Overcoming flow characterisation challenges and enhancing handling equipment selection for biomass and biowaste materials

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Abstract

Biomass and biowaste solids often have unique particle shapes and high moisture content, posing significant challenges in handling processes. Due to the typically wide range of particle sizes, the flow properties of these materials cannot be accurately characterised using traditional methods. Key challenges in characterising the flow properties of biomass and biowaste include extreme particle size variation, high compressibility of materials, irregular particle shapes causing flow issues, and high moisture content impacting handling properties. This paper presents a case study demonstrating and examining the effectiveness of existing characterisation techniques for biomass and biowaste, specifically for applications in storage silos and discharge. The study showcases the fundamental physical properties of biomass and biowaste, along with the unique behaviour they exhibit. The investigation explores methods for flow property characterisation and introduces a classification system based on physical format. This system aids in selecting suitable characterisation techniques and handling methods for specific materials. The case study illustrates how the challenges of irregular particle shapes, high compressibility, and elevated moisture content can be identified using the discussed classification system and characterisation techniques. Additionally, this highlights best practices in selecting and designing material handling equipment to address these specific challenges in biomass and biowaste management.

1 Introduction

The reliable flow of bulk solids from hoppers and silos has remained a persistent engineering challenge for over half a century. A major advancement in this domain came during the early 1960s, when Jenike introduced a scientific method to design hoppers that would reliably discharge material under gravity alone, without reliance on external flow aids such as vibrators or air cannons. This methodology, detailed in his seminal publications Bulletin 108 and Bulletin 123, laid foundation for modern hopper design by linking flow behaviour to material properties through shear testing and wall friction analysis [1]. Despite the robustness of Jenike's approach, practical observations indicate that flow obstructions remain commonplace across industrial installations. Anecdotal and industry evidence reveal that hoppers frequently require external intervention, such as hammering, vibration, or the use of air injection devices—to maintain flow. The widespread commercial success of aftermarket flow aids underscores this issue; in fact, more companies profit from manufacturing flow aids than from designing hoppers and silos themselves [2].

In the UK, Solids Handling and Processing Association (SHAPA), a trade body representing over 100 manufacturers and service providers in the solids handling sector, lists more suppliers of discharge aids (22) than of silos (19) in its directory—remarkably, with 7 companies appearing in both categories [3]. This overlap highlights an implicit industry norm: discharge aids are often viewed as an inseparable complement to silo design.

Within the academic and specialist consultancy communities, the Jenike method remains a standard for designing hoppers that perform reliably. Its application, with evolved test methodologies, has led to the successful implementation of thousands of hopper designs over the decades. Yet, many hoppers in the industry operate effectively without ever employing this methodology. Of the 19 silo manufacturers listed by SHAPA, only 2 possess in-house shear testing capabilities, and only 4 others are known to periodically outsource such services [4]. This implies that although Jenike's design method is effective, it is not universally adopted, nor always essential, for achieving acceptable performance.

A further complication arises with the increasing use of non-traditional materials such as biomass and recycled waste, which often consist of irregular, large, or fibrous particles. These materials pose significant challenges for standard shear cell testing and may not conform to the cohesive flow assumptions underpinning Jenike's arching (tendency of a material to arch at the outlet of hopper) and ratholing (phenomenon of the material sticking around the walls of the hopper) models. For instance, shredded plastics, chopped straw, or municipal solid waste often exhibit free-flowing characteristics in cohesion terms, yet demonstrate poor flowability due to mechanical interlocking or bulk geometry effects [4]. This paper addresses these gaps by exploring both limitations and the ongoing relevance of traditional flow

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characterisation and design methodologies in the context of modern materials and processing technologies.

2 Introducing the novel classification system

Effective management of bulk solids flow is critically dependent on an accurate understanding of material behaviour. A novel classification system has been developed to categorise powders and granular materials based on their flow characteristics and physical properties.

