Shock, Ballistic and Blast Properties of Granular Materials.

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Coimbra June 2016 – Invited Talk

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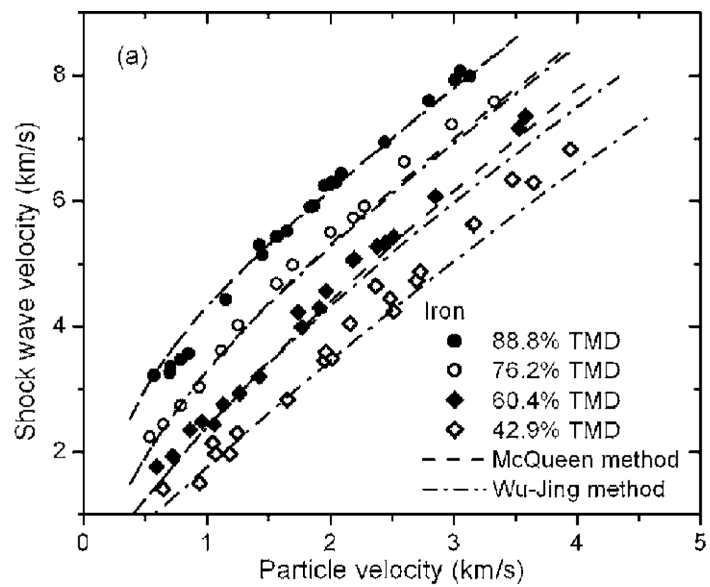
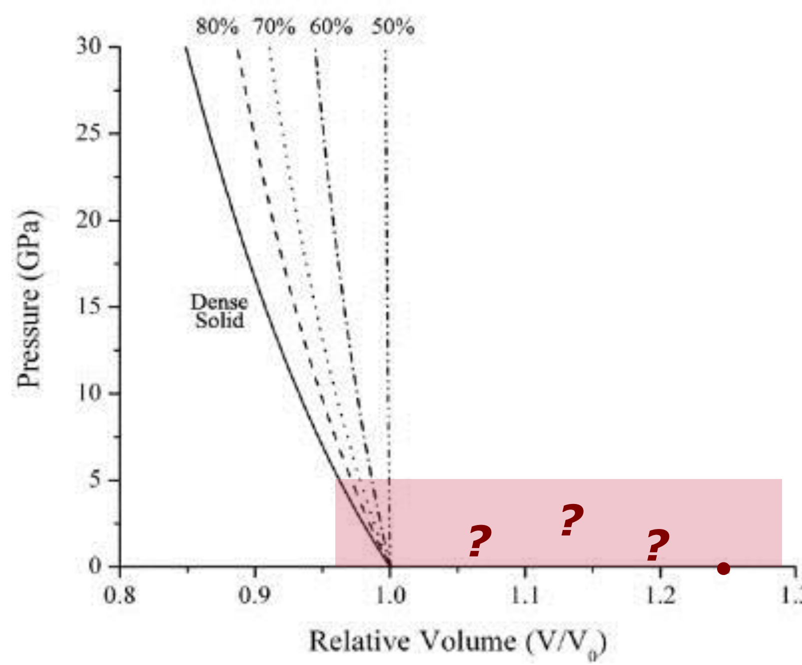
Powders under shock loading

Response of powders to intense loading is reasonably mature

Porous models (McQueen, Wu-Jing, etc.) enjoy moderate success *once significant void volume is eliminated*





Densification process ignored

Densification at low stresses

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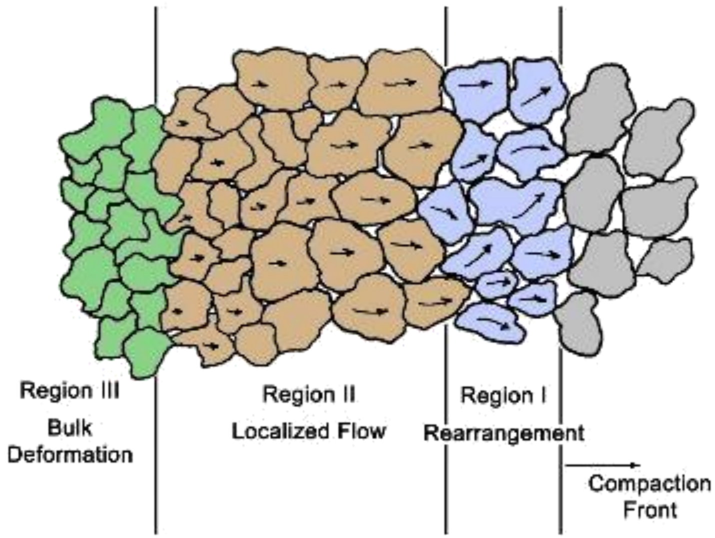
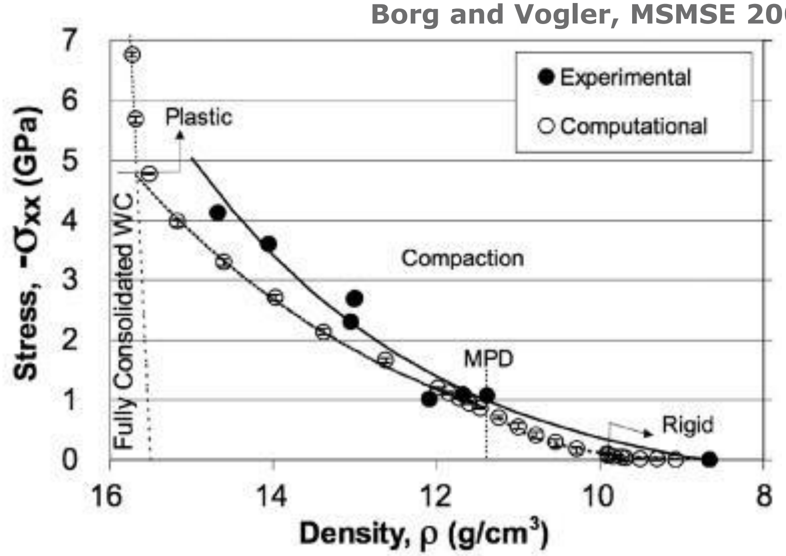


Borg and Vogler, MSMSE 2009



Several regions associated with the densification of granular materials under shock compression: rigid / compaction / bulk plastic

Models for compaction are generally exercises in curve-fitting, insensitive to microstructure

Compaction

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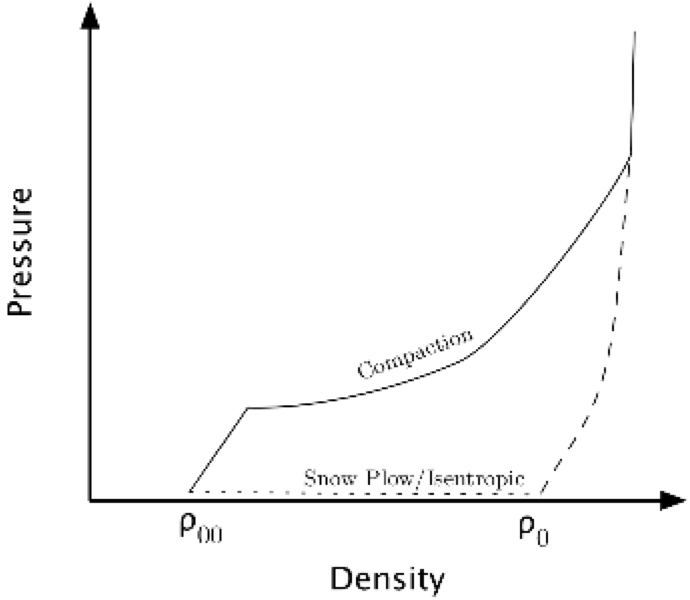
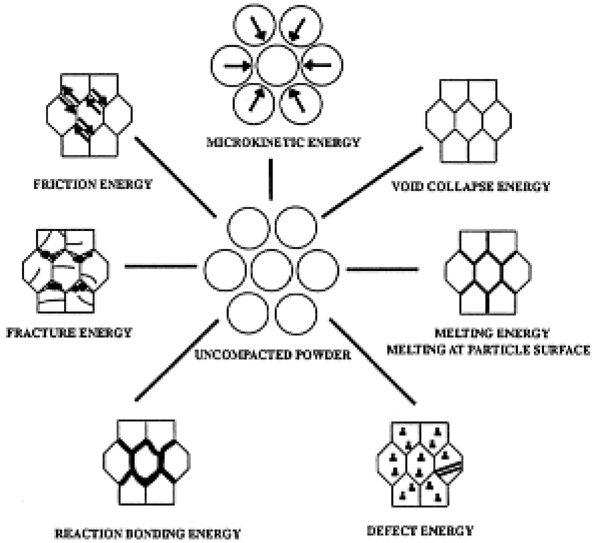


COMPACTION

- States with porosity.
- Significant energy absorption.
- Dominated by meso-structure of granular material.



Meyers. Benson & Olevsky. Shock Consolidation: Microstructurally-Based Analysis and Computational Modeling. Acta matter 1999,

ENERGY DISSIPATION

- Compaction energy associated with porosity removal.
- Quasi-static or dynamic – Benson et al. JAP 1997
  - Processes present in quasi-static compaction.
  - Processes ONLY in dynamic compaction.

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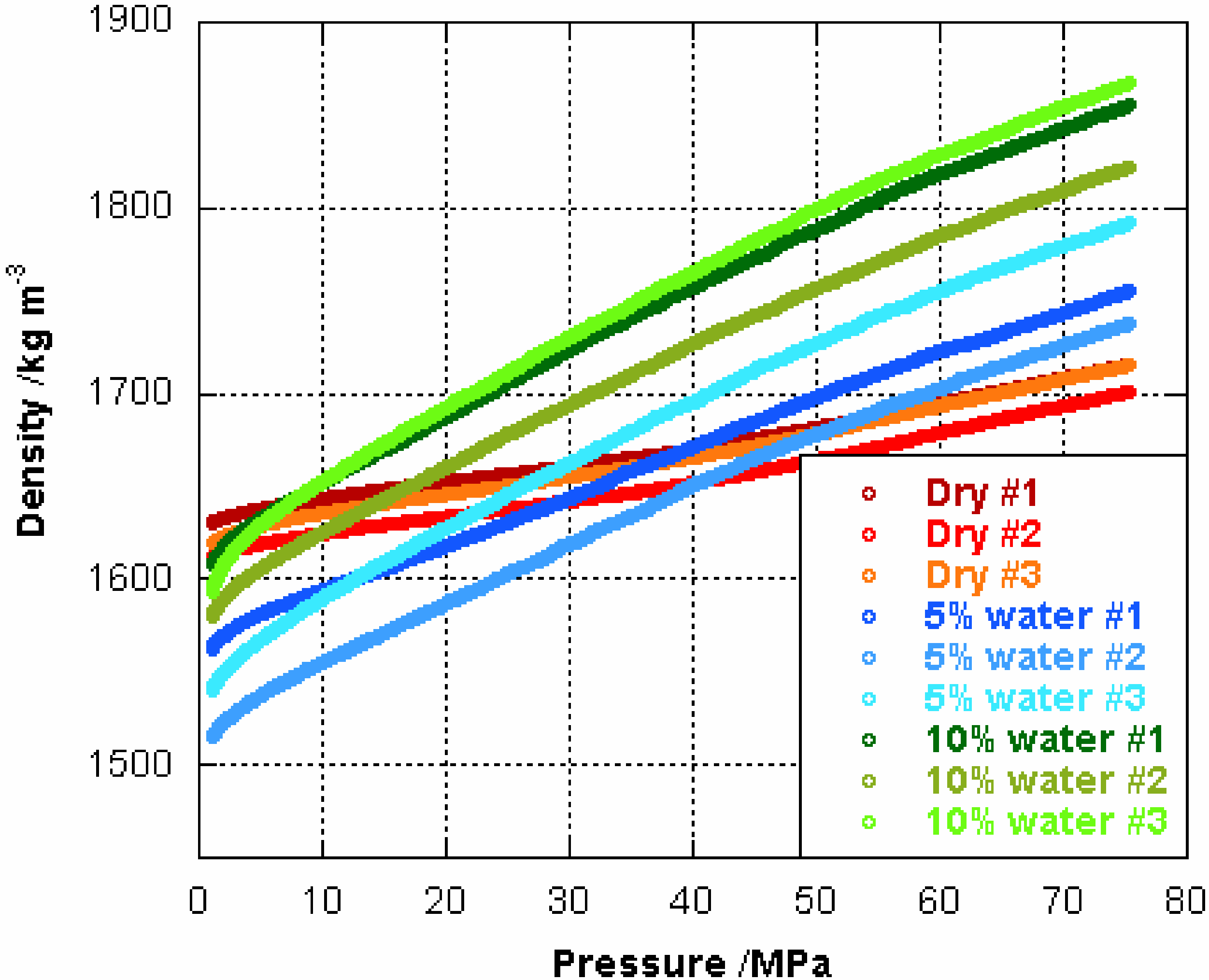
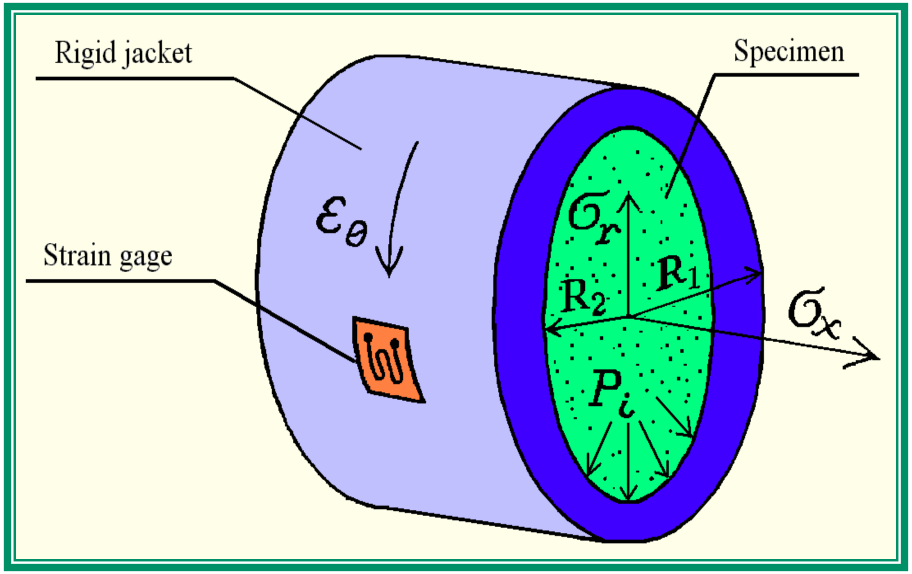
Low-Rate : Moisture Content



W. G. Proud et al., SCCM 2007

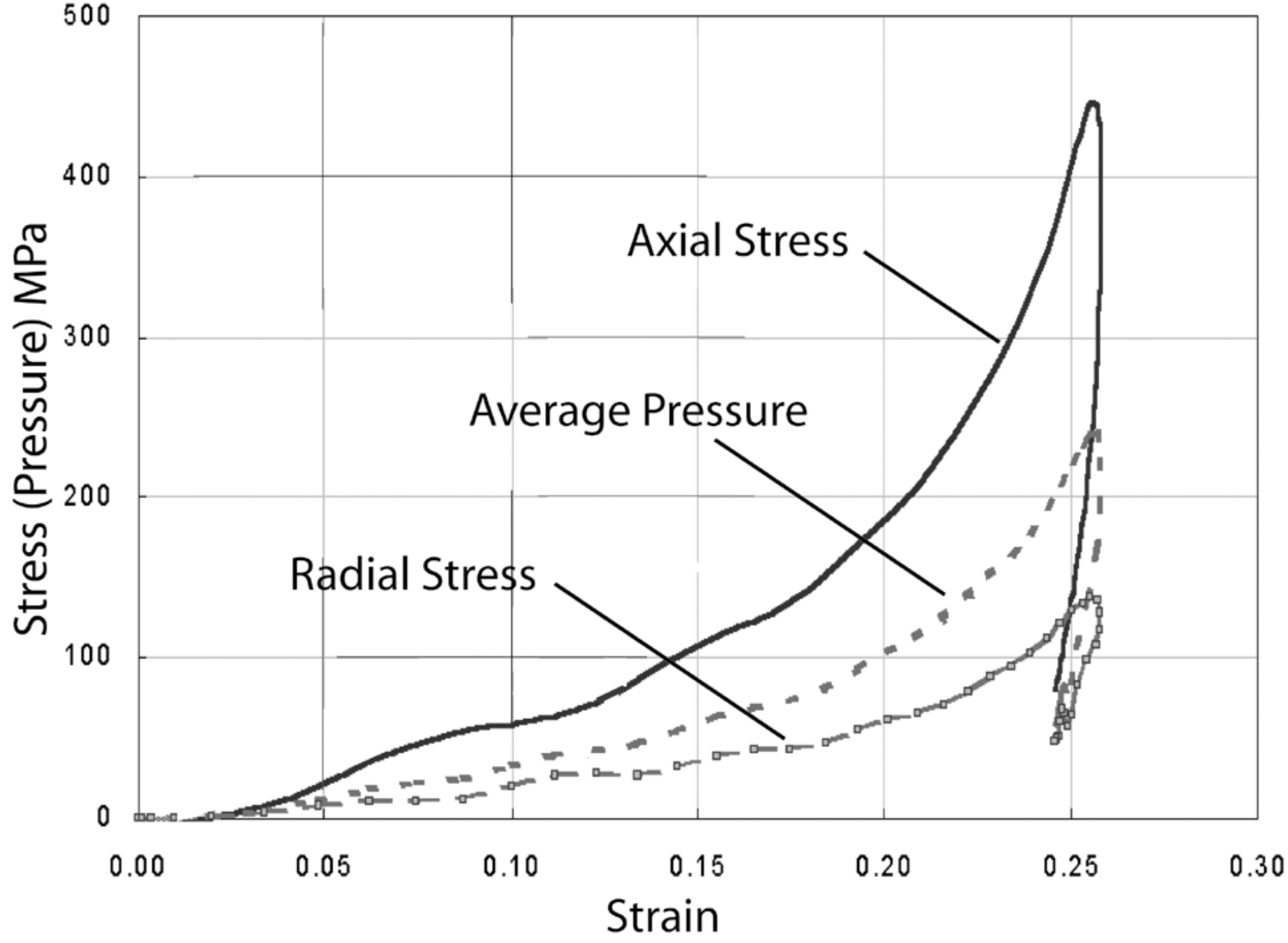
Intermediate Strain Rates - SHPB

Stress components in a specimen and in the confined jacket



Bragov *et al*., International Journal of Impact Engineering 35 (2008) 967–976

Data obtained



Sample Arrangement (High-stress)

