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# Numerical analysis of strain rate sensitivity in ball indentation on cohesive powder Beds

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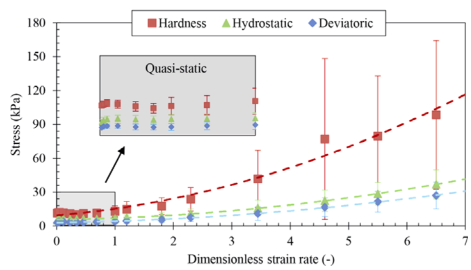
## HIGHLIGHTS

- Flowability of cohesive powders in the intermediate range of strain rates has been investigated.
- Effects of strain rate on bed hardness is analysed using DEM.
- Stresses are almost constant up to a dimensionless strain rate of 1.
- For dimensionless strain rates greater than 1, the stresses become rate dependent.
- Fluctuations in the stresses are negligible in the quasi-static regime, but not beyond.

## GRAPHICAL ABSTRACT

Stresses become strain rate dependent for dimensionless strain rates greater than unity. Below this limit the quasi-static regime is observed. There are notable fluctuations beyond the quasi-static regime, and the data presented here are averaged.

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## ABSTRACT

In the shear deformation of powder beds beyond the quasi-static regime the shear stress is dependent on the strain rate. Extensive work has been reported on the rapid chute flow of large granules but the intermediate regime has not been widely addressed particularly in the case of cohesive powders. However in industrial powder processes the powder flow is often in the intermediate regime. In the present work an attempt is made to investigate the sensitivity of the stresses in an assembly of cohesive spherical particles to the strain rate in ball indentation using the Distinct Element Method. This technique has recently been proposed as a quick and easy way to assess the flowability of cohesive powders. It is shown that the hardness, deviatoric and hydrostatic stresses within a bed, subjected to ball indentation on its free surface, are dependent on the indentation strain rate. These stresses are almost constant up to a dimensionless strain rate of unity, consistent with trends from traditional methods of shear cell testing, though fluctuations begin to increase from a dimensionless strain rate of 0.5. For dimensionless strain rates greater than unity, these stresses increase, with the increase in hardness being the most substantial. These trends correlate well with those established in the literature for the Couette device. However the quantitative value of the strain rate boundary of the regimes differs, due to differences in the geometry of shear deformation bands. Nevertheless, this shows the capability of the indentation technique in capturing the dynamics of cohesive powder flow.



## 1. Introduction

In industrial processes such as mixing, blending, handling and storage reliable powder flow is important for product quality and a consistent production rate. Understanding the flow characteristics of the powder can avoid wastage, machinery maintenance problems

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and downtime in such processes. Strain rate is particularly of great importance since in the shear deformation of powder beds beyond the quasi-static regime the shear stress is dependent on the strain rate (Tardos et al., 2003). Extensive work has been reported on the rapid chute flow of large granules (Savage, 1979) but the intermediate regime has not been widely addressed, particularly for cohesive powders. However in industrial powder processes the powder flow is often in the intermediate regime, for which the specification of an operational window in terms of strain rate for reliability and control is highly desirable. Tardos et al. (2003) classified powder flow into three regimes based on the shear strain rate of the process. At very low strain rates, the frictional forces between particles are predominant and the shear stress is independent of the strain rate, hence this is termed the quasi-static regime. In the other extreme at very high strain rates, that is, the dynamic regime, the flow is characterised by rapid and short duration collisions between particles rather than the friction between them and hence the particle inertia is influential. There has been extensive work for this regime, in which it has been shown that the shear stress varies with the square of strain rate (Savage and Sayed, 1984; Bagnold, 1954; Campbell and Brennen, 1985). Between the quasi-static and dynamic, inertial regimes lies the intermediate regime, where both collisional and frictional interactions between the particles influence the flow characteristics (Tardos et al., 2003). There exist a number of test methods for evaluation of flow behaviour of powders, such as the unconfined compression test (Parrella et al., 2008), shear test (Schulze, 1994) and a few recently developed techniques, such as the Sevilla powder tester (Castellanos et al., 2004) the raining bed technique (Formisani et al., 2002) and the ball indentation method (Hassanpour and Ghadiri, 2007). All of these methods evaluate the incipient flow at very low strain rates (i.e. the quasi-static regime), and hence cannot depict the strain rate sensitivity of powder flow. The only method by which the intermediate regime has been analysed is the Couette device of Tardos et al. (2003), where the powder is sheared between two concentric cylinders (with the axis being vertical). The inner cylinder is rotated at different rotational velocities whilst the outer cylinder is stationary, forming a shear band in the gap. It was confirmed that during the quasi-static regime the stresses were independent of the strain rate. For the intermediate regime the dependency of the shear stress on the dimensionless strain rate $\gamma^*$ (as given by Eq. (1)) is with a power index less than 2.

