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Rapid and Reliable Flow Property Testing - A Modified Uniaxial Approach

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ABSTRACT

The flow function of an iron ore material governs its flowability characteristics in material handling chains of the resource industry. A uniaxial compression test is able to obtain a flow function more rapidly comparing to the Jenike direct shear test, nevertheless, results often exhibit lower rankings using the former method. This study aims to investigate the fundamental stress states within the test specimen that led to this phenomenon, and to introduce a new uniform density specimen preparation method for a uniaxial compression test in order to achieve comparative flow functions as per a Jenike direct shear test. The minimisation of the wall friction effect and the achievement of the critical state when preparing a uniaxial specimen were explicitly discussed. Experimental investigations on flow functions of a suite of Australian iron ore samples were conducted using both the uniform density uniaxial compression test and the Jenike direct shear test. Results from both methods were indicated to be comparable providing the specimen exhibited cohesive flow behaviours. The outcome of this research enabled a rapid and reliable flow function testing method for cohesive iron ore materials.

INTRODUCTION

The rapid consumption of near surface iron ore deposits in Australia has led to mining deeper deposits which are located close or even beneath the water table (Geoscience Australia, 2008). The resulting increase of the inherent moisture for the run-of-mine material leads to more cohesive and adhesive behaviours, which cause poor flowability in material handling chains (Plinke, Prigge, & Williams, 2016). Therefore, it is an industry standard to monitor the flowability of bulk materials to minimise potential blockages. The flowability of bulk materials is governed by the flow function, which is a correlation between the unconfined yield strength with respect to the major principle stress (Jenike, 1964). Among various testing methods devised to measure the flow function, the Jenike direct shear test (JDST) is widely accepted; and this test is particularly relevant to the design and efficient operation of bulk solids storage and handling systems for an extensive range of industries, such as those involved in the mining and processing of iron ore (A. W. Roberts & Scott, 1978). Nevertheless, the Jenike direct shear test is, of necessity, rather time consuming where the aim for reliable and reproducible results, requires an experienced operator to perform the pre-consolidation, pre-shear and shear procedures, from which a flow function is obtained (as demonstrated in Figure 1). For more efficient flowability monitoring of cohesive iron ore materials, the requirement for a simpler, more rapid testing method has a high priority.

Figure 1. Flow function derivation from Jenike direct shear tests.

Based on the foregoing objective, the uniaxial compression test represents a potential method to obtain flow functions [5-6]. Its simplicity and shorter testing time are often preferred in industrial practice (Schulze, 2008). As shown in Figure 2 (a), in a conventional uniaxial compression test, the sample is poured into a cylindrical mould and consolidated under a pre-determined normal stress σ_1. The applied load corresponding to the consolidating stress is then removed followed by the careful retraction of the cylindrical mould to leave a free standing, consolidated cylindrical test sample without lateral constraint. The sample is then subjected to an increasing normal compressive stress until failure occurs. The normal stress at failure is deemed to be the unconfined yield strength σ_c. The stress σ_c corresponding to the consolidation stress σ_1 defines one point on the flow function graph. The test is repeated for at least two other consolidation stresses to obtain a flow function.

Figure 2. Uniaxial compression test. (a) conventional uniaxial compression testing process; (b) typical flow function comparison between two testing methods.

Since σ_1 and σ_c are determined directly, the test is simpler to perform and less time consuming than the Jenike test which requires the values of minor principle stress σ_2 and unconfined yield strength σ_c to be derived indirectly from the yield loci as illustrated in Figure 1. In the case of bulk materials of quite low cohesive strength, the uniaxial test requires minimum consolidation level to be applied to the specimen to ensure the sample remains intact under the influence of the gravitational forces after removing the mould. Most critically, the flow functions obtained through a uniaxial test often exhibited lower rankings when comparing to the Jenike direct shear test (Schwedes, 2003). This is illustrated in Figure 2 (b) which compares the flow functions of an iron ore material obtained through both methods. For the uniaxial tester, the problem centres around the wall friction in the mould, often referred to as the Janssen effect (Nedderman, 2005) causing non uniformity of the major consolidation stress σ_1 which reduces exponentially

with respect to the specimen depth. This has been attributed to the underestimation of the flow function using the uniaxial compression test.

Based on the foregoing comments, the purpose of this paper is to critically evaluate the uniaxial test in relation to the Jenike direct shear test with aim of establishing a sample preparation procedure to achieve the necessary critical consolidation state for the uniaxial compression test to ensure the validity of the flow function determination.

UNIFORM DENSITY SPECIMEN PREPARATION METHOD

In order to achieve the required uniform density in the uniaxial test sample, a defined pre-consolidation procedure needs to be established and included as an integral part of the sample preparation. The "undercompaction" specimen preparation method (Ladd, 1978) is the basis for the procedure adopted in this study in order that a uniaxial specimen to reach the comparable compaction state to that of a Jenike direct shear test sample. Rather than targeting a normal stress (σ_1) during the sample preparation, in this case the method targets a final bulk density for the test specimen. Therefore, it is firstly necessary for a bulk density test utilising the Jenike compressibility tester (ASTM International, 2014).

