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Some influences on wall friction measurements - a preliminary investigation

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Abstract

The concept of measuring the friction between a bulk solid and a wall material is very simple. However, experience together with previous wall friction measurement research suggest that variables that influence wall friction values are difficult to quantify and, so far, are proving unreliable to predict with any degree of confidence. In this paper some preliminary test results are presented for different bulk solids on different wall plates where variables examined include particle size distribution, moisture content, test cell size and shear speed. The outcomes presented confirm the authors' belief that with the present state of knowledge about wall friction it is dangerous to estimate appropriate wall friction values to use in design without undertaking measurements designed to duplicate field conditions as closely as possible. The results also emphasize the necessity for further in-depth research on this challenging topic!

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investigation, friction, measurements, wall, preliminary, influences

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Some Influences on Wall Friction Measurements
A Preliminary Investigation

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The concept of measuring the friction between a bulk solid and a wall material is very simple. However, experience together with previous wall friction measurement research suggest that variables that influence wall friction values are difficult to quantify and, so far, are proving unreliable to predict with any degree of confidence.

In this paper some preliminary test results are presented for different bulk solids on different wall plates where variables examined include particle size distribution, moisture content, test cell size and shear speed.

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1. Introduction

Given the variable nature of bulk solid materials, flow property testing of a representative sample is advisable as an aid to reliable equipment design. In particular, having reliable estimates of boundary or wall friction is particularly important when designing such items as hoppers for mass-flow, transfer chutes that are effective and when calculating bin wall loads and feeder loads.

Wall friction is traditionally measured using a Jenike direct shear tester or an annular shear cell tester as described by Schwedes [1]. The Jenike shear tester (JST) setup for measuring wall friction is a popular tool used to analyse the kinematic wall friction angles and cohesion of a bulk solid when slid on a surface as described in the Standard Shear Testing Technique (SSTT) [2].

According the SSTT, the JST is suitable for coarse particles with a diameter up to 5 percent of the shear cell diameter but typically particles above 4mm are removed. Removing the coarser particles has been accepted as a valid technique to obtain reliable and conservative wall friction angles as the fine particle are of more interest for determining the maximum strength and boundary friction of a bulk solid, especially to achieve mass-flow in bins.

A number of researchers have undertaken wall friction measurements (van den Bergh & B. Scarlett [3], Scott & Keys [4], Haaker [5], Iqbal [6], Pillai et al. [7], Han [8]) investigating the effect of various variables on wall friction angle. The most comprehensive investigation has been undertaken by the Working Party on the Mechanics of Particulate Solids (WPMPS) with the outcome that generalising the influences on wall friction angle remains an elusive goal.

In this paper some preliminary test results are presented for different bulk solids on different wall plates where variables examined include; 1) particle size distribution, 2) moisture content, 3) shear cell size and 4) shear speed.

The outcomes presented confirm the authors' belief that with the present state of knowledge about wall friction it is dangerous to estimate appropriate wall friction values to use in design without undertaking measurements designed to duplicate field conditions as closely as possible. The results also emphasize the necessity for further in-depth research on this challenging topic!

2. The WPMPS Wall Friction Project

For a number of years the Working Party on the Mechanics of Particulate Solids of the European Federation of Chemical Engineering (WPMPS) has been undertaking a research program that compares wall friction measurements undertaken in various test laboratories using the 'same' test procedures (on Jenike direct shear tester) with the 'same' bulk solid on the 'same' wall plates. Three bulk solids (limestone, sand and soda ash) and three wall materials (mild steel, stainless steel 304-2B and a high density polyethylene) were included in the trials. The initial results published in 1999 by Haaker [5] showed considerable variability in the results provided by the various laboratories. For example one set of results for sand on stainless steel grade 304 with a 2B polished finish (SS304-2B) under reducing normal stresses are shown in Figure 1.

