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Interrogating Heterogeneous Compaction of Analogue Materials at the Mesoscale Through Numerical Modeling and Experiments

James G. Derrick^{1,a)}, Michael E. Rutherford^{2,3}, Thomas M. Davison¹, David J. Chapman^{2,3}, Daniel E. Eakins^{2,3} and Gareth S. Collins¹

¹*Department of Earth Science and Engineering, Imperial College London, SW7 2AZ*

²*Institute of Shock Physics, Imperial College London, SW7 2BW*

³*Solid Mechanics and Materials Engineering, Department of Engineering Sciences, University of Oxford, OX5 1PF*

^{a)}Corresponding author: jgd10@ic.ac.uk

Abstract. Meteorites are classified by their relative exposure to three processes: aqueous alteration; thermal metamorphism; and shock processes. They constitute the main evidence available for the conditions in the early solar system. The precursor material to meteorites was bimodal and consisted of large spherical melt droplets (chondrules) surrounded by an extremely fine porous dust (matrix) with a high bulk porosity ($> 50\%$). We present experiments and simulations, developed in tandem, investigating the heterogeneous compaction of matter analogous to these precursor materials. Experiments were performed at the European Synchrotron Radiation Facility (ESRF) where radiographs of the shock compaction and wave propagation were taken *in-situ* and in real time. Mesoscale simulations were performed using a shock physics code to investigate the heterogeneous response of these mixtures to shock loading. Two simple scenarios were considered in which the compacted material was pure matrix or pure matrix with a single inclusion. Good agreement was found between experiment and model in terms of shock position and relative compaction in the matrix. In addition, spatial variation in post-shock compaction was observed around the single inclusion despite uniform pre-shock porosity in the matrix. This shock-induced anisotropy in compaction could provide a new way of decoding the magnitude and direction by which a meteorite was shocked in the past.

INTRODUCTION

Meteorites are among the most studied rocks in existence because they are our primary source of information about the conditions present in the early solar system [1, 2]. By decoding the processes meteorites have been exposed to, and when, the conditions of the early solar system can be inferred. Meteorites are classified by their relative exposure to three processes: aqueous alteration, thermal metamorphism, and impact processes. Impact processes include low velocity collisions ($< 1 \text{ km s}^{-1}$) between planetesimals in the early solar system [1] as well as later higher speed collisions between asteroids, the parent bodies of meteorites. Shock classification of meteorites has traditionally been calibrated against relatively non-porous materials [3]. However, it seems likely that the first solids to form in the Solar System were highly porous. Porous matter responds very differently to shock in comparison to continuous materials [4]. In addition, the first solids were bimodal and recent numerical studies have suggested that the low-velocity collisions could have produced large temperature variations ($> 500\text{K}$ on the mm-scale) in the matrix whilst leaving chondrules relatively unaffected because of this [1, 2].

To provide experimental support for the nature of shock compaction of primitive solids, and investigate the temperature dichotomy, we devised a joint experimental and numerical approach. Experiments were performed at the European Synchrotron Radiation Facility (ESRF) utilising state-of-the-art, *in-situ*, mesoscale X-ray imaging techniques [5] and numerical models were performed with the shock physics code iSALE [5, 6]. The experiments were used to validate iSALE's numerical models which can subsequently be used to investigate experimentally inaccessible features such as temperature or pressure.

METHODOLOGY

To investigate the heterogeneous compaction of this bimodal mixture we consider two simple scenarios: compaction of a pure fine-grained, highly porous granular material analogous to the precursor of meteoritic matrix material and compaction of the same material with a single non-porous inclusion of similar composition. Investigating the pure matrix scenario allows for straightforward validation of the numerical model and characterisation of the shock's passage. Increasing the complexity of the system with one chondrule enables the consideration of the interaction between shock and inclusion in detail.

The experiments and simulations were based on the same geometry. A 25 mm \times 12.7 mm cylindrical sabot with a 2 mm \times 12.7 mm copper flyer, attached to one end, with an incident velocity of $\approx 600 \text{ ms}^{-1}$ struck a copper or polycarbonate (PC) driver that was $\approx 2.6 \text{ mm}$ thick. This transferred the shock into the particle bed, which was contained by a 9.8 mm \times 6 mm aluminium cell and a PMMA window (full geometry in Figure 1). Fine powdered silica (Sipernat silica 320-DS) was used as a matrix analog because of its high porosity and small grain size ($\sim 7 \mu\text{m}$). A matrix of porosity (ϕ) of $\phi \approx 70\%$ was used. A single borosilicate glass rod (8 mm in length, 1 mm diameter), was used as the chondrule analog because of its comparable density to solid silica.

