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# Evaluation of Static and Dynamic Properties of Energy Absorbers for Explosion Resistant Elements

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**Abstract:**

*This paper describes experimental investigation on the response of new advanced materials to low and high velocity load. The main aim of the experiments is to improve the behaviour of sandwich structures under dynamic loading, in particular explosion. Two types of porous raw particle materials based on expanded glass and ceramics in combination with polymeric binder were used to design a new type of blast wave energy absorber. The effect of binder amount and type of filler on the static and dynamic properties of designed materials was evaluated. Bulk density, compressive and flexural strength under quasi-static load were determined on prism specimens. Izod impact strength characteristics were evaluated as well. Numerical simulations were conducted to determine the dynamic response of the material in sandwich structure, using implicit/explicit solver LS-Dyna. As the last step, the developed material was used as the interlayer of blast resistant litter bin, and its functionality was verified by real field blast tests.*

**Keywords:**

*blast energy absorber, expanded glass, expanded ceramics, numerical simulation, blast test*

## 1. Introduction

Bomb attacks are unfortunately a 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 such an impact loading.

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The function of the impact energy absorber is to absorb kinetic energy and to convert it to a different kind of energy, preferably irreversibly. This can be realized by plastic deformation, friction or crushing of brittle materials. Materials based on porous particles and resins are materials with high potential of impact energy absorption, as their void content is high. 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, densifying and absorbing energy. Those energy dissipation processes is expected considerably more significant to other wave effects as acoustic power loss or energy loss in the absorber fill and absorber case interface. 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 (typically micron sized) particles with different properties.

## 2. Materials and Procedures

Mixtures of materials for experimental tests were prepared by stirring filler particles with polymeric binder in laboratory mixer. Two different types of particles were used as the filler – expanded glass and expanded ceramics. Properties of the particles are listed in Tab. 1. Epoxy resin was used as the binder. Different volume fraction of resin (8 to 14% by volume, with 2% step) was mixed with the filler. Two sets of specimens were manufactured, mix proportions are listed in Tab. 2.

*Tab. 1 Properties of the filler*

| Particle | Colour | Bulk density [kg m$^{-3}$] | Density [kg m$^{-3}$] | Particle size [mm] |
|---|---|---|---|---|
| Exp. glass | grey | 250 | 450 | 0.5÷1 |
| Exp.ceramics | brown | 575 | 850 | 0.5÷1 |

*Tab. 2 Composition of the mixture*

| 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 |

To obtain the physical and mechanical properties under quasi-static load, the prism specimens of the dimensions of $40 \times 40 \times 160$ mm were prepared. 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 Tab. 3.

*Tab. 3 Quasi-static and dynamic properties of the specimens*

| Specimen | Bulk density [kg $m^{-3}$] | Compressive strength [MPa] | Flexural strength [MPa] | Impact strength [kJ $m^{-2}$] |
|---|---|---|---|---|
| G8 | 331 | 2.3 | 1.1 | 1.3 |
| G10 | 343 | 3.3 | 1.4 | 1.5 |
| G12 | 355 | 4.6 | 1.3 | 1.5 |
| G14 | 362 | 4.6 | 2.2 | 1.9 |
| C8 | 731 | 6.3 | 3.6 | 1.3 |
| C10 | 752 | 7.6 | 4.1 | 1.6 |
| C12 | 760 | 9.7 | 4.9 | 2.1 |
| C14 | 791 | 10.4 | 6.7 | 2.9 |

Quasi-static compressive deformation curves of materials were recorded from the gradable pressure loading vs. specimen compression relationship, with 5mm/min loading velocity.

The prism specimens with the dimensions of $40 \times 20 \times 100$ mm were prepared by shaping the material to the steel mould, the Izod test according to the ČSN EN ISO 180 was performed to determine the impact strength of designed materials and to evaluate the dynamic response of the specimens. A pendulum swings on its track and strikes a cantilevered specimen. The energy lost (required to break the sample) as the pendulum continues on its path is measured from the distance of its follow through. The result of the Izod test is reported in energy lost per unit of specimen cross-sectional area. The average values of five specimens are summarized in Tab. 3.

