Particle Breakage Mechanics in Milling Operation

L.G. Wang [*], J.Y. Ooi, C. Labra, X.Z. Chen, J.F. Chen[**], J. Sun

[*] University of Sheffield, UK

University of Edinburgh, UK

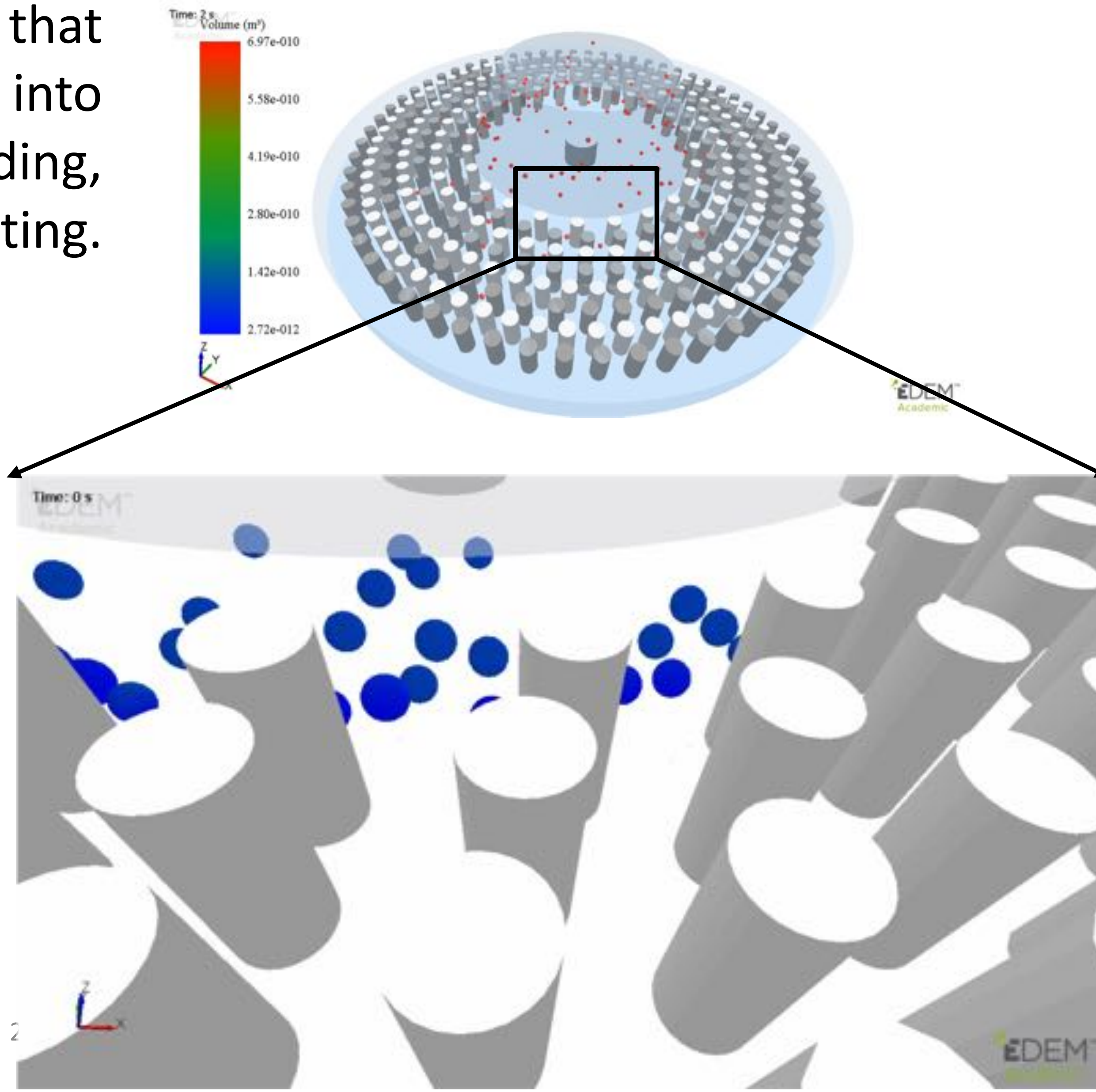
[**] Queen's University Belfast, UK

Cambridge, 18 March 2019

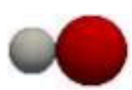
The University Of Sheffield.

Mill (Grinding)

A mill is a device that breaks solid materials into smaller pieces by grinding, crushing, or cutting. (Wikipedia)



Type of mills:

- Pin mill 
- Hammer mill 
- Ball mill et al. 

Type of particles:

- Zeolite
- Alumina
- Limestone et al.

Understand grindability

Material-dependent function

- Density
- Young's modulus
- Hardness
- Poisson ratio
- Yield stress
- Strength
- ……

Mill-dependent function

- Machine type
- Machine size
- Grinding tools
- Revolution speed
- Solid holdup
- Feed rate
- ……