2.1 Class 1: Free-Flowing powders

Class 1 materials are characterised by their inherently good flowability, which is reflected in their inability to form stable arches or rat-holes under gravity discharge conditions. These materials generally include:

- **Morphology**: Rounded or angular particles, but without extreme elongation or flatness.
- **Size criteria**: A median particle size (d_{50}) typically above ~100 µm in dry conditions.
- **Moisture sensitivity**: For surface-wet materials, flow remains free as long as no more than 15% of the particles are below 4 mm.
- **Flow** : These materials demonstrate free-flowing characteristics in both static and dynamic situations.

Examples of Class 1 materials include dry grains, coarse granules, pellets, free-flowing minerals, and wet but coarse particulate systems where inter-particle adhesion is negligible. Their performance in hoppers is generally predictable, with minimal risk of flow obstructions when stored in reasonably designed vessels.

2.2 Class 2: Cohesive powders

Materials in Class 2 exhibit measurable cohesion, leading to flow difficulties such as arching or rat-holing in inadequately designed hoppers. These powders often pass a simple field test—forming a stable ball when compressed by hand. Their cohesive nature arises from several physical and chemical phenomena:

- **Inter-particle forces**: Including capillary bridges from moisture or oil (meniscus effects), plastic deformation in soft particles, or van der Waals forces in very fine powders (typically with $d_{50} < \sim 100$ µm).
- **Particle size and moisture effects**: In surface-wet conditions, materials with more than 15% of particles below 4 mm typically fall into this class.
- **Time-dependent**: Many materials exhibit time consolidation, whereby cohesive strength increases with storage duration.

Common examples include fine powders, soya meal, surface-wet clays. Unlike Class 1, these materials often require careful characterisation and tailored hopper design—using methods such as shear testing—to avoid flow problems.

2.3 Locating the boundary between Class 1 and Class 2

Particle size and surface moisture content are primary parameters that distinguish free-flowing from cohesive powders, while the surface energy of dry particles plays a secondary role. Because these properties vary continuously, so does the flow behaviour across the powder spectrum.

To demarcate the boundary between Class 1 and Class 2, the widely accepted criterion originally proposed by Jenike is recommended. This involves the position of the material's Flow Function curve (defined as ratio of consolidation stress to failure strength) relative to a reference line of slope 1:10 on the Flow Function graph. Materials with a Flow Function curve lying below this boundary typically require less stringent hopper design considerations, while those above the line are prone to flow problems and require detailed characterisation and design adaptations.

2.3.1 Particle size – for dry bulk solids:

Smaller particle size lifts the Flow Function curve as shown in fig. 1 below for soda ash.

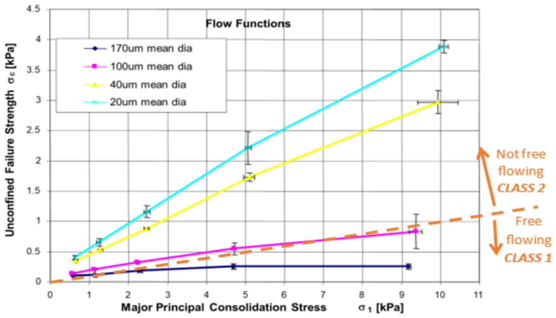

Fig. 1. Effect of particle size on Flow Function of dry soda ash

For other materials, the transition between free-flowing and non-free-flowing behaviour occurs at varying particle sizes, primarily influenced by differences in surface energy. However, for dry powders, this variation generally has minimal practical impact. The most notable exception is metal powders, which tend to transition from free-flowing to cohesive behaviour at around 50 microns. Conversely, it is rare to encounter dry materials with median particle sizes above approximately 150 microns that do not exhibit free-flowing characteristics. Therefore, it can be stated with reasonable confidence that the boundary between Class 1 and Class 2 dry bulk solids lies within the median particle size range of 50 to 150 microns.

