Shock compression of geological materials

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Abstract. Understanding the shock compression of geological materials is important for many applications, and is particularly important to the mining industry. During blast mining the response to shock loading determines the wave propagation speed and resulting fragmentation of the rock. The present work has studied the Hugoniot of two geological materials; Lake Quarry Granite and Gosford Sandstone. For samples of these materials, the composition was characterised in detail. The Hugoniot of Lake Quarry Granite was predicted from this information as the material is fully dense and was found to be in good agreement with the measured Hugoniot. Gosford Sandstone is porous and undergoes compaction during shock loading. Such behaviour is similar to other granular material and we show how it can be described using a P-α compaction model.

1. Introduction
Geological materials are defined as naturally occurring and coherent aggregates of one or more mineral [1]. In turn, minerals are defined as naturally occurring homogeneous solids with a definite chemical composition and a highly ordered atomic arrangement [1]. This definition encompasses a large group of materials which can demonstrate a variety of different physical properties.

During borehole blast mining operations, explosives subject geological materials to shock compression. The compressive stresses witnessed by the rock ranges from the detonation pressure of the explosive down to zero, depending on the distance from the explosion. The maximum detonation pressure achievable from Ammonium Nitrate Fuel Oil (ANFO) mixtures used in mining operations is 10 GPa [2]. The region of interest for this application is therefore from 0 to 10 GPa, which are comparatively low stresses compared to most shock studies [3].

2. Composition
Geological materials occur naturally so their compositions are usually unknown. The composition needs to be measured for complete understanding as it is required for analysis of results and application of modelling and theory. Two geological materials were examined in this study:

- Lake Quarry Granite (LQG)
- Gosford Sandstone (GS)

These samples were chosen as they had different microstructures: GS was porous, while LQG was fully dense. The minerals present in the two geological materials were identified by using Energy-Dispersive X-ray spectroscopy (EDX) [4] to measure their atomic composition and then comparing these results with reference spectra in a minerals database. X-ray computed tomography (XCT) [5] was used to generate a representative three-dimensional image of the microstructure of each
geological material. Image processing was used to measure the relative abundance of each mineral. The measured compositions of the geological materials are shown in table 1.

### Table 1. Geological material compositions measured using EDX and XCT.

| Mineral                        | Volume Fraction (%) |
|--------------------------------|---------------------|
| **Lake Quarry Granite**       |                     |
| Orthoclase, (K\(_{0.86}\),Na\(_{0.14}\))AlSi\(_3\)O\(_8\) | 74.8 ± 1.1          |
| Bronzite, (Fe\(_{0.55}\),Mg\(_{0.45}\))SiO\(_3\)    | 25.2 ± 1.1          |
| **Gosford Sandstone**         |                     |
| Quartz, SiO\(_2\)             | 77.3 ± 0.7          |
| Muscovite, KAl\(_2\)(AlSi\(_3\))O\(_10\)(OH)\(_2\) | 1.5 ± 0.5           |
| Porosity                       | 21.2 ± 0.2          |

3. Elastic sound speeds

The longitudinal and shear sound speeds of the geological materials were measured with 5MHz ultrasonic transducers using a time of flight method. Densities were calculated from the mass and volume of 3 cm side length cubes of the geological materials. The mass was measured using a high precision balance. The volume was determined by measuring the dimensions of the cubes using a digital micrometer. The elastic constants were calculated from these sound speeds and densities [6] and are shown in table 2.

### Table 2. Elastic constants of the geological materials calculated from their longitudinal sound speeds, shear sound speeds and densities [6].

|                          | Lake Quarry Granite | Gosford Sandstone |
|--------------------------|---------------------|-------------------|
| **Longitudinal sound speed (km s\(^{-1}\))** | 5.43 ± 0.02        | 2.33 ± 0.03       |
| **Shear sound speed (km s\(^{-1}\))**       | 3.50 ± 0.02        | 1.46 ± 0.03       |
| **Density (g cm\(^{-3}\))**               | 2.666 ± 0.003      | 2.096 ± 0.015     |
| **Shear modulus (GPa)**                 | 32.6 ± 0.3         | 4.45 ± 0.16       |
| **Bulk modulus (GPa)**                  | 35.1 ± 0.4         | 5.4 ± 0.2         |
| **Young’s modulus (GPa)**               | 74.7 ± 0.4         | 10.5 ± 0.2        |
| **Poisson’s ratio**                    | 0.146 ± 0.007      | 0.18 ± 0.02       |

GS has a significantly lower sound speed compared to single crystal Quartz [7], its major solid component. This disparity was due to the extended wave path required to avoid pores and soft inter-grain contacts which delayed wave propagation through GS.

4. Plate impact experiments

The Hugoniots of LQG and GS were measured through a series of plate impact experiments using a 50.8 mm (2 inch) smooth bore single stage light gas gun at the Cambridge Plate Impact Facility [8]. The impact velocities were between 0.25 and 0.90 km s\(^{-1}\) and three different flier materials were used: Copper C101, Aluminium alloy Al6082 (BS-He30) and Poly(methyl methacrylate). The target design consisted of three plates of material separated by manganin stress gauges and is shown in figure 1. The stress gauges were surrounded by 0.02 mm Mylar sheet to ensure their survival during shock loading.
The shock speed \( U_S \) in each experiment was obtained by measuring the delay between rise times of the front and rear stress gauges and using the thickness of the middle rock plate. The impact velocity was measured using a series of shorting pins. The particle speed \( u_P \) of the target in each experiment was calculated using impedance matching and the Rankine-Hugoniot relationships [3]. Figures 2 and 3 show the measured Hugoniot of LQG and GS, respectively, in \( U_S-u_P \) space.