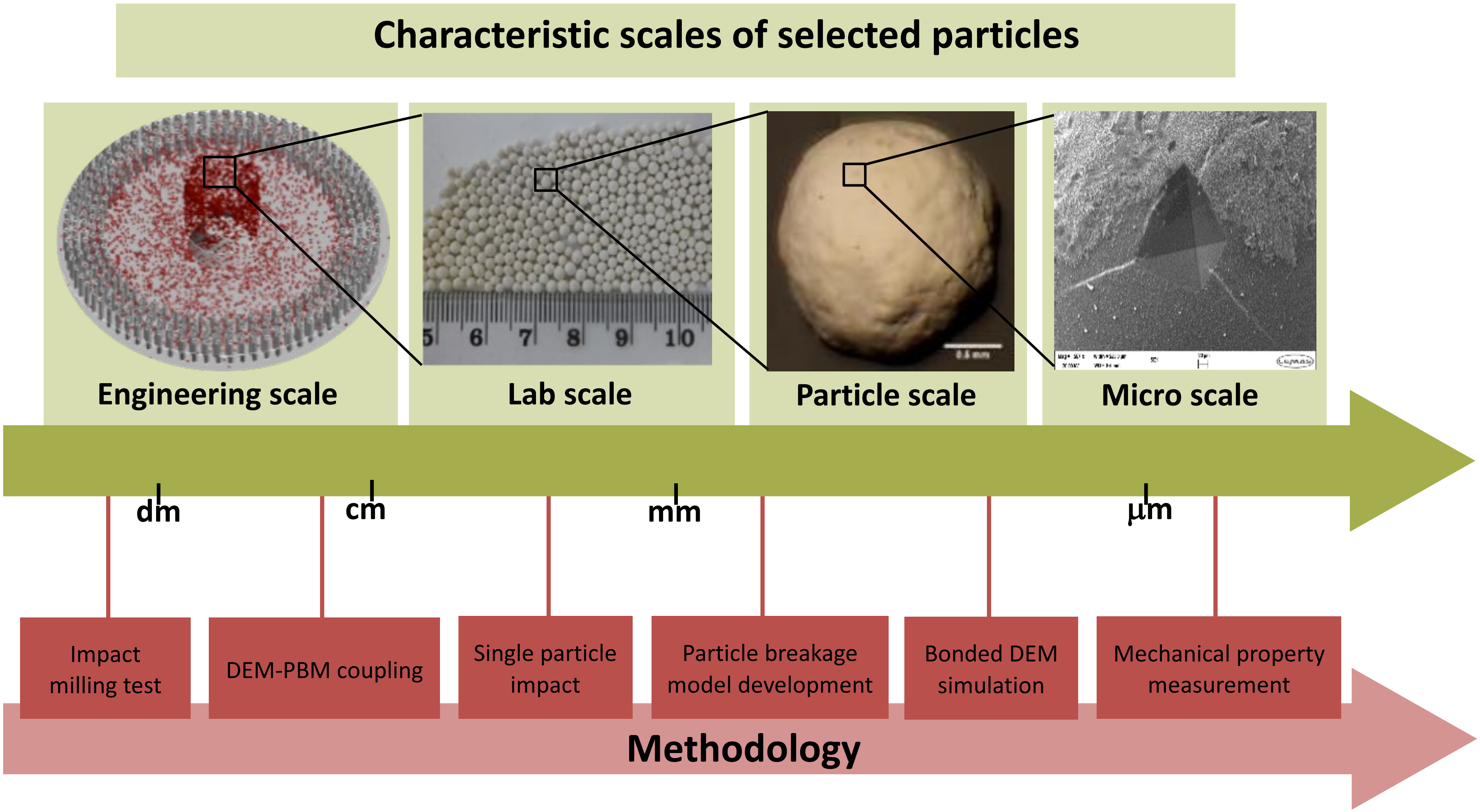
Multiscale strategy

Exp. measurement and DEM simulation

Milling tests and DEM-PBM coupling

Grindability prediction

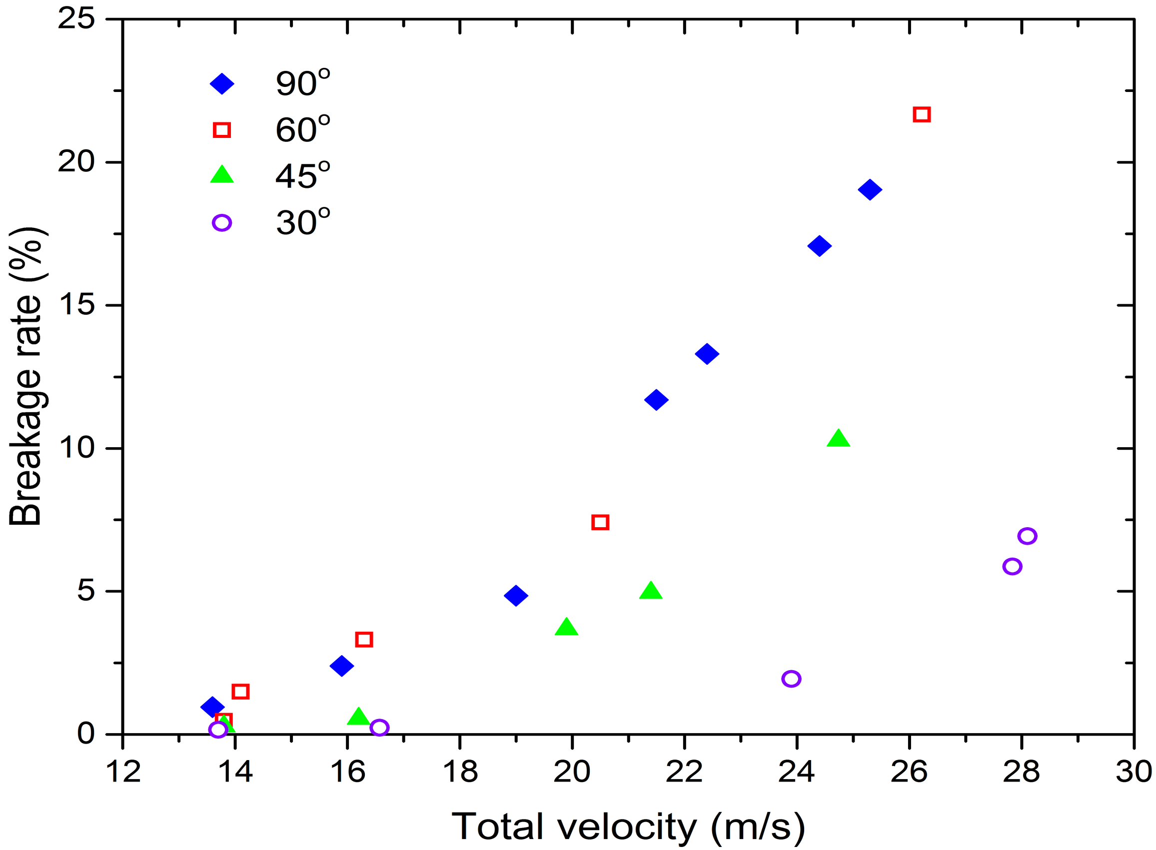
Multiscale Modelling of Grindability

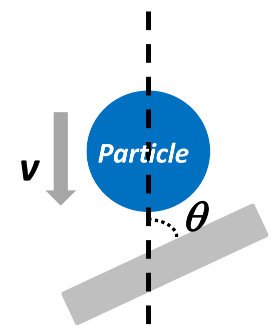


Schematic illustration of multiscale modelling of material grindability

Breakage Vs Impact Velocity and Impact Angle (Zeolite 1.4-1.7 mm)