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. The numerical material model was based on the quasi-static compressive test of the sample in closed space. This measurement was realized on the prism specimen with diameter and length ratio equals three. An illustrative stress versus volumetric strain curve built on the measurement of material based on ceramic particles is shown in Fig. 1.

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 modelling crushable foam with optional damping and tension cut-off – was selected for numerical investigation of the designed materials.

Tension is treated as elastic-perfectly-plastic at the tension cut-off value. The volumetric strain is defined in terms of the relative volume. The relative volume is defined as the ratio of the current to the initial volume. This material model requires the input of six parameters: density of material, modulus of elasticity, Poisson’s ratio, stress strain curve, tensile stress cut-off, and damping coefficient. The first four parameters were found experimentally. However, tensile cut-off and viscous damping coefficient were obtained from the literature [5]. Materials C10 and G10 were selected for numerical analysis.

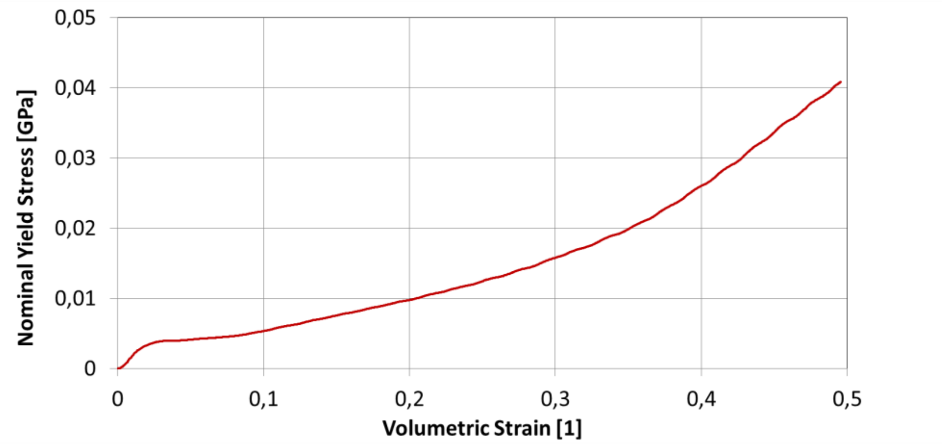


*Fig. 1 Quasi-static compressive deformation curve of analysed material*

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 (in our case the litter bin) is placed on a 25 mm concrete block. Around at least half of the perimeter (180 degrees) of the test object 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. Check panels serve for evaluation of test results, as they capture all potential secondary fragments created by test object. The test layout is depicted in Fig. 7. A check panel consists of a steel frame with the dimensions of $1 \times 2$ m, holding a hardboard-polystyrene-aluminium plate sandwich. Spheres of C4 plastic explosive weighting 1540 g, which is equivalent of 2000 g TNT, were used as a testing charge. This specific explosive was selected to follow the methodology M-VTÚO 11/11, which defines C4 as the test charge. The charge was detonated in the middle of the inner space of the tested vessel. 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.

## 3. Results and Discussion

### *3.1. Physical and Mechanical Properties*

The results of measuring physical and mechanical properties of materials with different amount of the binder are summarized in Tab. 3. The flexural, compressive and impact strength increase with the decreasing amount of filler with a 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 – a smaller binder caused insufficient coherence of the specimens, the binder dosage higher than 14 vol. % led to the creation of inhomogeneity in specimen cross-section due to flowing down of the binder to the bottom of the mould.

