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Shock Wave Structure in Particulate Composites

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Abstract

An experimental study of shock wave profiles in particulate composites of various compositions is undertaken to determine how shock width and rise times depend on the mean particulate size. The composites under examination serve as a model for concrete or polymer bonded explosives, based upon the impedance mismatch between the relatively stiff particulates and compliant matrix. Polymethyl Methacrylate (PMMA) and glass spheres ranging in size from 100μm to 1000μm are used in concentrations of 30% and 40% glass by volume for experiments with a single bead size, and up to 50% glass by volume for multi-mode particle size distributions. A linear change in shock wave rise time is observed as a function of mean particulate diameter.

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Keywords: Shock wave, Particulate composite, Impact

Nomenclature

C	Material bulk wave speed [km/s]
H	Target plate thickness [mm]
T_g	Glass transition temperature [ºC]
u_p	Particle velocity [km/s]
U_s	Shock speed [km/s]
VFG	Volume Fraction of Glass
Z	Shock impedance [GPa/km/s]
Greek symbols	
ρ	Density [g/cm^3]
τ	Shock wave rise time [ns]

1. Introduction

The aim of this study is to quantify the effects of particulate size and density on the development of shock wave structure in particulate composites. Particulate composites are of general interest due to the fact that the material microstructure is similar across a wide range of engineering materials, such as high strength concrete and polymer bonded explosives (PBX).

This subset of materials is characterized by high modulus and density particulates embedded in a relatively soft matrix. Concretes and PBX have extremely complicated microstructures in terms of particle size, shape, and placement. The microstructural properties of concrete and PBX determine their shock behavior – the shock speed, shock profile, and dissipation of shock energy. Shock response in these materials is critical to armor integrity and explosive stability and sensitivity. By controlling the amount of energy reflected at interfaces and the dominant length scale in the composite, the particle acceleration (as determined by the time it takes to go from a quiescent pre-

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stress state to a maximum pressure state) may be controlled. The length scale of interest in this study is the mean particle diameter.

In order to isolate the effects of particle size, a model particulate composite is designed and used to simplify the composite geometry and fabrication process. The similarity parameter chosen as the design constraint is known as the shock impedance ratio. Shock impedance, Z, is defined as the product of the bulk wave speed in a material multiplied by its density.

$$Z_i = \rho_i C_i \tag{1}$$

The impedance ratio is then the shock impedance of the inclusions divided by the shock impedance of the matrix. For the materials of interest, the impedance ratio range is 2-10 [1, 2]. A model material with an impedance mismatch within that range may be made in a compression molding process with Polymethyl Methacrylate (PMMA) and glass spheres of various sizes. The geometrical and interface constraints of the PMMA and glass model composite can be finely tuned and adjusted to explore a variety of experimental problems. Choosing spherical glass beads fixes the dominant length scale to the diameter of the beads used in the composite fabrication. Experiments are performed with bead diameters starting near the width of a shock wave in pure PMMA, and increasing by an order of magnitude. Glass beads are obtained in bulk, and manually sieved to a narrow range using wire mesh screens. Size distribution across the range is approximately uniform. Wire mesh screens were sourced from an industrial supply company (Grainger, Los Angeles, CA). Table 1 includes the as sieved bead size specifications.

Table 1. Silica glass bead sizes

Nominal Bead Size [μm]	Average Size [μm]	Minimum Size [μm]	Maximum Size [μm]
100	110	104	116
300	294	281	307
500	522	503	541
700	693	681	704
1000	1006	980	1031

1.1. Sample Preparation

The model material must meet several requirements in order for it to be used as a model for concrete and PBX. Two options that were considered to make particulate composites with rigid inclusions are casting and molding. PMMA is available in monomer (MMA) form for casting as well as powders for compression molding. PMMA may also be heat treated to relieve or take advantage of residual stress introduced in the molding process to control interface properties. Composites can be made with strong, perfect transparent interfaces or thermally shocked to produce weaker interfaces. This
study focuses on strong interfaces, which are more straightforward to simulate. The PMMA powder and glass bead composites contain a random distribution of beads with no evidence of settling or clumping. An even, random distribution mimics the common composites of interest to this study, and is also readily comparable to simulations on geometries with randomly generated particulate location distributions.