Once a targeted specimen bulk density is selected, the sample is compacted with a pre-defined number of layers. An optimal percentage of pre-consolidation is applied to the first (bottom) layer. This arrangement ensures the achievement of a uniform density along the sample height. When a test specimen is compacted in layers, the compaction of each succeeding layer can further densify the sample below it. This was overcome using the undercompaction principle. As illustrated in Figure 3, each layer was typically compacted into a lower density than the final desired value by a predetermined percent of undercompaction U_n. The U_n value in each layer was linearly varied from the bottom to the top layer, with the bottom layer having the maximum U_n value.

Figure 3. Principle of the uniform density specimen preparation method.

By way of background, research involving many cyclic triaxial tests performed on moist coarse grained soil samples (Ladd, 1978; Vucetic & Dobry, 1988), showed that maximum shear strength was achieved when utilising a 5% "undercompaction" for the first (bottom) layer and a total number of ten layers. These setting were adopted in this iron ore study for preparing the uniaxial compression test specimens. For equal height for each layer, based on a predetermined specimen bulk density and particle properties, the accumulative mass of material for layer - i was determined using the following equation.

1) $$\text{Accumulative mass} = \rho_d \left(1 + \frac{m_0}{100}\right) \frac{\pi D^2 H}{4 n_{all}} \left[n_i - \frac{U_{n0}}{100}\left(\frac{n_{all} - n_i}{n_{all} - 1}\right)\right]$$

where U_{n0} was the percent undercompaction for the first layer (5%); n_i was the number of layer - i; n_{all} was the total number of layers; ρ_d was the dry bulk density; m_0 was the initial moisture content; D and H are, respectively, the diameter and height of the test specimen. The required mass of the material for each layer was placed into a split mould and compacted to the required height with a tamping rod. The sample surface between layers was scratched prior to preparing the next layer. The specimen was fully formed after 10 sub lots of material were compacted into a sample mould.

EXPERIMENTAL SCHEME

Following the above procedure, the resulting bulk density of the obtained specimen corresponded to a sample prepared using the similar twisting action in a Jenike direct shear test. To examine the influence of the uniform density sample preparation method on flow functions obtained from the uniaxial compression test, a comparative experimental program with the Jenike direct shear test was performed on a suite of iron ore samples.

A total of four iron ore samples were selected for the experimental investigation. All samples were obtained through a series of crushing and screening from the onsite operation. Materials were subsequently homogenised and sieved down to -4 mm size fraction. Where bulk solids composed of particles of a large size range from coarse to fines, it is the fine particles that contribute to the solid's cohesive strength (A. Roberts, 1993). Each sample was then prepared at moisture contents covering the nominal operational range. The material properties for all materials were tabulated in Table 1. The particle size distribution of the samples was also shown in Figure 6.

Figure 4. Particle size distribution of all samples.

For each sample, a bulk density test was initially conducted following the ASTM standard (ASTM International, 2014). Results for all four samples at different moisture contents were shown in Figure 7. A suite of Jenike direct shear tests was then conducted on each sample with a 101.6mm outer diameter (4") shear cell following the ASTM standard (ASTM International, 2015). In terms of the uniaxial compression test, both the conventional and the uniform density specimen preparation methods were used on each sample for comparative analysis. On the uniform density uniaxial compression test (UDUCT), five different bulk density values corresponding to a wide range of normal stresses were selected to undertake the test and to derive the flow function.

Figure 5. Bulk density test results for all samples.

The uniaxial shear tester utilised in this research was shown schematically in Figure 6. The tester was designed to accommodate an 80 mm in diameter and 160 mm in height specimen. Once the sample was prepared, the confining walls were then retracted, after which the top loading disc was driven by the pneumatic actuator to compress the specimen. The resulting unconfined yield stress was measured. Three tests were performed on each sample.

Figure 6. Image and schematic of the uniaxial compression tester used in this study.

RESULTS AND DISCUSSION

Flow Function Comparisons

Comparative flow functions of the uniaxial compression tests using the conventional and uniform density sample preparation methods were initially obtained and compared in Figure 7. Using the conventional sample preparation method, sample IO-B at 9.2% and IO-C at 12.1% collapsed under the gravity force; therefore, no flow functions were obtained. Whereas, all samples prepared using the uniform density method were able to stand the gravity force. Comparing flow functions obtained in both tests, it was observed that higher ranking was achieved using the uniform density sample preparation method across all samples. Therefore, it was suggested that shear strength was enhanced when samples were prepared using the uniform density method.

Figure 7. Comparative flow function results obtained through conventional uniaxial compression test (UCT) and the uniform density uniaxial compression test (UDUCT) for all samples.

Jenike direct shear test results were also obtained and subsequently compared to flow functions from the uniform density uniaxial compression tests. Figure 8 demonstrated the comparative results between the two tests. It was indicated that the ranking of the flow functions between the two tests matched well for samples with relatively higher moisture contents, including

- IO-A at 6.5%, 7.9% and 9.9 %;
- IO-B at 13.7% and 16.8%;
- IO-C at 18.5% and 20.6%;
- IO-D at 11.6% and 13.6%.

