

Gas percolation through sand

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Abstract. Previous research has determined the shock properties of quartz sand. The effect of the physical processes occurring with varying moisture content and particle size were shock presented. In this study the same quartz sand, in a column is subjected to blast waves over a range of pressure. The diagnostics used are pressure sensors and high-speed photography. The effect of grain size on propagation time and the effect of moisture content are determined. Aspects of particle and liquid movement are also discussed. While the velocity of the percolation through the bed is primarily controlled by grain size the effect of moisture and liquids reveals a more complex dependence.

1. Introduction

Granular materials are of interest in a wide range of applications; however, here the interest is on the effect of gas percolation through columns of material. When explosives are detonated within granular materials, the particles immediately around the explosive tend to be shattered and compacted by the primary shock wave. This produces compact material which expands before fracturing. When this fracturing occurs the product gases can percolate through relatively undamaged material. Previous studies have concentrated on the shock properties of a quartz sand of mean particle size 215 microns both in dry [1-4], 5, 10, 20 and 22% weight water [5]. The main result from this was that water did not significantly affect shock propagation in the range dry to 10% weight water. At higher moisture levels the shock propagation was faster and the shock rise time shortened with increasing water content. This was probably due to the porosity, voids and gas spaces in the material, falling to a level similar to the compression caused by the shock stress.

Under lower strain rate loading, in Hopkinson Pressure Bars and in Drop-weight systems, sand particles in the sample, dry or with moisture, did not shatter under impact loading until a stress of 0.2-0.3 GPa was applied. At higher dynamic stresses the material shatters and compacts with increasing regularity and rapidity, reducing the thickness of the stress or shock front, and producing increasing compaction. Related research on low-level shocks reveals a pre-cursor wave moving through the skeletal connections of the nascent bed, which has a relatively fixed velocity. Eventually this pre-cursor wave is not observed, due to the increasing shock velocity seen with increasing stress.

Overall the shock propagation of this sand has been well studied and reported. The features and processes seen in the shock process are also reported by many other researchers in this field. The aim here is to examine this well-characterized material under the much lower stresses and strain rates associated with gas percolation and determine if the same processes and dependencies occur.

2. Experimental

Five different ranges of grain size were studied; micrographs of representative grains are shown in figure 1, the range of grain sizes in table 1.



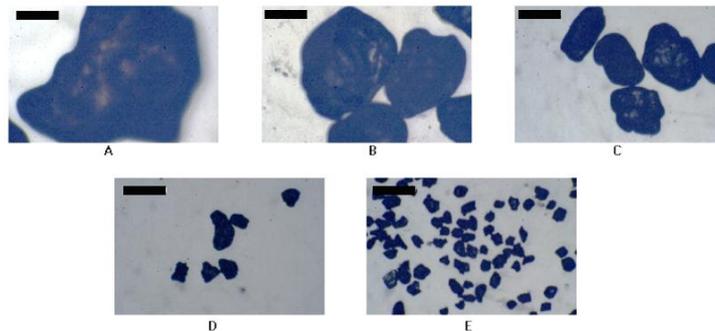


Figure 1. Micrographs of the grains used. All images are at the same magnification and the black bar present at the top of each image is 500 microns long.

Table 1. Range of grain size in each sample.

Sample	Grain Size (microns)
A	1180-2360
B	600-1180
C	300-600
D	150-300
E	90-150

Table 2. Porosity for Sand-Water/Sand-Oil mixtures.

Sand-water mixes (wt ratio)	Volume % Porosity
Sand (dry)	43
20:1	38
20:4	22
20:6	11
20:8	3

Figure 2 is a schematic of the equipment used in this experiment. The sample was poured into the steel chamber, a tube 22.1 cm long and with an inner diameter of 6 mm. This was bolted onto the frame; the driving chamber was pressurized with nitrogen gas. Once the desired pressure was reached, the solenoid release button was depressed releasing the gas through the sample. The output of pressure sensors, time resolution 10 microseconds, positioned at the top and bottom of the chamber recorded the signals. The peak to peak time was recorded in each case this gives a measure of the time the gas pulse takes to percolate through the sample.