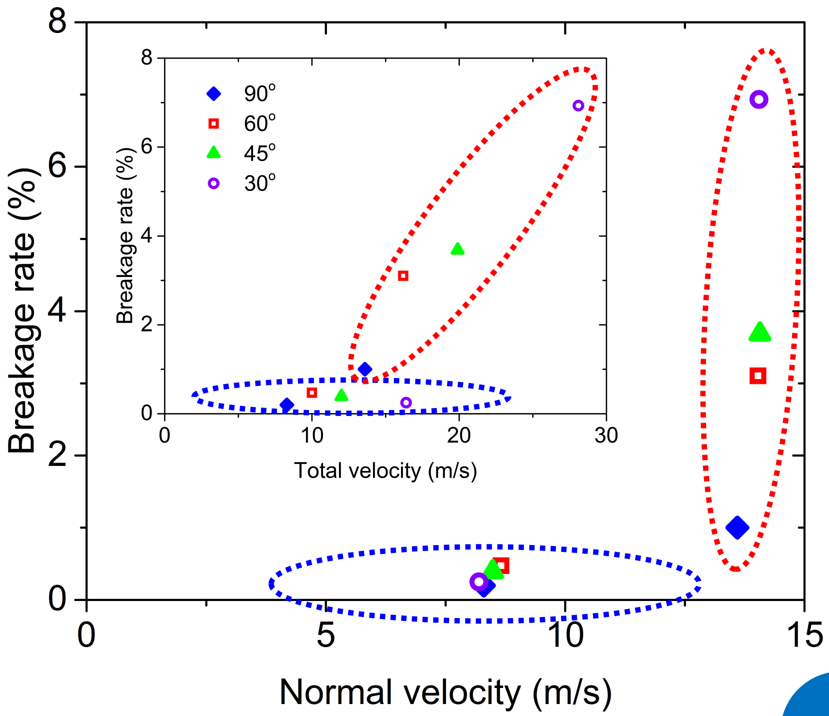
- Breakage ratio remains low below impact velocity of 15 m/s
- Breakage ratio increases dramatically over 15 m/s and increases with increasing impact angle (90° is normal impact)

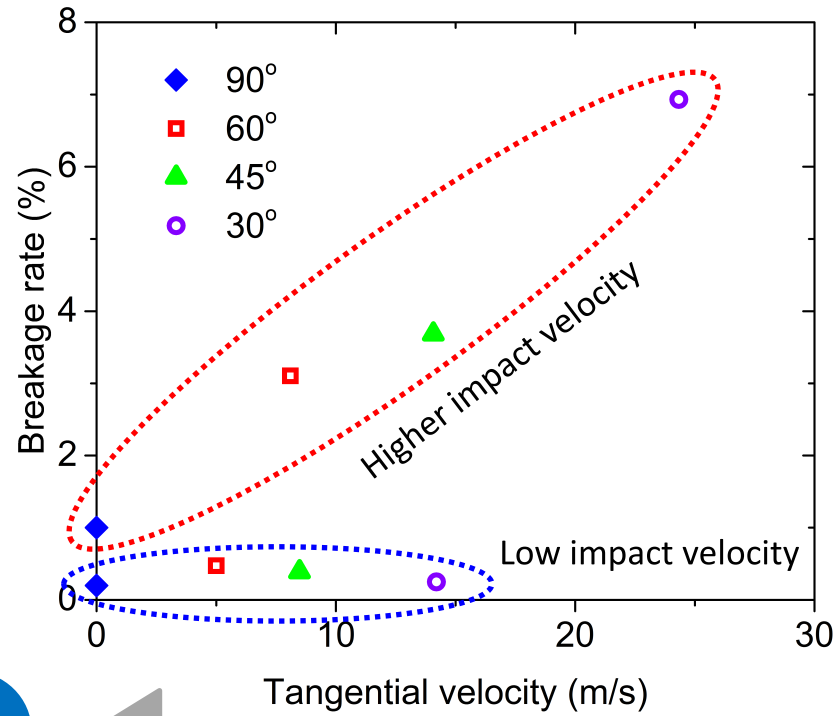


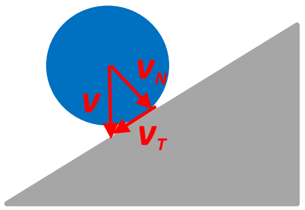


Tangential Velocity Component Contribution

- Results below show breakage at different impact angles for a low normal velocity (~8 m/s) and a higher normal velocity (~14 m/s)
- At low normal velocity, tangential velocity has a negligible effect
- At high normal velocity, breakage ratio increases with increasing tangential velocity - implication for breakage model development







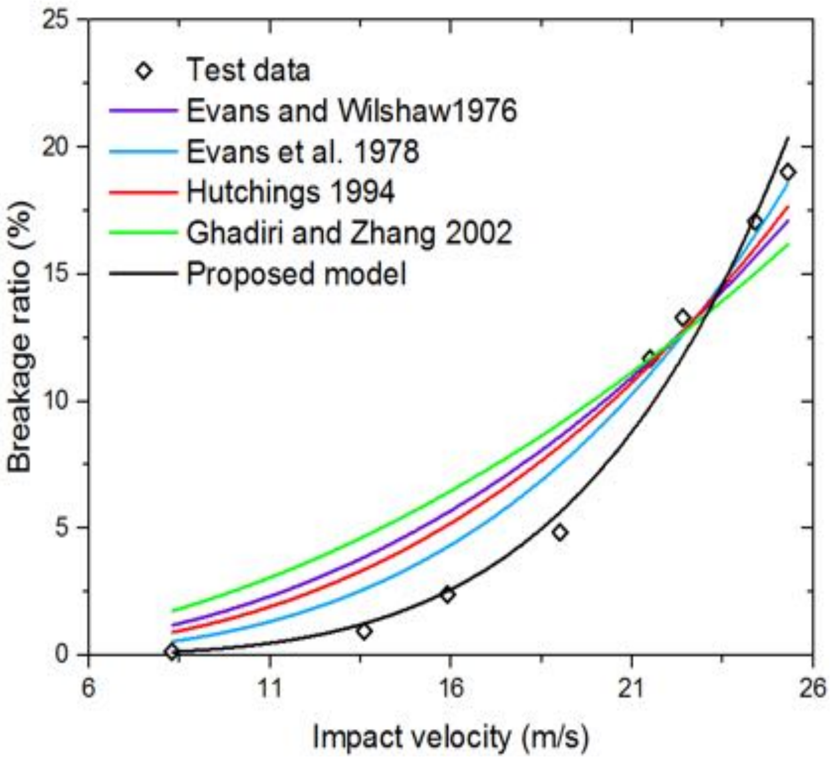
Model Considering Lateral Cracks under Normal Impact

- Assume: lateral crack responsible for chipping mechanism;
- Most existing models based on crack length from static or quasi-static analyses;
- Only Evans et al. (1978) used radial crack length under impact loading;
- Based on lateral crack length from impact damage (dynamic) analysis, a new model is developed for breakage ratio ε:

$$\varepsilon = \frac{V_{det}}{V} = \frac{\pi {c_l}^2 h}{\frac{4}{3}\pi R^3} = \frac{3{c_l}^2 h}{4R^3} \propto \frac{\rho^{1/4} R^2 H^{1/2}}{k_c^{5/2}} v^{9/2}$$

V_{det}=detached vol., V=total vol., c_l=lateral crack length, h=crack depth, R=radius, H=Hardness, v=impact vel., k_c= fracture toughness

