NOVA

University of Newcastle Research Online

nova.newcastle.edu.au

Chen, W., Roberts, A. & Williams, K. et al (2017) On uniaxial compression and Jenike direct shear testings of cohesive iron ore materials, Powder Technology Vol. 312, Issue 1 May 2017, p. 184-193

Available from: <http://dx.doi.org/10.1016/j.powtec.2017.02.037>

© 2017. This manuscript version is made available under the CC-BY-NC-ND 4.0 license
<http://creativecommons.org/licenses/by-nc-nd/4.0/>

Accessed from: <http://hdl.handle.net/1959.13/1352349>

ON UNIAXIAL COMPRESSION AND JENIKE DIRECT SHEAR TESTINGS OF COHESIVE IRON ORE MATERIALS

Wei Chen^{1a*}, Alan Roberts^{1b}, Kenneth Williams^{1c}, Jeremy Miller^{1d} and Jens Plinke^{1e}.

¹Centre for Bulk Solids and Particulate Technologies, The University of Newcastle, Callaghan, Australia 2308

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. Additionally, a simple compressibility index_I, based on the bulk density test of iron ore samples, was derived as a threshold to indicate if a uniform density uniaxial compression test can produce flow functions matching the Jenike direct shear test. The outcome of this research enabled a rapid and reliable flow function testing method for cohesive iron ore materials.

KEYWORDS: Flow Function, Uniaxial Compression Test, Jenike Direct Shear Test, Iron Ore, Compressibility Index

1. 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 [1]. 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 [2]. 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 [3]. 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 [4]. 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.

* Corresponding author: Wei Chen

Centre for Bulk Solids and Particulate Technologies, Newcastle Institute for Energy and Resources, The University of Newcastle, Callaghan, Australia 2308. Email: W.Chen@newcastle.edu.au; w.chentbs@gmail.com

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 [7]. 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 [8]. 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 [9] 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.

2. STRESS STATES IN TEST SPECIMENS

The influence of the wall friction effect on the uniaxial compression test outcomes can be investigated through Hvorslev and Roscoe surfaces [10-11]. As demonstrated in Figure 4, the Hvorslev surface defined the shear strength of a specimen in the three dimensional space consisting of the voids ratio, normal stress and shear stress. In a Jenike direct shear test, the specimen was largely not affected by the wall friction effect due to the material being compacted into relatively thin layers, which resulted the specimen in the stress state of $HS_{(0)}$, with $S_{(0)}$ on the critical state line on the Roscoe surface and normal stress of $\sigma_{(0)}$ and voids ratio of $e_{(0)}$. Whereas, in a conventional uniaxial compression test, the effective normal stress applied to a test specimen was reduced to $\sigma_{(1)}$ due to the wall friction effect, which resulted the specimen shifting from $HS_{(0)}$ to $HS_{(1)}$ stress state. This effectively leads to higher voids ratio - $e_{(0)}$ and lower yield locus comparing to the stress state of a Jenike direct shear test specimen.

Previous studies have attempted to overcome the wall friction effect in the uniaxial compression test. Some successes were achieved employing mathematical procedures to correct the uniaxial flow functions [12-13]. Nevertheless, the corrected factor often varied according to the material type, thus no unified theory was developed. Maltby and Enstad [14] adopted the triaxial test specimen preparation method by wrapping a membrane around the sample and adding lubrication between the membrane and mould wall to minimise the wall friction effect. Alternatively, an infinite layer specimen preparation method was utilised attempting to eliminate the wall friction effect [15]. Both methods resulted flow functions approaching the Jenike direct shear testing result. However, the testing procedure was rather complex and, from a practical point of view, rather inefficient.

Figure 3. Analysis of the wall friction effect on the stress state of a uniaxial specimen comparing to the Jenike direct shear test specimen on the Hvorslev and Roscoe surfaces.