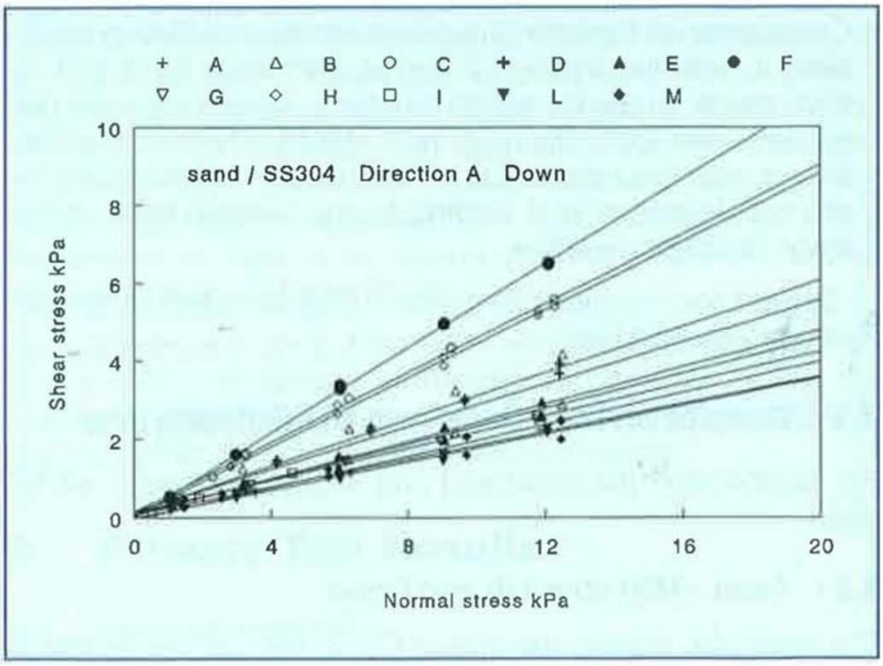

Figure 1 – Wall Friction Measurements with Sand on SS304-2B (Haaker [5])

Haaker concluded that the rather high variations in the wall friction angles measured were generally thought not to be acceptable. No clear explanation for the deviations was found and noted that the work underlies the need for a better understanding of wall friction in bulk solids handling.

The WPMPS has continued with further round-robin test programs in which an attempt to have closer control over the one bulk solid (an acrylic powder) and two wall plates (aluminium and SS304-2B) delivered to the laboratories and to provide each laboratory with a more rigid test procedure. The latest results were presented at the meeting of the WPMPS held with CHoPS in Friedrichschafen, Germany, September 2012, McGee [9].

The wall friction angles measured on aluminium and stainless steel are given in Figure 2.

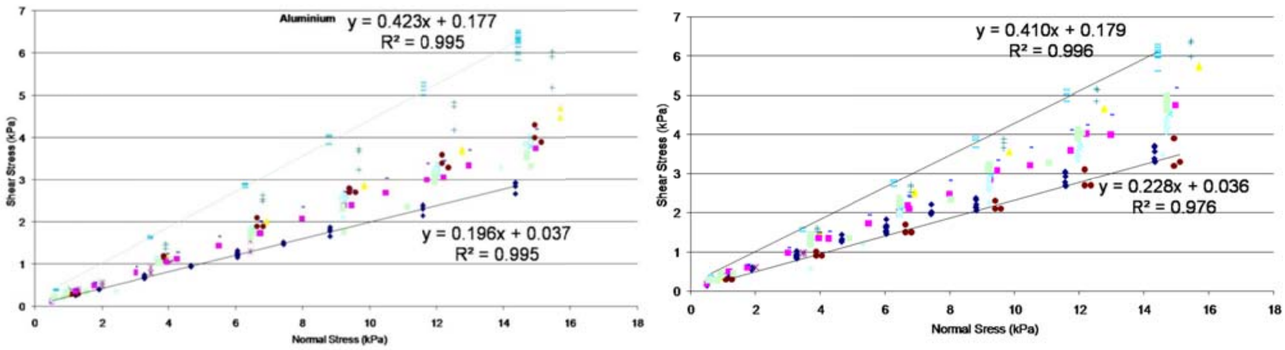

Figure 2 – Wall Friction Angle vs Normal Stress for Acrylic Powder on Aluminium (Left) and Stainless Steel (Right) (McGee [9])

McGee concluded that the results showed some improvement over the initial results (Haaker [5]). Individual labs seemed to achieve internally consistent results but a wide range was observed between the extreme results obtained.

It has been enlightening to see the vast variability in the resulting estimates of wall friction. Maybe the measurement or wall friction is not as simple as it seems.

3. Wall Friction Characteristics of Product Coal

In this section, the wall friction characteristics of product coal are examined on SS304-2B. Further examination of the wall friction characteristics of product coal are provided in the work of Lawler [10]. The particle size distribution of the coal is shown in Figure 3 where the top size of product is 19mm and the median particle diameter, d_{50}, is 5.9mm.