- Close agreement between proposed model and impact test data



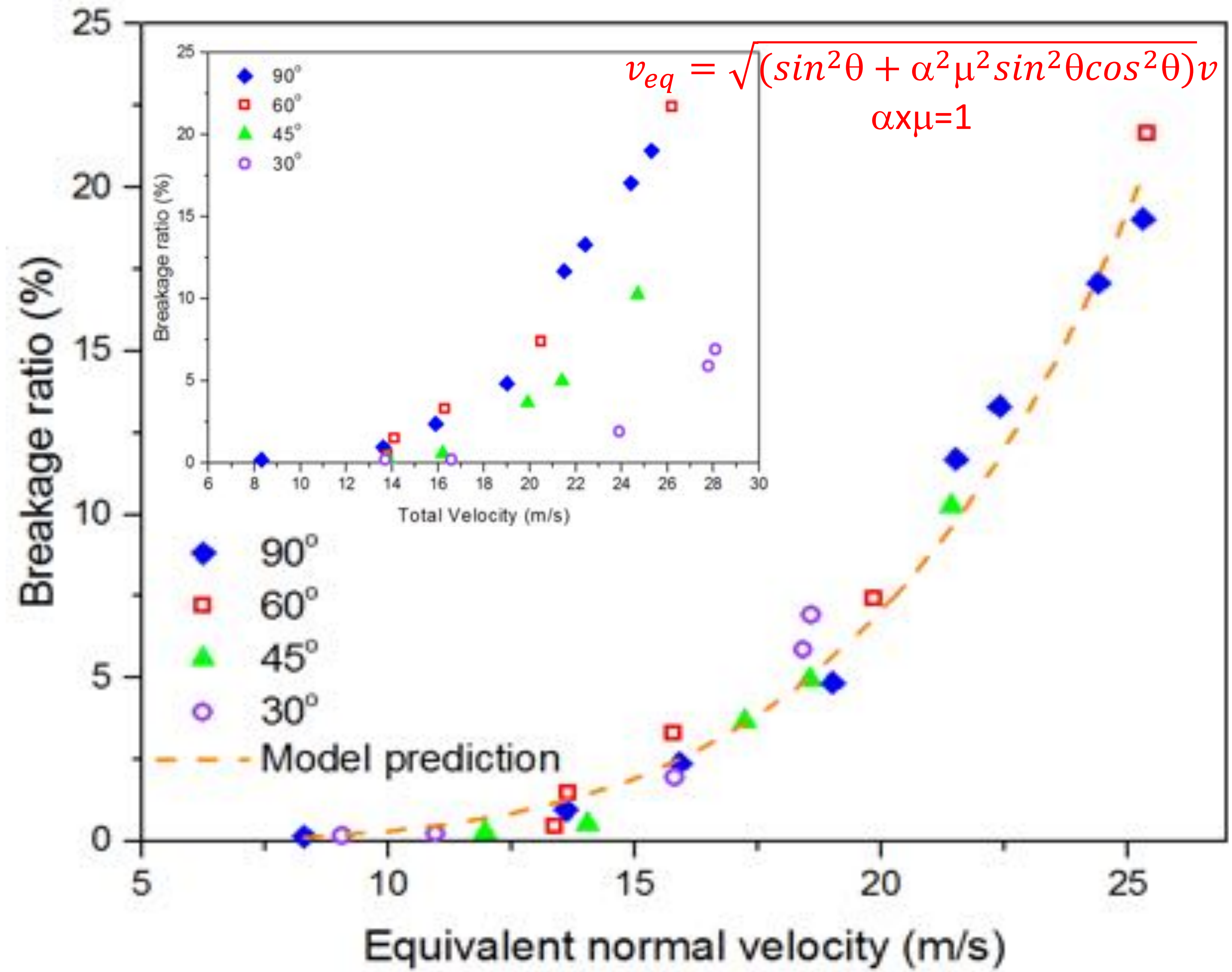
Model Considering Oblique Impact

- All previous models only considered the normal component of the impact velocity: the tangential component is ignored
- Experimental evidence has shown the significance of tangential component
- The effect of the incidence angle may be considered using the following equivalent velocity:

$$v_{eq} = \sqrt{(sin^2\theta + \alpha^2\mu^2 sin^2\theta cos^2\theta)}v$$

where v_{eq} is the equivalent velocity, v is the total velocity, θ is the incident angle (=90 deg when normal), μ is the dynamic friction coefficient between particle and impact surface, α is a coefficient.

