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On uniaxial compression and Jenike direct shear testings of cohesive iron ore materials

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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 compared 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 the 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, 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.

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 Fig. 1). For more efficient flowability monitoring of cohesive iron ore materials, the requirement for a simpler, more rapid testing method has a high priority.

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 Fig. 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. (See Fig. 3.)

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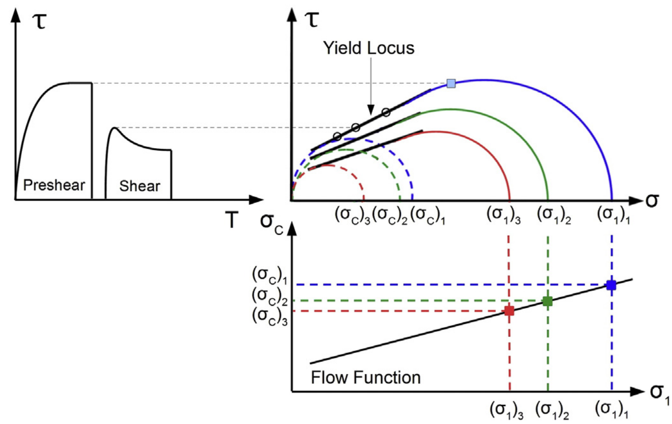

Fig. 1. Flow function derivation from Jenike direct shear tests.

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 Fig. 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 Fig. 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 Fig. 3, 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.

While the wall friction effect may be minimised through the 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 Fig. 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.

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

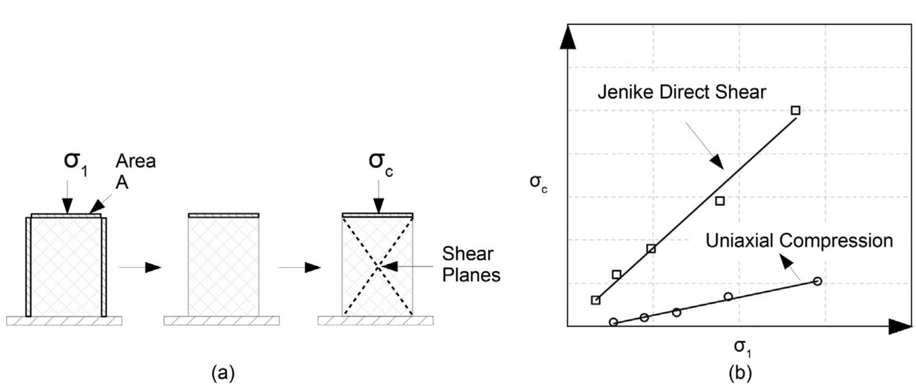

Fig. 2. Uniaxial compression test. (a) conventional uniaxial compression testing process; (b) typical flow function comparison between two testing methods.