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A modified flowability classification model for moist and cohesive bulk solids

Wei Chen *, Alan W. Roberts

Centre for Bulk Solids and Particulate Technologies, The University of Newcastle, Callaghan 2308, Australia

A R T I C L E I N F O

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A B S T R A C T

The Jenike flowability classification is designed to indicate the handleability of bulk solids in material handling processes. However, for moist, cohesive bulk solids, it may fail to represent the true flowability/handleability at high consolidation stresses. The study presented in this paper introduces a modified flowability classification model aiming to improve the flowability/handleability prediction across a wide range of consolidation pressures. The evolution of the flow function of bulk materials under increasing moistures is initially discussed, based on which the Jenike flowability classification is reviewed. The modified flowability classification is then derived by considering the flow/no flow condition for mass flow hopper designs under both low and high consolidation stress states. The influence of the bulk material type and general operational conditions are also taken in account in deriving the modified classification method. A suite of bulk solids with a wide range of material properties are selected in an experimental program to validate the modified flowability classification. Results suggested the modified flowability classification is able to more accurately indicate the overall flowability/handleability of the bulk solids independent of the applied major consolidation stress.

1. Introduction

Flow properties and behaviours of run-of-mine ore materials are heavily influenced by the inherent moisture. The excessive moisture contained in the bulk solids emerges from mining ore deposits near or under the water table [1], as well as that due to heavy rainfall and tropical storms. The increase of the inherent moisture leads to more cohesive and adhesive behaviours, which cause poor flowability in material handling chains [2]. It is therefore important for the mining industries to monitor the flowability of bulk materials to ensure efficient handling and minimise potential blockages.

There two main types of handling problems involving moist and cohesive minerals [3]:

- Type 1: Arching and ratholing
  H1.1 – Aching over openings during gravity flow – low consolidation pressures
  H1.2 – Hang-ups and ratholing – high consolidation pressures
- Type 2: Blockages in chutes and transfers
  H2.1 – Adhesion and friction at low contact pressures
  H2.2 – Sliding in chutes and hoppers at high contact pressure.

Problems H1.1 mainly concern the outlet regions of mass-flow hoppers. Such hoppers may be an integral part of storage bins and silos, or located in the reclaim regions of gravity discharge stockpiles. Under mass-flow, consolidation pressures in the outlet region of the hoppers under flow conditions are quite low, being typically, but not exclusively, in the range 2 kPa to 20 kPa. Such handling problems may also occur in the outlet regions of funnel-flow bins, particularly in the case of rectangular shaped openings where arching across the openings can occur [4].

Problems H1.2 are the major concern of funnel-flow and expanded flow bins and gravity reclaim stockpiles [5,6]. In this case, the consolidation stresses are considerably higher than those linked to mass-flow. For storage bins operating under funnel-flow, the pressures, typically, may range from 100 kPa to 300 kPa depending on the bin size and bulk material properties. For gravity reclaim stockpiles, consolidation stresses may be as high as a Mega-Pa (MPa) as would be the case for a 40 m high iron ore stockpile [7–9].

Problems type H2.1 and H2.2 are mainly confined to chutes and transfers, but may also occur in storage bins [10,11].

With increasing moisture and resulting cohesive behaviours, accurate characterisation of the flowability for moist minerals becomes a priority. This is to ensure the material handling solution is directly relevant to the actual physical flow application. Flowability of a bulk material is characterised by the applied consolidation stress (σ_1) and the resulting unconfined yield strength (σ_c). Such a correlation is often obtained through an industry accepted testing method notably the Jenike direct shear test. Jenike [7,12] proposed a simple classification

* Corresponding author at: Centre for Bulk Solids and Particulate Technologies, Newcastle Institute for Energy and Resources, The University of Newcastle, Callaghan 2308, Australia.
E-mail address: W.Chen@newcastle.edu.au (W. Chen).

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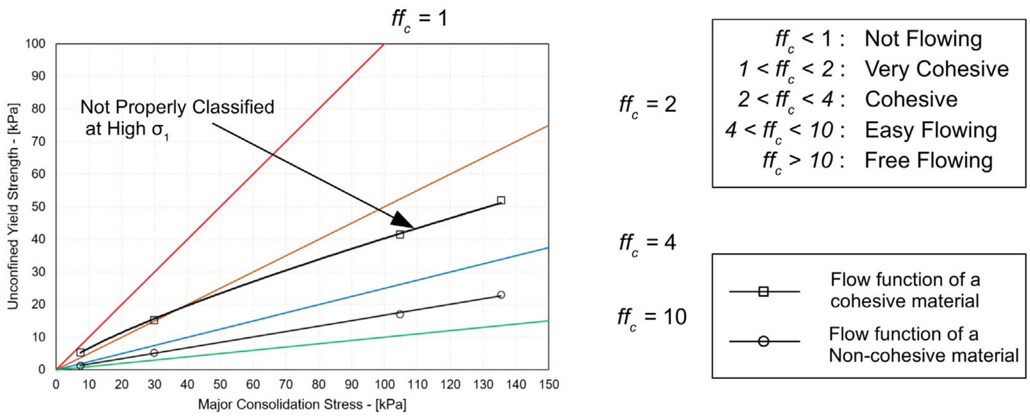

Fig. 1. Distribution of the non-cohesive and cohesive flow functions in Jenike flowability classifications.

to characterise a bulk material's flowability, ff_c, expressed as $ff_c = \sigma_1/\sigma_c$ based on the research on mass flow. As shown in Fig. 1, five flowability behaviours were categorised based on the numerical value of ff_c expressed.

