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Impact Compaction of a Granular Material

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Abstract

The dynamic behavior of granular materials has importance to a variety of engineering applications. Structural seismic coupling, planetary science, and earth penetration mechanics, are just a few of the application areas. Although the mechanical behavior of granular materials of various types have been studied extensively for several decades, the dynamic behavior of such materials remains poorly understood. High-quality experimental data are needed to improve our general understanding of granular material compaction physics. This paper will describe how an instrumented plunger impact system can be used to measure pressure-density relationships for model materials at high and controlled strain rates and subsequently used for computational modeling.

1. Introduction

The irreversible shock compaction of distended granular materials has a wide range of science and engineering applications. This paper finds motivation primarily from applications concerned with the impact and dynamic compaction of granular powders. Most of the fundamental principles, models, and analysis, however, have broader applications to shock compaction of a more diverse range of porous solids. Investigators have recognized for many years that most materials do not behave the same under static conditions as they do in a dynamic environment. The difference between static and dynamic behavior of powder materials is nicely detailed by Vogler et al. [1]. Scientists have used many different approaches to evaluate the mechanical properties of powder materials under rapid loading. High-quality experimental data is needed for the development of computational models of dynamic material events especially in the partially compacted range.

A coupled experimental and computational program was designed by Asay [2] to evaluate a porous granular material called Rigidax [3]. Cady [4] from Los Alamos National Labs performed a series of split-Hopkinson pressure bar tests and Graff [5] also from Los Alamos National Labs completed a series of Taylor Anvil impact tests providing information on the constitutive behavior on Rigidax. Reinhart [6] at Sandia National Labs produced material sound speed data and Hugoniot data. Once these data were in hand, initial CTH calculations were made to guide the experimental design. A series of instrumented gas gun experiments were conducted in which a range of initial densities and piston velocities was used to provide a quasi one-dimensional compaction wave. The experimental results were then used in CTH to begin to calibrate...
the equation of state and other material models required to begin to make predictions on the compaction response of the sample granular material.

2. Experimental Data and Test Techniques

Equation of state experiments was performed on Rigidax to obtain the principal Hugoniot of the full-density material. Rigidax is a tooling compound, which is a castable thermoplastic material. This section reveals results from compression tests, which were performed to obtain the strength characteristics. Lastly, the results from a series of dynamic compaction experiments are revealed, which were conducted at different packing densities to provide data for a compaction model.

2.1. Equation of State Tests

A series of eight flyer-plate Hugoniot tests were performed at the Sandia National Laboratory STAR facility [6] to acquire the data needed to compute the equation of state of the granular Rigidax material. The Hugoniot test results are provided in Table 1. The nominal theoretical solid density of the Rigidax material as given by the manufacturer is $\rho_0=1.44 \text{ g/cm}^3$. However, in Reinhart’s [6] test series the material initial solid density $\rho_0$ varied from 1.35 to 1.43 g/cm$^3$ with a mean solid density of $\rho_0=1.39 \text{ g/cm}^3$. This density is used as the nominal solid density of the Rigidax material for further calculations and numerical modeling.

Table 1. Hugoniot test results from Reinhart’s [6] test series.

<table>
<thead>
<tr>
<th>Shot Number</th>
<th>Impact Velocity, km/s</th>
<th>Particle Velocity, km/s</th>
<th>Shock Velocity, km/s</th>
<th>Initial Density, $\rho_0$, g/cm$^3$</th>
<th>Relative Volume $V/V_0$</th>
<th>Stress, $\sigma$, GPa</th>
<th>Density, $\rho$, g/cm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHE-1</td>
<td>0.610</td>
<td>0.571</td>
<td>3.476</td>
<td>1.353</td>
<td>0.836</td>
<td>2.686</td>
<td>1.620</td>
</tr>
<tr>
<td>MHE-2</td>
<td>0.999</td>
<td>0.873</td>
<td>3.914</td>
<td>1.366</td>
<td>0.777</td>
<td>4.667</td>
<td>1.758</td>
</tr>
<tr>
<td>MHE-4</td>
<td>2.344</td>
<td>2.726</td>
<td>6.904</td>
<td>1.425</td>
<td>0.605</td>
<td>26.822</td>
<td>2.355</td>
</tr>
<tr>
<td>MHE-5</td>
<td>2.691</td>
<td>2.229</td>
<td>5.981</td>
<td>1.434</td>
<td>0.627</td>
<td>19.111</td>
<td>2.285</td>
</tr>
<tr>
<td>MHE-6</td>
<td>4.788</td>
<td>3.169</td>
<td>7.347</td>
<td>1.416</td>
<td>0.569</td>
<td>32.966</td>
<td>2.490</td>
</tr>
<tr>
<td>MHE-7</td>
<td>5.870</td>
<td>3.876</td>
<td>7.894</td>
<td>1.416</td>
<td>0.509</td>
<td>43.331</td>
<td>2.782</td>
</tr>
<tr>
<td>MHE-8</td>
<td>0.510</td>
<td>0.410</td>
<td>2.796</td>
<td>1.375</td>
<td>0.853</td>
<td>1.576</td>
<td>1.611</td>
</tr>
<tr>
<td>MHE-9</td>
<td>1.768</td>
<td>0.410</td>
<td>2.796</td>
<td>1.375</td>
<td>0.853</td>
<td>1.576</td>
<td>1.910</td>
</tr>
</tbody>
</table>