A polymer powder of 75,000 MW (Polysciences, Warrington PA, P/N 04553) with a glass transition temperature, T_g, of 105°C is used as the matrix for the particulate composites in this study. Due to the discrepancy in molecular weight this material must be characterized in order to verify that existing PMMA simulation parameters can be used. Measured density of the molded and heat treated polymer is 1.1804 ± .001 g/cm^3 which is identical to values found in the literature for molding grade PMMA, and .01 g/cm^3, or less than 1% less than the density of cast acrylic sheet [3]. A bulk longitudinal wave speed of 2.680 ± .01 km/s was measured using ultrasonic piezo transducers. Standard values for silica glass include a density of 2.203 g/cm^3 and a bulk longitudinal wave speed of 5.93 km/s [4]. The above parameters yield an impedance mismatch for the model composite of 4.13, within the range of interest.

Next, the quality of the interface between the phases must be able to be controlled. For simplicity in initial tests and simulations, a perfect “welded” bond between the composite phases is assumed. The welded phases assumption negates the need for estimates on the friction coefficient at the interface, as well as the fraction of the interface area that is not well bonded. Typically, when one looks at concrete or PBX, an even distribution of particulates is noted.

Settling of aggregate in concretes is generally considered to be detrimental to its compressive strength and longevity in the field. The manufacturing process capable of guaranteeing the above conditions is compression molding. The 200 μm diameter PMMA granules support the various sized glass beads when mixed, and the plastic remains sufficiently viscous and confined when at temperatures above its glass transition temperature to prevent settling. An example is presented in Figure 1.

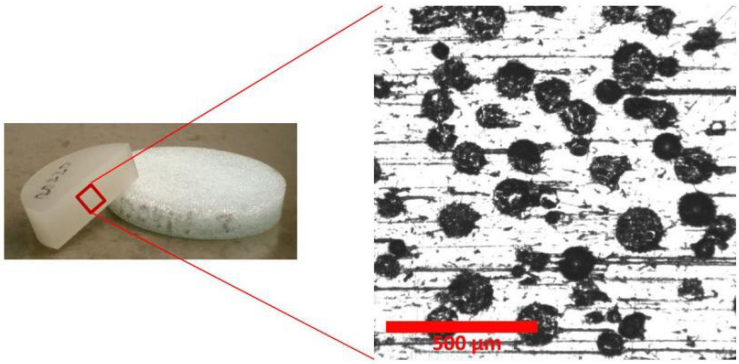


Fig. 1. Section view of PMMA / Glass bead model composite showing even bead distribution and minimal porosity

After undergoing the molding process, the composites are subjected to a two phase heat treating process. Samples are removed from the molding press and held at 150ºC for 12 hours in the mold before slowly cooling to relieve axial stress. After cooling, they are removed from the mold, and returned to a 150ºC oven for another 12 hours to relieve the residual radial stresses. This heat treating process ensures that the bond between the matrix and inclusions is maintained. Sample composites are then lapped, polished, coated with a 500 nm thick aluminum reflective layer for use with a heterodyne velocity interferometer (PDV).

1.2. Experimental Design

Experiments were performed on the 36mm bore propellant gun located at the California Institute of Technology. 6061 aluminum flyer plates 34 mm in diameter and 7 mm thick were launched at a nominal speed of u_{p0} = 1 km/s at 30 mm diameter PMMA / glass bead composite samples, as shown in Figure 2. Target thickness is nominally h = 7 mm to ensure that the shock wave structure has fully developed by its time of arrival on the rear surface of the target plate.