However, at lower moistures, the uniform density uniaxial compression test still led to under-estimation of the flow functions comparing to the Jenike direct shear test. Further investigation on the specimen failure behaviours indicated that these unmatched tests failed to achieve a peak unconfined yield stress during the compression loading. Figure 9 demonstrated the distinct axial stress – axial strain relationship during compression loading for both a flow function matched test case (Figure 9 (a)) and a flow function unmatched test case (Figure 9 (b)). In matched tests, the sample exhibited increasing shear strength when the compression load was initially applied. After a peak stress was achieved, the sample demonstrated some level of residual stress when continued the compression loading. Shear planes were clearly observed after the failure of the sample. In comparison, for unmatched tests, the sample quickly collapsed after showing some levels of shear strength. No clear shear planes were observed and free flowing behaviours were indicated. Such phenomenon was observed throughout all iron ore samples tested.

Figure 8. Comparative flow function results obtained through Jenike direct shear test (JDST) and uniform density uniaxial compression test (UDUCT) for all samples.

Figure 9. Distinct axial stress-axial strain behaviours in the uniform density uniaxial compression tests. (a) flow functions matched test cases; (b) flow functions unmatched test cases.

The flow function of a bulk material can also be categorised based on the Jenike flowability classification (Schulze, 2006), which was defined as

2) $$\mathrm{ff_c} = \frac{\sigma_1}{\sigma_c}$$

where σ_1 was the major consolidation stress and σ_c was the unconfined yield strength. $\mathrm{ff_c}$ characterised the following flow behaviours,

- $\mathrm{ff_c} > 10$: Free flowing, very low cohesion
- $4 < \mathrm{ff_c} < 10$: Easy flowing, low cohesion
- $2 < \mathrm{ff_c} < 4$: Cohesive
- $1 < \mathrm{ff_c} < 2$: Very cohesive
- $\mathrm{ff_c} < 1$: Not flowing

All flow functions from the uniform density uniaxial compression test were plotted against the Jenike flowability classification in Figure 10. Matched and unmatched flow functions to the Jenike direct shear test were differentiated. It was clearly observed that all matched flow functions from the uniform density uniaxial compression test were scattered in the cohesive ($2 < \mathrm{ff_c} \leq 4$) and very cohesive ($1 < \mathrm{ff_c} \leq 2$) regions. In comparison, the unmatched flow functions were distributed in the free flowing, very low cohesion ($\mathrm{ff_c} > 10$) and the easy flowing, low cohesion ($4 < \mathrm{ff_c} \leq 10$) regions. Consequently, it was suggested that, for iron ore materials, there existed an apparent cohesion threshold above which the uniform density uniaxial compression tests were able to produce comparable flow functions to the Jenike direct shear test. Under such cohesion level, the specimen exhibited low shear strength, therefore, free flowing behaviours were induced.

Additionally, it was indicated that a single Jenike flowability index $\mathrm{ff_c}$ was not suitable to define the overall flowability of an iron ore material, since a flow function often spanned over two classifications depending on the major consolidation stress (σ_1) level. From a practical perspective, the Jenike flowability classification was sensible in the low consolidation stress region where the mass flow regime dominates. However, at high consolidation stress, the linear extrapolation of the Jenike flowability classification appeared to under-estimate the material handling difficulties since the flow function tend to plateau and funnel flow is commonly observed for cohesive iron ore material under high consolidation stress (A. Roberts, 1999).

Figure 10. Distribution of the flow functions obtained through uniform density uniaxial compression tests (UDUCT) in the Jenike flowability classifications.

CONCLUSIONS

A comprehensive investigation was carried out on the comparative flow functions of cohesive iron ore samples obtained using the uniform density uniaxial compression test and the Jenike direct shear test. A suite of experimental tests on various iron ore samples were performed, and analysis on these results were presented. The study yielded the following major findings:

- A uniform density sample preparation method ensured the uniform and critical compaction in uniaxial compression test specimens were comparable to Jenike direct shear test specimens.
- Uniform density sample in uniaxial compression tests significantly enhanced the shear strength of specimens, and thus, producing improved flow functions comparing to the conventional uniaxial compression test.
- Flow functions of iron ore samples obtained using the uniform density uniaxial compression test were comparable to the Jenike direct shear test flow function when the material exhibited apparent

cohesive flow behaviours. Without sufficient cohesion stress, specimen exhibited free flowing behaviours, which resulted lower flow function rankings to Jenike direct shear test flow functions.

Consequently, a uniform density uniaxial compression test can be adopted during iron ore mining operation for rapid and reliable flowability indications. Once implemented, this method is able to increase the efficiency and reduce potential blockages of the material handling plants.