Comparison with Test Data

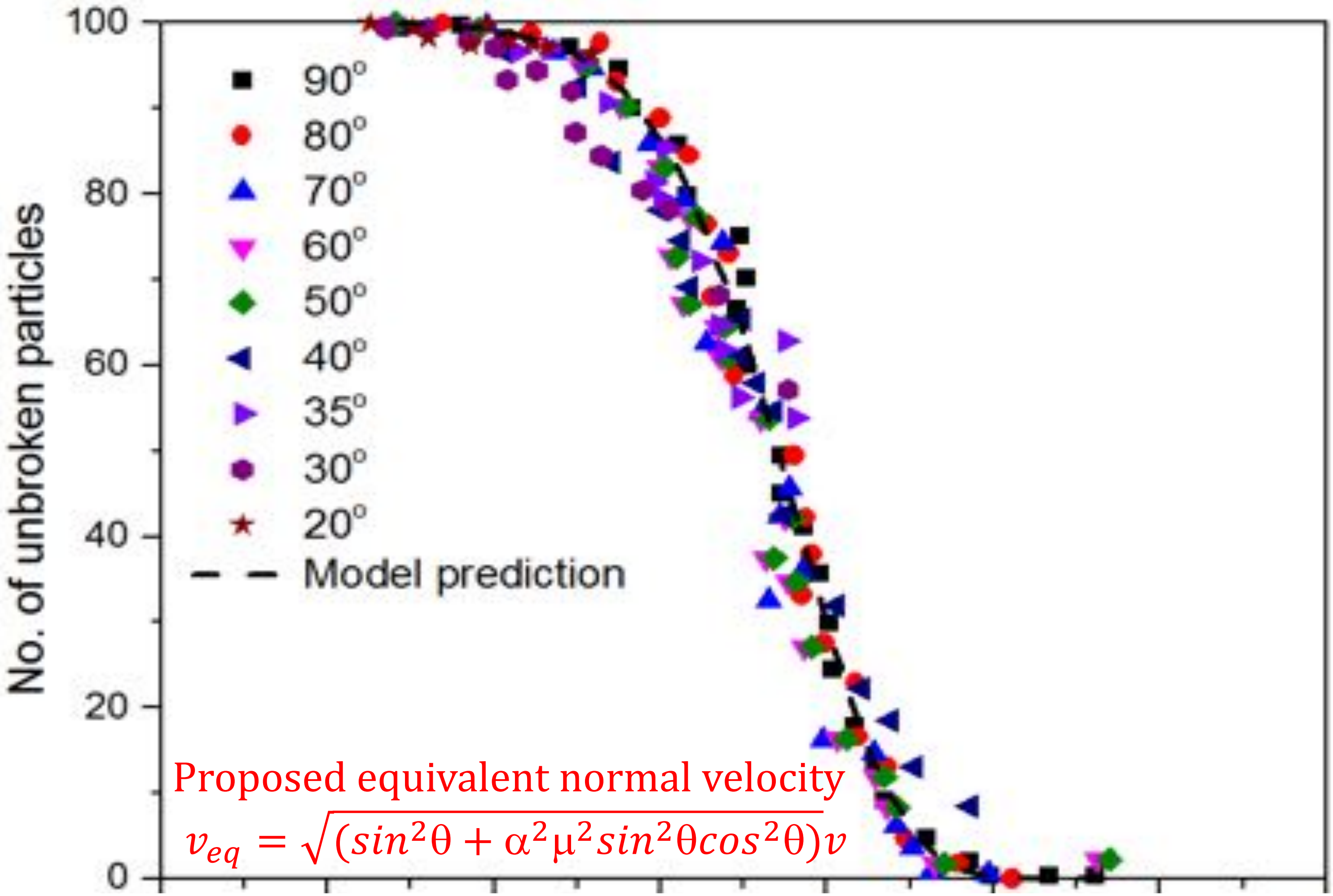


$$v_{eq} = \sqrt{(sin^2\theta + \alpha^2\mu^2 sin^2\theta cos^2\theta)} v$$

$\alpha \times \mu = 1$

Model Assessment: Fragmentation

Data source: Salman et al. (2003) Impact breakage of fertiliser granules



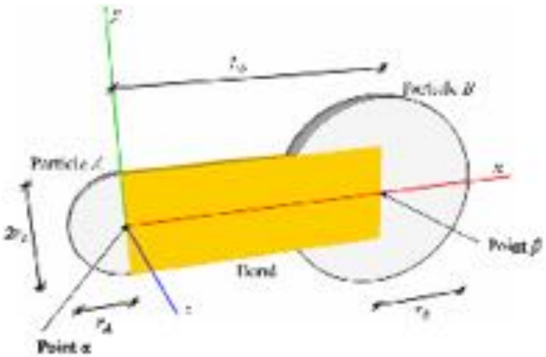
Proposed equivalent normal velocity

$$v_{eq} = \sqrt{(sin^2\theta + \alpha^2\mu^2 sin^2\theta cos^2\theta)}v$$

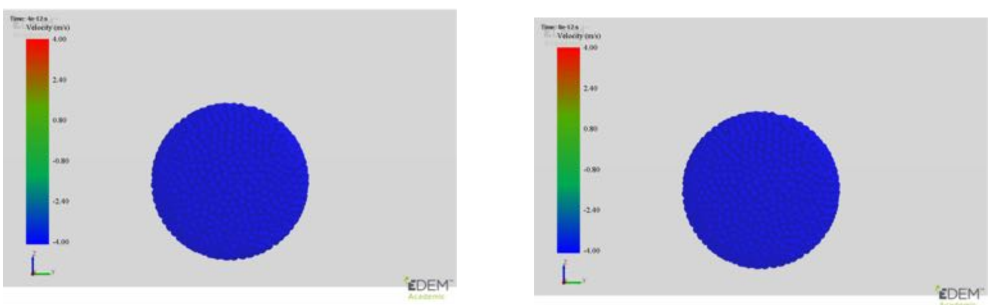
The equivalent normal velocity proposed successfully predicts the breakage under various oblique impact for both chipping and fragmentation (First model to consider impact angle!)

Bonded DEM Simulation

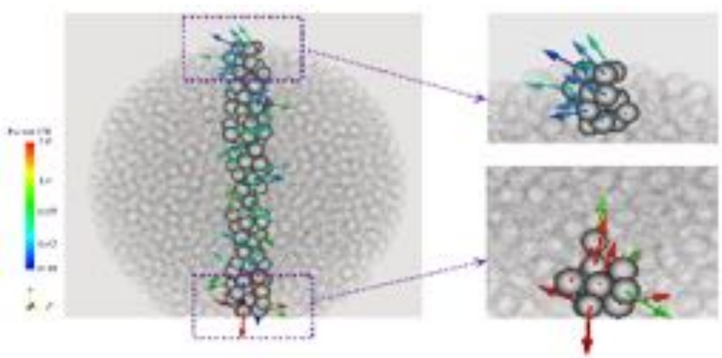
- A bonded particle model based on Timoshenko beam theory has been developed in Edinburgh (Brown et al. 2014)
- The model considers forces and moments response under compression, tension, torsion and bending loadings.

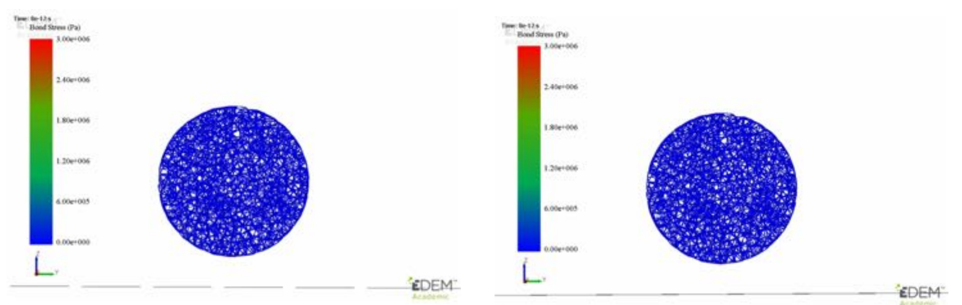


Bond between two particles



Velocity distribution during impact

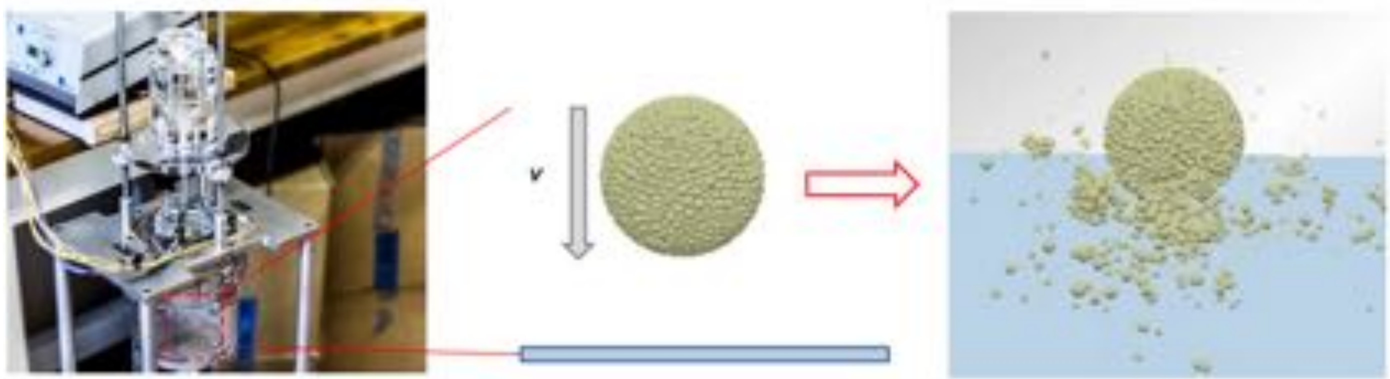




Tensile stress on bond network

- Help reveal the failure mechanism
- The model can be used to study various materials

