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Strength Measurements of Dry Indiana Limestone using Ramp Loading Techniques

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Abstract. An accurate method to control strain rates in dynamic compressions studies is to use the non-linear elastic property of fused silica to transform an initial shock into a ramp wave of known amplitude and duration. Fused silica when placed between a limestone specimen and a projectile allows strain rates in the range of 10^4/s. Ramp loading strain rates are higher than what can be produced on Hopkinson bars and lower than what shock experiments attain. Ramp wave compression tests have been performed on dry Indiana limestone at strain rates of approximately 10^4/s. The strength determined at the Hugoniot elastic limit under ramp loading along with Hopkinson bar measurements shows a significant strength increase with increasing strain rate.

Keywords: Limestone, ramp loading, isentropic compression, EOS, fused silica
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INTRODUCTION

Limestone is a geological material of interest to many dynamic applications. When found naturally, the material can be considerably porous. In the fully dense form, it exists as single crystals referred to as calcite and as a polycrystalline material it is known by many names such as marble (generally fully dense), Oakhall, Solenhofen, and Indiana limestone. These different names refer to the quarry from which the material is extracted. The porosity content for many of these limestones can vary from 0.5% to over 15% depending on where it is quarried.

High-pressure, high-temperature, behavior of limestone is considerably complex. Investigations utilizing ramp or isentropic loading techniques on limestone are limited. Isentropic loading introduces strain rates that are lower then that of shock loading. This can complicate the compression behavior of the material, mainly because of the rate dependence of the strength behavior. It is the purpose of this study to investigate the strength of Indiana limestone under isentropic loading at or around the Hugoniot elastic limit (HEL).

In this study, we have used fused silica as an intervening buffer material[1] to introduce isentropic loading. The strain rates obtained are approximately two orders of magnitude lower than those achieved under shock loading. The strain rates achieved on these current experiments are substantially reduced (10^4/s) when compared to the shock experiments, but are higher than those for Hopkinson bar experiments. This is anticipated to bridge the gap between lower strain rate experiments and those conducted under shock loading.

MATERIAL

The limestone (Indiana) used in this study was quarried from Elliot Stone Company[2] and is the same "lot" as those used in previous studies[3]. Average material properties for the limestone have been reported [3-5] and are shown in Table 1. The average bulk density and measured grain[4, 5] density from its constituents provide an average porosity of approximately 15%. Compressive strength (Table 1) had been estimated from depth-of-penetration versus striking-velocity experiments[3].

TABLE 1. Average Material Properties

Density (g/cm^3)	Water Content (%)	Porosity (%)	Compressive Strength (MPa)
2.30	0.16	15.0	63

Ultrasonic mappings of longitudinal and shear velocities were performed to identify samples with significant heterogeneities. Among the samples used, longitudinal velocities varied from 4.35 to 4.81 km/s while shear velocities were from 2.52 to 2.67 km/s. This is consistent with sample variations in previous work.[3, 6, 7]. Therefore, the average longitudinal, shear velocity values, c_L and c_S used in this study were 4.564 and 2.578 km/s respectively, and Poisson's ratio was calculated to be 0.261.

EXPERIMENTAL TECHNIQUE

To achieve a lower strain-rate experiment than is typically attained in shock experiments, fused silica is used as a buffer to introduce a finite rise time of the input stress. As shown in Fig. 1, fused silica is placed between the limestone and the impactor (which is also fused silica) that faces the projectile. At stresses below about 3.5 GPa, a ramp wave loads the limestone sample. The loading rate is dependant on the stress amplitude and the sample thickness of the fused silica. This is a consequence of the loading response of fused silica[1] for $0 < \sigma < 9$ GPa and is given by:

$$\sigma = 77.60\varepsilon\,(1 - 5.359\varepsilon + 39.098\varepsilon^2 - 89.252\varepsilon^3) \quad (1)$$

where σ is the shock stress and ε is the shock strain. Because the wave speed is a decreasing function of stress for stresses up to ~ 3.5 GPa, a ramp wave loads the limestone. The stress-strain curve is concave toward the strain axis which provides control of the rise time of the loading pulse by varying the thickness of the fused silica buffer at a given stress. The experiments in this study have been limited to 2.5 GPa. Fused silica elastic properties are such that an initial step wave will acquire a rise time of about 1 µs over a propagation distance of 25 mm; in this study we can expect a rise time of about 800 ns for the buffer dimension selected for this study (Table 2).