ACKNOWLEDGEMENTS

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FIGURES

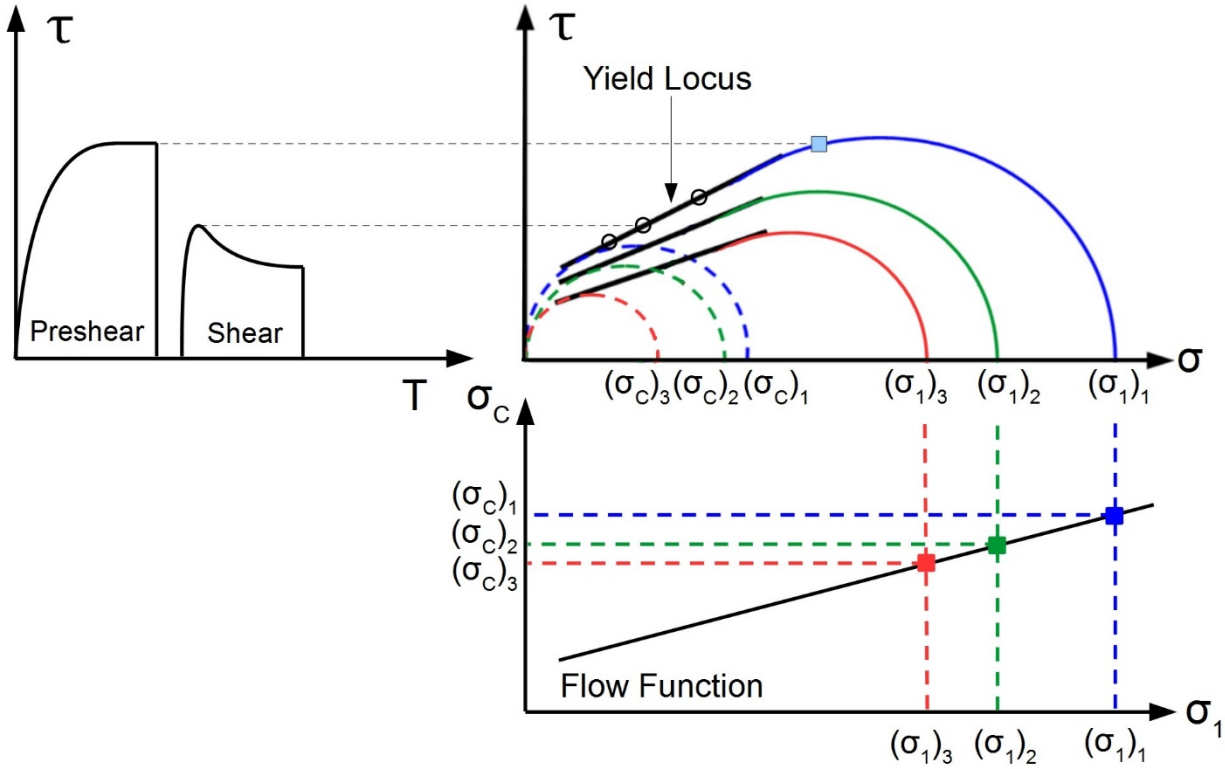

FIG 1 – Flow function derivation from Jenike direct shear tests.

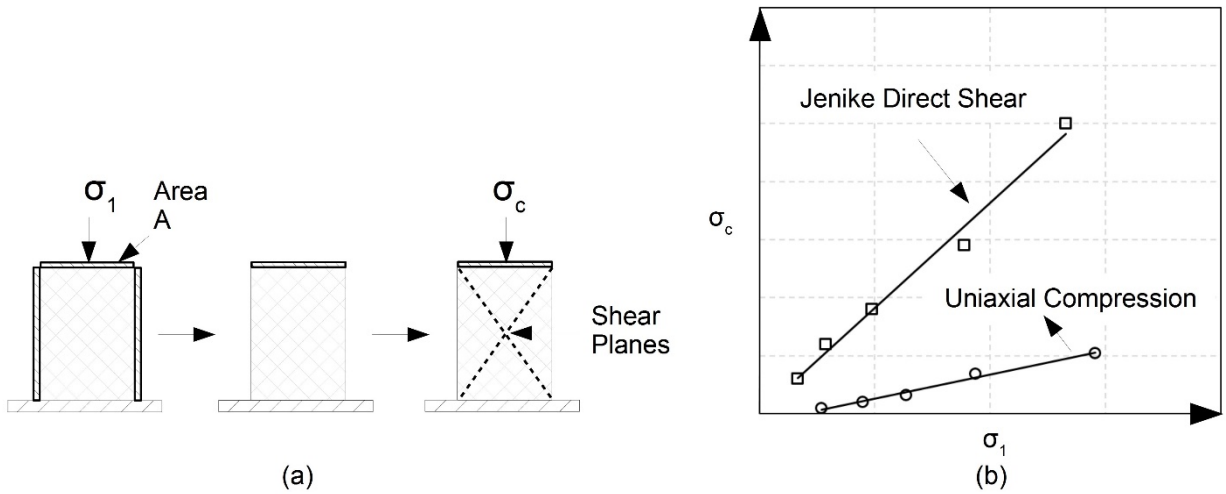

FIG 2 – Uniaxial compression test. (a) conventional uniaxial compression testing process; (b) typical flow function comparison between two testing methods.