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2.3.2 Moisture content:

Moisture on the surface (adsorbed moisture) raises the Flow Function curve as shown in fig. 2 below :-

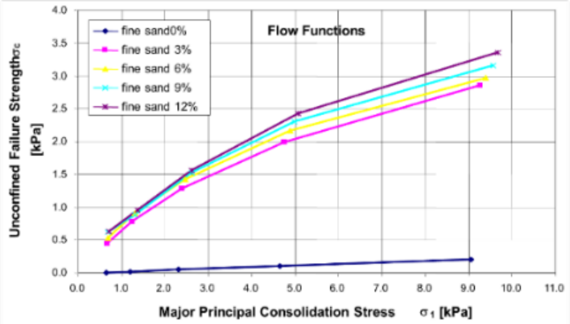

Fig. 2. Effect of surface moisture on the Flow Function of sand

For coarse particles—particularly those larger than approximately 5 mm—the material will typically remain within Class 1, regardless of its moisture content. However, when dealing with particle size distributions common in the mining and minerals industries, a widely recognised rule of thumb applies: if more than 15% of the material consists of particles smaller than 4.15 mm, the bulk solid is likely to exhibit poor flowability when wet, thus transitioning into Class 2.

In situations where the classification of a material is uncertain, a simple and practical diagnostic known as the "snowball test" has proven effective. By compressing a handful of the bulk material in one's hand and observing the result, a quick judgment can be made: if the compressed mass retains any coherent structure after the hand is opened, the material likely belongs to Class 2. If it crumbles and fails to hold shape, it can reasonably be classified as Class 1.

2.4 Special case: long, stringy particles (Class 3)

A third distinct category is recognised for materials composed of long, fibrous, or stringy particles. These materials exhibit highly irregular flow behaviour characterised by “nesting- mechanical interlocking”, which differs fundamentally from the cohesion-driven flow obstruction seen in Class 2 powders.

- **Examples**: Raw biomass (e.g., chopped straw, corn stover), shredded waste paper, municipal solid waste.
- **Flow characteristics**: These materials are notoriously difficult to handle and require specialised storage.
- **Mechanism of flow failure**: Unlike cohesive powders, their flow failure originates from mechanical entanglement and physical jamming rather than inter-particle adhesive forces.

The “nesting” phenomenon and its impact on hopper performance are the subject of ongoing study. The onset of Class 3 behaviour has been investigated using simplified geometries; for example, Owonikoko [5] demonstrated that rigid, identical cuboidal particles exhibit Class 3 characteristics when the length-to-diameter (L/D) ratio exceeds 2.5:1. However, in practical applications, materials exhibiting Class 3 behaviour typically consist of particles with highly variable sizes, shapes, and often a degree of flexibility. As a result, it is difficult to define this class based solely on geometric parameters, and empirical testing of representative samples is generally a more reliable approach.

2.5 Test to identify “Class 3” behaviour

To identify whether a bulk material exhibits Class 3 behaviour, the authors have developed a simple yet effective diagnostic method known as the rising tube test, illustrated below in fig 3. In this test, a vertical tube with an internal diameter substantially larger than the particle size is placed on a flat surface and filled with the test material. The material is allowed to settle naturally under gravity, without external compaction through vibration or mechanical stress. The tube is then carefully lifted vertically—using a mechanical guide such as a forklift to ensure alignment—while observing the behaviour of the exposed material column. For materials classified as Class 1 or Class 2, the exposed material will form a typical angle of repose as the tube rises. This occurs even for highly cohesive materials (Class 2), as the internal compressive strength of such materials remains lower than the applied vertical stress.

However, for materials exhibiting Class 3 behaviour, the situation is markedly different. As the tube is raised, the bulk solid maintains a vertical column with parallel sides, showing no angle of repose. This phenomenon results from the "nesting" or "layering" of elongated or irregular particles, which confers an internal compressive strength far exceeding the applied stress. If the unsupported column grows tall enough, it does not fail by shear but instead buckles laterally due to its structural rigidity.