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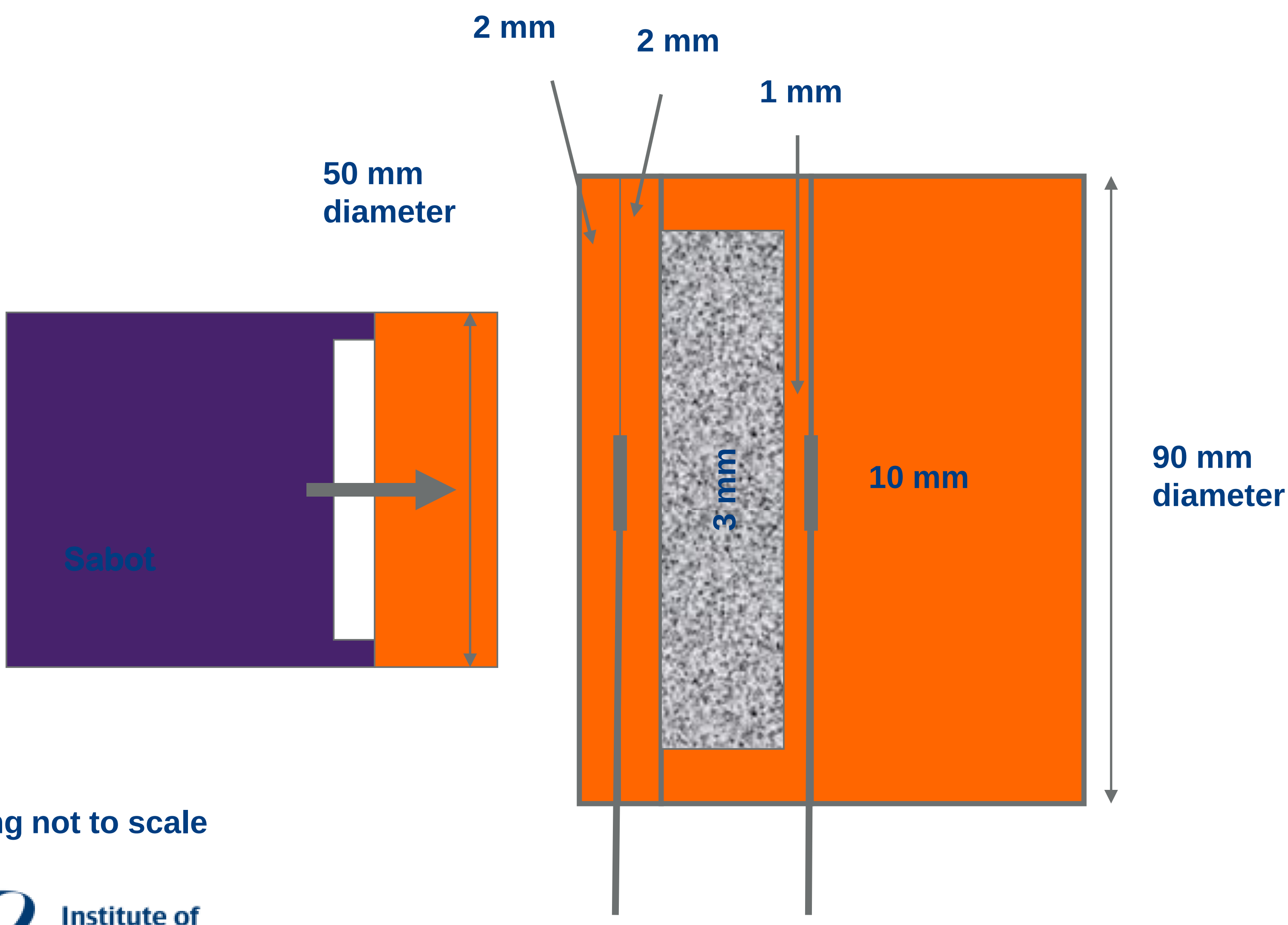

Drawing not to scale

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Plate-impact experiments

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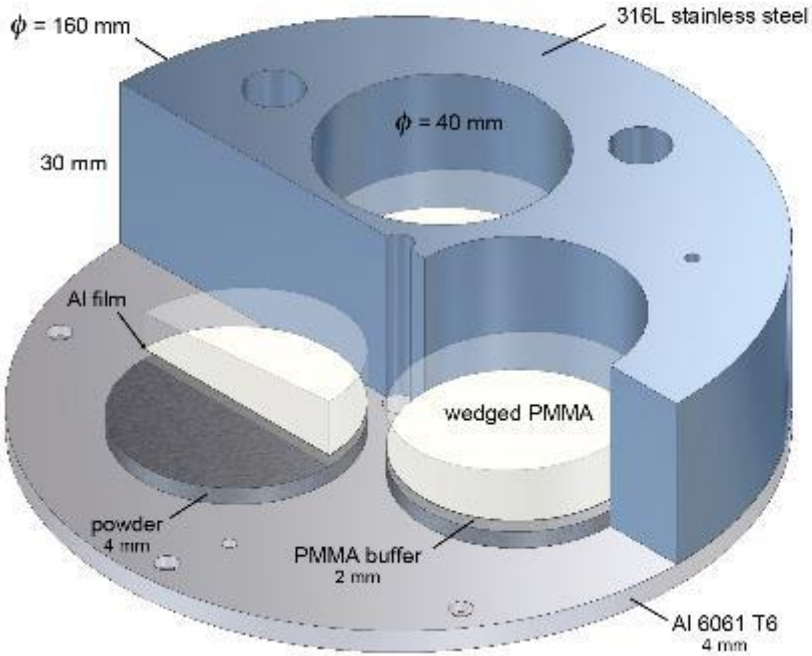

Measured tilt < 2 mrad

Multiple powder targets subjected to identical loading

8 HetV channels and two pins to measure sabot velocity, impact and breakout tilt, and target particle velocity

D. Eakins *et al.* SCCM 2011

Rear Gauge Variation

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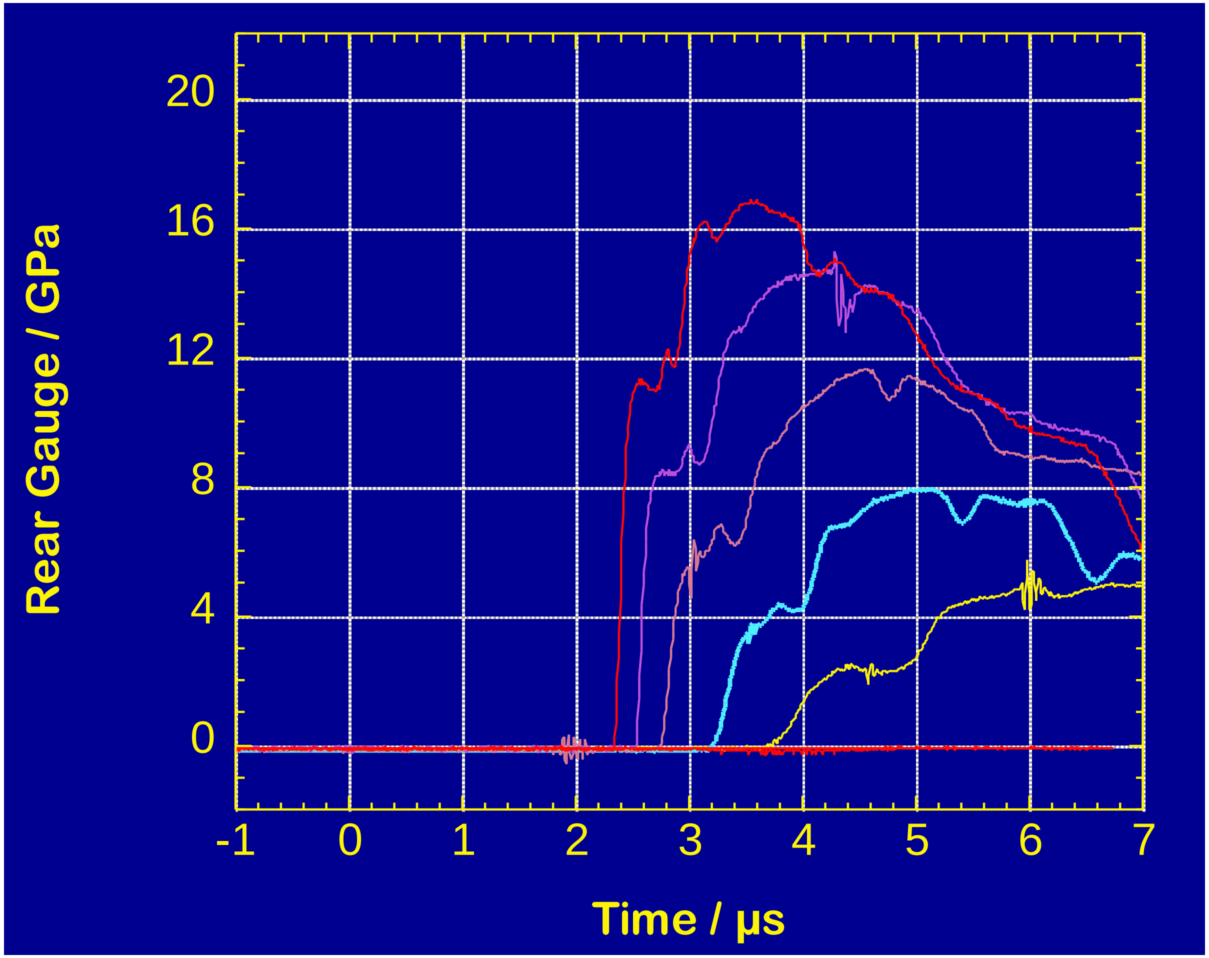

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Shock thickness / particle size

Rise time of first pulse

Shock velocity

200 m s^{-1}

- 1 μs rise time and U_s 1 mm μs^{-1}
- 1 mm or 4 grain particles

500 m s^{-1}

- 0.5 μs rise time U_s 1.4 mm μs^{-1}
- 0.7 mm or 3 grain particles

800 m s^{-1}

- 0.2 μs rise time and U_s 2 mm μs^{-1}
- 0.4 mm or 2 grain particles

Results Combined Stress + Pressure

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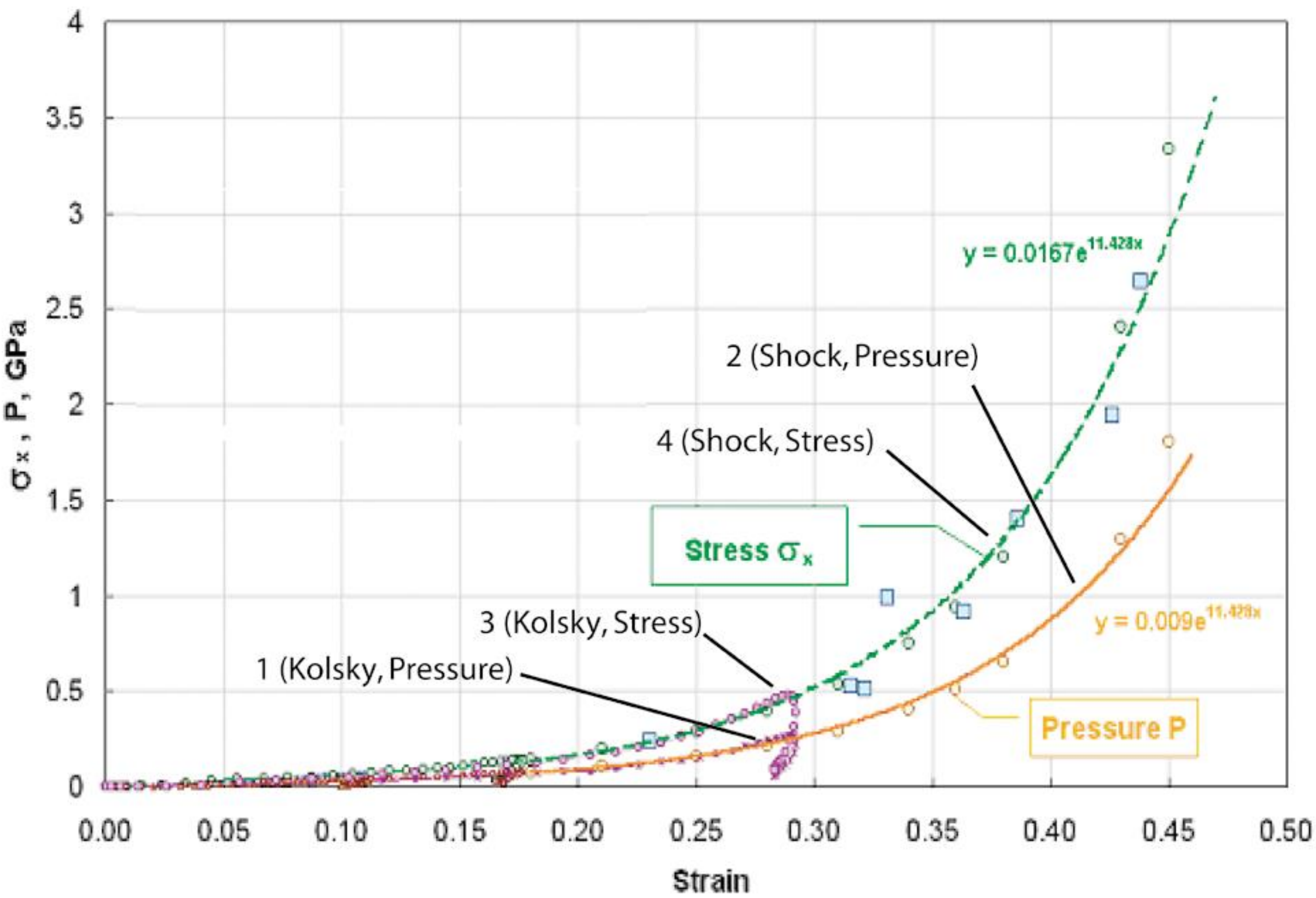

Initial Conclusions

- A given granular material compaction behaviour is self-consistent across the range of strain rates
- Probably due to the system being able to move from one compaction process to another in a ‘smooth’ fashion.
- Quantitative prediction of the compaction process is difficult and often a case of post-experiment curve fitting.
- **However – this is very much a first-order approximation**!
- So can we look at some aspects in more detail?

Compaction: Material Characterisation

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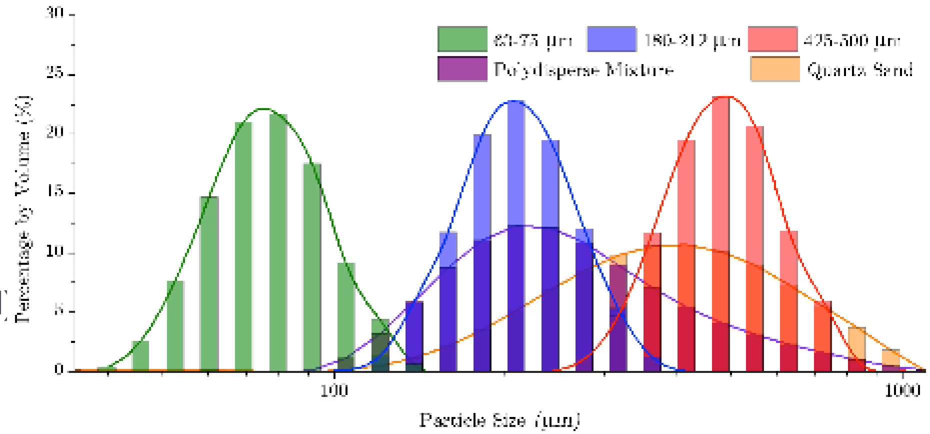
SAMPLE MATERIALS

- **Soda-lime glass microspheres – Whitehouse Scientific**
  - **3X monodisperse distributions**
  - **1X polydisperse distribution**
- **Quartz Sand – Eglin Air Force Base, Florida (Eglin Sand)**

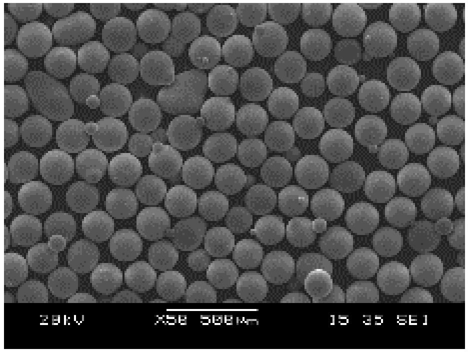


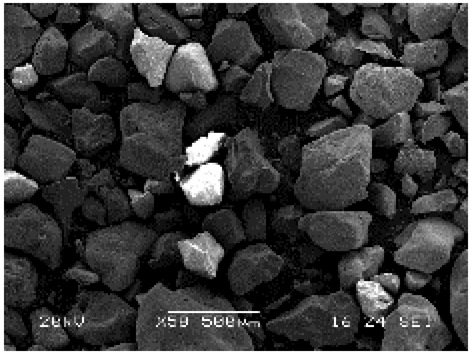
PARTICLE SIZE ANALYSIS

- **Malvern Mastersizer laser diffraction particle size analyser.**
- **Narrow distributions**

SCANNING ELECTRON MICROSCOPY (SEM)

- Spherical particles
- Some surface flaws.





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Quasi-static Compaction Experiments

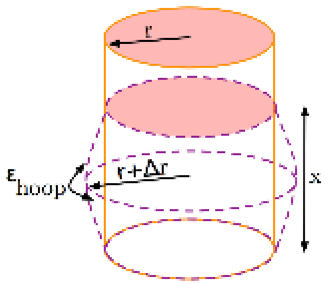
AIM

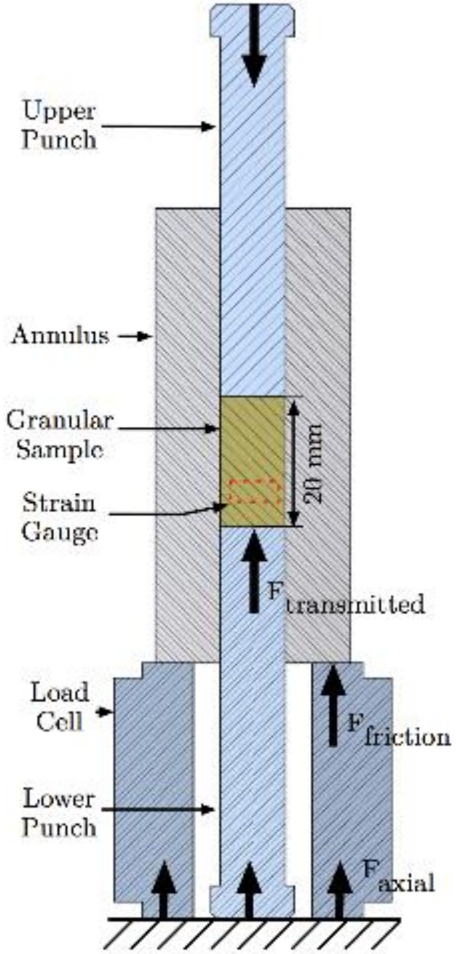
- Determine quasistatic response to easily analyse morphology changes within bed.

METHOD

- Wall friction effects reduced and removed.

- Sample volume calculated through displacement and annulus strain measurements.