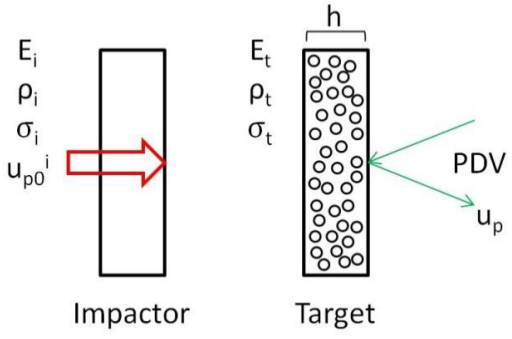


Fig. 2. Planar plate impact experimental set up

Time of arrival of the flyer plate and tilt is measured with shorting pins. An optical PDV probe tracks the flyer plate as it travels down the barrel to measure impact velocity. A modified multi-channel heterodyne velocimeter [5] is used to acquire velocity profiles at multiple points on the rear surface of the target plate. A downshifted reference laser is employed to improve time resolution at low particle velocities (10-100 m/s). Multiple points allow for statistical analysis of shock wave profile and an evaluation of the degree of spatial shock disruption.

Composites with single mode bead distributions are investigated in glass volume fractions of 30% VFG and 40% VFG. Higher volume fractions require that some of the included beads be of a different size to enhance mixing and prevent clumping. As such, composites with a bi-modal bead size distribution have been fabricated for further analysis. Rise times for each impact experiment as well as the measured shock speed are presented.

2. Experimental Results

2.1. Single Mode Bead Size Distribution Experiments

In order to quantify the degree of shock front disruption and spatial heterogeneity introduced by a random particulate composite, targets with 30% and 40% glass by volume were subjected to 1 km/s planar plate impacts with 6061-T6 aluminum flyer plates. Beads of each nominal size were molded into composites and tested separately. For a baseline, glass free heat treated PMMA targets were shot and compared to 2D CTH simulations of equivalent geometry. The measured shock speed, and free surface particle velocity were not sufficiently different from the literature [3] to update any CTH model parameters – the default Mie-Gruneisen parameters were used.

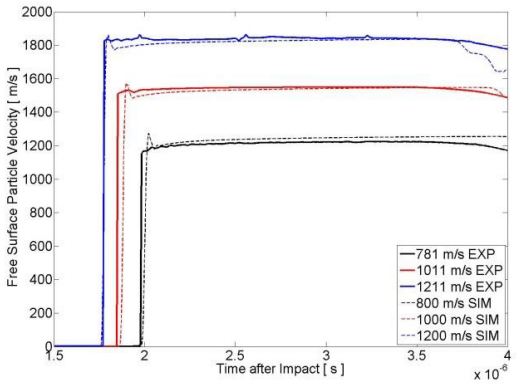


Fig. 3. PMMA validation experiments

A 10 ns 10%-90% rise time is observed in the 1000 m/s impact experiment (Red trace) shown in Figure 3. With the measured shock wave speed and a steady wave assumption, the shock width can be calculated to be approximately 40 µm. A difference in length scale of this fundamental length and the bead diameter are required in order for wave profile modification. Addition of particulates enhances scattering and dispersion, resulting in increased shock front thickness and wave profile modification. Wave profiles for the case of 40 % glass by volume are presented below for the 100µm, 500µm, and 1000µm average bead diameters.

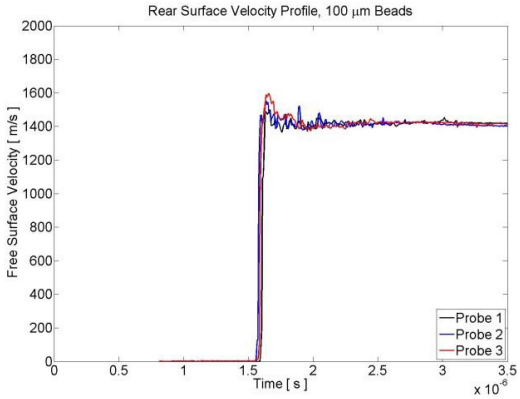
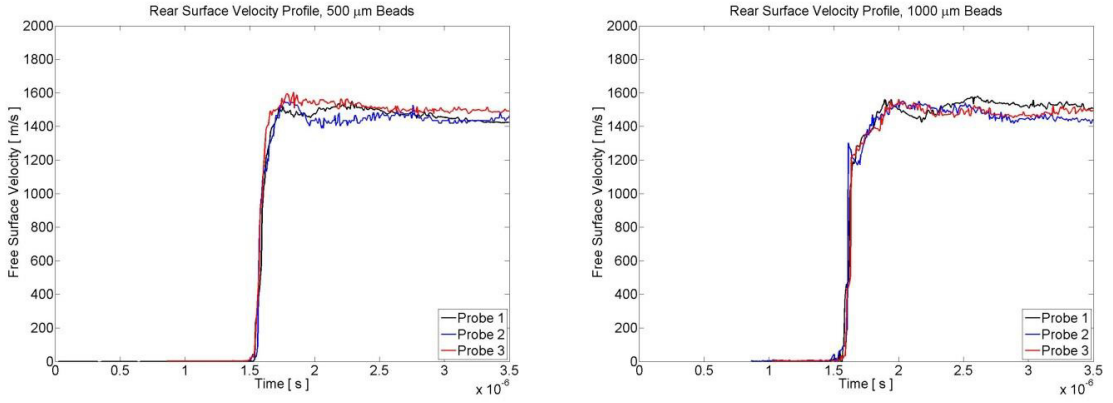