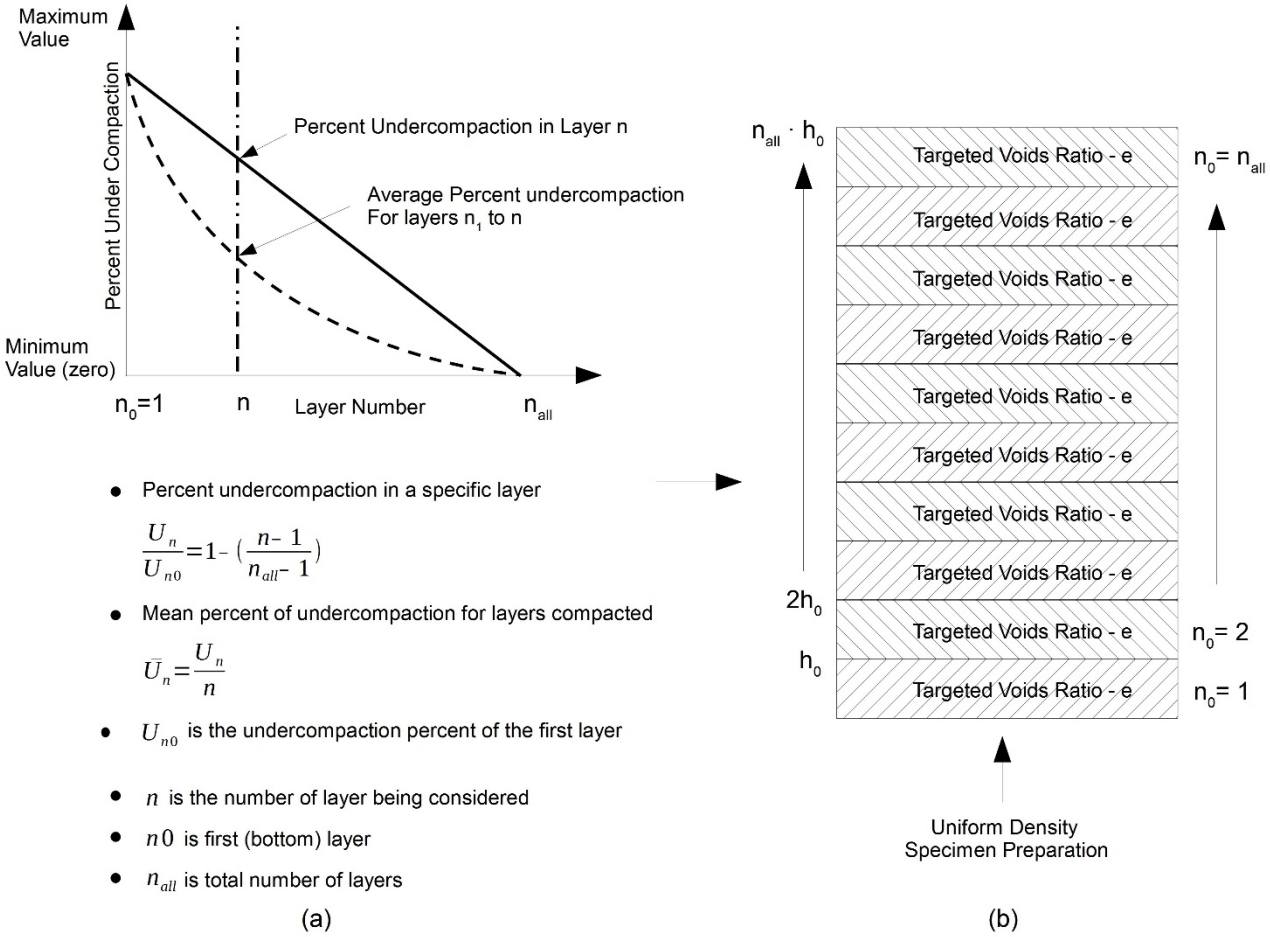

FIG 3 – Principle of the uniform density specimen preparation method.