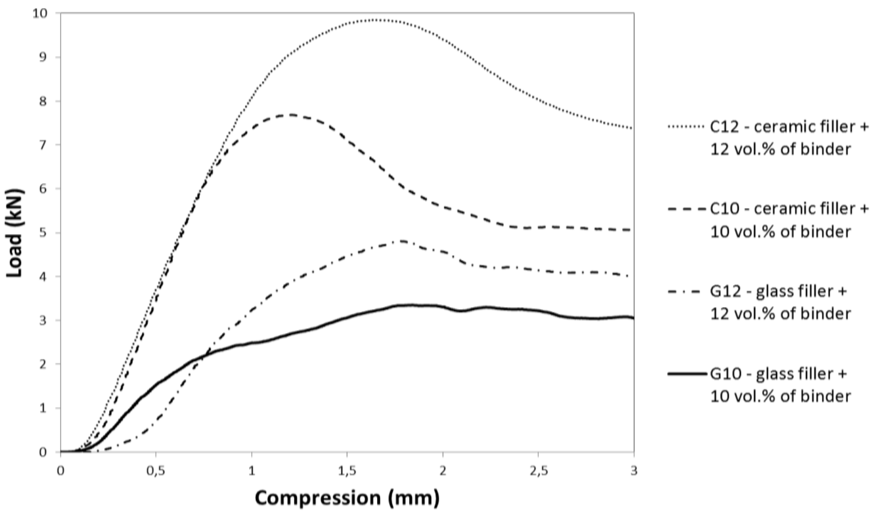


*Fig. 2 Deformation curves of materials with different filler type and binder amount*

The difference between the ceramic filler and the expanded glass filler compressive deformation curves is illustrated in Fig. 2. The deformation curves of the same filler but different binder amount show similarity except for the divergence between the maximum compression values. According to the results, the increase of energy absorption ability can be expected with increasing amount of the binder (when loaded in quasi-static mode). The manner of fracture can also be inferred from the deformation curves – the specimens with ceramic filler show sharper peak load, whereas the glass filler based specimens exhibit blurry peak load and oscillating character of the curve, which indicates gradual failure mode.

### *3.2. Numerical Investigation*

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 thick 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 the dependency curve stress versus volumetric strain. Those curves were obtained from previous quasi-static testing in closed space (see Fig. 1). The model was finely meshed to obtain accurate results.

FE model was built on the actual 3D geometry with the real thicknesses of the individual layers of materials. The interaction between parts was modeled using contact algorithm. Mechanical properties of the individual layers of materials were described by constitutive relations including Strength model, Equation of state (EOS) and Failure model as materials can only sustain limited amount of stress / deformation before they break / crack / cavitate (fluids).

Detonation of explosion and propagation of pressure waves into surrounding environment (Air) was simulated using Euler mesh. The energy absorbed in air was included in simulations. Interaction between blast wave and multi-layer armour was modelled by coupling mechanism for modelling fluid-structure interaction.

Acceleration (see Figs. 3, 4 and 5) and a dynamic deflection (see Fig. 6) on the back steel plate were observed during simulations. A significant decrease in acceleration peak value was observed in case of variants with implemented absorption materials compared to the sandwich without absorber.

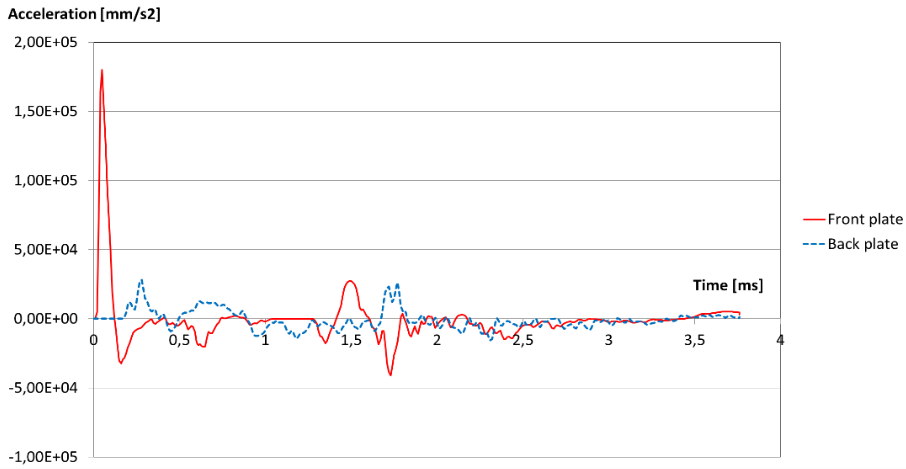


*Fig. 3 Acceleration of front and back steel plates of sandwich with material based on ceramics*