$$\gamma^* = \gamma \left(\frac{d_p}{g}\right)^{1/2} \tag{1}$$

where $\gamma$ is the strain rate, $d_p$ is the mean particle diameter and $g$ is the gravitational acceleration. For the dynamic regime, this dependency is to the power 2 (Savage and McKeown, 1983). Tardos et al. (2003) observed that the fluctuations of the stresses increased with the strain rate and that the width of the intermediate regime in terms of dimensionless strain rate was a function of the assembly concentration (Tardos et al., 2003). At low particle concentrations (high bed porosity), the width was relatively narrow, between dimensionless rates of 0.5 to 2 (Tardos et al., 2003).

In two commercial instruments the powder is also subjected to shear strains in the intermediate regime by a paddle penetrating whilst rotating in a powder bed (Freeman Powder Tester FT4 (Freeman, 2007; Bharadwaj et al., 2010) and PowderFlow Analyser by StableMicro Systems, Surrey, UK). However the complex paddle geometry provides a highly non-uniform strain field, where the powder strain and strain rate increase from the centre to the cylindrical wall. Recently Hare et al. (2011) have analysed the shear stress and strain fields around a rotating impeller and have quantified their radial and axial variations. Their work shows that the shear stresses are greatest in the vicinity of the front of the blades; the stresses reduce above the impeller and away from the impeller in the angular direction, providing a highly non-uniform strain field. Based on their work, the interpretation of paddle torque to elucidate the strain rate dependency of shear stresses using these commercial devices is difficult until systematic work on model materials with 'tuneable' and controlled bulk cohesion has been fully analysed.

Moreno-Atanasio et al. (2005) simulated uniaxial unconfined compression of cohesive beds using the Distinct Element Method (DEM) for a range of strain rates. They also found that the unconfined yield stress (UYS) did not depend on strain rate for small values of strain rate (less than $2\ s^{-1}$), and only exhibited dependency for larger values, where a linear relationship between UYS and strain rate was reported. A power law fit with a power index of 1.2 showed the best fit for the simulations data. The threshold strain rate which defined the limiting quasi-static rate was found to be slightly dependent on the inter-particle cohesion, where by increasing the cohesion the threshold was increased slightly. It was also shown that by increasing the pre-consolidation stress, the sensitivity of UYS to the strain rate decreased in the intermediate and inertial regimes, which is in-line with Tardos et al. (2003) findings on assembly concentration. It should be noted that possible effects of aeration were not considered in the above analysis.

In the present work an attempt is made to investigate the sensitivity of the stresses in an assembly of cohesive spherical particles in the ball indentation process (Pasha et al., 2013) using DEM. Again, the effect of air drag in this analysis is ignored.

### 1.1. Ball indentation technique

Hassanpour and Ghadiri (2007) proposed a test method for assessing the flowability of cohesive powders based on ball indentation on a powder bed. The method has a unique advantage as it can be performed on small amounts of loosely compacted powders. For the experimental indentation process, a powder sample is lightly consolidated into a cylindrical die which is made of low friction materials in order to reduce the effects of wall friction. The surface of the consolidated bed is then indented using a spherical indenter and the depth/load cycle is recorded from which the 'hardness' of the powder surface is inferred. For continuum solids, hardness represents the flow stress following a certain extent of strain (Tabor, 2000). The same approach has been explored for particulate solids by Wang et al. (2008), where it has been shown that the flow stress obtained by this method correlates well with the unconfined yield stress measurements obtained from shear cell and unconfined uniaxial compression test methods. Here we use the terms hardness and flow stress interchangeably. Hardness, $H$, is given by the ratio of the maximum indentation load, $F$, to the projected area of the impression,

$$H = \frac{F}{A} \tag{2}$$

where $A$ is the area of the base of the spherical cap that is formed by the impression. The projected area can be expressed in terms of the size of the indenter and depth of impression:

$$A = \pi(dh - h^2) \tag{3}$$

where $d$ is the indenter diameter and $h$ is the depth of impression.

## 2. DEM simulation of ball indentation process

For the analysis of contact force distribution and the resulting stresses in an assembly of particulate solids, the most appropriate