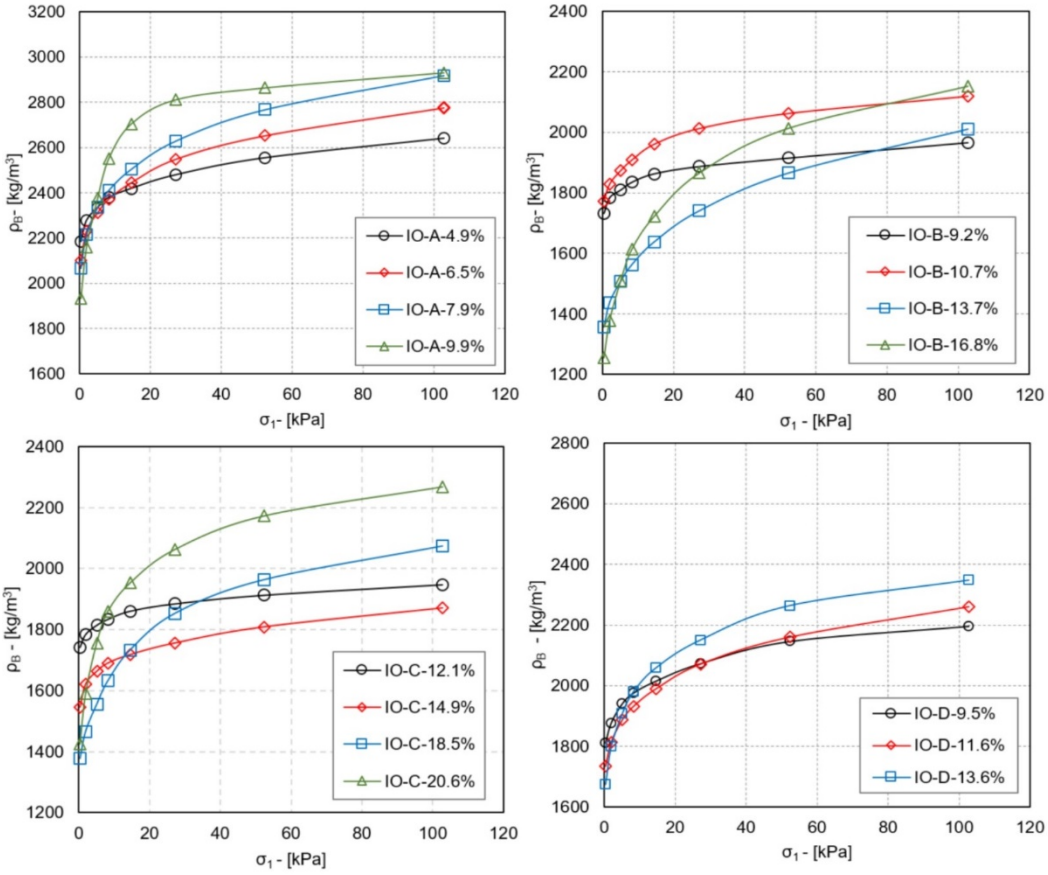

FIG 4 – Bulk density test results for all samples.

FIG 5 – Image of the uniaxial compression tester used in this study.

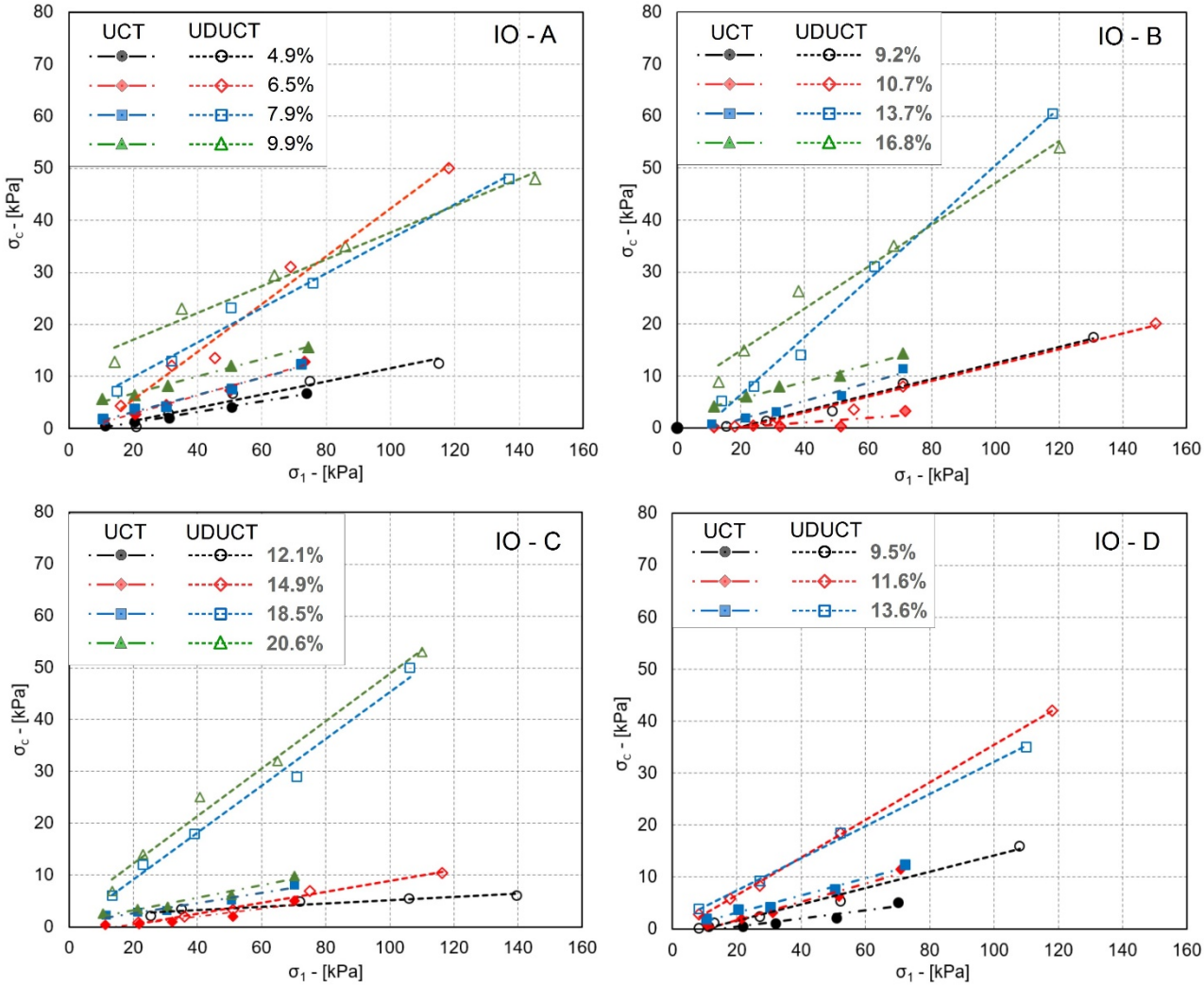

FIG 6 – Comparative flow function results obtained through conventional uniaxial compression test (UCT) and the uniform density uniaxial compression test (UDUCT) for all samples.