Fig. 4. Rear surface particle velocity history, 40% glass by volume 100µm beads

It is clear in Figures 4 and 5 that the shock width (as measured by the observed rise time and shock speed) increases with increasing particle size. As particulate size increases, the sharp square waveform is less visible as rounding of the waveform at the edges of the shock transition region becomes more pronounced. Further, the slope of the particle velocity trace decreases with increasing particulate size. While the final particle velocity level remains approximately constant, the material experiences less particle acceleration to get to that level.

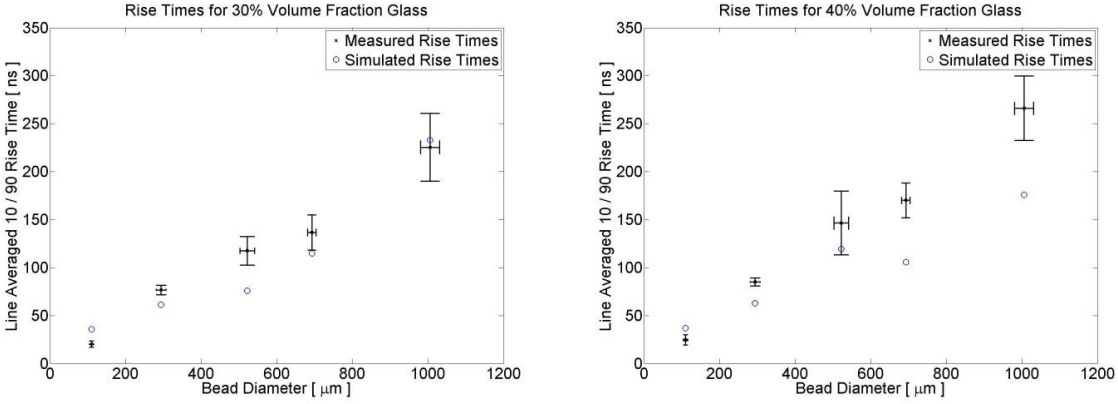
The observed shock speeds remain nearly constant for all bead sizes in each volume fraction range. The observed shock rise times are tabulated in Figure 6 for both the 30% glass and 40% glass by volume composites. CTH hydrocode simulations results are also presented. A linear increase of shock rise time is observed as the separation between the scale of the shock width in pure PMMA and the mean bead diameter grows. Scattering is also increased



(a) (b)

Fig. 5. Rear surface particle velocity history, 40% glass by volume a) 500μm beads b) 1000μm beads

by the number of interfaces present, as the rise times increase more rapidly for the higher volume fraction case. The 30% glass by volume experiments show more jagged rises, and sharp jumps early in the record (similar to Probe 2 in Figure 5b). The presence of more interfaces reduces the likelihood of a sharp pulse originating near the impact plane reaching the rear surface of the target plate. Shock widths are increased when more glass beads are present over the entire bead diameter range.