Generally, this classification is able to accurately capture material's physical flow performance when it is characterised as free flowing ($ff_c > 10$) or easy flowing ($4 < ff_c < 10$) materials. Flow functions located in these regions can extrapolate to the origin. In comparison, as soon as the bulk solids become moist and cohesive, a single Jenike flowability value is not capable of fully describing its flow behaviours. As shown in Fig. 1, the flow function of a cohesive material may span over dual or more flowability classifications [13–15]. Moreover, based on the Jenike flowability classification, a cohesive material can be indicated to exhibit poor flowability under low consolidations, and improved flowability at higher consolidations; whereas, the actual flow performance may not improve. Therefore, such classification may mislead the true flow characteristics in high consolidation scenarios.

Based on the foregoing comments, the purpose of this paper is to critically evaluate the stress state of moist and cohesive bulk solids, based on which an improved flowability classification is derived to indicate the material's flowability and its implied handleability in bulk material handling processes.

2. Flow properties of moist bulk materials

When moisture is present in bulk materials, it potentially adds bonding strength to the bulk solids [16]. As shown in Fig. 2 (a), there are three liquid bonding states in moist bulk solids, namely, pendular state, funicular state and capillary state, which are classified depending the percentage of moisture filling up the void space [17]. In pendular state, there is generally a small quantity of liquid in the bulk solids void space, and liquid bridges are mostly formed between individual particles. The weak tensile strength of the bulk material is caused by the liquid bridges. In the case of mono-sized spheres, the tensile strength σ_z may be estimated as [18],

$$\sigma_z = \frac{1-\varepsilon}{\varepsilon}\frac{\overline{F_H}}{d^2} \tag{1}$$

where ε is the voids ratio, d is the sphere diameter, and $\overline{F_H}$ is the mean adhesion force between two particles at a contact point. Unfortunately, since actual particles often exhibit random particle shape characteristics, determination of the tensile strength often relies on experimental measures.

When the moisture content is increased and material enters the funicular state, some voids within the particle assembly start to be filled with liquid. The resulting capillary pressure P_k from this portion of the moisture provides additional bonding strength [19]. Therefore, the total bonding strength from the moisture may be expressed as,

$$\sigma_z = \sigma_{z,b} + \sigma_{z,k} \tag{2}$$

where $\sigma_{z,\ b}$ and $\sigma_{z,\ k}$ are tensile strength from liquid bridging and capillary pressure, respectively. Depending on the saturation level

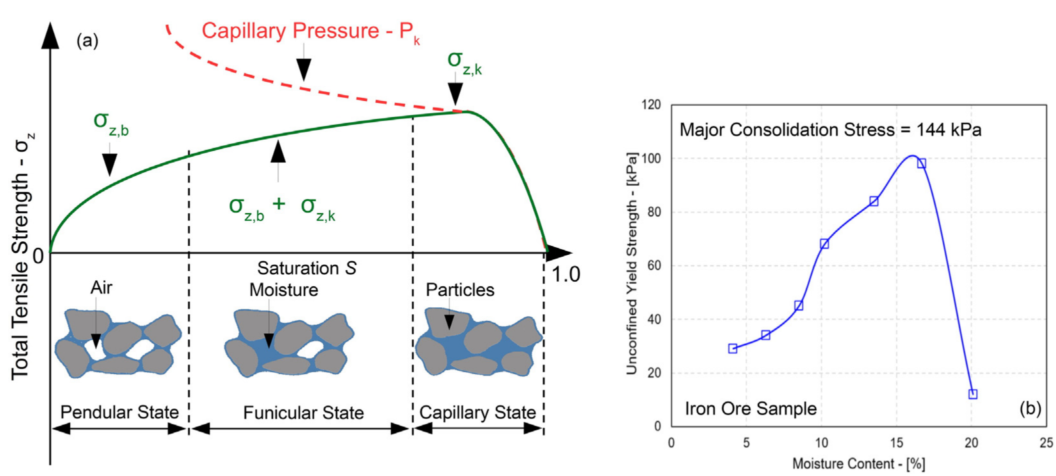

Fig. 2. (a) Dependence of total tensile strength on the moisture content and consolidation level of the moist bulk solids; (b) variation of bulk strength versus moisture content under a fixed major consolidation stress for a typical iron ore sample.