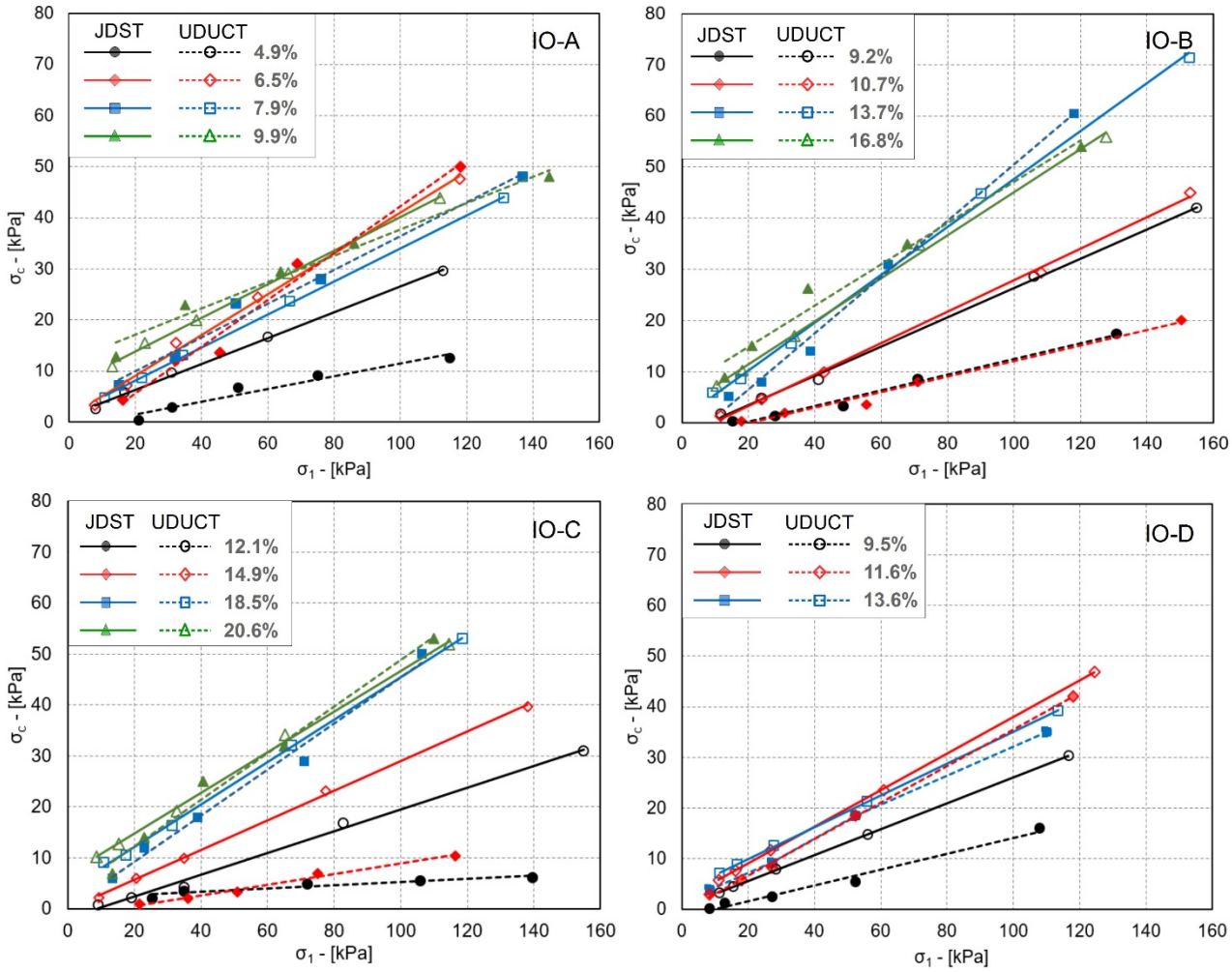

FIG 7 – Comparative flow function results obtained through Jenike direct shear test (JDST) and uniform density uniaxial compression test (UDUCT) for all samples.