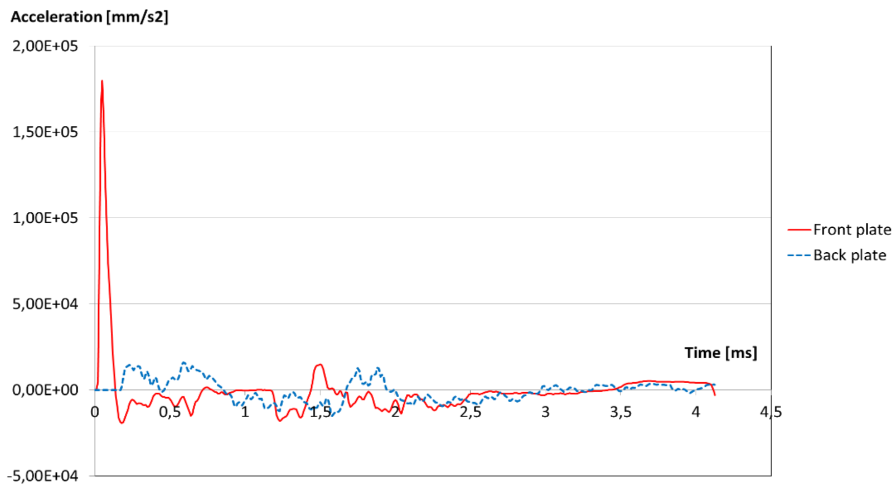


*Fig. 4 Acceleration of front and back steel plates of sandwich with material based on glass*

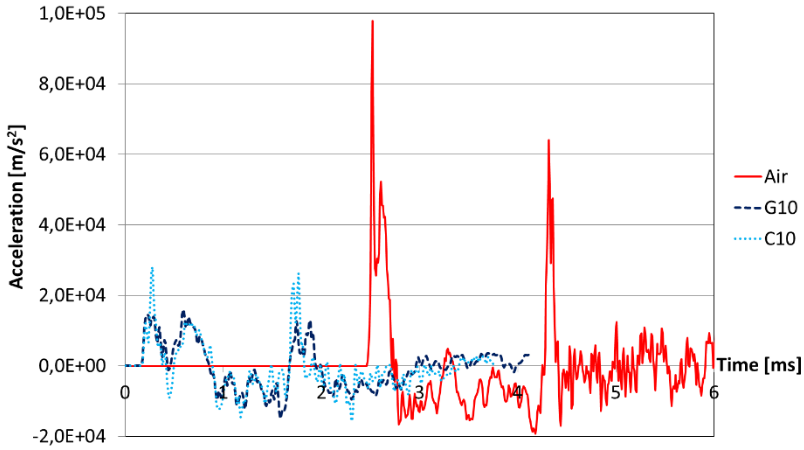


*Fig. 5 Acceleration of back steel plates: comparison of sandwiches with and without absorbers*