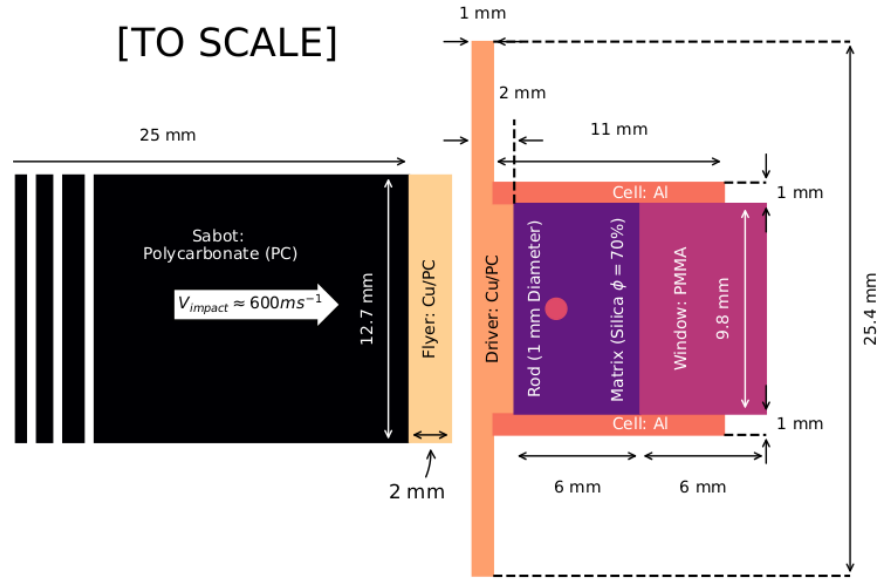


FIGURE 1. Full geometry (to-scale) used by experiments and models based on previous work by *Rutherford et. al* [5]. The impactor is only partially shown.

Experiments were performed at the ESRF on beamline ID19. Shots were performed using a 3 m, 12.7 mm bore, single stage light-gas gun aligned perpendicular to the X-ray beam. Radiographs were captured indirectly using a single crystal LYSO scintillator [5] imaged by a pair of PI-MAX4 cameras, each capable of taking two images. The cameras were triggered sequentially such that four radiographs were taken per shot with intervals of $0.878 \mu\text{s}$, $0.708 \mu\text{s}$, and $0.878 \mu\text{s}$ between each frame respectively. Their field of view was restricted to a $12.1 \text{ mm} \times 12.1 \text{ mm}$ square that encompassed the particle bed and some of the surrounding apparatus (Figure 2, 4) with an effective pixel size of $11.85 \mu\text{m} \times 11.85 \mu\text{m}$. In the single chondrule scenario a cylindrical rod oriented along the X-ray axis was used in place of a spherical bead to enhance contrast in the radiographs in a quasi-2D experiment.

The numerical models resolved the full geometry of the experiment and used cylindrical boundary conditions to model the pure matrix scenario because of its symmetry. A 2D plane strain geometry was used for the single inclusion scenario. The matrix was modeled as a continuous material and the porosity was not explicitly resolved. The $\epsilon - \alpha$ porosity model was used to describe compaction in this continuous material [7, 6]. The chondrule, however, was resolved in full. The full parameters and models employed in the simulations are summarised in Table 1.

Due to a large experimental uncertainty on the time of the first frame after impact, but a low uncertainty on the inter-frame times, the best match between the first radiograph and the model was taken as a reference time (labelled as

$T = 0 \mu\text{s}$ in all figures) for both. Experimental and numerical images are synchronized relative to this reference time.

TABLE 1. Full material models and parameters used (where applicable).

Material	Equation of State	Strength Model
Polycarbonate	Mie-Grüneisen [8]	Von-Mises
Aluminium	Mie-Grüneisen	Johnson-Cook [9]
Copper	Mie-Grüneisen	Johnson-Cook
PMMA	Tillotson [8]	Von-Mises
Silica (solid)	Mie-Grüneisen	-
Silica (matrix)	Mie-Grüneisen + $\epsilon - \alpha$ porosity model [7]	Drucker-Prager [10]

RESULTS: Pure Matrix

The shock position at each time appears to be in qualitative agreement between the radiographs and models when viewed side-by-side (Figure 2). However there appears to be a significant amount of bowing of the shock in the radiographs that is not present in the models. This may be related to inaccuracies in the release of the matrix off the cell wall in the models but this study is primarily interested in the uniform region and so this effect is not investigated here. The quantitative results were taken in a central column of 6 mm where the shock was considered to be relatively uniform to minimise the influence of bowing. The shock position was calculated as the absolute distance traveled, of the shock, from the driver's static location. The positions agree to within 10% in any frame and are in greatest agreement at early times. This suggests a disagreement in shock velocity (Figure 3). By considering the shock position in each frame and the relative elapsed time it is possible to calculate the average velocity of the shock between radiographs and the equivalent model frames. Whilst the velocity is greater in the models it never differs by more than 20% from the experiments (Figure 3).