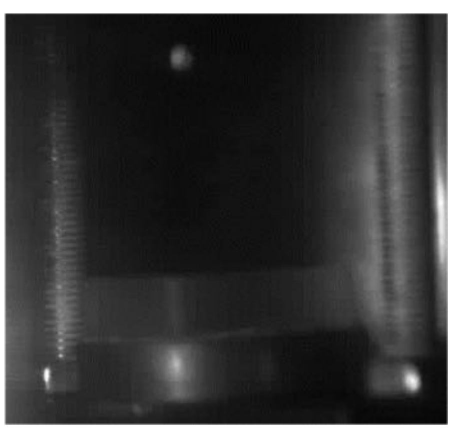
Impact DEM simulation-Zeolite



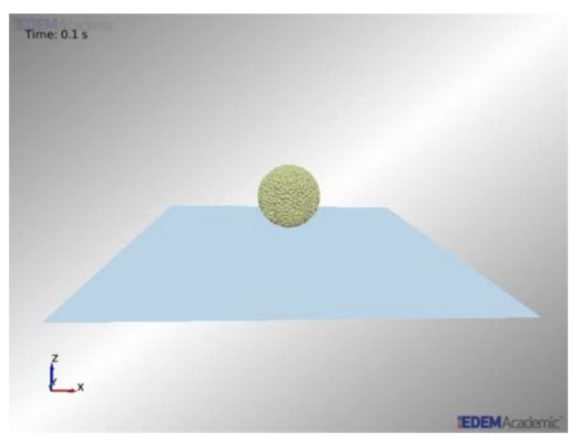
3687 constituent particles for a bonded particle

Single particle impact tester (courtesy from Leeds University)

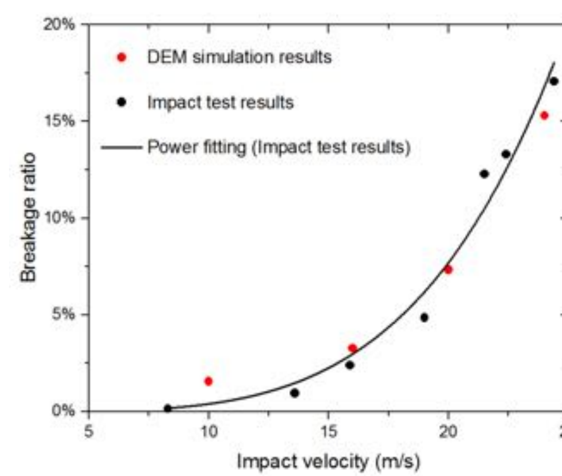
Edinburgh Bonded Particle Model simulation



30 m/s

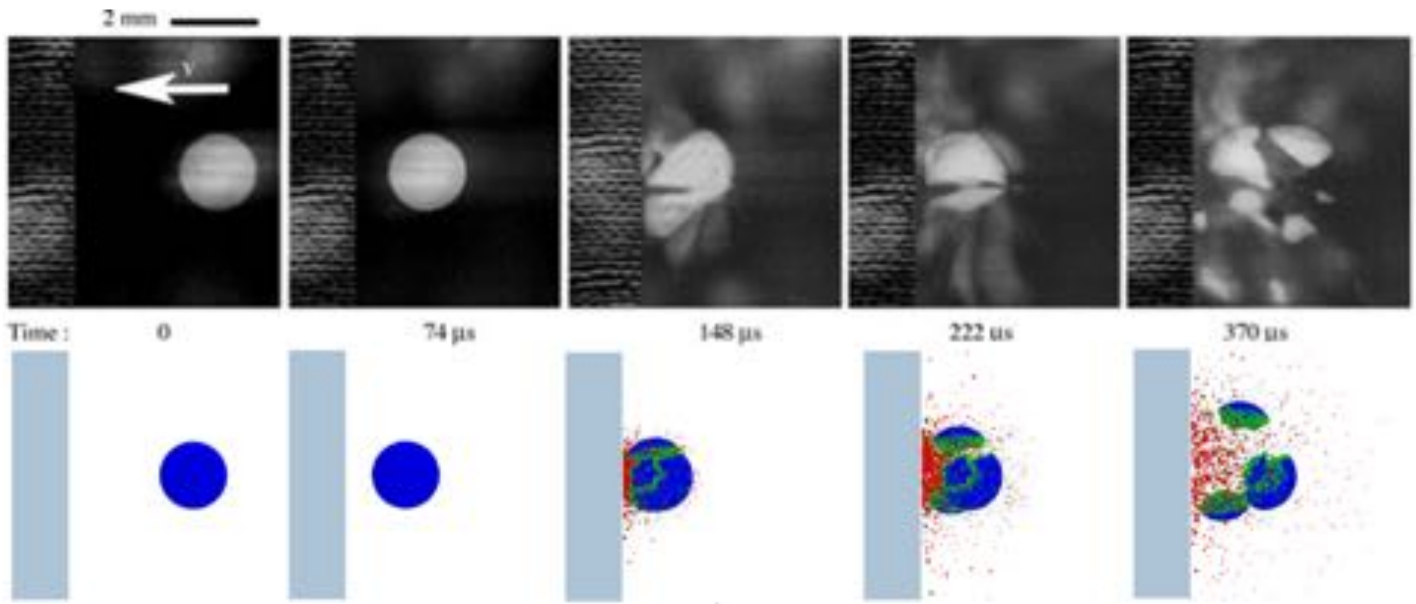


30 m/s

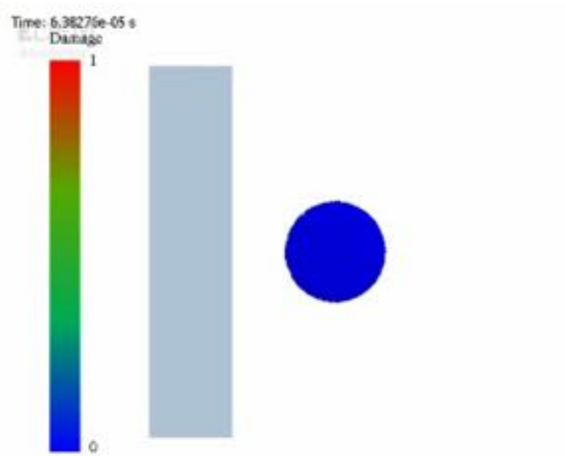


Good qualitative and quantitative agreement with experiment; 2.0 mm zeolite particle