Stress-Density Response

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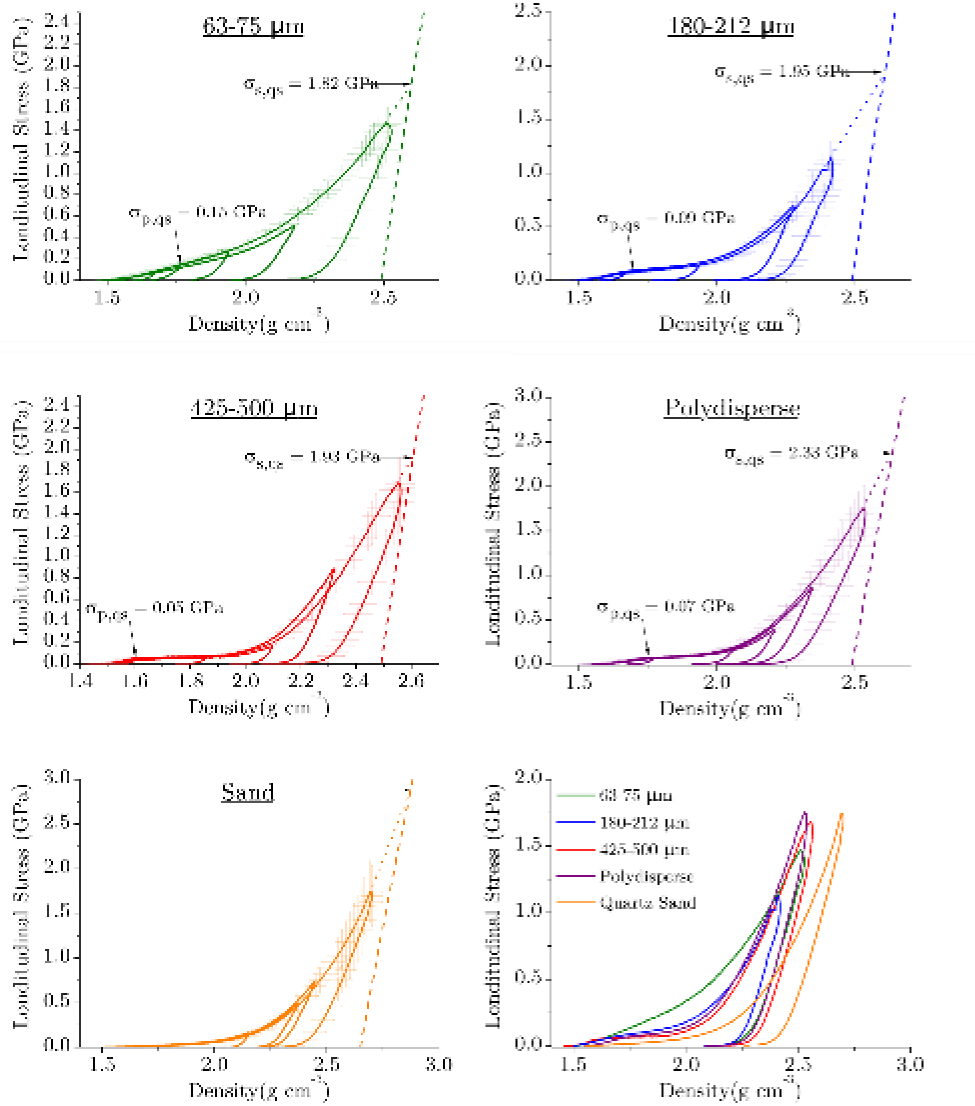
RESULTS

- Microsphere samples showed transition in loading curve indicating increasing strength with decreasing particle size (σ_p).
- More energy absorbed during compaction with smaller particles.
- No measurable transition in sand samples (σ_p=0).
- No trend in stress required to achieve full compaction (σ_p)
- Porosity was present in all compacted samples.



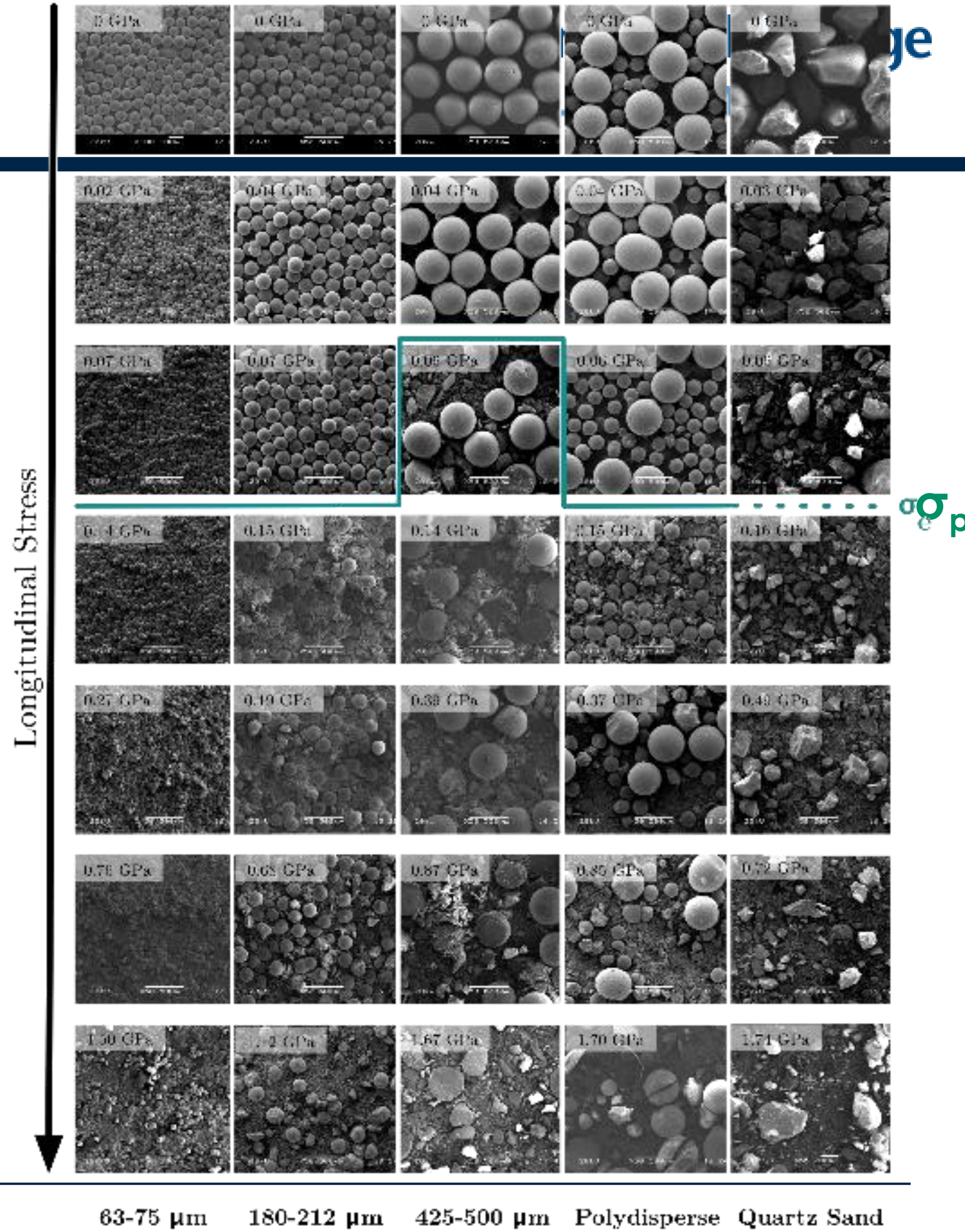
Post Loading Analysis

SPHERES

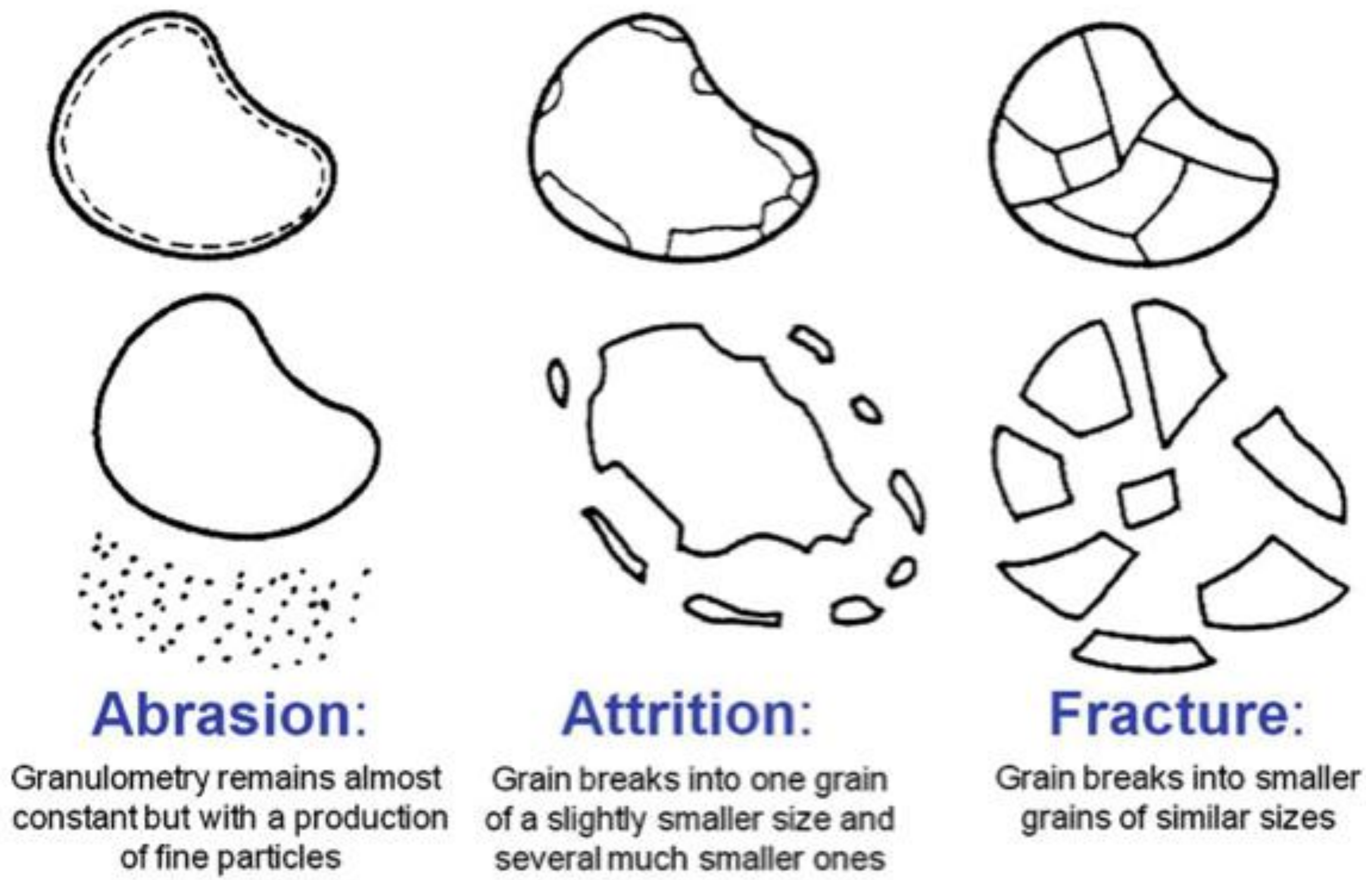
- No fracture seen in stresses below σ_p.
- Fracture initiates at σ_p
- Large amount of whole spheres beyond σ_p.

SAND PARTICLES

- Constant fracture even at minute loads.
- Difficult to determine which particles fractured



Particle Fracture Modes



W. Cooper and B. Breaux. Grain fracture in rapid particulate media deformation and a particulate media research roadmap from the PMEE workshops. Int J Fract. 2010

Shock Compaction Experiments

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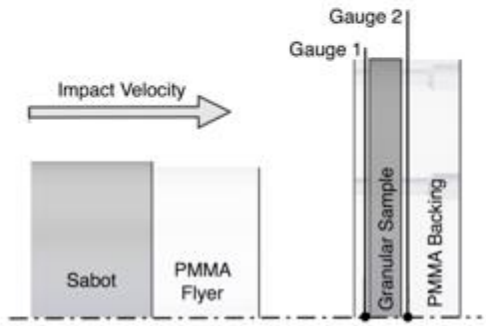
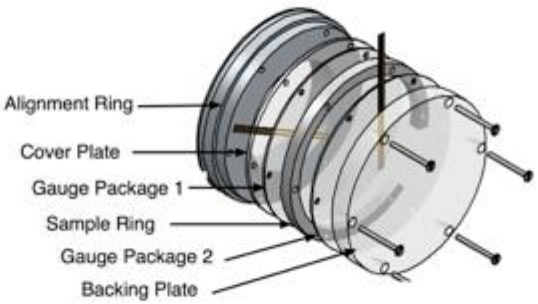
PLATE IMPACT TESTING

- 50 mm Single stage light gas gun
- 200 – 1000 ms^{-1} PMMA and Cu flyers
- Velocity: ± 1%
- Alignment: ± 2 mrad

CELL DESIGN

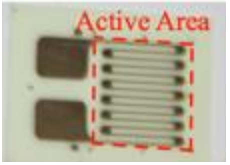
- PMMA encapsulation
  - » Impedance match to epoxy resin
  - » No "ring up" in gauges
  - » ± 4μm parallel
- Longitudinal stress gauges (LM-SS-125CH- 048)

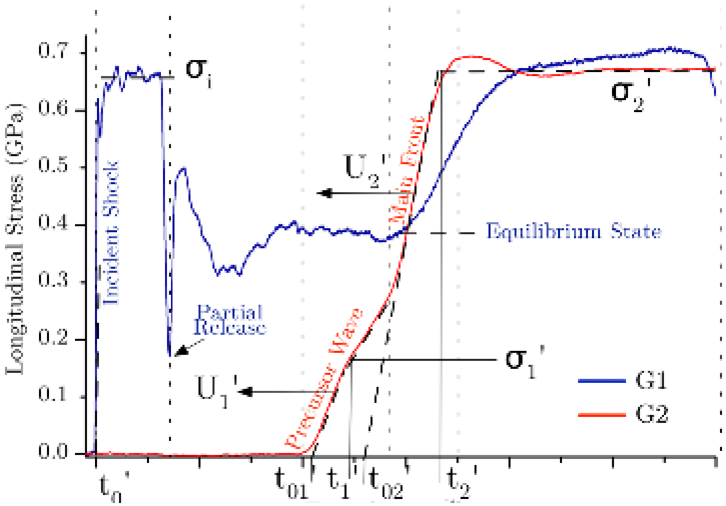




MANGANIN LONGITUDINAL STRESS GAUGES

- Piezo-resistive response to longitudinal stress
- Macro-scale measurement.
- 14.15 mm^2 active gauge area.





Shock-wave Evolution with Input Stress

Precursor

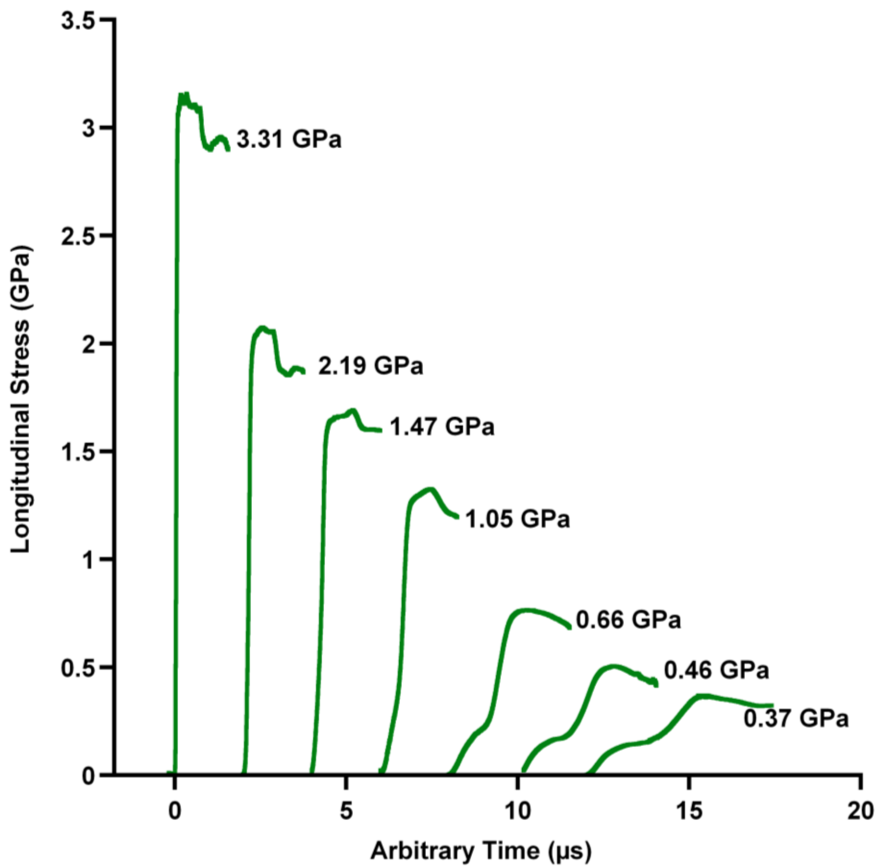
- Constant Stress
- Particle Rearrangement? *
- Decays with Input Stress

Shock

- Rise time decreases

Overshoot

- Proportional to bed thickness
- “Partial release due to particle fracture”*



*Tsembelis et al, 2002

Precursor Evolution – Bed Thickness

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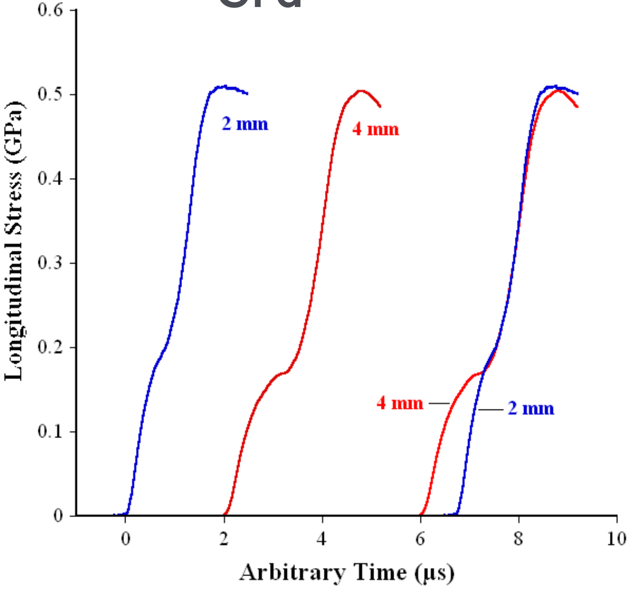
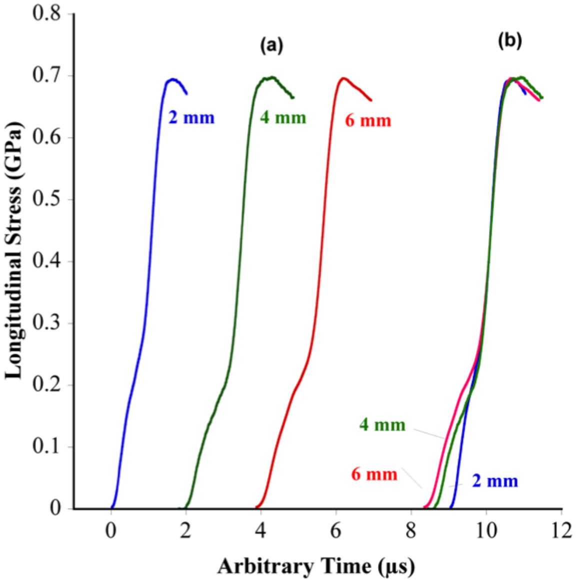
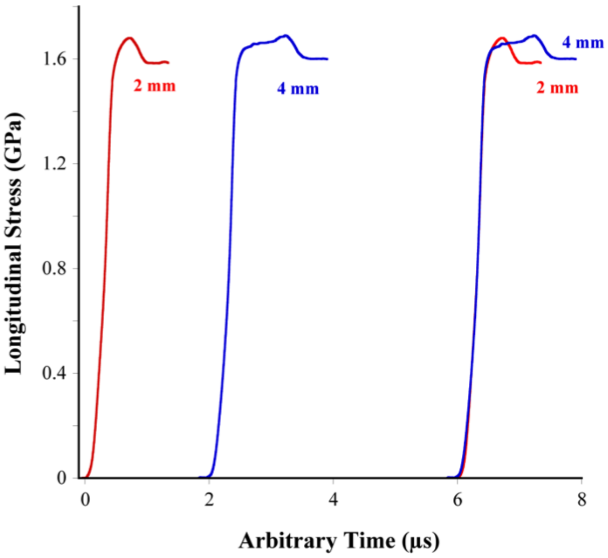
σ $_i$= 0.46 GPa