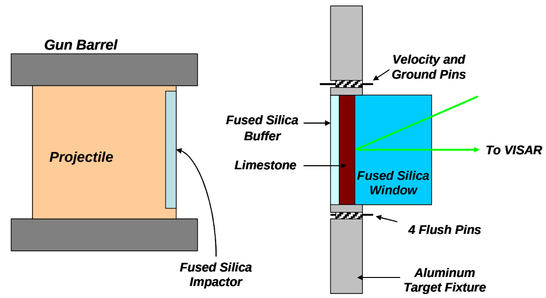

Figure 1. The configuration provides a method to obtain a lower strain-rate experiment then is typical with shock experiments. Fused silica is used as a buffer to introduce a ramp wave of a given applied input stress.

This implies that we should be capable of controlling the strain rate of the input pulse in the sample over the range from 10^4 to 10^6/s.

TABLE 3. Impact Conditions

Shot	Vel. (km/s)	Imp. (mm)	Buffer (mm)	Sample (mm)	Sample Density (g/cm^3)
LSAG-1	0.250	9.499	19.058	2.543	2.262
LSAG-2	0.251	9.455	19.126	5.024	2.290
LSAG-3	0.252	9.442	18.981	10.069	2.331
LSAG-4	0.250	9.467	19.119	7.531	2.292
LSAG-5	0.506	9.606	19.068	2.548	2.296
LSAG-6	0.498	9.526	19.116	5.027	2.296
LSAG-7	0.495	9.588	19.070	10.088	2.344
LSAG-8	0.500	9.580	19.060	7.536	2.306

Eight impact experiments were conducted to determine how the time-resolved ramp waves evolved during propagation through the limestone specimens. In this test series, four experiments were performed at ~0.25 km/s and four at ~0.50 km/s (impact conditions described in Table 3). For each velocity series, an impact generated compression wave propagated through the buffer and achieved a loading time of ~ 0.8 µs at the limestone sample. The varying specimen thickness was used to determine desired wave propagation characteristics. The sample was backed with another fused-silica plate for use as a laser window material. Diffused surface velocity-interferometry was used to measure the transmitted particle velocity profile at the sample-window material interface. Figure 2 represents the ramp load delivered to these specimens, and the observed wave profiles. This time correlated plot depicts both the calculated velocity history of the input pulse from the fused silica into the specimen and the observed velocity interferometer wave profiles at the interface of the limestone specimen and the window material. The predicted time of arrival for the shock propagation through the 20 mm driver of SiO2 and into the limestone specimen, is determined using the stress-strain relation shown is Eq. 1.

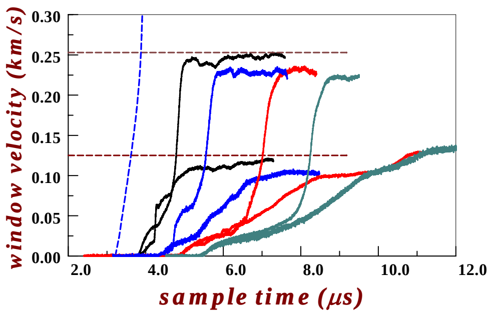

Figure 2. Time correlated wave profiles of Indiana Limestone. Dashed vertical line illustrates calculated velocity history of the input pulse from fused silica into the limestone. Dashed horizontal lines indicate maximum velocity input from fused silica into the limestone based on impact conditions. Time t=0 represents impact time at the fused silica buffer.

ANALYSIS

This section discusses an explicit Lagrangian ICE wavelet analysis program, ICE1[8], specifically developed to allow rapid calculations of stress-strain paths from ramp-loading experiments. Sound speed $c_L(u)$is measured for each set of wave profile data by dividing the sample thickness by arrival times of the wave profiles at a given particle velocity u. The differential form of the momentum conservation equation is then used to calculate the change in stress (dσ) for each step of u, going up the curve u(t). We now can calculate the continuous equation of state (EOS) relationship between stress, sound speed, particle velocity and density. Details of the analysis is based on work by Fowles and Williams[9], McQueen et al[10] and the above mentioned analysis routine[8].

EXPERIMENTAL RESULTS

In the experimental data shown in Fig. 2, particle velocity was measured through the entire loading history. Some features to note in the wave profiles is that we have a generally smooth rise to about 0.025 km/s, followed by an even more gradual rise to the peak value. In the lower velocity experiments, the loading appears isentropic. The profiles become more dispersive with increasing sample thickness, which may indicate that pore closure is not complete. The higher velocity experiments, a shock development is apparent however, we still see the smooth ramp to just above the HEL, at least on the thicker samples. The thinner samples (2.5 mm) exhibited an initial shock like behavior which is not anticipated in a ramp loading type experiment. The reason for this could mean a higher or lower porosity percentage lending to a higher/lower density for those samples.