While the wall friction effect may be minimised through experimental strategies discussed above, the specimen may still fail to reach the critical state if the critical voids ratio is not achieved. For the Jenike direct shear test, the limited travel of the top shear ring relative to the fixed base of the shear cell usually requires a series of applied twists of the cell lid carrying the applied normal load as an initial phase of the shear consolidation of the contained sample. The aim is to ensure the sample reaches the critical voids ratio (e_0) at the critical state – $HS_{(0)}$. This is illustrated in Figure 4 for the Hvorslev-Roscoe surfaces, without such “twisting” action to induce particle reassembly, a higher voids ratio (e_1) was often obtained leading to lower shear strength on $HS_{(1)}$, which occurred in a conventional uniaxial compression test. This phenomenon was also often observed in a bulk density compressibility test. When a sample was compacted with “twisting” axial load comparing to non-twisting axial load, higher bulk density was obtained using the former method. Therefore, apart from minimisation of the wall friction effect, it was also important to ensure the critical voids ratio within a test specimen to be achieved in a uniaxial compression test, without which the shear strength of a uniaxial specimen remained comparatively lower.

Figure 4. Analysis of the critical voids ratio on the stress state of a uniaxial specimen comparing to the Jenike direct shear test specimen on the Hvorslev and Roscoe surfaces.

Based on the above discussion, the critical voids ratio of the test specimen was suggested to be more crucial in determining the shear strength of the sample, which was not addressed in the conventional uniaxial compression test method. This research aims to adopt a uniform density specimen preparation method to achieve the critical state of a sample. A suite of experimental investigations will then be conducted to examine the performance of the proposed specimen preparation method on comparing flow functions to the Jenike direct shear method.

3. 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 [16] 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 [17].

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 5, 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 5. 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, [16, 18], 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.

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

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

125 preparing the next layer. The specimen was fully formed after 10 sub lots of material were compacted into a sample
126 mould.

127 4. EXPERIMENTAL SCHEME

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

132 A total of four iron ore samples were selected for the experimental investigation. All samples were obtained through a
133 series of crushing and screening from the onsite operation. Materials were subsequently homogenised and sieved down
134 to -4 mm size fraction. Where bulk solids composed of particles of a large size range from coarse to fines, it is the fine
135 particles that contribute to the solid's cohesive strength [19]. Each sample was then prepared at moisture contents
136 covering the nominal operational range. The material properties for all materials were tabulated in Table 1. The particle
137 size distribution of the samples was also shown in Figure 6.

138 Table 1. Material properties for selected iron ore samples.

139
140 Figure 6. Particle size distribution of all samples.

141 For each sample, a bulk density test was initially conducted following the ASTM standard [17]. Results for all four
142 samples at different moisture contents were shown in Figure 7. A suite of Jenike direct shear tests was then conducted
143 on each sample with a 101.6mm outer diameter (4") shear cell following the ASTM standard [20]. In terms of the uniaxial
144 compression test, both the conventional and the uniform density specimen preparation methods were used on each
145 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 7. Bulk density test results for all samples.

The uniaxial shear tester utilised in this research was shown schematically in Figure 8. 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.

5. RESULTS AND DISCUSSION

5.1 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 9. 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 9. 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 10 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 11 demonstrated the distinct axial stress – axial strain relationship during compression loading for both a flow function matched test case (Figure 11 (a)) and a flow function unmatched test case (Figure 11 (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.

186

187 Figure 10. Comparative flow function results obtained through Jenike direct shear test (JDST) and uniform density
188 uniaxial compression test (UDUCT) for all samples.

Figure 11. 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 [5], which was defined as

$$ff_c = \frac{\sigma_1}{\sigma_c}$$

where σ_1 was the major consolidation stress and σ_c was the unconfined yield strength. ff_c characterised the following flow behaviours,

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

All flow functions from the uniform density uniaxial compression test were plotted against the Jenike flowability classification in Figure 12. 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 ($2 < ff_c \leq 4$) and very cohesive ($1 < ff_c \leq 2$) regions. In comparison, the unmatched flow functions were distributed in the free flowing, very low cohesion ($ff_c > 10$) and the easy flowing, low cohesion ($4 < ff_c \leq 10$) 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 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 [21].

Figure 12. Distribution of the flow functions obtained through uniform density uniaxial compression tests (UDUCT) in the Jenike flowability classifications.