σ $_i$= 0.66 GPa



σ $_i$= 1.47 GPa



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Particle Size Effects

Prior Understanding

- Hugoniot is not affected by particle size (metal powders*)
- Shock-wave thickness is proportional to particle size (metal powders*)

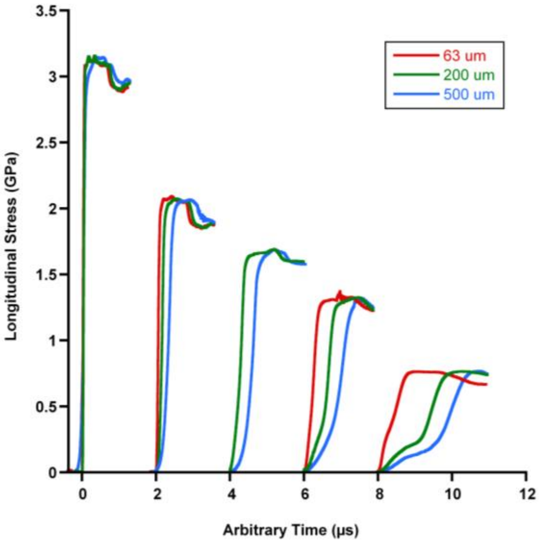
Current Conclusions

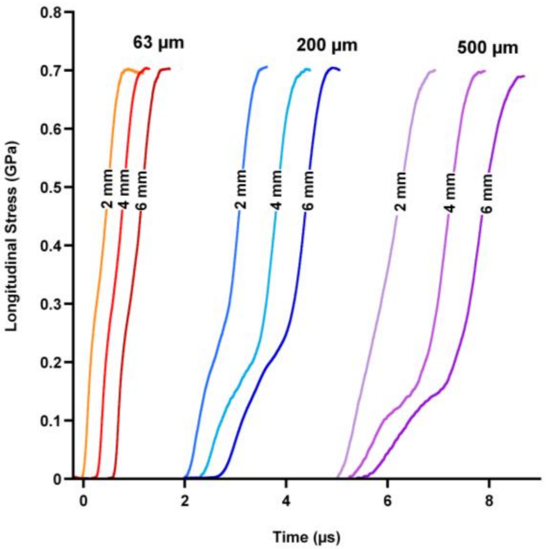
- Shock thickness is affected by particle size (mono-disperse) or some length scale
- Clear difference in shock TOA (U_S)

Ongoing Investigation

- Bi-dispersity
- Reduced porosity
- Particle size or pore size dependent

*Nesterenko, 2001





Shock Compaction Curves

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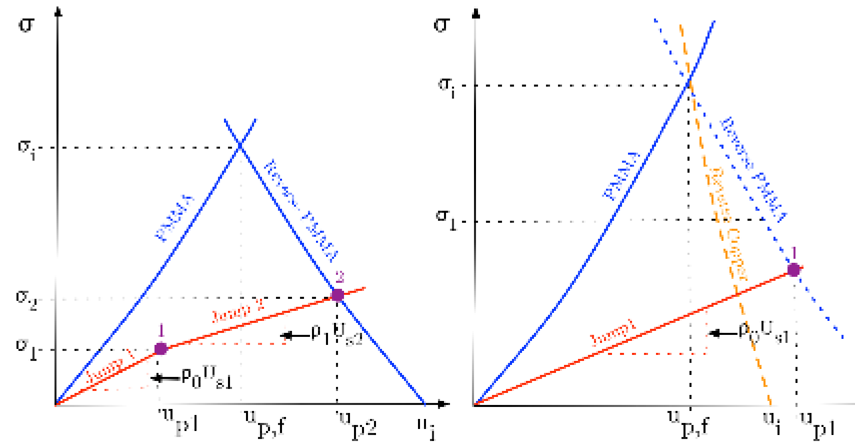
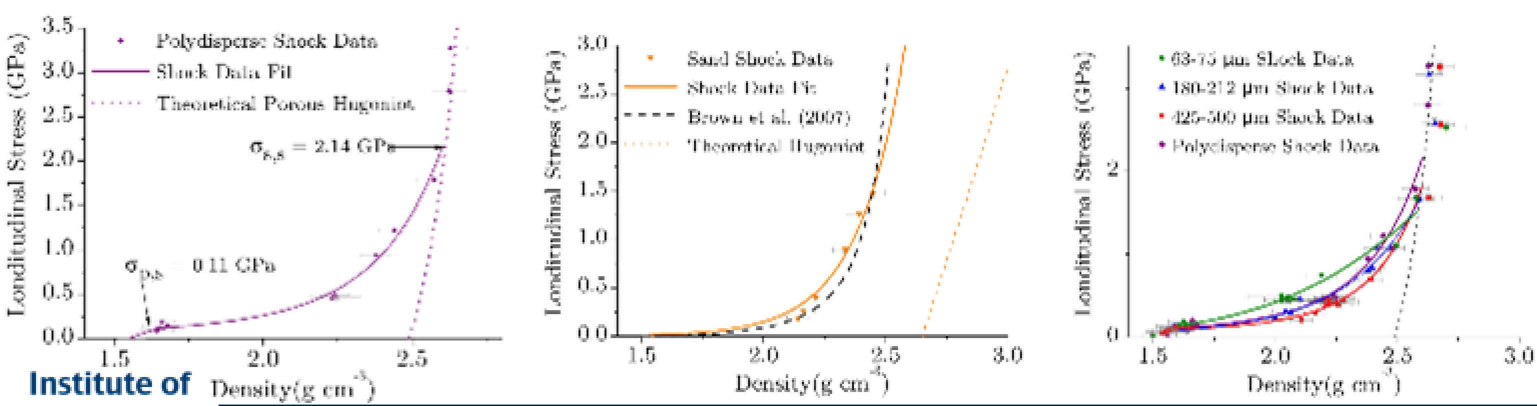
ANALYSIS PROCESS

- Linear fits to transmitted wave profiles.
- Wave velocity measured and jumps applied to infer densification.
- Relatively insensitive to wave magnitude

COMPACTION CURVES

- Precursor wave inferred initial jump.
- Magnitude increased with decreasing particle size.
- Microsphere curves intersected porous Hugoniots.
- No measureable precursor wave in sand.





Comparison Between the Strain Rates

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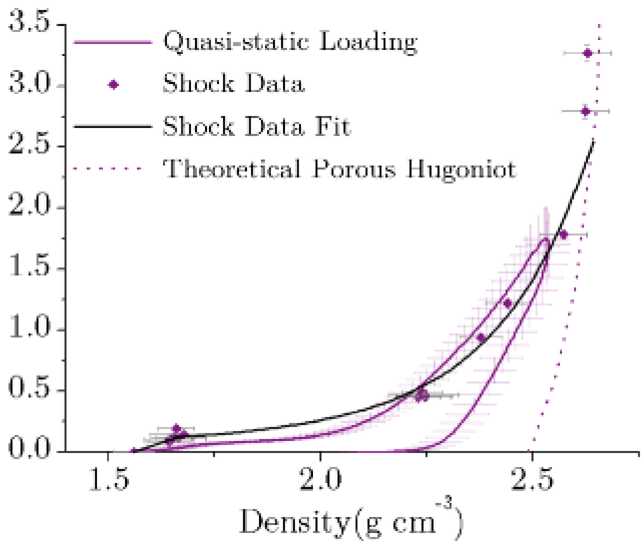
SPHERES

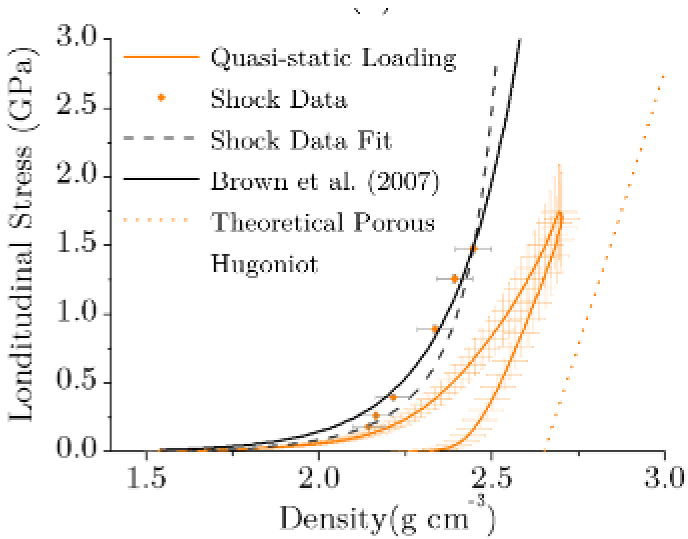
- Shock compaction curves agree with quasi-static curves.

- Initial strength of beds higher in shock compaction regime. More particle fracture?

SAND

- Curves do not agree.





Conclusions (Compaction)

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The compaction response is affected by particle size.

Beds of smaller particles have an increased macro-scale strength due to a likely increase in load carrying contacts at a boundary despite a reduced particle strength.

The compaction wave profile affected by particle size

The wave duration and features are dominated by particle size. The particle-elastic-limit of a bed produces a precursor feature.

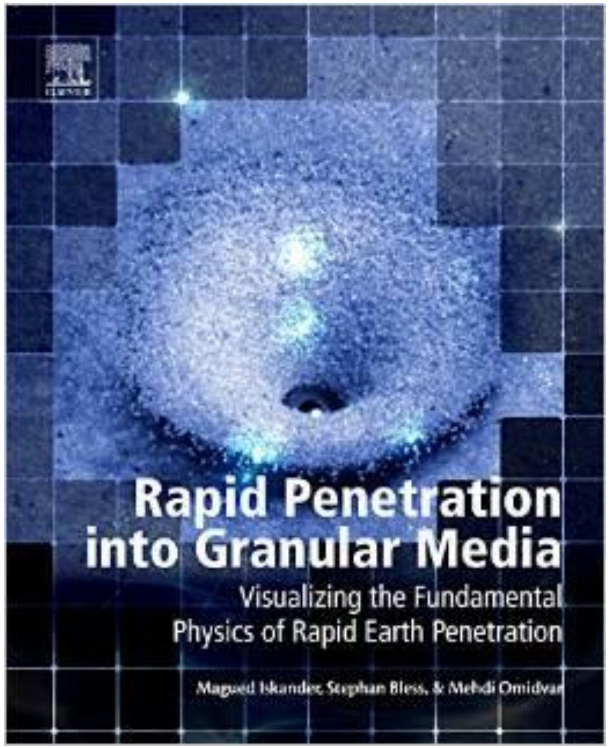
Compaction of Brittle granular materials

There are fracture dominated processes that are controlled by particle morphology. Beds of regularly shaped particles favoured an energy expensive total-fracture mechanism while irregular shaped particles abraded and rearranged thus consuming far less energy.

Quasi-static versus Dynamic processes

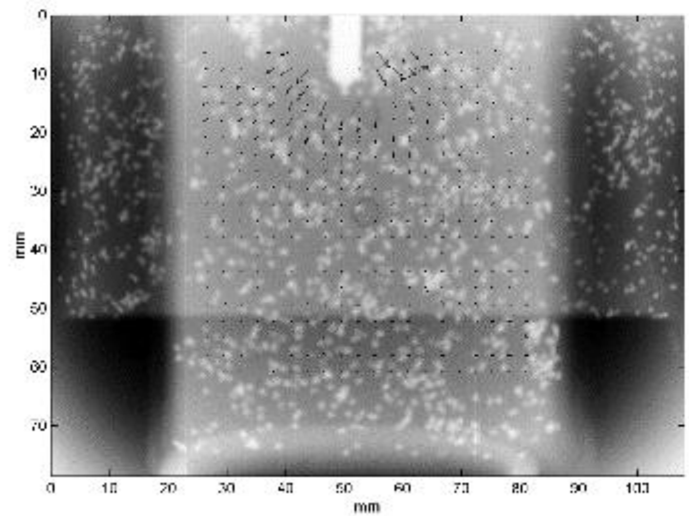
There was agreement with the low and high strain-rate loading data for spherical glass particles. The quartz sand data indicates there was a significant contribution from dynamic-only processes.

Ballistic Experiments (2001 onwards)



The use of digital speckle radiography to investigate the internal flow fields during the ballistic penetration of sand
J.W. Addiss , A.L. Collins , S.M. Walley*, W.G. Proud (2015)

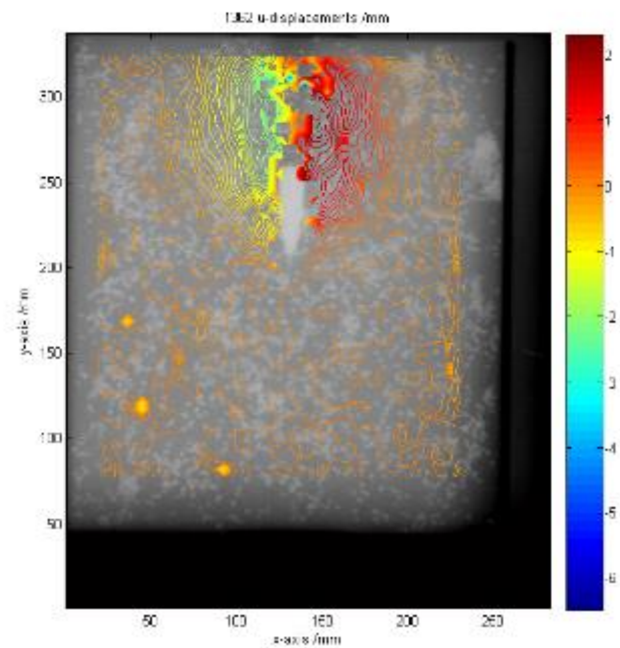
Sand Experiments



Digital Speckle Radiography

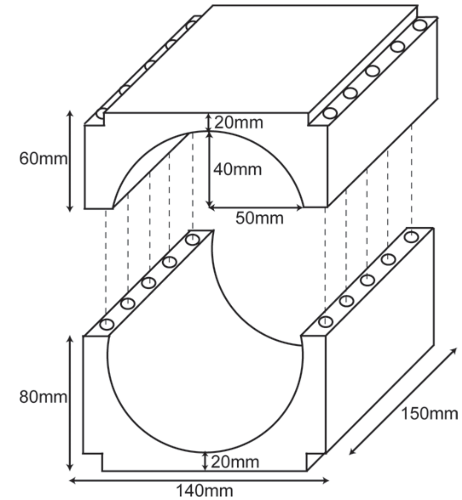
Digital Image Correlation
Flash X-rays
Embedded Particles

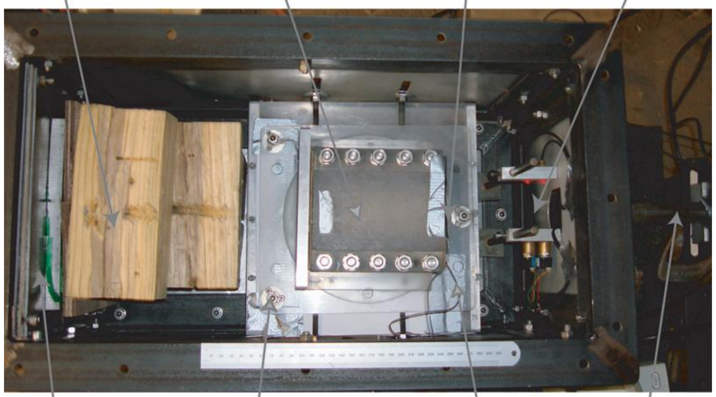
300 μm to 600 μm sand grains
$60 \times 70 \times 30$ mm^3 PMMA container
30 mm depth of sand
Copper rods 50 mm × 5.0 mm ∅, mass 8 g, v≈100 ms^{-1}



Experimental Setup

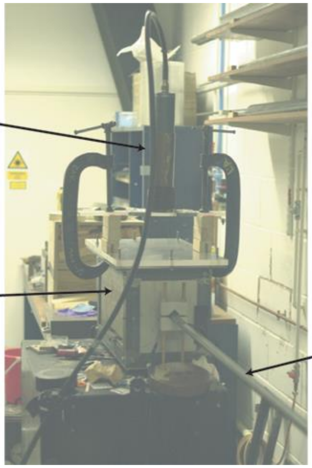
- Cylindrical sample of sand, 150 mm long and 100 mm diameter.
- Horizontal layer of randomly scattered lead pieces running along the length of the cylinder (in the central plane)





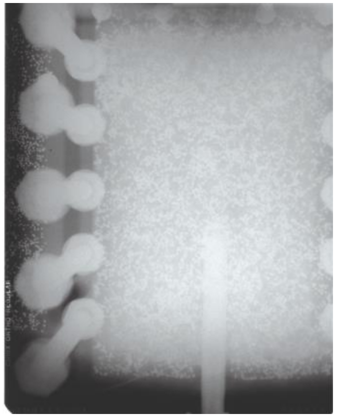
- Projectiles launched at 200 m/s using a light gas gun
- 10 mm diameter, 100 mm length, 55g and flat ended

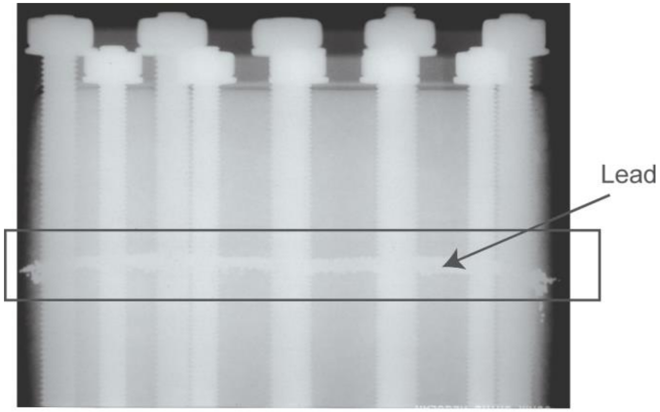
Experimental Setup



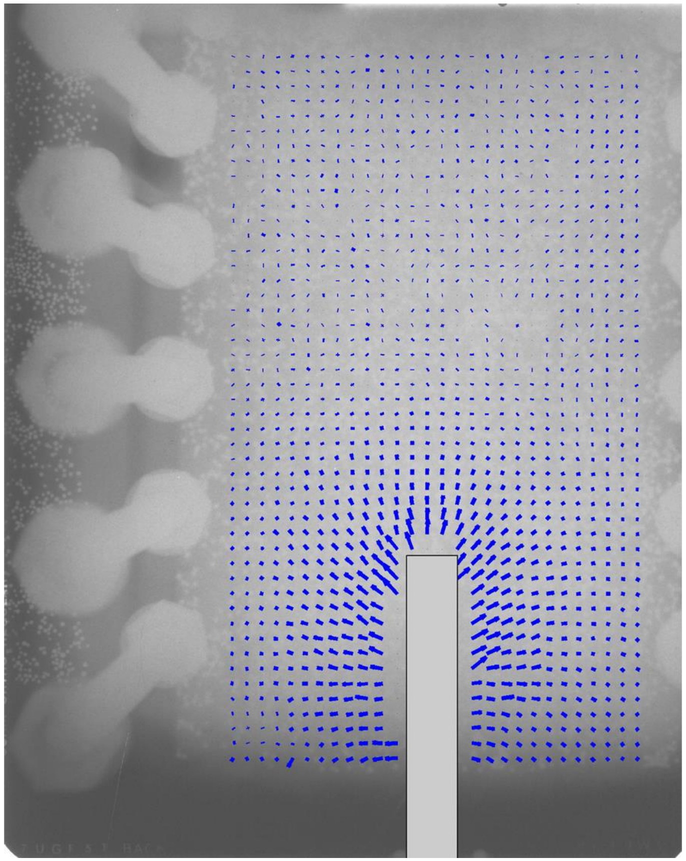
- **Flash x-ray head mounted above sample used to take x-rays before and during penetration**
- **Series of experiments carried out to build up a sequence of images showing the penetration**