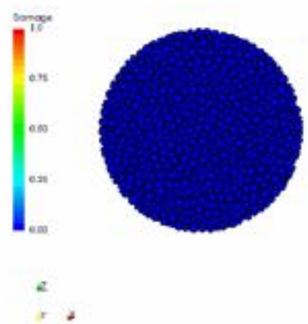
Impact DEM simulation-Alumina



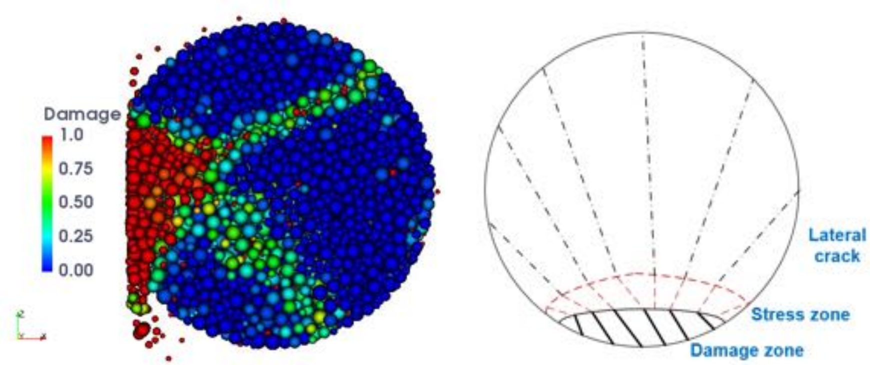
➢ **Comparisons between the simulation and the experiment of Antonyuk *etal* 2006**



Alumina: Impact velocity :23m/s



Diametrical slice

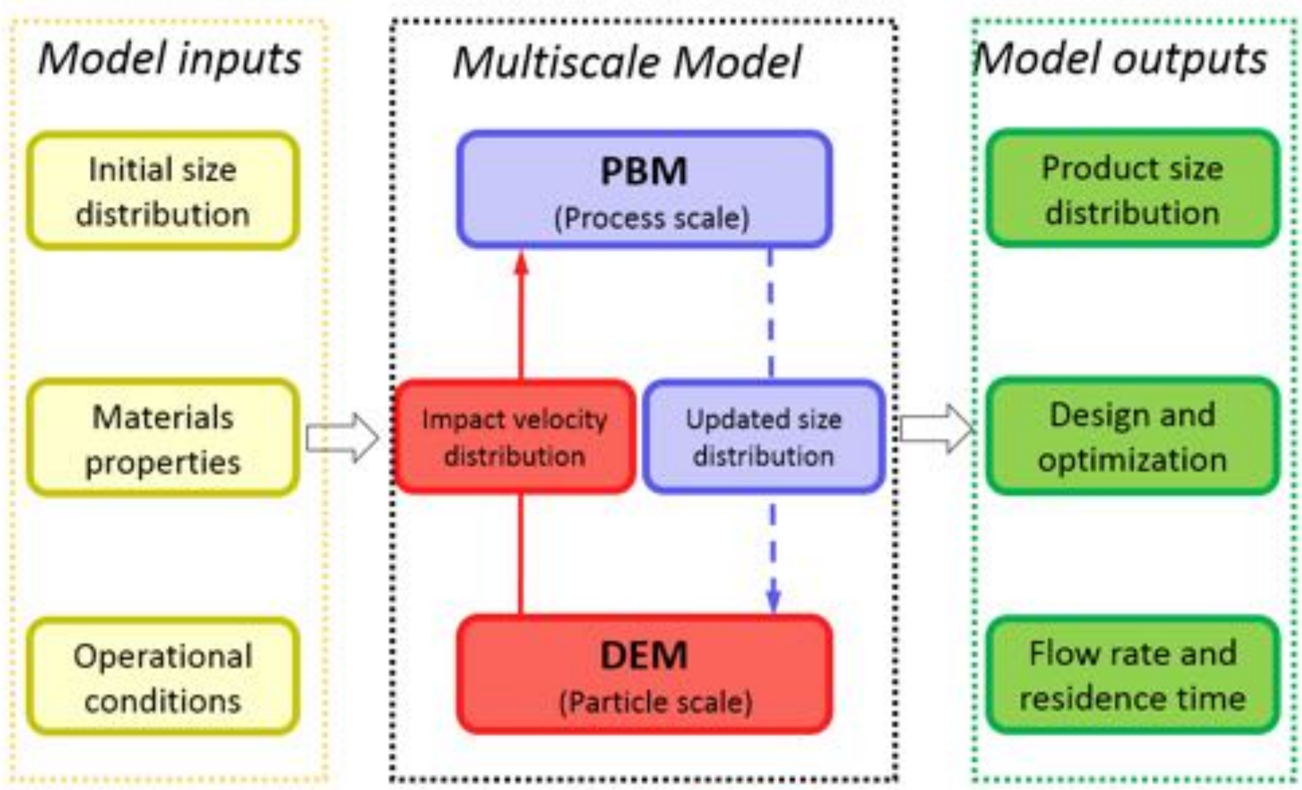


Failure mode

➢ **Cone crack initiated with secondary crack propagation leading to fragmentation (23 m/s)**

Motivation of DEM-PBM coupling

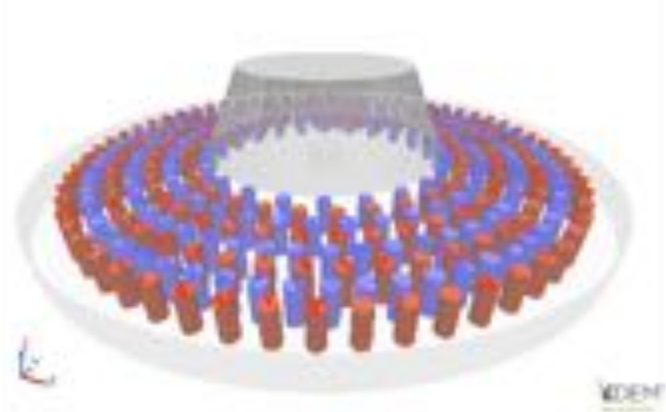
- Population balance model (PBM) is computationally efficient but empirically based modelling approach to model particle breakage.
- Discrete element method (DEM) can consider the effect mill geometry and operational conditions but computationally expensive.