3.1 The Effects of Particle Size

An increase in particle size is generally assumed to decrease the wall friction in bulk materials due to the decreasing surface area that comes in contact with the wall plate [6]. To examine the influence of particle size on wall friction, a series of tests were conducted on the JST where five particle size distributions were tested; -4mm, -9.5mm, -19mm, +4mm -9.5mm, and +9.5mm -19mm. Figure 4 shows the Wall Yield Loci (WYL) for coal oven dried at low temperature to negligible moisture levels. The results show that the dry -4mm and +4mm -9.5mm size distribution displays the lowest and highest wall friction characteristics respectively. Generally when the coal is dry the variation on wall friction with varying particle size distribution is minor.

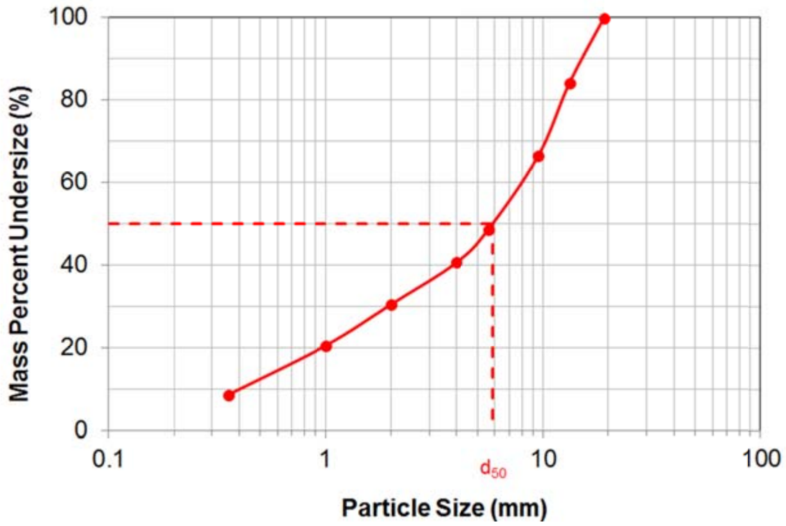

Figure 3 – Particle size distribution of product coal sample

Figure 5 presents the wall friction tests of the five size distributions of coal at a higher moisture level. The samples were prepared by sieving the "as received" coal to retain representative moisture levels for the various size distributions (i.e. fine material generally has greater propensity to retain more moisture). Figure 5 shows that greater wall friction is measured when the sample contains a proportion of fine particles. The greatest wall friction was measured on the full particle size distribution (-19mm) followed by the -4mm size distribution. Figure 5 indicates that greater cohesion is present when testing the -4mm and -9.5mm size distribution at low normal pressure.

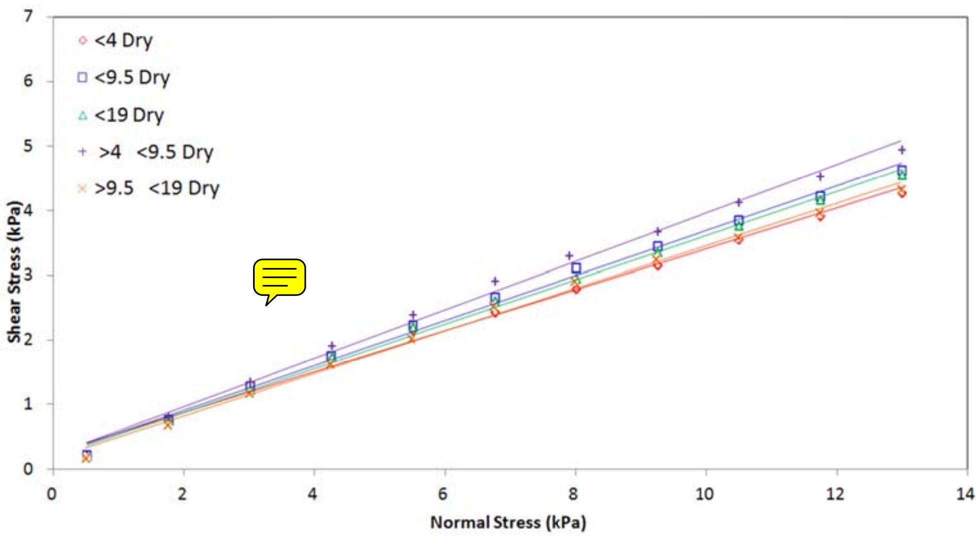

Figure 4 – Wall Yield Loci for various particle size distributions of dry coal on SS304-2B