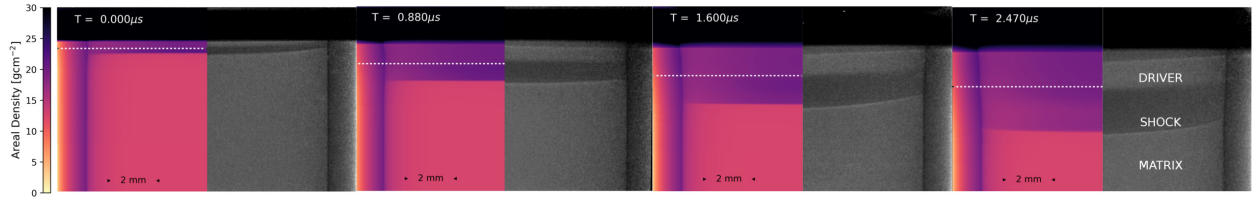


FIGURE 2. Pure matrix results overlay. The white dashed line is the location of the driver/powder interface in the models. Numerical results were projected from 3D onto a 2D plane, emulating the formation of a radiograph and are presented in areal density.

Unlike a traditional shock experiment the relative compaction of the matrix behind the shock is a feature that can be examined using these mesoscale imaging techniques. A direct comparison can be made with the models for additional validation. The comparison was made 0.5 mm ahead of the driver in both, at a fixed longitudinal position. There is good agreement between the two (Figure 3) although the experiment displays an approximate asymmetric gradient across the bed, which suggests an additional degree of heterogeneous compaction. This is may be caused by 'tilt' in the experiment, imperfect flatfielding or density variations in the pressed powder.

RESULTS: Pure Matrix With a Single Inclusion

The addition of a single inclusion did not affect the bulk features of the results significantly. Similarly to the pure matrix scenario the shock wave travels slightly faster in the models (Figure 4) and compaction in the matrix is $\phi \approx 50\%$, outside the area of effect around the inclusion. As the shock interacts with the inclusion it travels quickly through it, creating a protrusion or 'bulge' in the shockwave. This 'bulge' is most visible at early times and decays as the shock progresses. The perturbation in the models appears to decay at a faster rate than the experiment becoming almost invisible by the final frame, whilst the radiograph still displays it clearly. This is consistent with previous studies that investigated shock wave perturbation decay in granular matter [11].

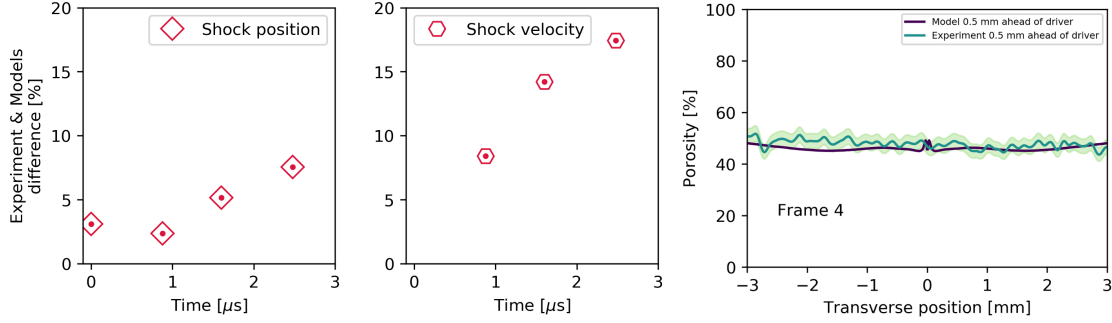


FIGURE 3. Quantitative variations between experiments and models as absolute percentage differences in shock position (far left) and shock velocity (middle). The relative final compaction, 0.5 mm ahead of the driver, of the last frame is presented as well (far right). The compaction was compared over a 6 mm band across the centre of the bed to avoid interference from the bowing and higher uncertainties near the aluminium walls. The ‘band’ around the experimental data represents the uncertainty on that compaction.