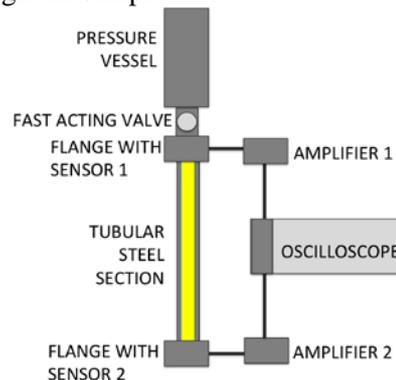


Figure 2. Schematic of experimental apparatus.

It is well known that granular samples can settle with shaking, the extent of this was studied. Preliminary tests showed negligible changes in pulse shapes or height during twenty repeated pulses at 20 bar pressure and a maximum decrease of approximately 10% in peak to peak time after a further ten pulses. All samples were studied at 10 bar pressure intervals between 10 and 40 bar with three repeats at each pressure. This ensured that the data taken was minimally affected by the effects of repeated pulses.

Experiments with; an empty chamber, the chamber filled with water, filled with oil or filled with a saturated water-sand or sand-oil were conducted. In all these cases the time to equilibrium was faster than the time resolution of the pressure gauges. This is to be expected, given the sample size and the sound speed of the materials.

3. Results and discussion.

Experiments were conducted for dry sand samples A-E. The pour density of the sand was in all cases $1.5 \pm 0.1 \text{ g-cm}^{-3}$, representing 43% volume porosity. Studies were also conducted with a 50:50 weight mix of A and E, giving approximately 18% volume porosity. Figure 3 shows the peak to peak time variation with the driving pressure. It can be seen that peak to peak time decreases with pressure and with increasing grain size. The A-E mix shows a response intermediate between the A and E samples, but very close to that of grain size E. Also shown are normalized pressure time traces for size C, time is normalized by adjusting the 25 and 75% peak pressure to the same in all cases, while pressure is normalized by peak pressure reached. In all cases the shape is the same, indicating the overall process followed the same *class* of dynamics i.e. the overall process can be described by the same theory.

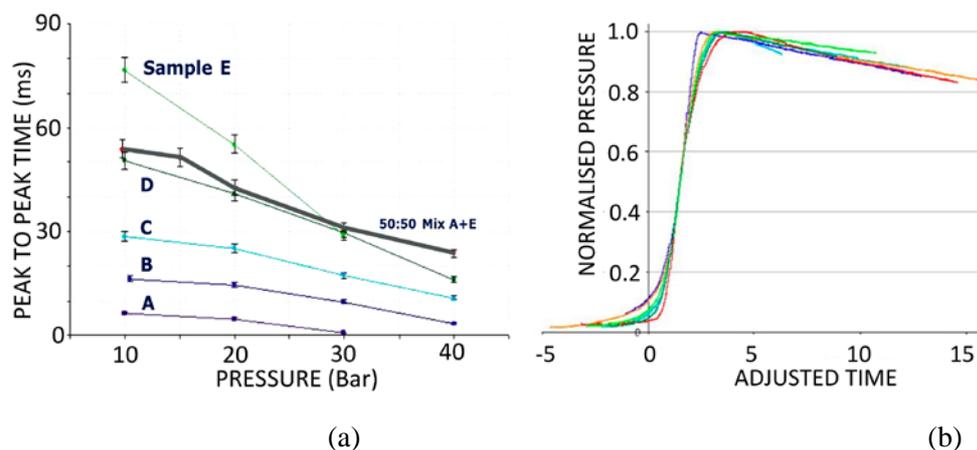


Figure 3. (a) Peak to peak time for different driving pressure and grain size. (b) Normalized graphs of the pressure profile seen at the base of the sand column.

To study the effect of adding water 20 g samples of sand were mixed with 1, 4, 6 or 8 g of water, the mix introduced into the chamber and the study repeated. For size C with 20:4 sand-water, 3 independent samples were made and studied, to determine the effects of sample to sample reproducibility. The range of gas porosity is shown in table 2.

Figure 4 shows the results for the effect of water content. When the sand-water mix is 3% porous the response is indistinguishable from that of saturated sand-water or water, except at the lowest driving pressure used. Dry sand and 20:1 sand-water are indistinguishable. The three repeats at 22% porosity indicate some variation with sample preparation but not significant enough to mask the trend. The material with the longest peak to peak time is 11% porous.