It is recommended that the top size of material tested in the standard Jenike shear cell is limited to 4mm in the SSTT, however it is possible to test material with a top size of 16mm but it is difficult to obtain reliable results (e.g. there is greater scatter in Figures 4 and 5 of the data points testing

+4mm samples). With higher moisture level and cohesion, Figure 5 indicates that wall friction is dependent on the fines present leading to higher wall friction. Figure 5 provides evidence that retaining a low ratio of the particle top size to the shear cell diameter helps to obtain reliable results and measure greater cohesion that is beneficial for bin design with critical arching conditions at low pressures.

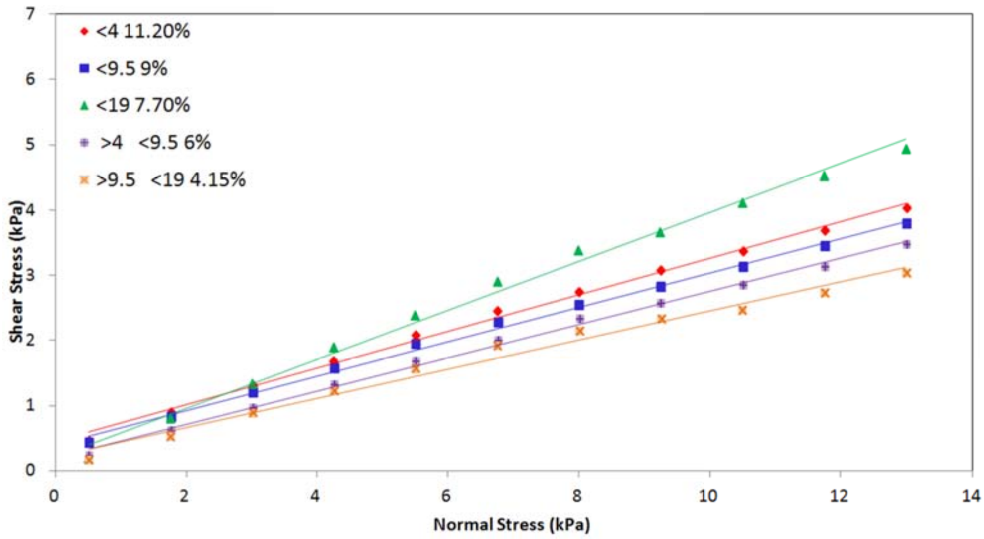

Figure 5 – Wall Yield Loci for various particle size distributions of moist coal on SS304-2B

3.2 The Effects of Moisture Content

One important variable that affects wall friction is the moisture content of a bulk material. When moisture is added to a bulk material, its bulk strength generally increases due to the presence of liquid bridges between the particles. This increases the ability of a bulk material to adhere to surfaces especially at low normal stress.

Figure 6 presents a comparison between the WYL of dry and moist coal with two size distributions of -4mm and -9.5mm measured on the JST. Figure 6 shows that higher friction is measured with the dry coal at higher normal pressures while greater friction and cohesion is measured with the moist samples at low normal pressure. When the coal is dry, greater friction was measured on the -9.5mm size fraction compared to the -4mm fraction. However, when the coal is moist, greater friction and cohesion was recorded on the -4mm size fraction. Figure 6 demonstrates that increasing the moisture level of the coal helps to reduce the force required to shear the coal on the SS304-2B at higher normal stress.