The shock speed in LQG remained constant with a mean value of \( 5.53 \pm 0.16 \) km s\(^{-1}\) and agreed with the longitudinal elastic sound speed measured previously, \( 5.43 \pm 0.02 \) km s\(^{-1}\).

GS initially behaved elastically then underwent compaction. The mean shock speed in the elastic region, \( 3.38 \pm 0.13 \) km s\(^{-1}\), did not agree with the longitudinal elastic sound speed measured previously, \( 2.33 \pm 0.03 \) km s\(^{-1}\), although there is significant uncertainty in the shock speeds in this region. The best fit linear \( U_S-u_P \) relationship to the compaction region was found to be

\[
U_S = 2.41 \pm 0.11 \text{ km s}^{-1} + 1.31 \pm 0.19 \text{ } u_P. \tag{1}
\]

5. Discussion

5.1. Lake Quarry Granite

The plate impact experiments showed the shock speed in LQG remained constant throughout the region investigated and agreed with the longitudinal elastic sound speed measured using ultrasonic transducers. This has been seen in other fully dense geological materials [9]. During compression of
LQG, the mineral grains remained elastic due to their high strength. As LQG was fully confined no reorganisation was possible, even if there was failure at the grain boundaries, which explains why the shock speed remained at the longitudinal elastic sound speed throughout.

As LQG remains elastic, the Hugoniot can be predicted using composite theory \[10\]. An upper bound and lower bound prediction for a material property can be obtained using the Voigt and Reuss rules of mixtures \[10\] defined by

\[
X = f_1X_1 + f_2X_2 + f_3X_3 + \ldots \tag{2}
\]

and

\[
\frac{1}{X} = \frac{f_1}{X_1} + \frac{f_2}{X_2} + \frac{f_3}{X_3} + \ldots, \tag{3}
\]

respectively, where \(X\) is the material property of the composite, \(f_i\) is the volume fraction of the \(i\)th component and \(X_i\) is the material property of the \(i\)th component.

Using mineral sound speeds from the literature \[11\] and equations (2) and (3), the longitudinal elastic sound speed of LQG was predicted to be \(5.48 \pm 0.18 \text{ km s}^{-1}\). This prediction agreed with the measured elastic longitudinal sound speed, \(5.43 \pm 0.02 \text{ km s}^{-1}\), and mean shock speed of the plate impact experiments, \(5.53 \pm 0.16 \text{ km s}^{-1}\).

5.2. Gosford Sandstone

GS was 21% porous and underwent compaction during the plate impact experiments. This resulted in a variation in shock speed, see figure 3.

A linear \(U_S-u_p\) relationship was found to fit the compaction region. This has previously been seen in shock studies on sands \[12\] and sandstones \[13\], although the coefficients were different due to the different initial porosities. Shock compaction in sands and sandstones are similar and it can useful to consider results from both materials.

A common method for describing shock compaction of powders and granular media is the \(P-\alpha\) compaction model \[14\] which has previously been applied to sands \[12\]. The model takes into account grain compression by considering the distension, \(\alpha\), defined by

\[
\alpha = \frac{V(\sigma,T)}{V_s(\sigma,T)} = \frac{1}{1-\varphi}\tag{4}
\]

where \(V(\sigma,T)\) is the volume of the porous material, \(V_s(\sigma,T)\) is the volume of the fully dense material at the same stress, \(\sigma\), and temperature, \(T\), and \(\varphi\) is the porosity.

The distension is equal to one when a material is fully dense. The \(P-\alpha\) compaction model requires a distension function which relates stress and distension. Previously, polynomial forms have been suggested for the distension function \[12\]. The form of the distension function that best fit the GS plate impact data was found to be

\[
\sigma = A e^{-k\alpha}, \tag{5}
\]

where \(A\) and \(k\) are constants.

The plate impact data for GS was converted into \(\sigma-\alpha\) space using the Rankine-Hugoniot relationships \[3\], equation (4) and the fully dense Quartz Hugoniot \[7\]. The best numerical fit to the GS plate impact data was found to be

\[
\sigma = 1.45 \times 10^5 \text{ GPa} \ e^{-9.8 \alpha}. \tag{6}
\]

The best fit \(P-\alpha\) compaction model and GS plate impact data are shown in figure 4.
6. Conclusions
This study examined two geological materials, Lake Quarry Granite and Gosford Sandstone, one fully dense and one porous. The compositions of the geological materials were characterised in detail and their elastic sound speeds were measured. A series of plate impact experiments were performed to measure the Hugoniot of the materials in the stress region of interest to blast mining, 0 to 10 GPa.

LQG was found to have a constant shock speed throughout. The shock speed in the plate impact experiments was found to agree with its longitudinal elastic sound speed. The agreement was due to the mineral grains remaining elastic and as no reorganisation was possible due to confinement. Using the composition and mineral properties from the literature, the Hugoniot of LQG was predicted using composite theory which agreed with both the plate impact and ultrasonic transducer measurements.

GS was porous and, after a small elastic region, compacted under shock loading which resulted in a variation in shock speed. A P-\(\alpha\) shock compaction model with an exponential distension function was found to best fit the compaction region GS plate impact data.

Knowledge of the composition was required in analysis of both LQG and GS which demonstrates the importance of characterising the composition as well as the shock response when studying geological materials.

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