave from the explosion of 100 g TNT at a distance of 100 mm from the front side centre of the sandwich. Both materials were described with model Crushable foam. This material model is based on dependency curve stress versus volumetric strain.

TABLE II
COMPOSITION OF THE MIXTURES

Specimen	Filler type	Volume fraction of binder (%)
G8	Glass	8
G10	Glass	10
G12	Glass	12
G14	Glass	14
C8	Ceramics	8
C10	Ceramics	10
C12	Ceramics	12
C14	Ceramics	14

TABLE III
CALCULATED RELATIVE ABSORBED ENERGY

Specimen	Relative absorbed energy (%)			
	Striker velocity 7 m.s^{-1}	Striker velocity 14 m.s^{-1}	Striker velocity 22 m.s^{-1}	Striker velocity 26 m.s^{-1}
G8	81.1	83.0	83.7	86.1
G10	80.1	82.7	83.2	85.0
G12	75.1	80.1	79.4	80.1
G14	70.1	79.1	76.1	75.6
C8	84.2	86.3	92.3	91.9
C10	83.1	86.3	92.1	92.8
C12	80.2	82.1	86.7	89.0
C14	76.6	79.2	81.3	82.4

Those curves were obtained from a static testing of real specimens. The model was finely meshed to obtain accurate results. Acceleration (see Figs. 3, 4) and a dynamic deflection (see Fig. 5) on the back steel plate were observed during simulations. A significant decreasing in acceleration value was observed in case of variants with implemented absorption materials. Similarly the dynamic deflection of the back steel plate decreased from 18.3 mm in variant with air gap to 13.5 mm in variant with ceramic-based absorption material. It is about 26.2% reduction (20.8% reduction with the second glass based absorption material).

Results obtained from the numerical investigation indicate that the material based on ceramics is more effective than the glass based one, which corresponds well with the obtained results of energy absorption values.

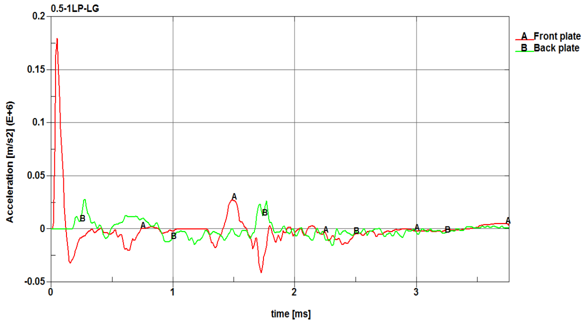

Fig. 3 Aceleration of front and back steel plates of sandwich with material based on ceramics

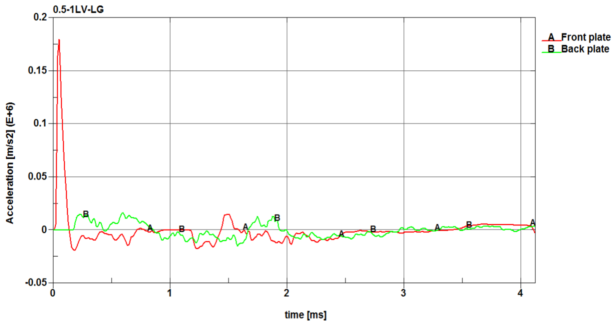

Fig. 4 Acceleration of front and back steel plates of sandwich with material based on glass

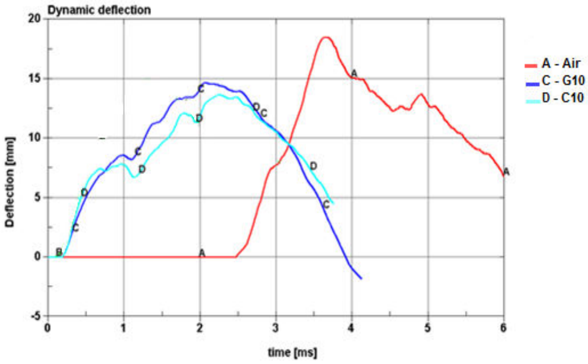

Fig. 5 Dynamic deflection of the back steel plate of the sandwich

The numerical simulations of real element (blast resistant litter bin) with the layer of material based on ceramics were conducted to verify the effect of the designed absorber on the element blast resistance. Fig. 6 shows the difference between designed litter bin without and with the absorbing layer. Wheras the vessel without the inner absorbing layer failed and cracks were created, in the case of element with the layer of the designed absorbing material only the deformation of the outer layer occurred without any rupture and fragmentation.

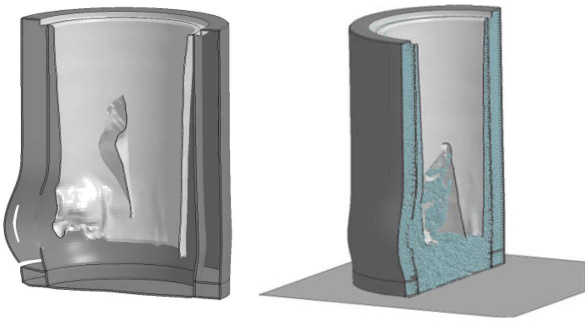

Fig. 6 Litter bin without and with the absorbing layer after simulated blast test

Real blast tests were conducted according to the methodology described above. Test layout is depicted in Fig. 7. The overall litter bin integrity was preserved, only the deformation of both inner and outer layer was observed. No secondary fragments were created (see Fig. 8), the check panels remained clear without any penetration. Real blast tests of manufactured litter bin confirmed the numerical analysis.

Fig. 7 Blast test layout

Fig. 8 Litter bin after real blast test

IV. SUMMARY

This paper presents the results of the experimental works dealing with the static and dynamic response of advanced blast in energy absorbers. Two types of filler (based on expanded glass and ceramics) in combination with four dosages of binder were investigated to obtain the values of compressive and flexural strength under quasi-static load, bulk density and relative absorbed energy at four strain rates.

The aim of conducted research was to determine the influence of the filler type and content on the material behaviour when subjected to load, both quasistatic and dynamic, and to assess the strain rate sensitivity in connection with material composition. The effect of the advanced absorption materials was verified by numerical simulations and blast tests on real element – blast resistant litter bin.

Following conclusions can be formulated from presented research:

- The amount of filler does not influence the strain rate sensitivity in the investigated range of filler amount.
- The amount of the binder affects the absorbing capacity of the material significantly. The higher the binder dosage, the lower the relative absorbed energy. The materials with lower amount of binder provide the structure with higher voids ratio and size, which creates good environment for blast wave decomposition.
- 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.
- Good agreement was concluded between the results of the blast experiments and simulations. Numerical simulation is an excellent tool to reduce the costs connected with the development of blast resistance materials and products, as it can lower the amount of the very expensive field blast tests.
- Adjusted material model Crushable foam can be successfully used for numerical simulations of presented types of the materials.

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.

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