- **X-ray images analysed with a DICC algorithm to calculate displacements**

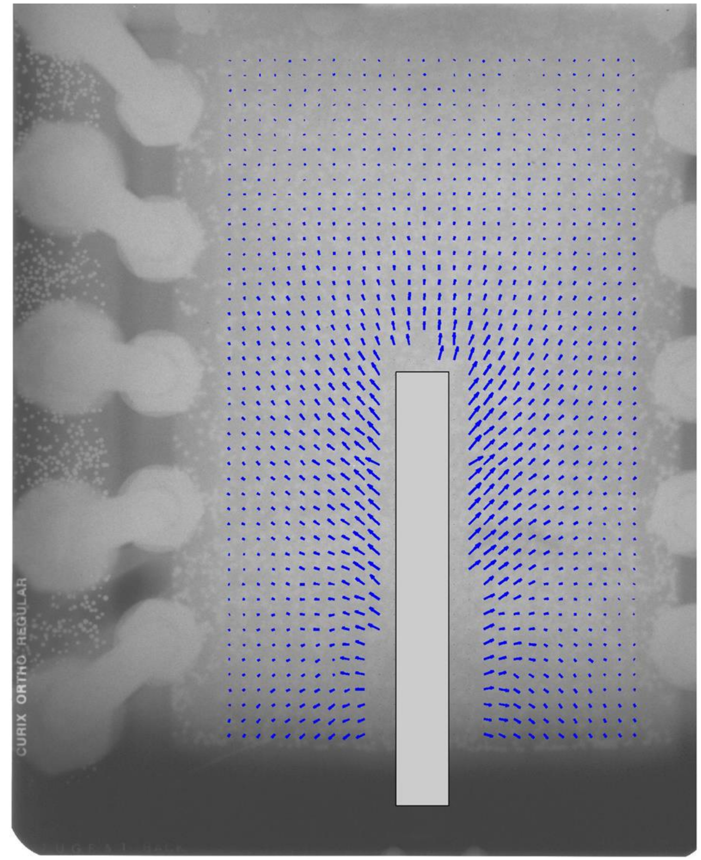




Measured Displacements



250us after impact



450us after impact

Comparison – with and without lead layer

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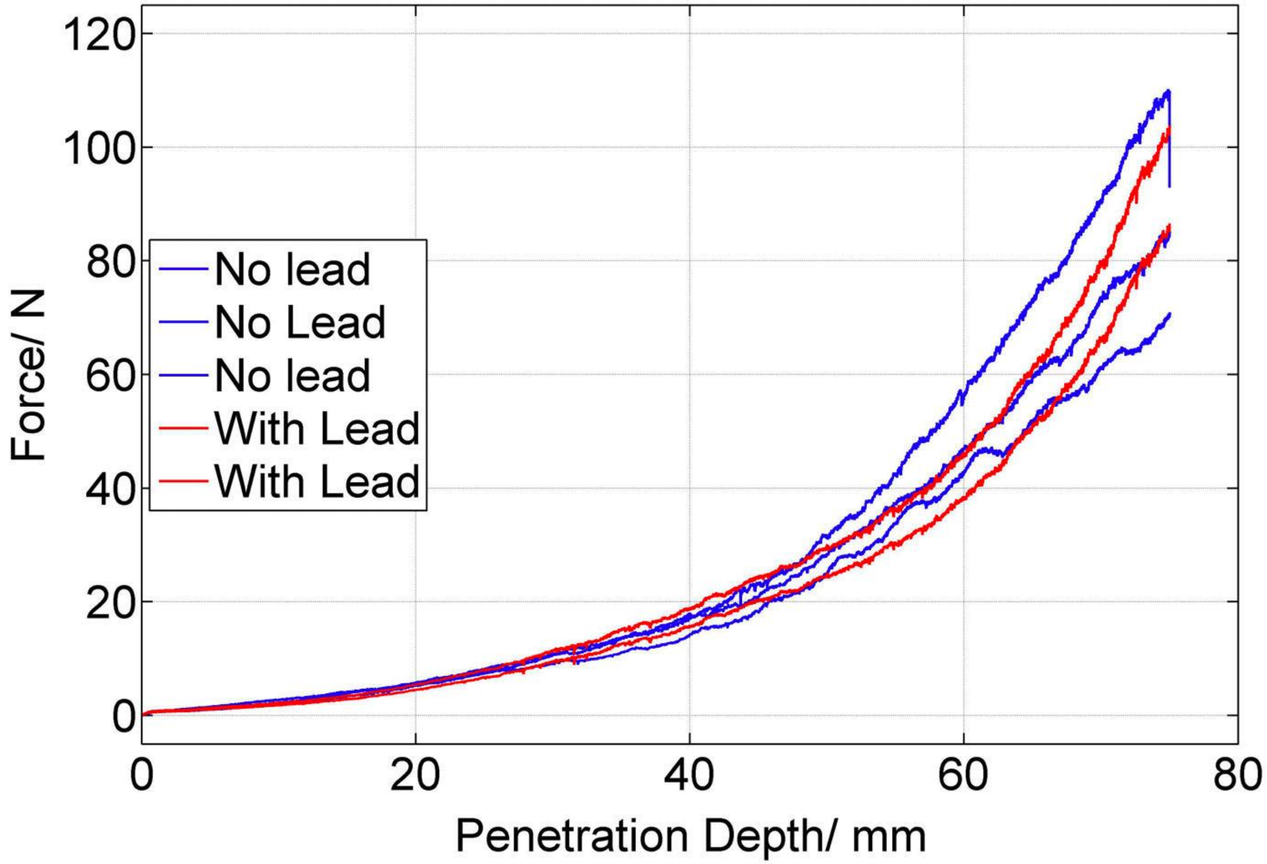
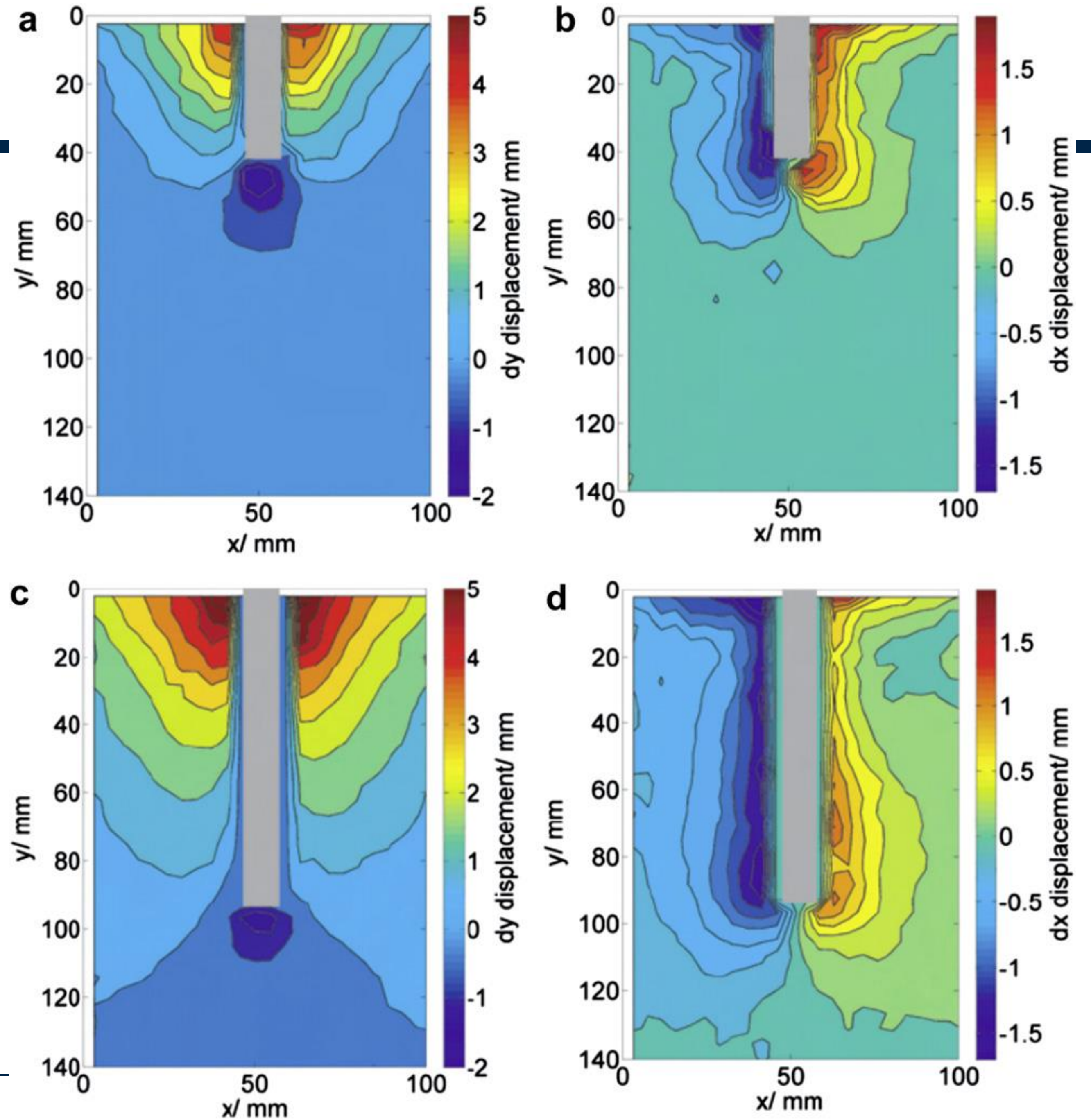


Low Rate Penetration 1.5 mm/min



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Dynamic Penetration (200 m s^{-1})

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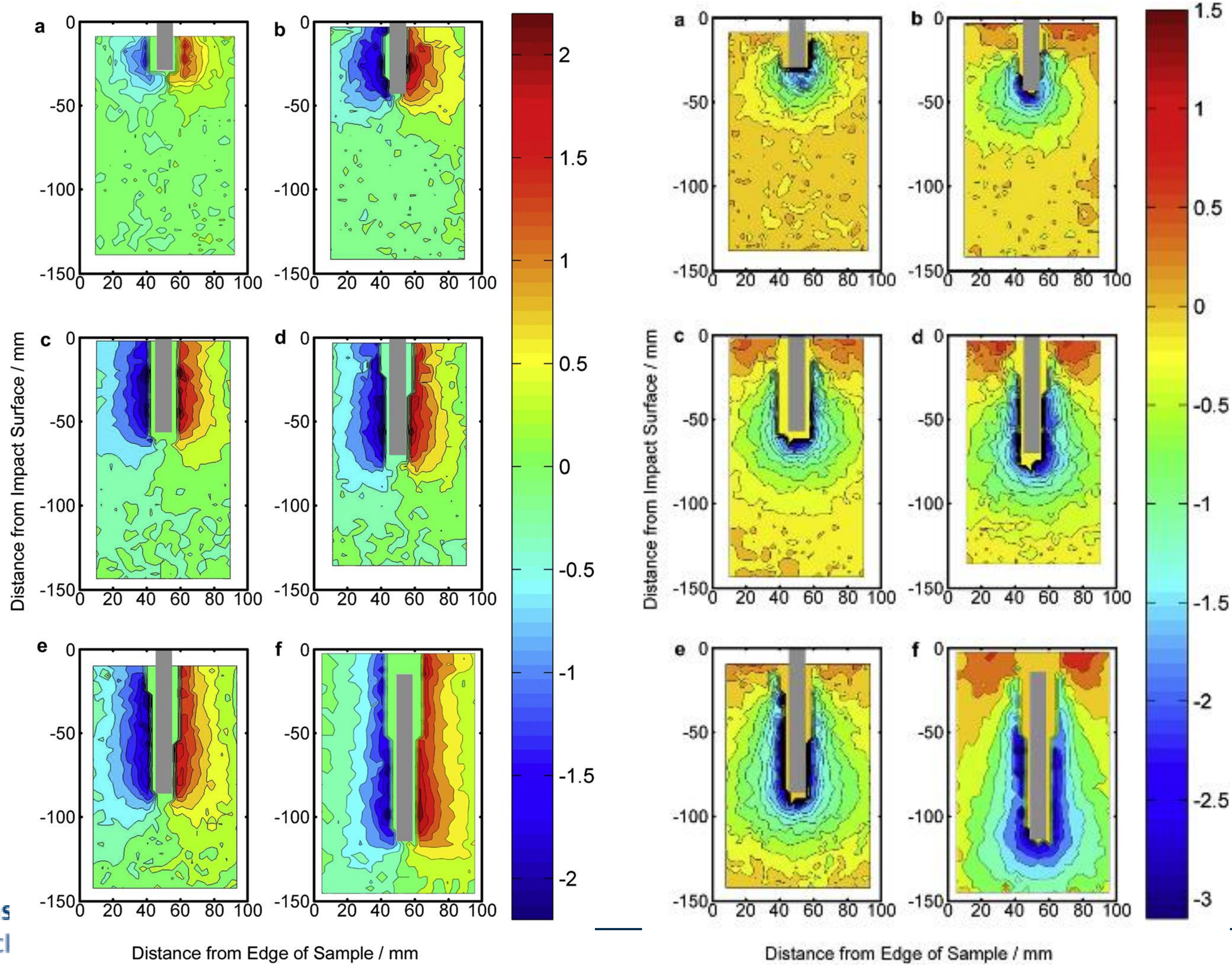
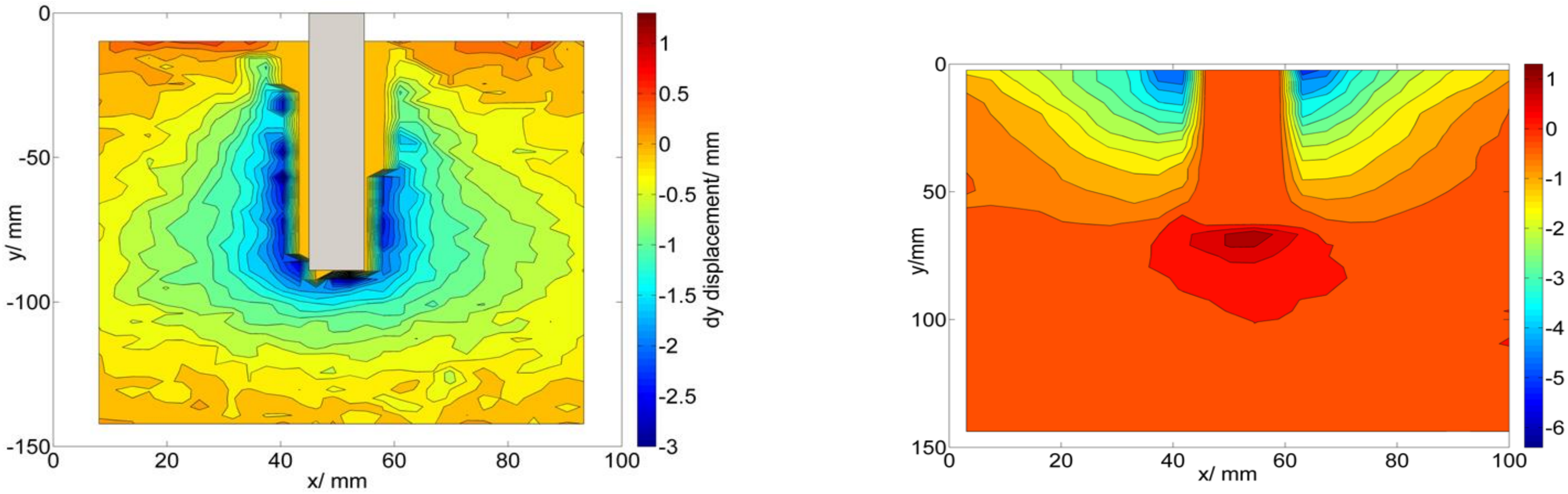


Comparison – Quasi-Static to Dynamic



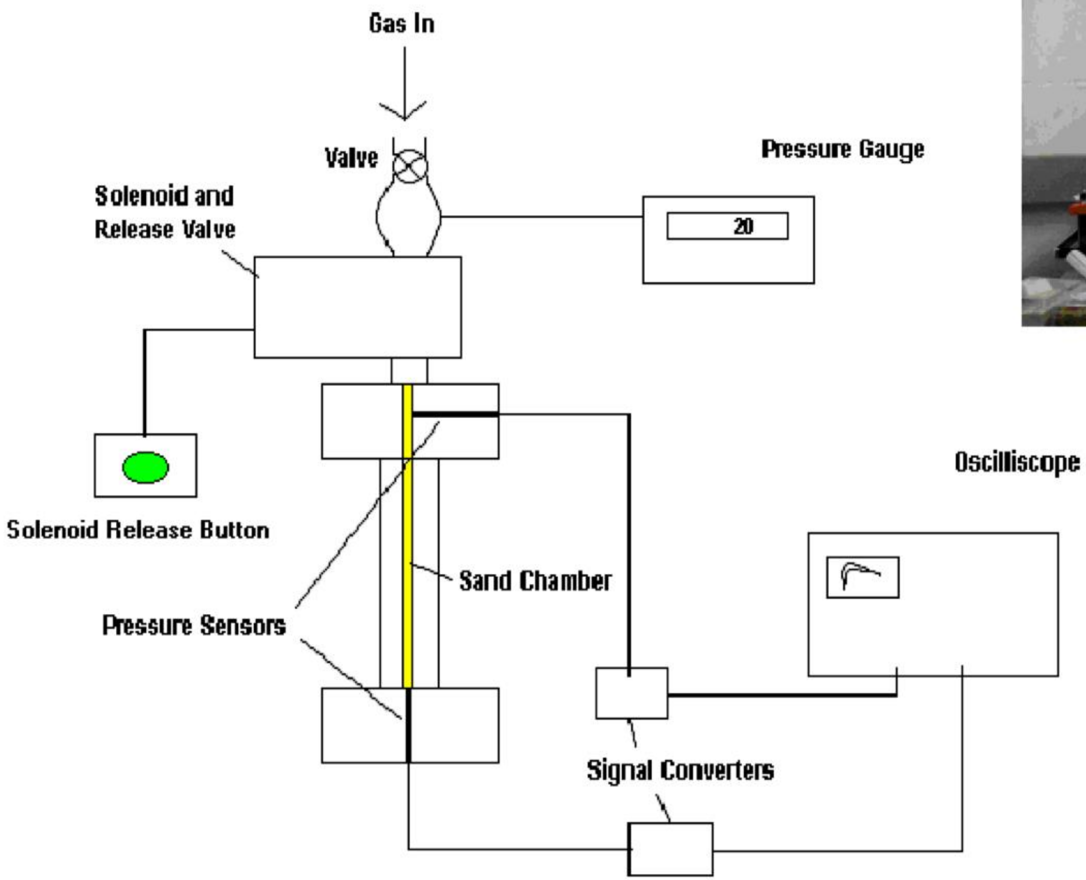
- In the quasi-static case most of the material down to the rod tip is moving upwards
- There is no travelling compaction wave in the material