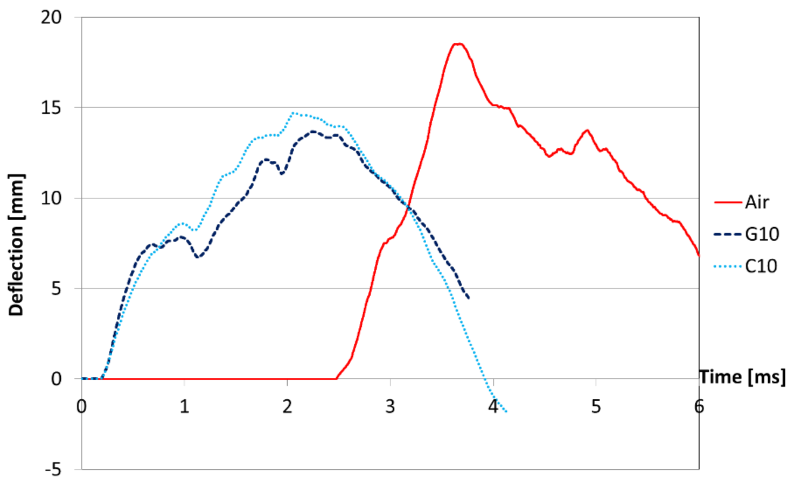


*Fig. 6 Dynamic deflection of the back steel plate of the sandwich*

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, which is about 26.2% reduction. 20.8% reduction was achieved in case of glass-based absorption material.

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. Whereas 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.

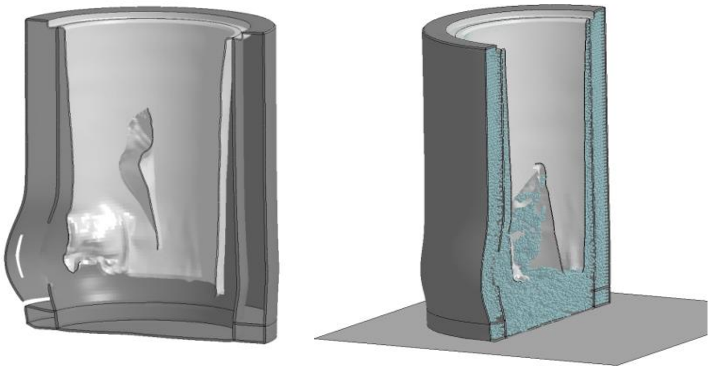

*Fig. 6 Litter bin without and with the absorbing layer after simulated blast test*

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. 7 right), the check panels remained clear without any penetration. Real blast tests of manufactured litter bin confirmed the numerical analysis results.

*Fig. 7 Blast test layout (left) and element after the blast test (right)*

## 4. Summary

This paper presents the results of the experimental works dealing with the static and dynamic response of advanced blast energy absorbers. Main advantage of this sort of materials is (except for easy manufacturing technology and inflammability) their easy shaping to complicated spaces. Simply mixed, they can be compacted directly to the construction interspaces. 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 impact strength. 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 quasi-static and dynamic. The effect of the advanced absorption materials was verified by numerical simulations and blast tests conducted on real element – blast resistant litter bin.

Following conclusions can be formulated from the presented research:

- The values of all monitored mechanical parameters rise with increasing binder: filler ratio. This fact could be stated for both ceramics and glass filler systems with steeper trend and higher absolute values in the former.
- The amount of the binder affects the absorbing capacity at quasi-static load expressed as the area under the compressive deformation curves. The higher the binder dosage, the higher the relative absorbed energy at quasi-static load. The glass based absorbers exhibit lower potential of energy absorption.
- Higher initial strength of the filler brings better mechanical properties of final composite at both quasi-static and impact load.
- The numerical simulation was focused on comparison of dynamic response of absorbers with different filler particles. The dynamic deflection of blast impacted sandwich structure was determined. The sandwich with ceramic based absorber overcame the glass based one: 26.2% reduction of the dynamic deflection was achieved compared to the sandwich without absorber layer, whereas only 20.8% reduction was achieved in the case of sandwich with inner layer created by glass based material. Higher initial strength of the filler material and better bonding strength brings better absorbing capacity. In both cases, the reached value of the deflection reduction is high, which predetermined this class of materials suitable for several shock wave absorbing applications.
- 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 the presented types of 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.

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