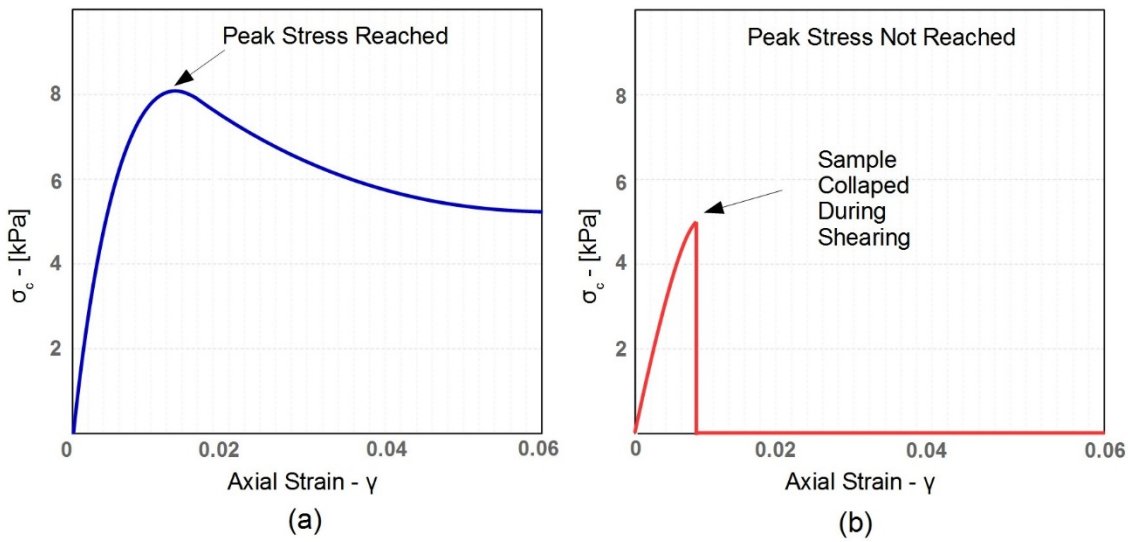

FIG 8 – Distinct axial stress-axial strain behaviours in the uniform density uniaxial compression tests. (a) flow functions matched test cases; (b) flow functions unmatched test cases.

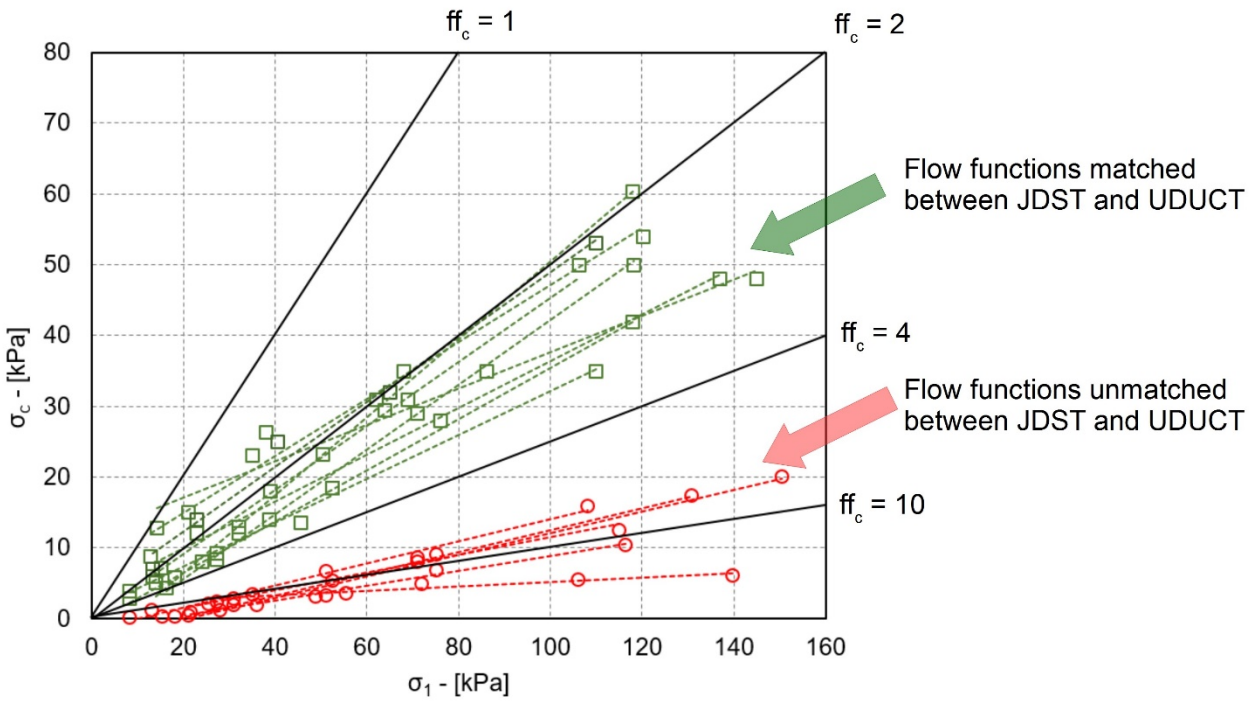

FIG 9 – Distribution of the flow functions obtained through uniform density uniaxial compression tests (UDUCT) in the Jenike flowability classifications.

TABLES

TABLE 1

Material properties for selected iron ore samples.

Sample Label	Particle Density – kg/m^3	Moisture Content
IO-A	4600	4.9%
		6.5%
		7.9%
		9.9%
IO-B	4400	9.2%
		10.7%
		13.7%
		16.8%
IO-C	4200	12.1%
		14.9%
		18.5%
		20.6%
IO-D	4300	9.5%
		11.6%
		13.6%