The sound speeds of the Rigidax materials were also determined and are shown in Table 2. A material bulk wave speed was calculated from the values in Table 2 by using eq. 1. A Poisson’s ratio $\nu = 0.351$ was calculated from the measured sonic wave speeds using eq. 1 and eq. 2 and solving for $\nu$. The resulting expression for $\nu$ is obtained by combining eqs. 1 and 2 which results in eq. 3.

Table 2. Sound speed values for Rigidax material.

<table>
<thead>
<tr>
<th>Elastic Wave Speed, $C_l$, km/s</th>
<th>Shear Wave Speed, $C_s$, km/s</th>
<th>Bulk Wave Speed, $C_o$, km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.16</td>
<td>1.035</td>
<td>1.80</td>
</tr>
</tbody>
</table>

$$C_o = \sqrt{C_l^2 - \frac{4}{3}C_s^2} \quad (1)$$

$$\frac{C_l}{C_o} = \sqrt{\frac{3(1-\nu)}{1+\nu}} \quad (2)$$

$$\nu = \frac{C_l^2 - 2C_s^2}{2C_l^2 - 2C_s^2} \quad (3)$$
Figure 1. Rigidax linear $U_r$ vs. $U_p$ data from Reinhart. Shock velocity at zero particle velocity is plotted as an open black circle.

2.2. Compression Tests to Determine Material Strength

In addition to the equation of state, constitutive properties that define the strength and fracture behavior are required. The Johnson-Cook (JC) plasticity model was used in this study mainly for the ease of calibrating the parameters to match the material response. The JC plasticity model is most likely not the best choice for this viscoplastic material, but it does provide a first step in defining the deviatoric response of the material. The development of the JC parameters is detailed in a draft report provided by Asay [2]. A separate analysis on the JC parameters was performed by Lee and Caipen [7], which provided a much stiffer JC model. The derived strength parameters provided by Asay [2] were used for computational simulations. The JC parameters are listed in Table 3. A Johnson-Cook fracture model was also derived from a series of split-Hopkinson pressure bar tests [4] and Taylor Impact experiments [5]. The fracture parameters used for the computational simulations are also found in Table 3. Equations 4 and 5 represent the Johnson-Cook flow stress and the Johnson-Cook equivalent plastic strain at fracture respectively.

\[ Y \equiv (A + B \varepsilon^p)(1 + C \ln \dot{\varepsilon})(1 - T_{m}^w). \]  

Table 3. Johnson-Cook strength and fracture model parameters for the Rigidax material.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>n</th>
<th>m</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
<th>T_{ref}</th>
<th>T_{melt}</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPa</td>
<td>MPa</td>
<td>°C</td>
<td>°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.36</td>
<td>117</td>
<td>0.057</td>
<td>0.463</td>
<td>11</td>
<td>0.017</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0223</td>
<td>-1.2</td>
<td>20.0</td>
<td>80.0</td>
</tr>
</tbody>
</table>

\[ \varepsilon_p^f = \left(D_1 + D_2 \exp(-D_3 p / Y)\right)\left(1 + D_4 \ln \dot{\varepsilon}\right)\left(1 - T_{H}^w\right). \]  

2.3. Dynamic Compaction Tests

The dynamic compaction concept is illustrated in Figure 2. This configuration is an adaptation from an instrumented DDT tube experiment test fixture used by McAfee et al. [8]. The test fixture resembles an experimental design called a Campbell’s tube [8]. Campbell’s tube uses a pyrotechnic to drive a piston into an instrumented sample chamber. The concept shown in Figure 2 uses a gas-gun launched impactor to drive the piston into the sample chamber.