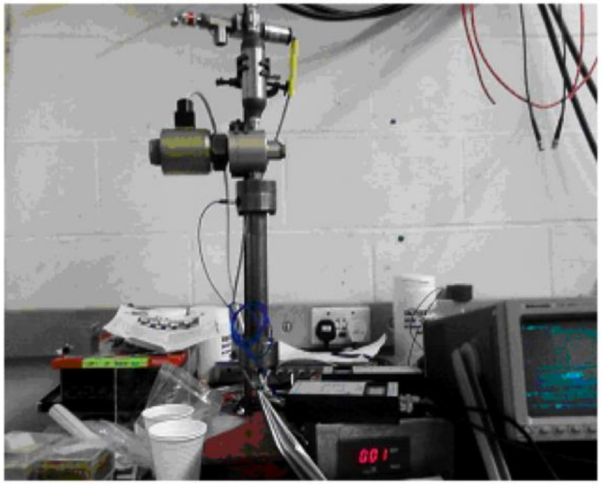
Conclusions (Ballistic)

- The higher the impact velocity (strain rate) – the smaller the volume of the granular material involved.
- There is a definite compaction wave in the higher rate systems
- Particle motion dominates at lower rates
- Particle rotation – occurs but is not measured in these experiments

Blast Response (SCCM 2013)

Acknowledgement: David Johnson/Ray Flaxman/Bob Marrah/Matthew Leal & Ian Hewitt





Sand Column
6mm diameter
210 mm long

Sands used

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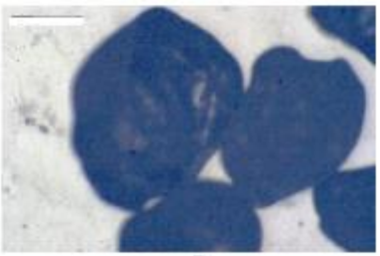
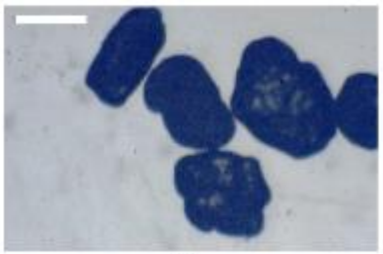
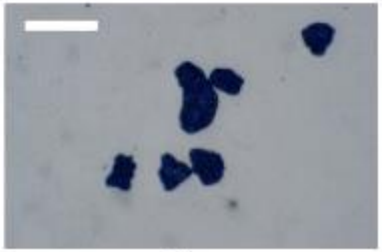
A



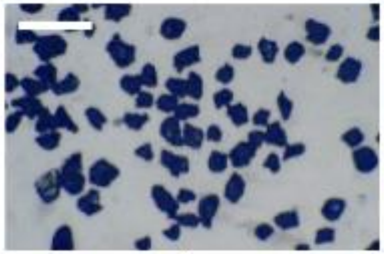
B



C



D



E

Quartz Sand
dry = 43% porous
(all sizes)

Sand Size Type	Size - Manufacturers Specification (µm)
A	1180-2360
B	600-1180
C	300-600
D	150-300
E	90-150

Peak to Peak Effect of Water Content

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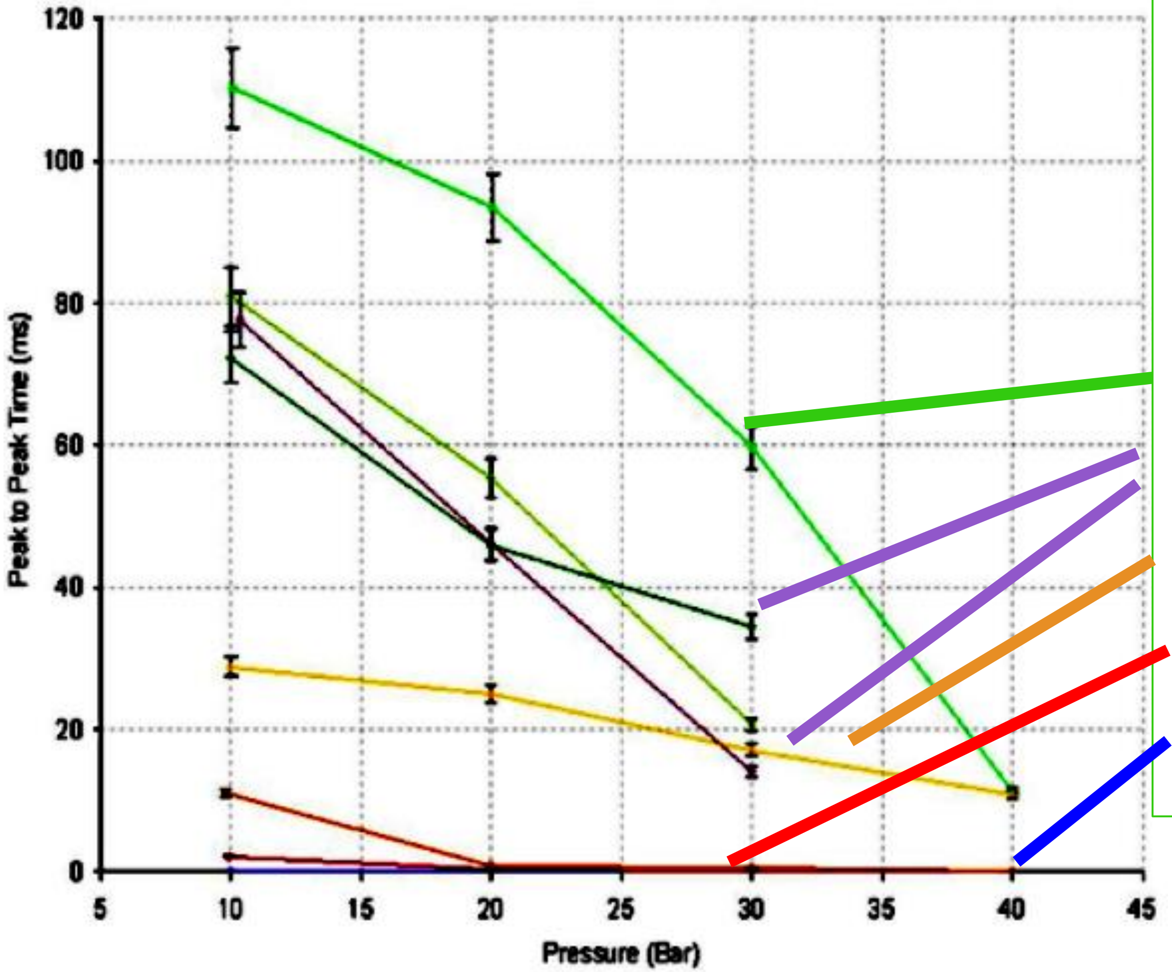

Sand = 57% volume (+/- 3%)
1.5 g / cm^{-3}

Water = added by mass
(0.5:10 / 2:10 / 3:10 / 4:10)

Porosity ~ gas volume

Sand /Water – 11% Porous

Sand / Water – 22% Porous

Dry Sand (43% porous) and Sand/Water – 38% porous

Sand/Water – ~3% porous

Water

Shock Tube

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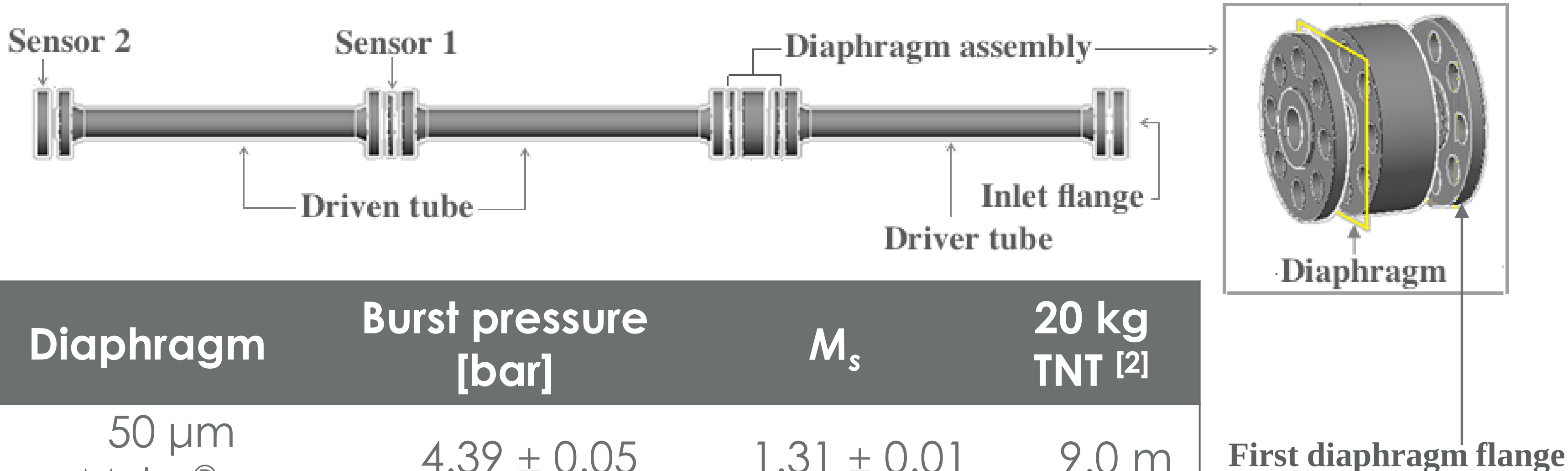

Diaphragm	Burst pressure [bar]	M_s	20 kg TNT [2]
50 µm Mylar®	4.39 ± 0.05	1.31 ± 0.01	9.0 m
23 µm Mylar®	2.12 ± 0.03	1.26 ± 0.01	10.8 m
40 µm Al	1.43 ± 0.01	1.20 ± 0.01	12.6 m

- **Whole driver tube → full-volume**
- **Blanking flange, 10% charging length → small-volume**

Bed Length : 2 mm Spheres: Pulse Shape

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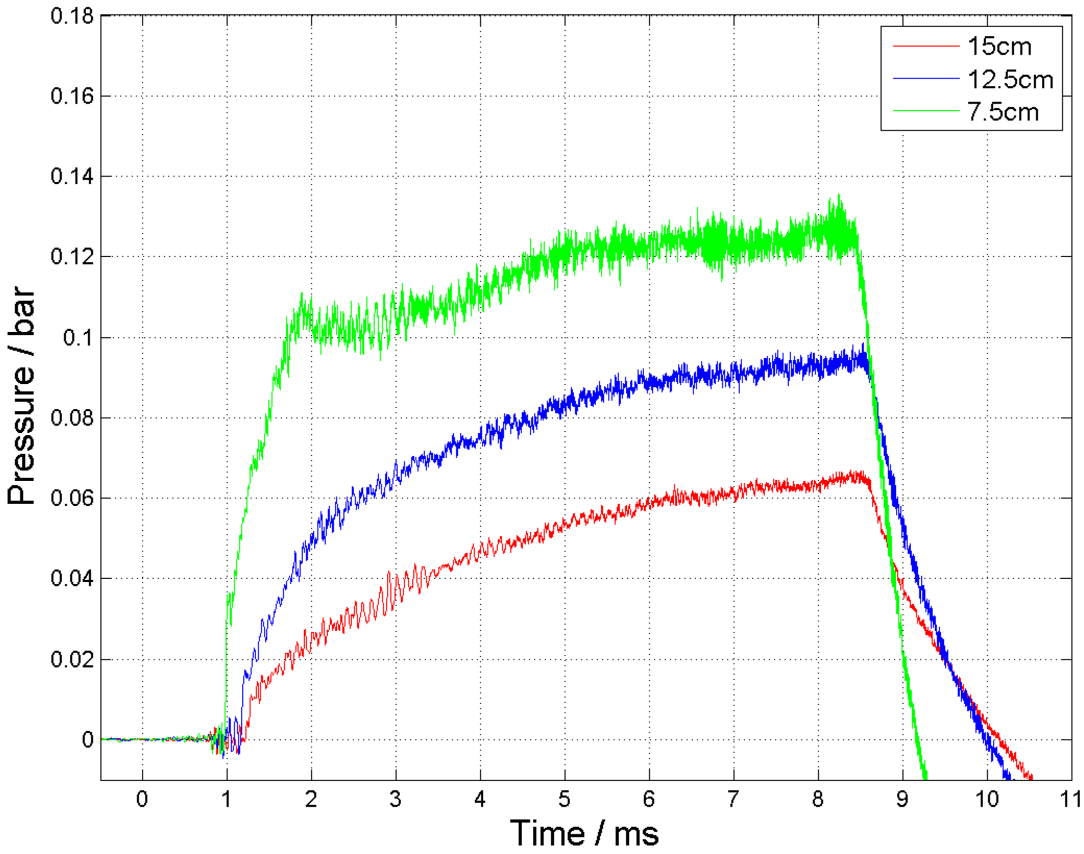

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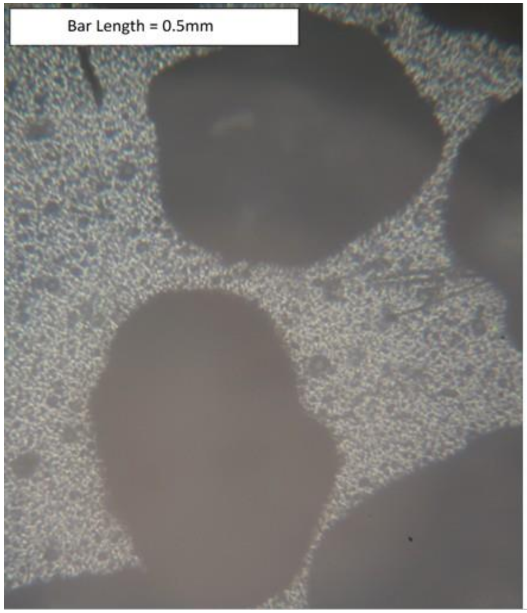
Dry and Dampened Beds

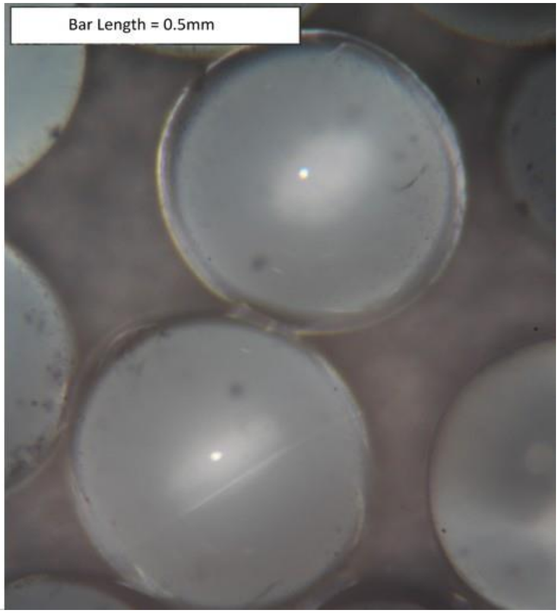
Dampened Beds

Material	Quoted Size
Small Sand	$300-600\mu m$
Large Sand	$1.18-2.36mm$
Small soda lime glass spheres	$400-600\mu m$
Large soda lime glass spheres	1.5 ± 0.03

small sand & small spheres

white bar= 0.5 mm





Permeability, Porosity and Saturation

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Material	Permeability (mm^2)
Small Sand	$1.85(\pm 0.19)\times 10^{-5}$
Large Sand	$1.13(\pm 0.02)\times 10^{-3}$
Small Spheres	$7.14(\pm 0.01)\times 10^{-5}$
Large Spheres	$1.99(\pm 0.01)\times 10^{-3}$

Porosity : 0.27 Sand / 0.38 Spheres
Roundness*: sand = 0.45 / spheres = 1.0

Porosity = fraction of void
Permeability = ability of a fluid to pass through it

*RP Jensen *et al.*, Effect of particle shape on interface behavior of simulated granular materials. *International Journal of Geomechanics*, 1(1):1–19, 2001.

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Input and Output Pulses

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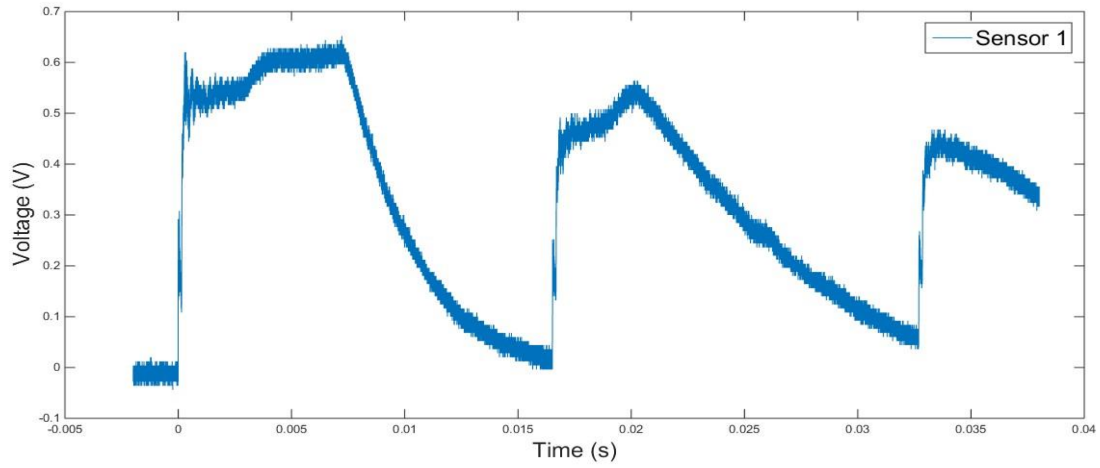
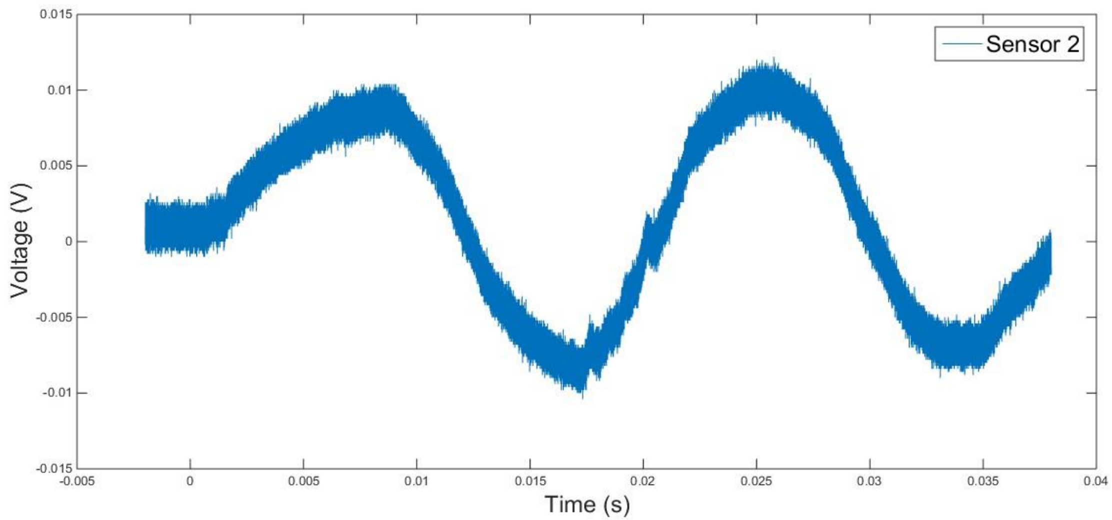
10 cm Bed
Small Sand





Propagation Time / Pressure (Dry)