The stress-strain curves shown in Fig. 3 were calculated for all the experiments at the two different impact velocities. These two stress-strain curves were deduced from ICE1[8] by simultaneously comparing the wave profiles at the different sample thickness for each impact velocity. Therefore, the stress strain data below provides an average interpretation of all the tests performed at each impact velocity.

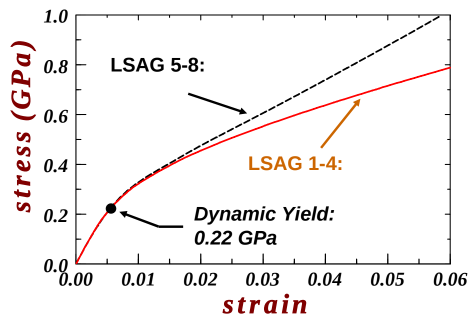

Figure 3. Stress strain plot of various thickness of limestone at two different input conditions.

Fig. 3 provides details of the magnitude of the stress at the yielding of the material. Dynamic yielding in material response has been shown to provide a two wave structure in the loading[9, 11] wave so one can conclude that the initial break (Fig. 3) is the onset of yielding in the limestone. From the analysis routine previously described, this corresponds to a stress of 0.22 GPa. This stress agrees with previous shock experiments[5].

STRENGTH AT THE HEL

One of the principle focus's of this study was to estimate the strength at or around the HEL under higher strain conditions than can be achieved in

Hopkinson bar experiments, yet lower strain rates than previous shock experiments[5, 6] on Indiana limestone. For one dimensional compression, the stress determined in shock experiments is the stress normal to the shock front. This can be denoted by σ_x and at the HEL it value is given by $\sigma_x=\sigma_{hel}$. Elastic theory states, $\sigma_y = \sigma_z$, parallel to the wave front, are related by σ_x by; $\sigma_y = \sigma_z = (\nu/(1-\nu))\,\sigma_x$, where ν is Poisson's ratio. The maximum shear stress is given by $\tau_{max} = [(1-2\nu) / (1-\nu)](\sigma_{hel}/2)$, where τ_{max} is the maximum shear stress, ν is Poisson's ratio, and σ_{hel} is the determined stress at the onset of dynamic yielding. For the case of uniaxial stress, the maximum shear strength at the HEL, thus is related to the strength Y_{hel} by:

$$Y_{hel} = 2\tau_{\max} \qquad (2)$$

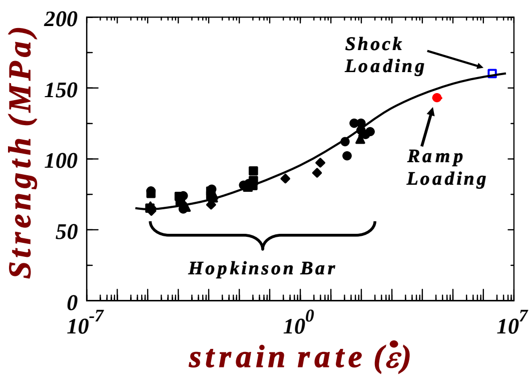

Figure 5. Strain rate sensitivity of the compressive strength of Indiana limestone. Ramp and shock loading data is expressed as an average of multiple experiments. Ramp loading experiments were analyzed by Lagrangian methods on all waveforms at the various thicknesses.

Figure 5 compares the ramp loading experiments with shock and Hopkinson bar data[5, 7]. As was concluded by the Hopkinson bar technique, the compressive strength of Indiana limestone appears to be still increasing with increasing strain rate, however the shock data may be indicating that the increase in strength (10% per decade[12]) with strain rate may be decreasing.

SUMMARY

We have used fused silica as a pulse shaping technique to introduce ramp loading into Indiana "dry" limestone. The strain rates achieved on these experiments are substantially reduced (10^4/s) when compared to the shock experiments, but higher than those for Hopkinson bar experiments. The strength of 0.140 GPa indicates that the strength is increasing as a function of strain rate. This technique bridges the gap between lower strain rate experiments and those conducted under shock loading for Indiana limestone. The results of this study suggest a continuous increase in the failure or compressive strength of the material with increasing strain rate.

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