5.2 Indication of cohesive thresholds based on confined compressibility

The bulk density curves for all iron ore samples also showed correlations with whether a uniform density uniaxial flow function was able to match the corresponding Jenike test flow function. As shown in Figure 7, the bulk density curves for all flow function matched test cases appeared to span in larger bulk density ranges comparing to the unmatched test cases. This was particularly evident for sample IO-B and IO-C. The bulk density curve essentially reflected the compressibility of an iron ore sample, and can be defined as

$$3) \quad \Psi = \frac{\rho_B(\sigma_1) - \rho_B(0)}{\rho_B(0)}$$

where $\rho_B(\sigma_1)$ and $\rho_B(0)$ were the bulk density under σ_1 and zero normal stresses. Since the material mass input into a bulk density test cell was fixed, therefore,

$$4) \quad \rho_B(\sigma_1) \cdot V(\sigma_1) = \rho_B(0) \cdot V(\text{cell})$$

where $V(\sigma_1)$ and $V(\text{cell})$ were the sample volume under a normal stress of σ_1 and the bulk density test cell volume. Therefore, Eq. (3) can be transformed to

$$5) \quad \Psi = \frac{\rho_B(\sigma_1) - \rho_B(0)}{\rho_B(0)} = \rho_B(\sigma_1) \frac{1 - \frac{V(\sigma_1)}{V(\text{cell})}}{\frac{V(\sigma_1)}{V(\text{cell})}} = \frac{V(\text{cell})}{V(\sigma_1)} - 1$$

Since an identical cross-sectional area applied to $V(\sigma_1)$ and $V(\text{cell})$, Eq. 5 can be expressed as,

$$6) \quad \Psi = \frac{H(\text{cell})}{H(\sigma_1)} - 1 = \varepsilon$$

where $H(\text{cell})$ and $H(\sigma_1)$ were cell height and the sample height under normal stress of σ_1 . ε was also referred as the axial strain in the confined compression test. Therefore, it was viable to transform all bulk density curves into an axial strain-axial stress chart as shown in Figure 13. From the figure, it was clearly indicated that there existed a

compressibility threshold exceeding which the uniform density uniaxial compression test was able to produce comparable flow functions to Jenike direct shear test.

The variation of the compressibility of an iron ore sample at different moistures was predominantly due to the clay minerals, such as Kaolin, contained in the material [22]. An important characteristics of the clay content in the iron ore material was inducing the macro shrink-swell behaviours. At moist state, the sample tended to swell, thus producing higher volume change under a normal load. Conversely, at dry state, shrink behaviour was exhibited, resulting smaller volume change under a normal consolidation stress.

In the meantime, the cohesive behaviour of the iron ore sample was also due to the combined clay-moisture effect [23]. For an iron ore sample, the apparent cohesion emerged as soon as the material was moistened to a certain degree. This often led to the overall enhancement of the shear strength when adding more water to the sample. As previously discussed, the uniform density uniaxial compression test was only able to produce comparable flow functions to the Jenike direct shear test when cohesive behaviours were exhibited by the iron ore sample. Therefore, based on the above analysis, it was suggested that the compressibility can be utilised as a threshold to indicate the apparent cohesive flow behaviour of an iron ore sample, since the two macro properties of an iron sample due to the combined effect of the clay content and moisture were cohesion and compressibility.

Figure 13. Correlations between normalised axial strain and axial stress for all samples.

The logarithmic like axial strain-axial stress correlations shown in Figure 13 can be converted to quasi-linear relationships as shown in Figure 14. By this means, the compressibility of a sample can be simply represented by the slope of the linear fitting for axial strain-logarithmic axial stress correlation, which was defined as,

$$\varphi = \frac{\varepsilon}{\log_{10}(\sigma_1)}$$

All fitting function parameters were tabulated in Table 2. Results indicated that the uniform density uniaxial compression test on an iron ore sample was able to produce comparable flow functions to the Jenike direct shear test, providing the

compressibility $\frac{\epsilon}{\log_{10}(\sigma_1)}$ of the sample obtained in the bulk density test exceeds 0.152. Practically, such empirical compressibility index can be utilised to indicate the cohesive flow behaviours of the iron ore material by simply conducting a bulk density test. A simple and fast uniform density uniaxial compression test can be subsequently performed if quantitative assessment on the flowability of the iron ore material is required. The shorter turnaround time based on this arrangement for flowability monitoring is able to reduce the material handling blockages during the iron ore mining operation.

Figure 14. Quasi-linear correlation between the axial strain to axial stress.

Table 2. Quasi-linear parameters for the twisted axial strain – axial stress correlations.

6. CONCLUSION

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.

- The compressibility of an iron ore sample obtained through a bulk density test can be utilised to indicate if a uniform density uniaxial compression test can produce flow functions matching the Jenike direct shear test. This was due to the correlation between the compressibility and cohesion properties induced by the combined effect clay and moisture content within the sample.