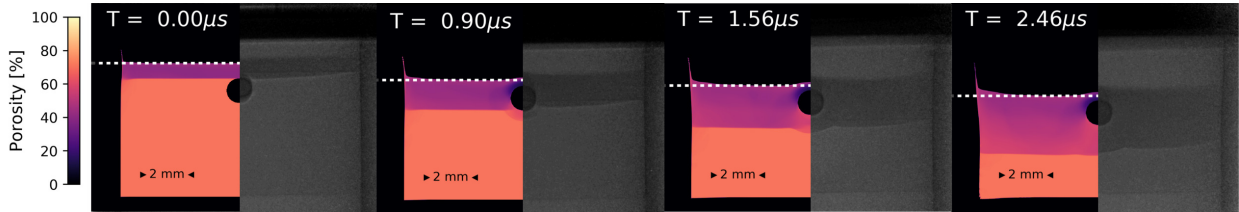


FIGURE 4. Matrix containing a single inclusion results overlay. Simulations were 2D and had plane-strain boundary conditions; half is cropped to compare with radiographs and the white dashed line is the furthest location of the driver/powder interface in the models. The models do not have cylindrical symmetry and are not projected as in Figure 2, instead the porosity field is plotted. Simulations and experiment position is calibrated through the position of the inclusion.

When comparing relative compaction in the matrix 0.25 mm ‘leeward’ and 0.15 mm ‘shockward’ of the chondrule, we observe a distinct porosity anisotropy around the inclusion in both experiments and simulations (Figure 4). This effect appears to affect the matrix within one particle radius (approximately) of the surface of the chondrule. The porosity in the leeward direction (away from the driver) from the chondrule is slightly higher close to the chondrule compared to matrix at the same longitudinal position. The reverse is true in the shockward direction (toward the driver); the matrix close to the chondrule is lower in porosity compared with matrix at the same longitudinal position either side. This feature is distinct in simulations but less clear in the experiments. This may be a consequence of experiments not being exactly 2D: ~ 1 mm of unaffected matrix at either end of the rod will contribute to the radiograph, which is a representation of integrated line density. The porosities are in good agreement either side of the chondrule, with simulation results lying well within experimental uncertainty (Figure 5). In general the experiments show the same effect but to a lesser extent; the shockward porosity is not as low and the leeward porosity is not as high but the spatial extent of the porosity anomaly is in agreement.

CONCLUSIONS

This work has investigated the compaction of mixtures analog to precursor meteorite matter through real-time, *in-situ*, mesoscale, experiments at the ESRF [5] and numerical models using the iSALE shock physics code [6]. Two scenarios were considered, compaction of a pure fine-grained, highly porous granular material analogous to the precursor of meteoritic matrix material and the same material with a single non-porous inclusion of the same composition. The purpose of the study was to interrogate the behaviour of the shock interaction between matrix and chondrules. Shock position and the relative compaction of the matrix were in good agreement between the experiments and models. The main differences were in non-uniformity such as bowing of the shock and asymmetric effects such as tilt or density variations. This was prominent in experiments but absent in models. In order to make a useful comparison

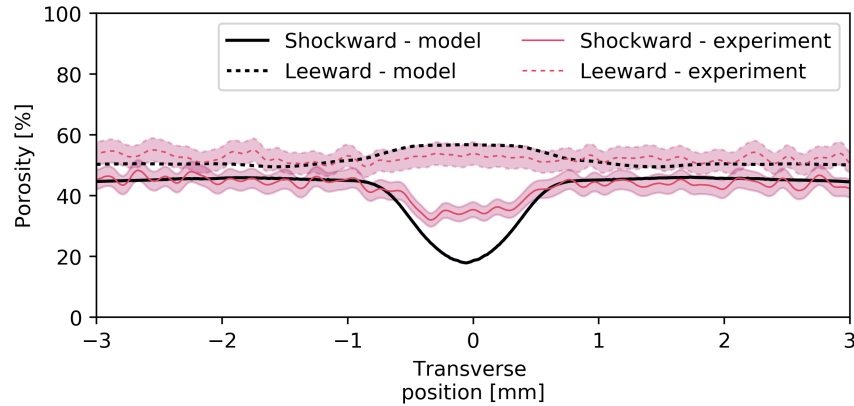


FIGURE 5. Line plots of final porosity (frame 4) in the experiments and simulations taken 250 μm leeward of the inclusion and 125 μm shockward of it. Only the central 6 mm has been considered to avoid effects of tilt on the results. Experimental porosity was calculated using an X-ray absorption model which took the measured radiographic contrast as an input. [12]

only the central 6 mm of the bed was considered in the analysis to avoid the effects of the bowing. In the single inclusion scenario the experiment and model were in good agreement in terms of shock position and compaction. In addition, the final porosity around the inclusion was strongly anisotropic in both; the chondrule appeared to ‘protect’ the matrix in its lee resulting in a higher porosity on that side with a lower porosity on the opposite side. This porosity distribution has similarities with features observed in known meteorites, such as NWA 5000. If these are formed by the same process they potentially present a new way of decoding the shock magnitude and direction that meteorites were exposed to.

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