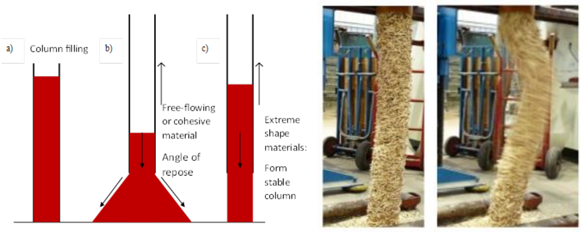

Fig. 3. (Left) column of around 7 diameters high formed by match-sticks of L/W ratio of approx. 2.5:1 in the “rising tube” test, and (right) eventual failure by buckling of the column

Below is shown the tendency of a shredded “medium density fibreboard” (“MDF”) material to arch at a hopper outlet, and its corresponding behaviour in the “rising column test”. This material is dry and non-cohesive but due to its extreme particle shape, as shown in fig 4, will not flow in a converging hopper.


(a) (b)

Fig. 4. (a) Shredded MDF material blocking in hopper outlet due to “nesting” (b) The MDF material forming a vertical column in the “rising tube test”

3 Characterisation and design considerations for different classes of bulk materials

The classification framework proposed provides not only a basis for identifying powder behaviour but also serves as a guide for appropriate testing.

3.1 Class 1: Free-Flowing powders

Materials falling into Class 1 are inherently free-flowing and do not exhibit tendencies to arch/rat-hole. For such materials, core flow discharge designs are typically sufficient, and extensive flow property testing (cohesive strength measurements) is generally unnecessary. An exception arises when particle size or density segregation is a concern, or when the material is sensitive to ageing or spoilage over time. In such cases, a mass flow design is preferred to ensure first-in, first-out material movement.

3.2 Class 2: Cohesive powders

Class 2 materials exhibit cohesion due to interparticle forces such as capillary bridging, plastic deformation, or van der Waals attraction. These materials are prone to flow obstructions such as arching and rat-holing, especially in hoppers with insufficient outlet size or poorly chosen geometry. For reliable handling, the full Jenike methodology should be applied, including measurement of the flow function, wall friction, and time consolidation behaviour.

3.3 Class 3: Interlocking and structurally stable particles

Class 3 materials—such as fibrous, elongated, or irregularly shaped particles—exhibit mechanical interlocking or "nesting" effects that generate compressive strength far beyond what is captured by conventional bulk solids testing. For these materials, the classical Jenike design methodology is ineffective and should not be employed. Core flow configurations are unsuitable, as rat-holing is virtually inevitable. Even mass flow hoppers must be designed with very limited convergence to avoid structural failure in the bulk solid. These materials are best handled in live-bottom vessels with parallel walls and minimal consolidation pressure. Specialised discharge aids such as non-compacting feeders or tube feeders may be required to break the internal structure and promote reliable discharge.

3.4 Exclusion of caking materials

It is important to note that this classification system explicitly excludes materials that are prone to caking—the irreversible agglomeration or hardening of particles over time. Caking can occur across all three classes if the following mechanisms are active:

- Plastic deformation under applied stress (leading to solid-state flow),
- Moisture cycling (resulting in liquid bridging, dissolution, and re-solidification),
- Chemical reactions or recrystallisation at particle contact points.

The behaviour of caking materials requires a separate analytical approach and is beyond the scope of this classification framework.

4 Conclusion

This study has demonstrated, through both experimental insights and established material behaviour, that bulk solids can be reliably categorised into three distinct flow behaviour classes. Each class presents unique challenges in storage and discharge. The proposed classification framework offers a practical and accessible means of guiding material handling decisions. By applying straightforward diagnostic tests, engineers can more rapidly assess the likely flow behaviour of bulk solid, identify associated risks, and select appropriate design methods. This approach not only improves the reliability of equipment performance but also helps avoid unnecessary testing and over-engineering, ultimately saving time and resources.

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