A total of five tests were conducted using a compressed gas-gun (3-in diameter). The piston assembly was packed internally with the Rigidax material. The Rigidax wax was ground by hand, sieved to yield the desired cut size, and then the cylinder tube was filled incrementally. Each fill increment being packed to proper density with a wooden dowel.
Dynasen, CA-1135 piezoelectric pins were used to measure the compaction wave velocity in the material. The pins were then inserted into the cylindrical tube until they protruded 1/8 inch into the material bed. The piston and projectile velocities were measured using PDV [9,10]. In order to provide for consistent analysis, and because of the signal noise inherent when making measurements in these granular materials, the compaction wave arrival was assumed as the time at which the piezo pin signal produced a voltage of +/-50 mv. The time of arrival was then plotted and analyzed using a linear least squares routine. Time zero of each test varied depending on gas gun timing.

Figure 3 shows the hemispherical impact surface and the launch projectile assembly. This figure also shows drawings of the gas gun launch projectile. A hemispherical impact surface (see Figure 3) is affixed to the front of the launch projectile to minimize the effects of yaw. The launch projectile provided a lightweight means of propelling the hemispherical impact surface at the piston assembly illustrated in Figure 2. Figure 4 shows a schematic of the 3-inch diameter gas gun.
The conditions of the dynamic compaction experiments and the results are shown in Table 4.

Table 4. Gas gun compaction test results relative to a $\rho_0=1.39$ g/cm$^3$.

<table>
<thead>
<tr>
<th>Shot Number</th>
<th>Projectile Velocity m/s</th>
<th>Compaction Velocity m/s</th>
<th>Peak Piston Velocity m/s</th>
<th>Packing Density, $\rho_0$ g/cm$^3$</th>
<th>Particle Size mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>270</td>
<td>792</td>
<td>75</td>
<td>0.94 (68%)</td>
<td>120-300</td>
</tr>
<tr>
<td>2</td>
<td>208</td>
<td>744</td>
<td>94</td>
<td>0.94 (68%)</td>
<td>300-600</td>
</tr>
<tr>
<td>3</td>
<td>209</td>
<td>992</td>
<td>90</td>
<td>1.15 (83%)</td>
<td>300-600</td>
</tr>
<tr>
<td>4</td>
<td>230</td>
<td>1218</td>
<td>90</td>
<td>1.15 (83%)</td>
<td>300-600</td>
</tr>
<tr>
<td>5</td>
<td>211</td>
<td>940</td>
<td>81</td>
<td>1.33 (cast, 96%)</td>
<td>300-600</td>
</tr>
</tbody>
</table>

Figure 5 shows the plunger PDV data for the five gas gun compaction tests. This initial experiment used two different configurations for the piezo pins located at the same axial position in the tube; one set was implemented as-received, while the other set had a nylon sleeve around the circumference to isolate the pin from spurious signals in the tube walls. As expected the insulated pins reported 2-3 $\mu$s later with the exception of the first set which were 8 $\mu$s apart. However, within experimental error, the measured compaction velocities were equivalent. This experiment used a much finer particle size (120-300 mesh) than the remaining four experiments.

![Figure 5: Overlay comparison of the PDV data from the five tests showing the velocity history of the plunger motion.](image)

Shots 1 through 4 used ground Rigidax powder while shot 5 used Rigidax material that was cast into place. For this final test, the pins were inserted as the melted material was poured around them. A melt temperature of approximately 80 °C was used, and this may have affected the poling of the PZT crystals. The signals from this test were not as clean as the previous shots, but the timing appears to have still been reliable.

Table 5 reveals the Hugoniot data obtained from the dynamic compaction experiments. The peak piston velocity is used as the material particle velocity $u_p$ and the measured compaction velocity as the material shock velocity $U_s$. The Hugoniot density and stress were computed from eqs. 6 and 7, which are the Hugoniot relations for the expressions of conservation of mass and momentum across a shock front in a porous material.

$$h = 0 \int \left( \frac{U_p}{U_s} \right)$$

(6)

$$h = u_p U_s$$

(7)
<table>
<thead>
<tr>
<th>Shot Number</th>
<th>Particle Velocity, (u_p)</th>
<th>Shock Velocity, (U_s)</th>
<th>(\rho_0)</th>
<th>Distension</th>
<th>Density, (\rho_h)</th>
<th>Stress, (\sigma_h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.075</td>
<td>0.792</td>
<td>0.940</td>
<td>1.48</td>
<td>1.038</td>
<td>0.056</td>
</tr>
<tr>
<td>2</td>
<td>0.094</td>
<td>0.744</td>
<td>0.940</td>
<td>1.48</td>
<td>1.076</td>
<td>0.066</td>
</tr>
<tr>
<td>3</td>
<td>0.090</td>
<td>0.992</td>
<td>1.115</td>
<td>1.21</td>
<td>1.236</td>
<td>0.093</td>
</tr>
<tr>
<td>4</td>
<td>0.090</td>
<td>1.218</td>
<td>1.115</td>
<td>1.21</td>
<td>1.204</td>
<td>0.122</td>
</tr>
<tr>
<td>5</td>
<td>0.081</td>
<td>0.940</td>
<td>1.330</td>
<td>1.05</td>
<td>1.455</td>
<td>0.101</td>
</tr>
</tbody>
</table>