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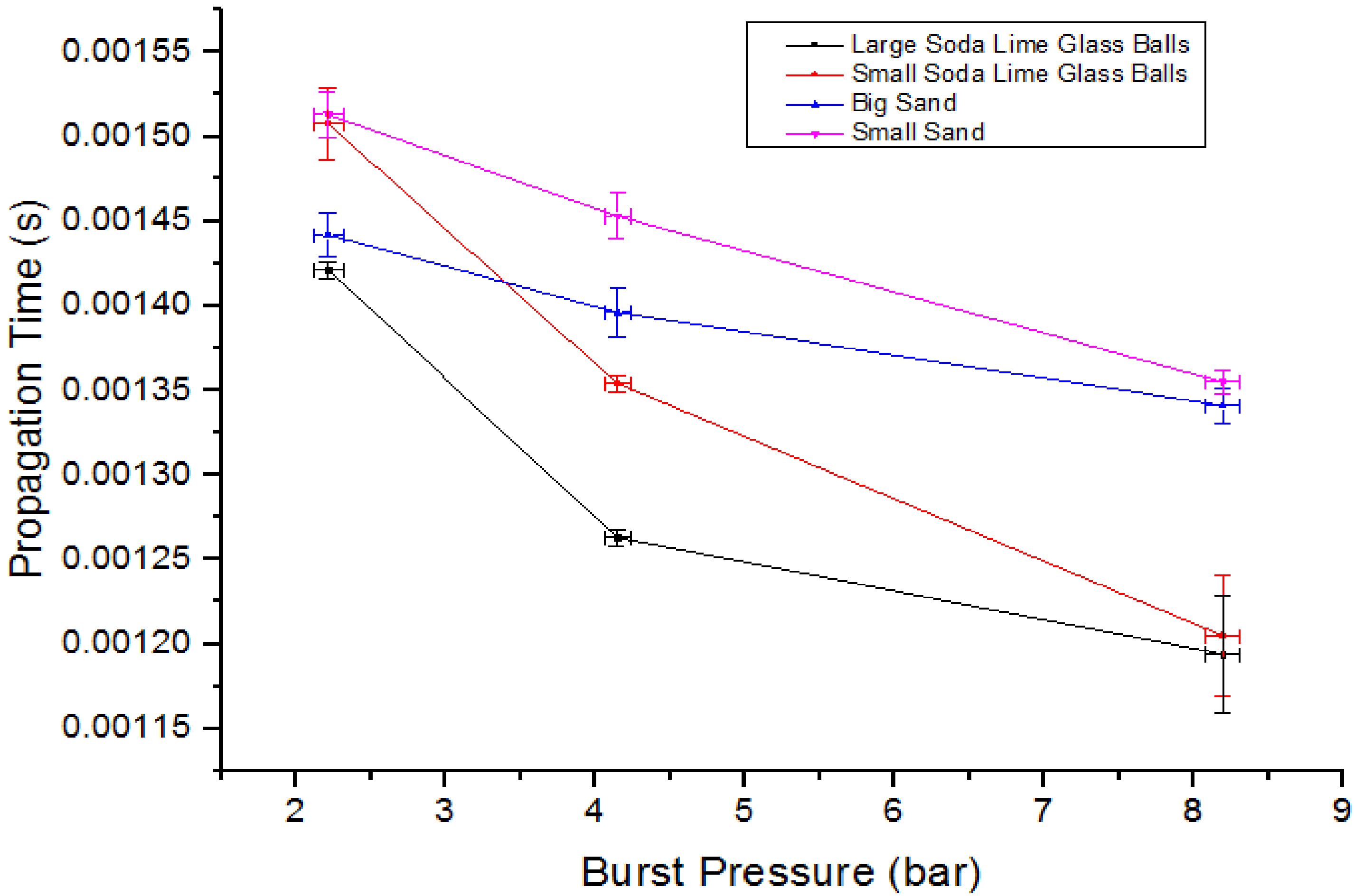
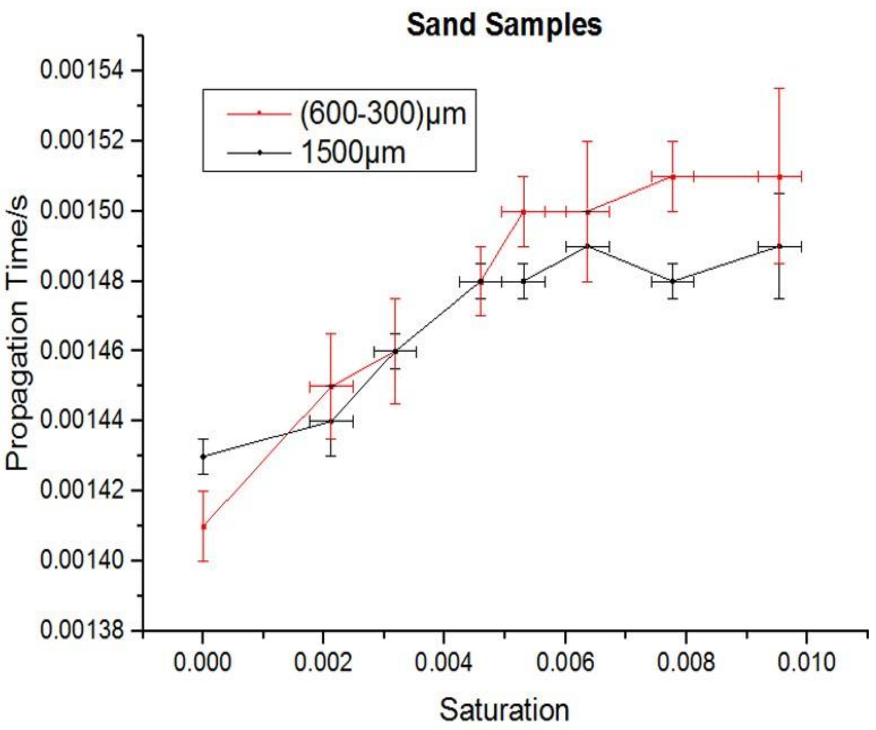
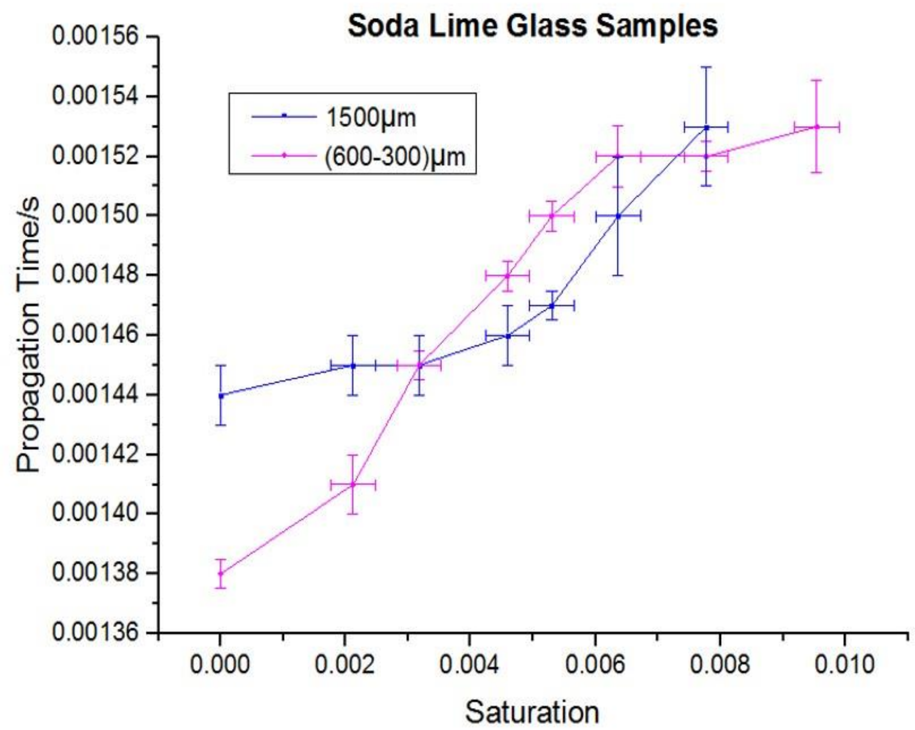


Propagation Time v Saturation





10 cm long granular bed

Energy Transmittance / Saturation

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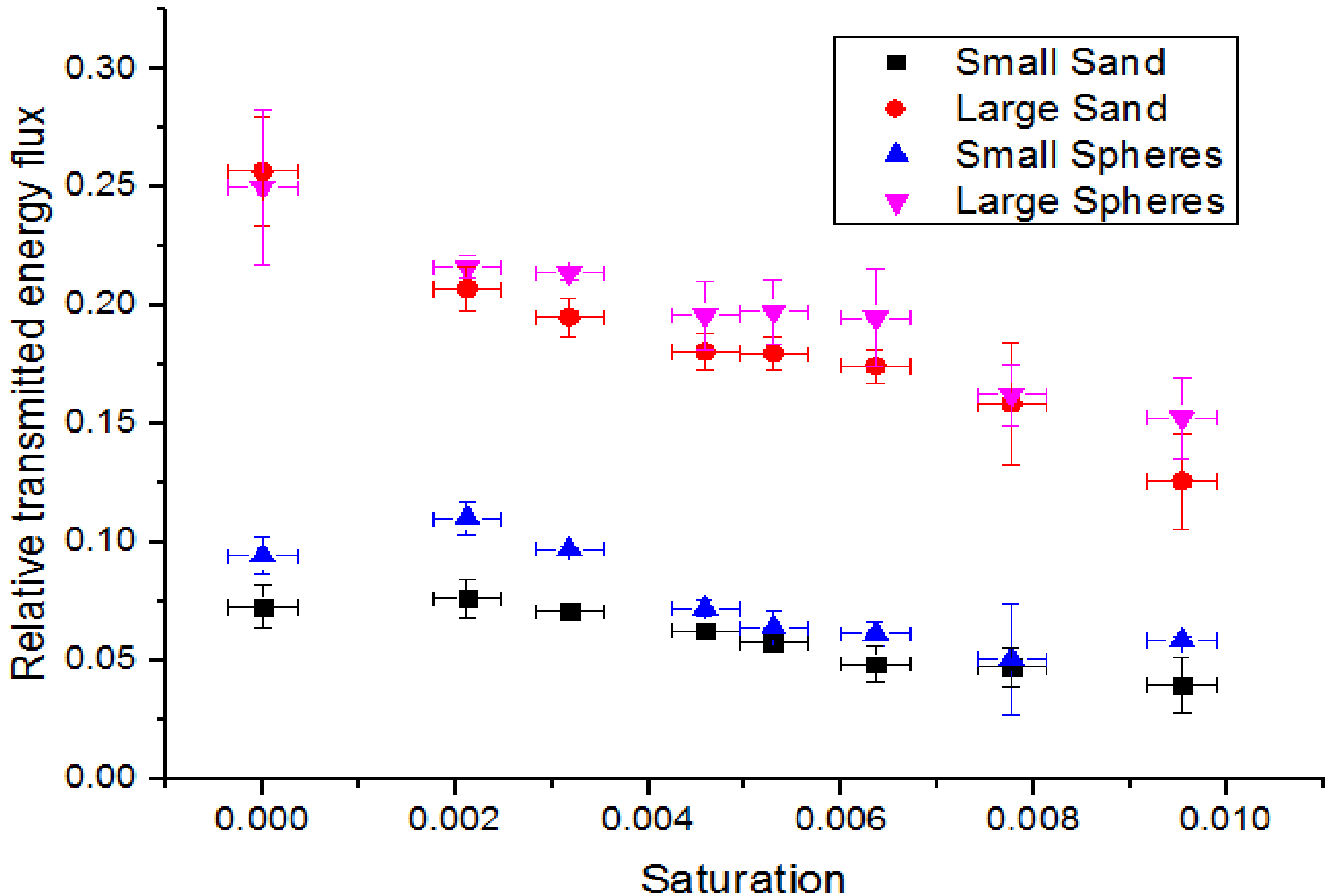

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Conclusions (Blast)

- Grain size has an effect, more marled at low pressures
- Porosity has an effect
- Grain morphology seems to dominate at high pressures
- Small additions of water / oil etc has a marked effect on the system.

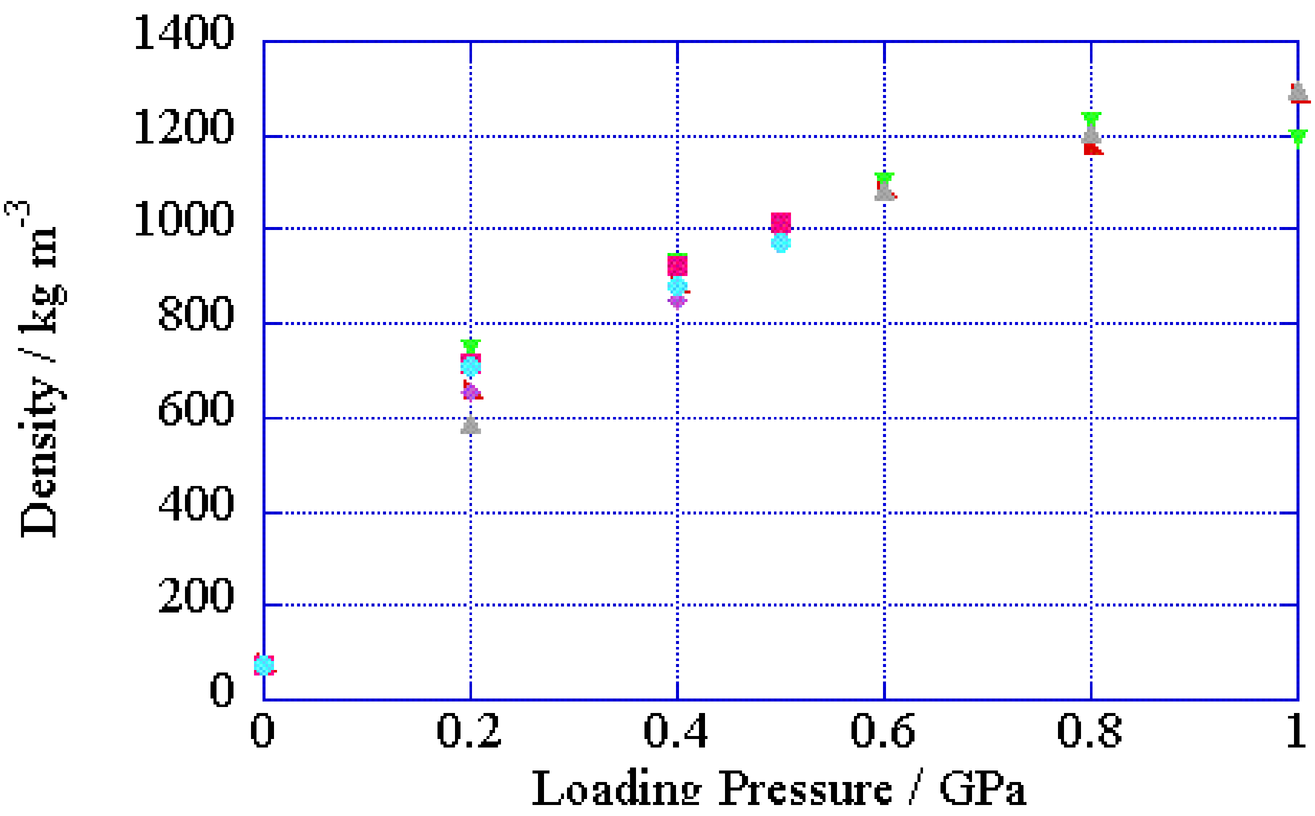
Other Effects ….

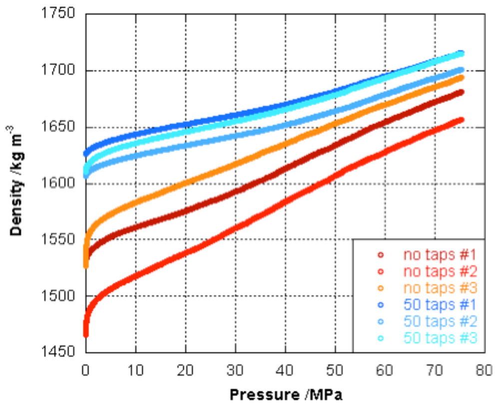
Does the shock wave obey ‘simple’ Rankine-Hugoniot relationships?

What is the sound speed in sand (it is well known it is frequency dependant)