➢ DEM can provide particle scale information to inform PBM predictions

DEM Simulation of Impact Pin Mill

pin mill UPZ100 from Hosokawa

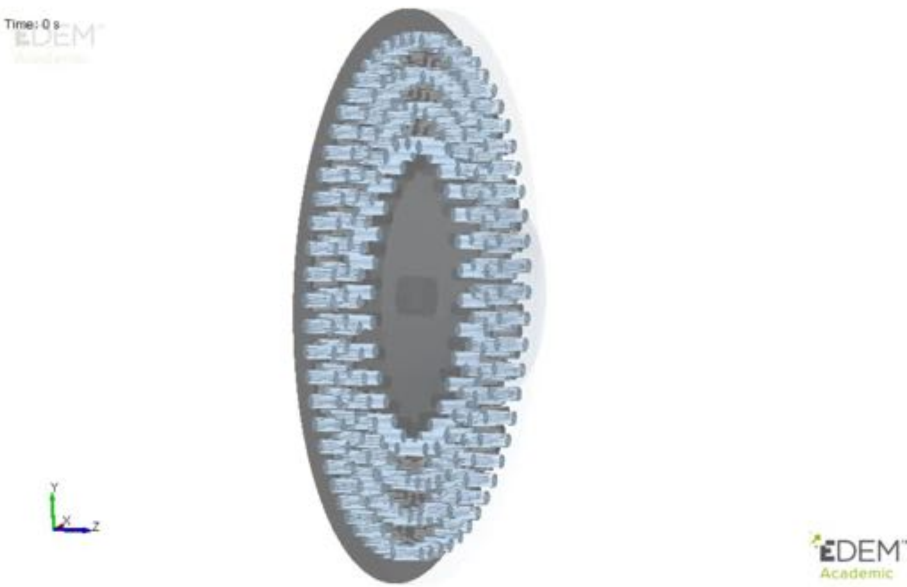


Sketch of DEM simulations

Simulation parameters for Alumina particle

Parameters	Value
Particle density (kg/m^3)	3370
Particle diameter (mm)	1.1
Particle Poisson's ratio	0.3
Particle Young's modulus (GPa)	15
Coefficient of restitution	0.82
Coefficient of static friction	0.37
Coefficient of Rolling friction	0.1
Pin density (kg/m^3)	7850
Pin Poisson's ratio	0.25
Pin Young's modulus (GPa)	81

➢ Parameters from lab characterization and calibration



➢ Pin region is the active region

DEM-PBM Upscaling Prediction

Population balance model

$$\frac{\partial M_p(x,t)}{\partial t} = -S_M(x)M_p(x,t) + \int_0^{\infty} S_M(y)M_p(y,t)b_M(x,y)\,dy$$

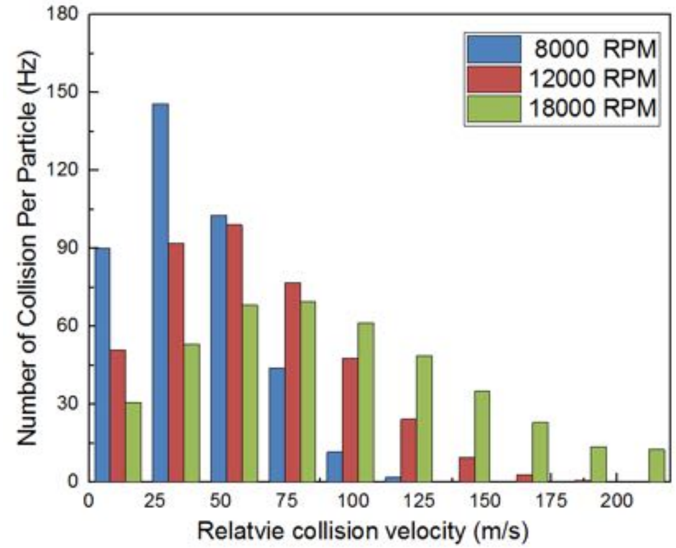
Breakage rate

$$S_M(x) = Sc_M\left[1-\exp\left(-f_{mat}x\left(W_{m,kin}-W_{m,\min}\right)\right)\right]$$

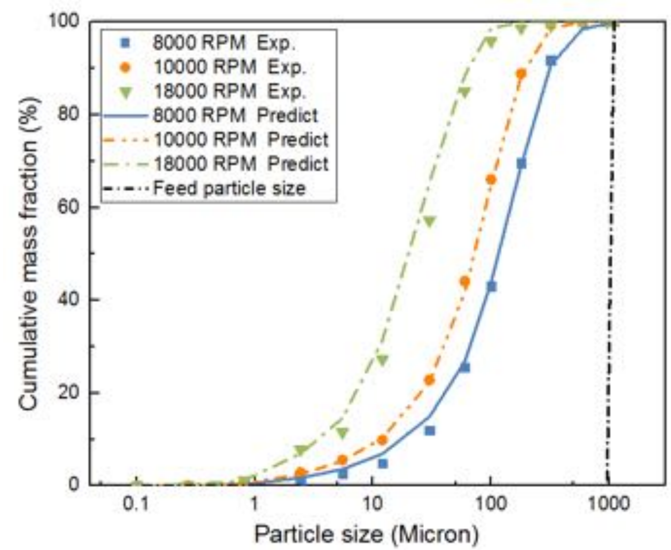
Cumulative breakage Distribution

$$B_M(x,y) = \frac{1}{2}\cdot\left(\frac{x}{y}\right)^q\cdot\left(1+\tanh\left(\frac{x-x'}{x'}\right)\right)$$

- The PSD of the other three rotating speeds were well predicted



Impact velocity distribution from DEM



Product particle size distribution predictions

Conclusions and Prospective

- Static, indentation and impact loading tests were deployed to characterise particle property
- A new model for particle breakage under impact loading was proposed including the effect of impact angle
- Chipping and fragmentation of particle under impact were captured using the Edinburgh bonded DEM model
- A multiscale framework of DEM-PBM coupling was proposed to predict the milling behaviour of impact pin mill

Acknowledgement:

Sponsor

International Fine Particle Research Institute (IFPRI)

Sixe-year project to establish generic framework for material grindability

Industrial Collaborator

Hosokawa Micron Ltd. UK; DEM Solutions Ltd

Co-workers

Dr. Alvaro Janda, Particle Analytics

Drs. JP Morrissey and Zeynep Karatza, Edinburgh University

Prof. Mojtaba Ghadiri, Leeds University

Dr. Colin Hare, Surrey University

Dr. Tannaz Pak , Teesside University

Drs. C. Viggiani and E. Ando from Université Joseph Fourier, Grenoble

Drs. L. Tavares and M. Carvalho,Laboratorio de Tecnologia Mineral, Brazil