In order to validate the experimental compaction technique on the granular Rigidax material, we plotted the compaction tests shock velocity \(U_s\) and particle velocity \(u_p\) on the same plot as the data obtained by Reinhart [6] for the fully dense material as shown in Figure 1.

\[
U_s(p) = \sqrt{\frac{p}{\rho_0} \left(1 + \frac{1}{\rho_0} \right)} \quad \text{and} \quad u_p(p) = \sqrt{\frac{P}{\rho_0} \left(1 + \frac{1}{\rho_0} \right)}, \quad \text{where}
\]

\[
(p) = \frac{1}{\rho_0} \left(1 - \frac{1}{\rho_0} \right) \left(1 - \frac{1}{\rho_0} \right) \quad \text{and} \quad (p) = 1 + \frac{C_s^2}{2S_0p}
\]

We also computed the porous Hugoniot curves for the three material distensions using eq. 8, where \(S_0=1.518\), \(C_s=2.432\) km/s, and \(\rho_0=1.39\) gm/cm³. Figure 6 displays a comparison between shock Hugoniot data and the dynamic compaction data.

Figure 6: Comparison of shock Hugoniot data of solid Rigidax and the Hugoniot data obtained from the five porous compaction experiments.

3. The Computational Model

The material modeling approach described here represents a combination of a framework that describes the low-pressure compaction of a heterogeneous mixture of component materials and an equilibrium high-pressure equation of state (EOS). This model is called the enthalpy-based-shock-compression (EBSC) model [11]. The EBSC model simulates the compaction behavior of a mixture from mechanical crush through extreme pressure loadings. The EBSC model is implemented in Sandia National Labs shock physics code CTH [12]. The low-pressure crush response of the EBSC model is implemented within the p-\(\lambda\) model framework [13,14]. The EBSC model is an engineering approach designed to address mixtures of components and multiple states of compaction (e.g., uncompacted where \(\lambda=0\) to fully compacted where \(\lambda=1\)). EBSC model concept is illustrated in Figure 7.
4. Applying the Computational Model

CTH was used to model the compaction experiments using the EBSC material model for the porous granular Rigidax. Figure 8 shows a comparison between experimental PDV data and CTH calculations of the plunger motion. We use CTH tracer points within the plunger geometry to track the plunger motion for this comparison. The main difference between the CTH calculations and the experimental results is CTH does not incorporate friction forces into the equations of motion of the plunger system. The missing frictional force results in CTH over-predicting the plunger acceleration at early times, which yields an over-predicted peak plunger speed as seen in Figure 8. The PDV data and CTH calculations resolve the early time elastic waves in the piston, while the reverberating elastic waves in the piston at later times are not easily depicted in the PDV data.

A CTH time sequence representing shot 5 (96% packing density) is shown in Figure 9 (a). The scale represents the value of $\lambda$, which is a measure of the level of compaction in the material between numerical values of 0 (no compaction) and 1 (full compaction). The driver impacts the plunger and pushes the plunger for approximately 2 cm of travel and is then decoupled from the plunger by the front deflection plate. The decoupling (based on CTH calculations) occurs roughly around 190 $\mu$s (refer to Figure 8) and creates the elastic ringing on the down slope of the plunger speed time history. This ringing is evident in the CTH calculations when time $> 150$ $\mu$s. Based on observation of the plot in Figure 8, the essence of the compaction problem is modeled reasonably well with CTH and the CTH calculation compares well to the PDV data, even with the exclusion of friction forces that may exist in the plunger system. Figure 9 (b) is the post-test centerline section of the piston and cylinder from shot 1. This image depicts the uniform compacted end state of the Rigidax material.
Figure 9: (a) A sequence of CTH results for shot 5 showing the driver impacting the piston and the evolution of the compaction wave. (b) The post-test centerline section of the plunger and cylinder from shot 1.

5. Closure

Both experimental and computational studies of the compaction of a porous wax material were explored. The PDV technique was used with PZT pins to successfully measure compression velocities of the axisymmetric samples. The methodology has contributed useful validation data of mixture compaction properties under high strain rates and benchmarks for numerical analysis of the porous material. This dynamic compression technique has proved to be successful in determining low-pressure compaction response of porous mixtures. Simulation and experiment agree well with each other even with the exclusion of frictional forces in the CTH model.

Acknowledgements

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References