In the shock regime, the porosities in the range 11% - 3% are associated with dramatic changes in the shock velocity of the material. Here this dramatic change is also seen. In shock regimes little difference is seen in shock velocity with a sand-water until ratios of 20:4 were used, this trend is also seen here. The main difference between this percolation data and shock data is that shock speed is unaffected until a 20:4 ratio is reached where the shock speed increases rapidly with saturation. Here, for gas percolation, the overall velocity of the system decreases upon adding water until it increases markedly as the porosity drops below 20%.

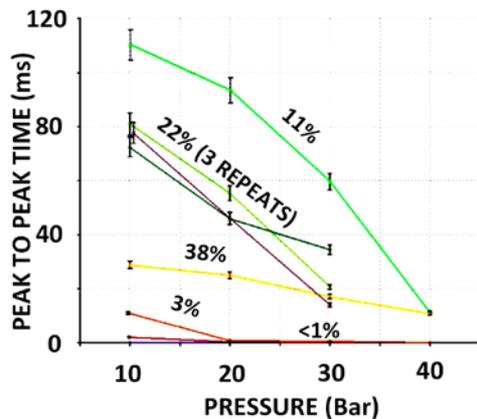


Figure 4. Peak to peak time for fraction C sand:-water mixes. The percentage is the residual porosity of the mix

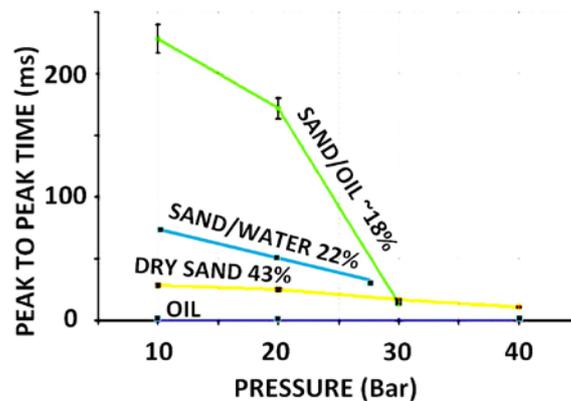


Figure 5: Peak to peak time for sand-oil mix in comparison with oil, dry sand and sand-water 22% porosity

Using a transparent column in place of the steel chamber and high-speed photography showed that the entire column compressed by less than 1 mm under the highest pressure pulse used. The pressure pulse did not cause extensive liquid movement at the bottom of the column. With the largest sand grains it could be seen that occasionally small droplets of liquid, 1-5 droplets per column, droplet diameter ~ 200 microns, could move about 10 grain widths under the gas flow.

Studies were conducted using a castor oil-based lubricant (Weldtite) in place of water. The mass of oil added was adjusted to take account of the measured oil density, 1.18 g cm^{-3} , the overall aim being to obtain approximately the same sample porosity as for sand-water mixes. The viscosity of this oil, was approximately 1000 times higher than water: measured as $985 \times 10^{-3} \text{ Pa-s}$ compared to $0.89 \times 10^{-3} \text{ Pa-s}$ at 25°C .

With the castor oil the qualitative trends were the same as water, but the peak to peak time was considerably increased. As shown in figure 5 this could result in a four-fold increase in peak-to-peak times. High-speed photography showed limited grain movement and fewer liquid droplets moving, on average 1 per column for the highest pressures and largest sand grain size. A similar trend was found with mineral oil

4. Conclusions

The peak to peak times increase as the grain size decreases. Samples of equal weight mixtures of two grain sizes result in peak to peak times closer to that of the smaller grain size. While this may seem intuitive, there is an obvious porosity difference involved. The scaling of the response pulses shows similar kinematics in all cases.

If a liquid is introduced then the time for a pressure pulse to pass through the chamber is increased, until close to the point of liquid saturation, when it reduces dramatically. The peak to peak time can be doubled in the case of 22% porous sand water. This time can be increased by a factor of 4, over dry sand, for samples which have oil in place of water.

While the limiting porosities for these changes are similar to those seen in shock experiments, which use higher stresses and much higher rates, the details of the effect is markedly different. The liquid would seem to slow gas motion through the pores.

Overall the system depends on (a) a critical porosity level, above which the material behaves as saturated (b) a porosity below which the percolation is unaffected by the precise porosity used (c) the driving pressure and (d) the presence and viscosity of the liquid present.

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