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

The authors are grateful for the financial assistance of the ARC Research Hub for Advanced Technologies for Australian Iron Ore.

REFERENCE

- [1] Geoscience Australia, Sustaining the mineral resources industry – overcoming the tyranny of depth. 2008.
- [2] J. Plinke, J.-D. Prigge, and K. C. Williams, "Development of new analysis methods for the characterization and classification of wet sticky ores," *Powder Technol.*, vol. 294, pp. 252–258, 2016.
- [3] A. W. Jenike, "Storage and flow of solids, bulletin no. 123," *Bull. Univ. Utah*, vol. 53, no. 26, 1964.
- [4] A. W. Roberts and O. J. Scott, "An investigation into the effects of sinusoidal and random vibrations on the strength and flow properties of bulk solids," *Powder Technol.*, vol. 21, no. 1, pp. 45–53, 1978.
- [5] D. Schulze, "Flow properties of powders and bulk solids," *Braunschweig/Wolfenbu ttel, Ger. Univ. Appl. Sci.*, 2006.
- [6] A. Kwade, D. Schulze, and J. Schwedes, "Determination of the stress ratio in uniaxial compression tests," *Powder Handl. Process.*, vol. 6, no. 1, p. 61, 2013.
- [7] D. Schulze, "Powders and bulk solids," *Behav. Charact. Storage Flow*. Springer, 2008.
- [8] J. Schwedes, "Review on testers for measuring flow properties of bulk solids," *Granul. matter*, vol. 5, no. 1, pp. 1–43, 2003.
- [9] R. M. Nedderman, *Statics and kinematics of granular materials*. Cambridge University Press, 2005.
- [10] K. H. Roscoe, An. Schofield, and C. P. Wroth, "On the yielding of soils," *Geotechnique*, vol. 8, no. 1, pp. 22–53, 1958.
- [11] M. J. Hvorslev, "Über die Festigkeitseigenschaften gestörter bindiger Böden: With an abstract in English, no. 45. Danmarks naturvidenskabelige samfund, i kommission has GEC Gad, 1937.
- [12] S. Wiche, A. Roberts, and W. McBride, "Development and Application of a Uniaxial Type Flowability Tester for Characterising Bulk Solids," in *Particulate Systems Analysis*, 2005.
- [13] L. Parrella, D. Barletta, R. Boerefijn, and M. Poletto, "Comparison between a uniaxial compaction tester and a shear tester for the characterization of powder flowability," *KONA Powder Part. J.*, vol. 26, no. 0, pp. 178–189, 2008.
- [14] L. P. Maltby and G. G. Enstad, "Uniaxial tester for quality control and flow property characterization of powders," *Bulk Solids Handl.*, vol. 13, p. 135, 1993.

321 [15] J. C. Williams, A. H. Birks, and D. Bhattacharya, "The direct measurement of the failure function of a cohesive
322 powder," *Powder Technol.*, vol. 4, no. 6, pp. 328–337, 1971.

323 [16] R. S. Ladd, "Preparing test specimens using undercompaction," 1978.

324 [17] ASTM International, "ASTM D6683-14, Standard Test Method for Measuring Bulk Density Values of Powders
325 and Other Bulk Solids as Function of Compressive Stress," West Conshohocken, PA, 2014.

326 [18] M. Vucetic and R. Dobry, "Cyclic triaxial strain-controlled testing of liquefiable sands," in *Advanced triaxial
327 testing of soil and rock*, ASTM International, 1988.

328 [19] A. Roberts, *Basic principles of bulk solids storage, flow and handling*. Institute for Bulk Materials Handling
329 Research, 1993.

330 [20] ASTM International, "ASTM D6128, Standard test method for shear testing of bulk solids using the Jenike
331 shear cell. ASTM International." West Conshohocken, PA, 2015.

332 [21] A. Roberts, "Handleability or flowability, Centre for Bulk Solids and Particulate Technologies, The University of
333 Newcastle, Australia," 1999.

334 [22] H. H. Murray, "Traditional and new applications for kaolin, smectite, and palygorskite: a general overview,"
335 *Appl. Clay Sci.*, vol. 17, no. 5, pp. 207–221, 2000.

336 [23] E. Çokça, O. Erol, and F. Armangil, "Effects of compaction moisture content on the shear strength of an
337 unsaturated clay," *Geotech. Geol. Eng.*, vol. 22, no. 2, pp. 285–297, 2004.

338