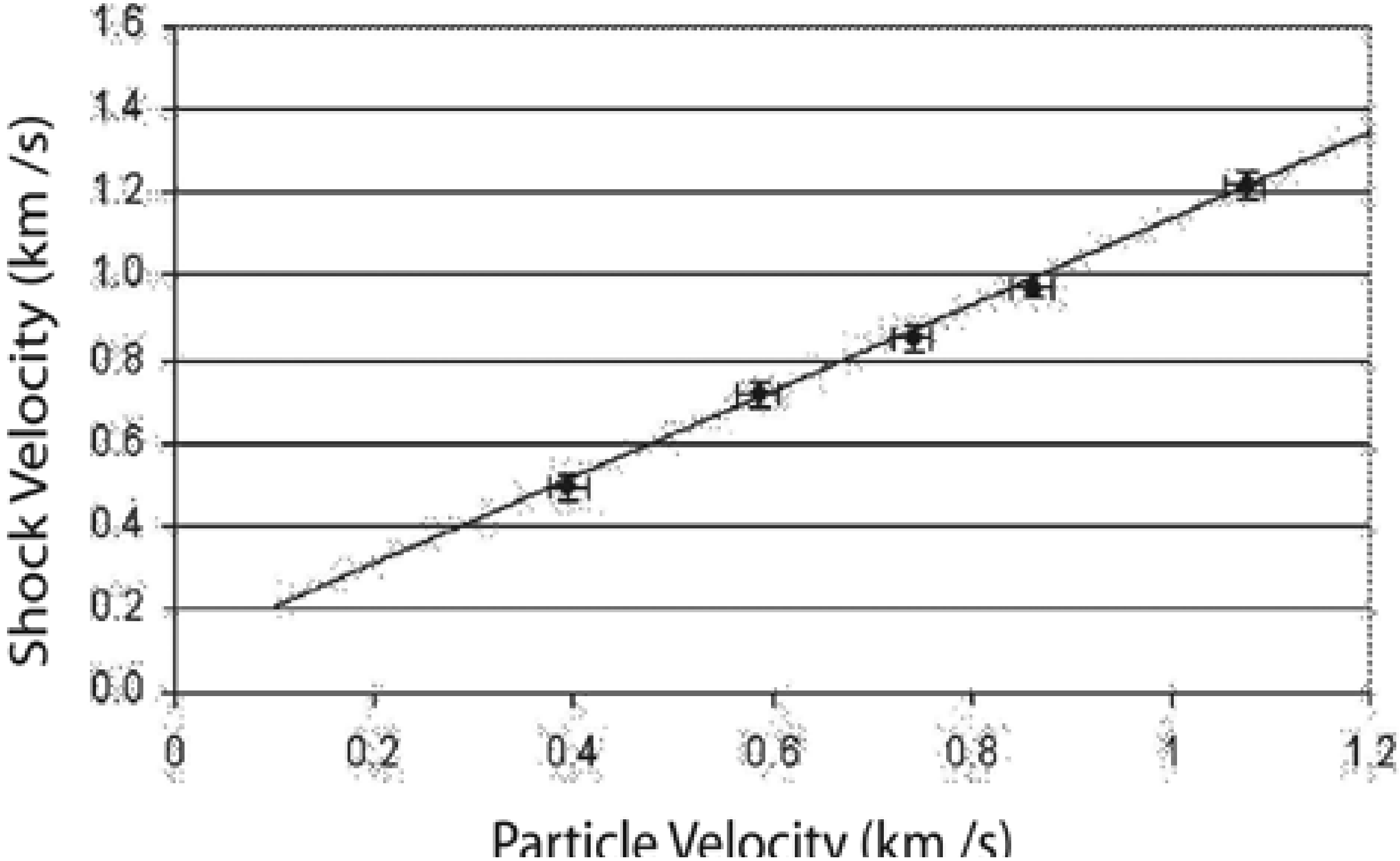
Extreme 5% TMD Low Density Silica Dust

Low-rate

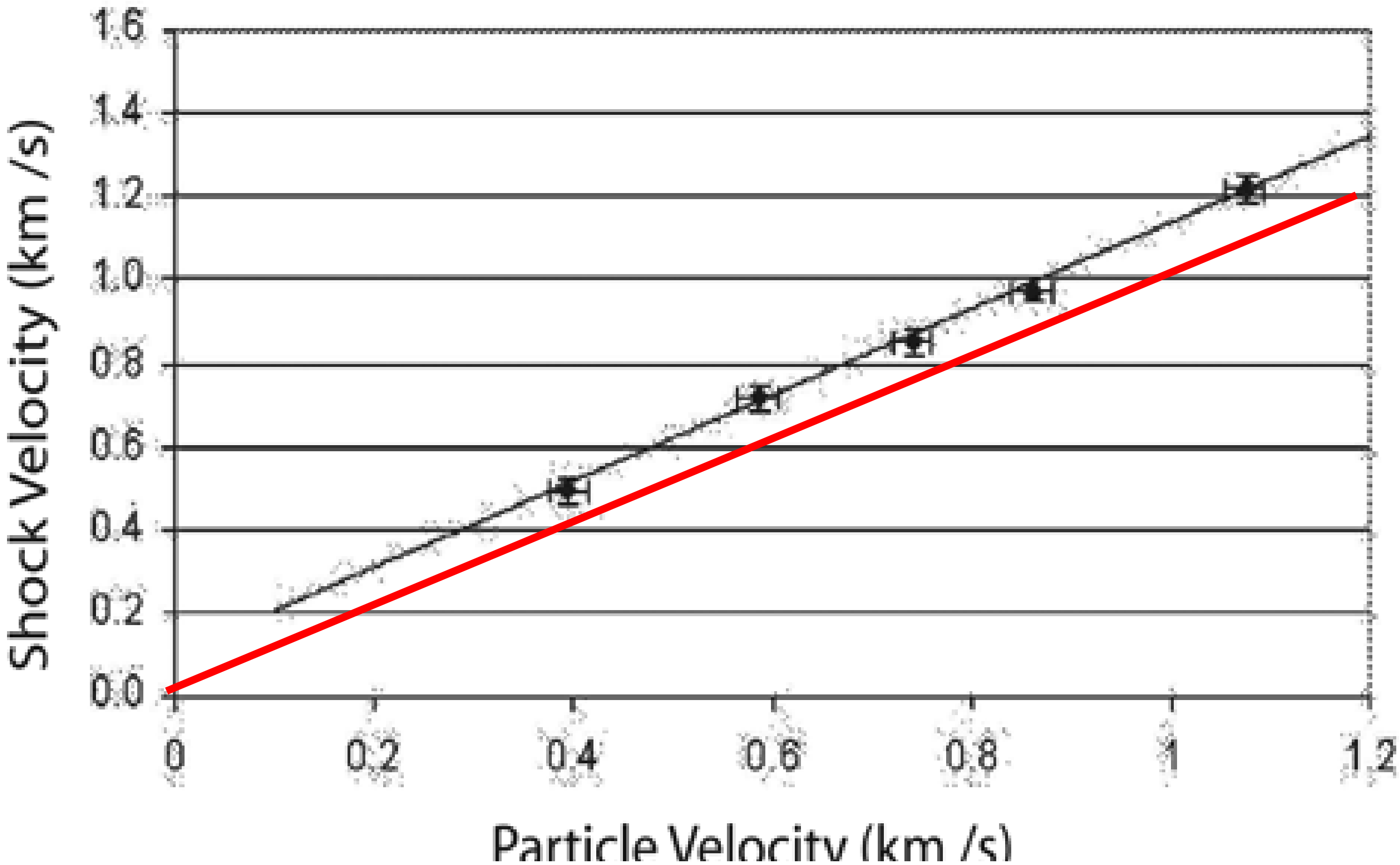




"Hugoniot"


Shock Velocity (km /s)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
0.2
0.4
0.6
0.8
1
1.2
Particle Velocity (km /s)

Hugoniot v. Compaction Line



Sound Speed - 2 mm Glass Spheres

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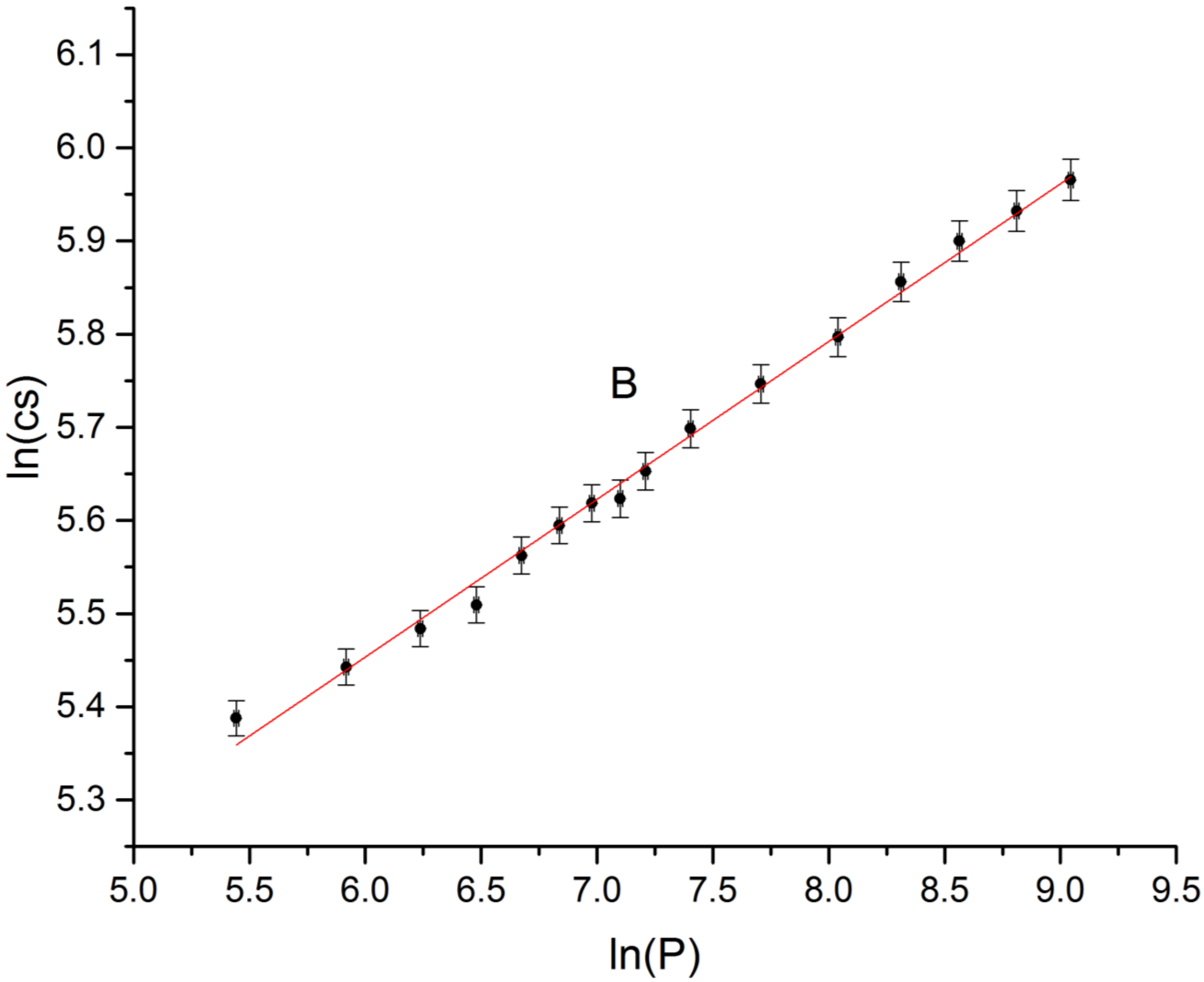
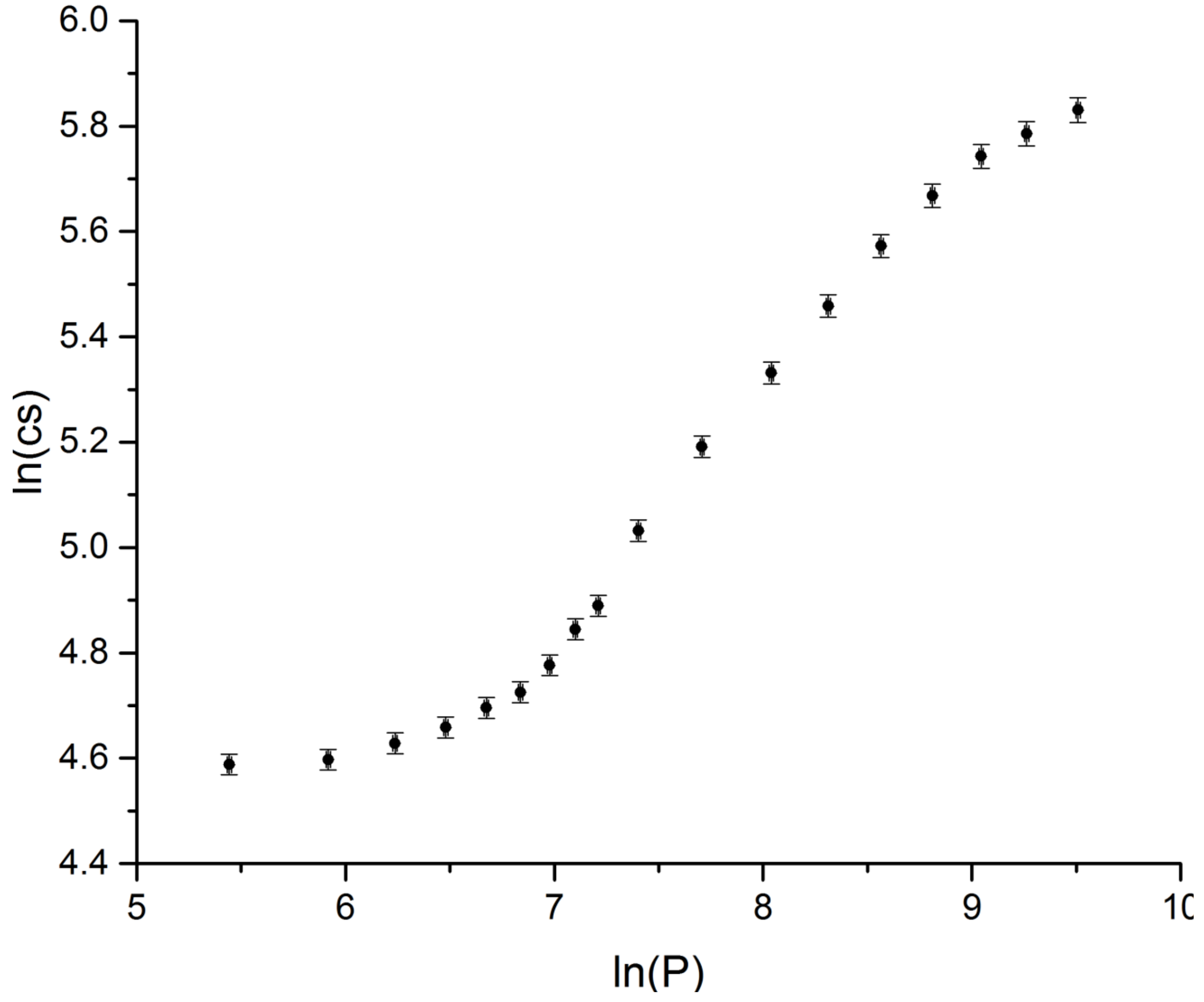


Simple Property – Sand - Sound Speed



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Need to define the starting conditions

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What is the required output?

Physical Understanding (science-engineering driven)

Approximate Behaviour (application driven)

Natural Material

Constructed Material

Many ways of doing this, optimally - something simple to apply/ define

Particle Size Distribution

Material Type

Morphology

Contact Points

Before fracture / compaction etc.

A Modelling Framework

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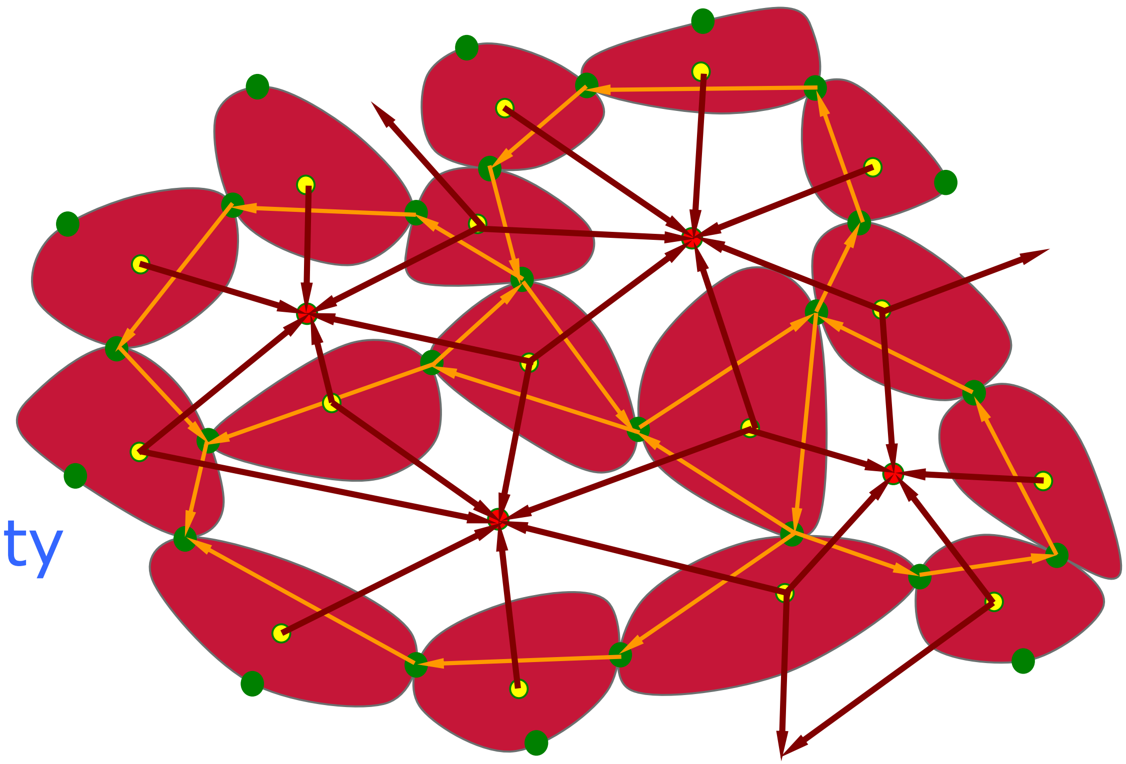

Parameters to determine

Connectivity
Particle Size
Stability v Instability
'Rattlers'
Grain Rotation

1. RB & SFE, Phys. Rev. Lett. 90, 114303-114306 (2003);
2. 2. RCB & RB, Phys. Rev. Lett., 88, 115505-115508 (2002))
3. 3. RB & SFE, Eur. Phys. J. E 19 , 23-30 (2006)
4. 4. RB, SFE & SMW, Chapter on: *Granular systems, in The Oxford Handbook of Soft Condensed Matter, Eds. E.M. Terentjev and D.A. Weitz, (Oxford University Press, Oxford, UK, 2015)*

Quadron Tessalation

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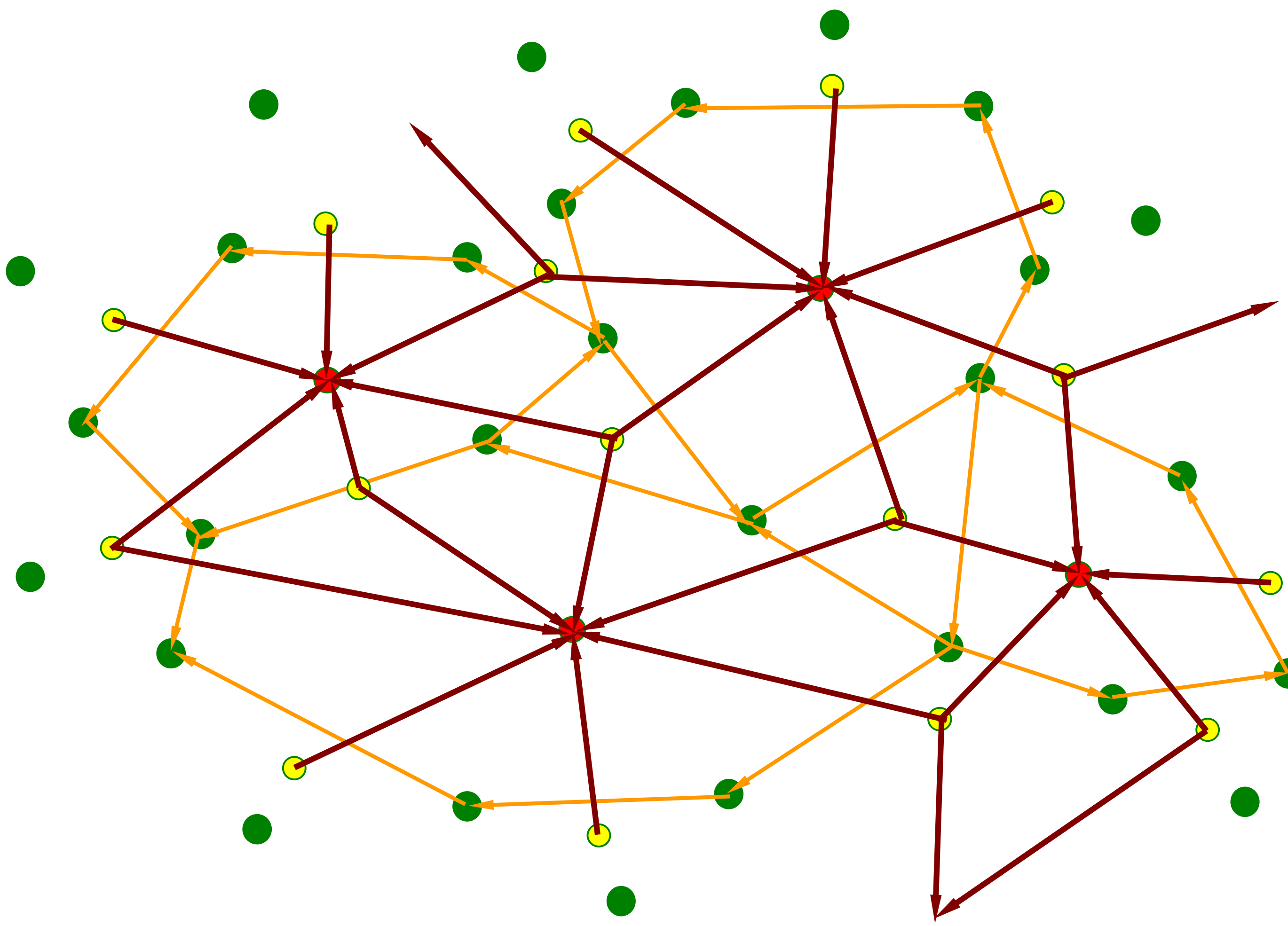

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Conclusion

- Many phenomena are partially understood (many models)
- Strain rate dependence is complex across the strain rates
- Properties within a material class are reproducible
- Start Conditions are important

- Use of Synchotron-based studies to look in depth at high-rate compaction

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