(a) (b)

Fig. 6. Shock 10%-90% rise time for a) 30% glass by volume b) 40% glass by volume as a function of mean bead diameter for 7.1mm thick composites

Larger spreads on rise time were observed for composites with a lower volume fraction of glass than for higher volume fractions. The reduced number of interfaces and greater mean distance between particulates contribute to a less evenly disrupted shock front. In lower volume fraction composites, relatively large regions of PMMA allow for the disrupted front to shock up again. This behavior results in regions with large rise times and regions with

relatively short rise times on the same sample. Sufficient interface density is required for optimal shock front disruption and ensuring that all regions of the composite experience reduced particle acceleration.

As volume fraction is increased to enhance interface density, manufacturing defects caused by the difference in thermal expansion coefficients between the particulates and matrix can cause cracking and separation of the beads from the matrix. Use of multiple bead sizes within the PMMA / glass bead composite reduces the occurrence of cracking. Samples with up to 50% glass by volume have been tested in this manner.

2.2. Bi-Modal Bead Size Distribution Experiments

Bi-modal composites were designed with a 30% glass by volume base of 500 μm or 1000 μm diameter beads to which "interstitial" beads were added in increments of 10% by volume. At the time of this writing, three composites were complete and tested: 500 μm-30% + 100 μm-10%, 1000 μm-30% + 500 μm-10%, and 1000 μm-30% + 500 μm-20%.

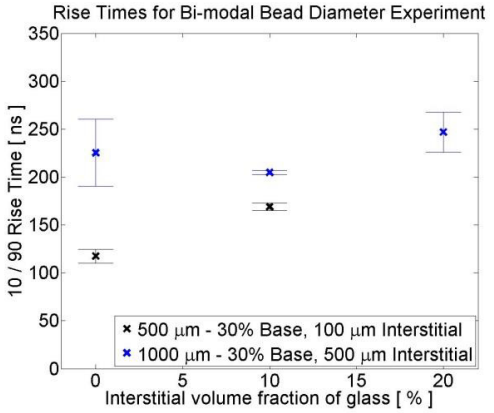


Fig. 7. Bi-modal bead diameter rise time results for 500μm and 1000μm bead based composites

While the data set available at this time is small, two interesting trends are present. As discussed in the Single Mode bead diameter composite studies uneven shock front disruption for larger beads at 30 % glass by volume leads to large uncertainty bounds for the shock rise time. Even with the addition of 500 μm beads at 10% and 20% by volume, uncertainty remains large. It is probable that the 1000 μm beads are approaching the limit of effective scattering, and as such, dominate the shock response of the composite. Therefore, other than providing an effective means of reducing spatial heterogeneity in the shock response, the interstitial 500 μm beads do not enhance the scattering potential of the composite.

An increase in shock rise time is observed for the 500 μm base composite case with the addition of 100 μm interstitial beads. At this time, only 10% by volume of interstitial beads have been added resulting in a composite with a total of 40% glass by volume. The addition of the interstitial beads enhanced scattering and spreading of the shock front, and the rise time appears to approach the limit defined by the 1000μm bead case.

3. Conclusions and Future Work

A model particulate composite has been developed as a model for engineering materials of interest such as high strength concrete and polymer bonded explosives. The interface properties, particulate size, and interface shape / density may be precisely controlled without having the drawbacks and facility restrictions involved with using concrete and explosives. The shock wave structure and width of composites with impedance mismatch ratios between 2 and 10 may be controlled by tuning the mean particle diameter. A linear scaling of shock width with particulate diameter has been observed for particulate diameters between 2 and 25 times the average shock width in the pure matrix material.

Bi-modal particle diameter based composites were also examined. Composites with more than one dominant bead size offer better packing and ease of manufacturing at higher volume fractions of glass. In cases with large base particulate beads, the shock wave is well spread, and only minimal changes to the shock structure are observed.

When interstitial beads are added to composites with smaller base particulate beads (500 μm base), the rise time approaches the limit defined by the largest bead composites.

Work in progress includes composites with base bead diameters of 300 μm and 700 μm with various sized interstitial beads. Each composition will also include composites with higher volume fractions of glass, up to 60 % glass by volume. The highest volume fraction composites will be used to verify the 220 ns – 250 ns shock rise time limit observed for the largest particulates. The effects of complex microstructure on shock speed will also be examined.

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