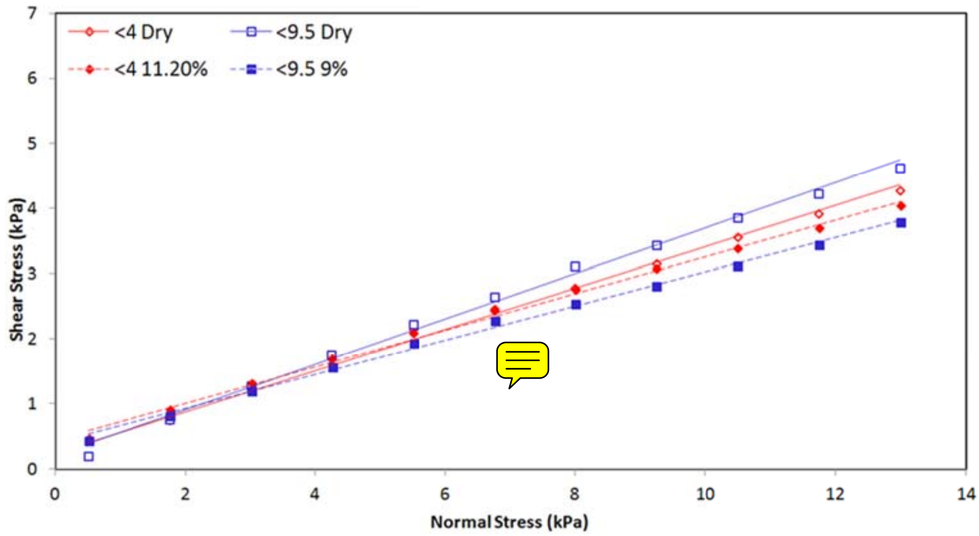

Figure 6 – Wall Yield Loci for various particle size distributions of dry and moist coal on SS304-2B

3.3 The Effects of Shear Cell Size

The standard Jenike direct shear tester uses a shear cell with an inside diameter of 95.25mm [8]. A new Large Scale Wall Friction Tester (LSWFT) was developed by Grima et al [11]. The LSWFT shown in Figure 7 was designed based on similar principles to the JST but utilises a larger shear cell with an inside diameter of 300mm. The machine applies a monotonically decreasing normal force to the shear cell using a pneumatic cylinder and force feedback. For further details on the design and operation of the LSWFT, the reader is referred to Grima et al [11].

Figure 7 – Setup of LSWFT (Left) and comparison of shear cell on JST and LSWFT (Right)

Figure 8 shows the wall friction test results of dry coal measured on the JST and LSWFT using a -4mm and -9.5mm size distribution of coal. Greater wall friction was recorded on the LWSFT for the dry coal especially at higher normal stress. When the line of best fit is extended to the ordinate axis, the line passes close to the origin indicating that the coal is cohesionless, however if a linear regression is used to estimate the cohesion from the Jenike data, greater cohesion is estimated.

When the moisture level of the coal is increased in Figure 9, the variation of the WYL between the -4mm and -9.5mm coal tested on LSWFT tester and -4mm coal tested on the JST are negligible. The LSWFT shows a notable increase in the cohesion of the coal with a higher moisture level. However, the JST predicts marginally greater cohesion using linear extrapolation. Figure 9 suggests that testing the fines (-4mm) on the JST for a moist coal provides similar conservative (worst case) results to the LSWFT.

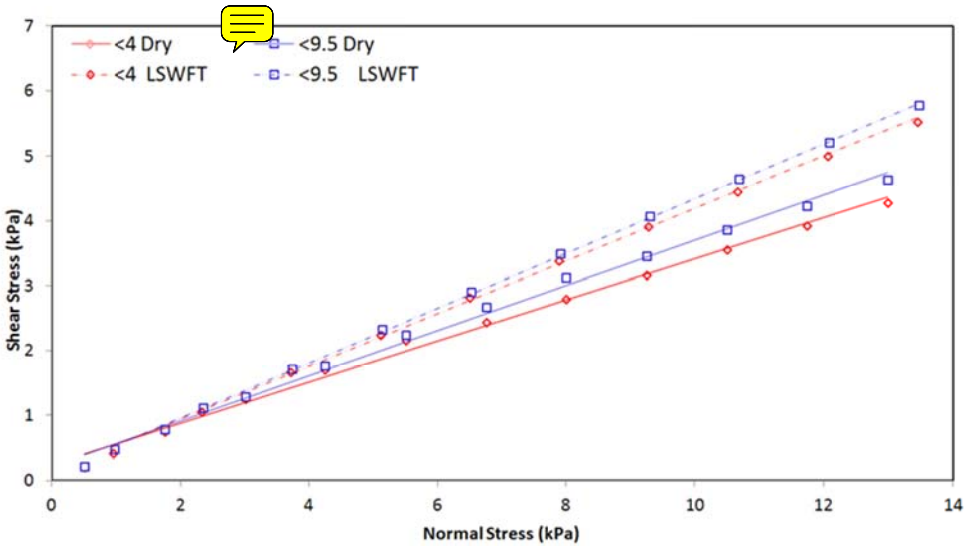

Figure 8 – Wall Yield Loci for various particle size distributions of dry coal on SS304-2B tested on JST and LSWFT

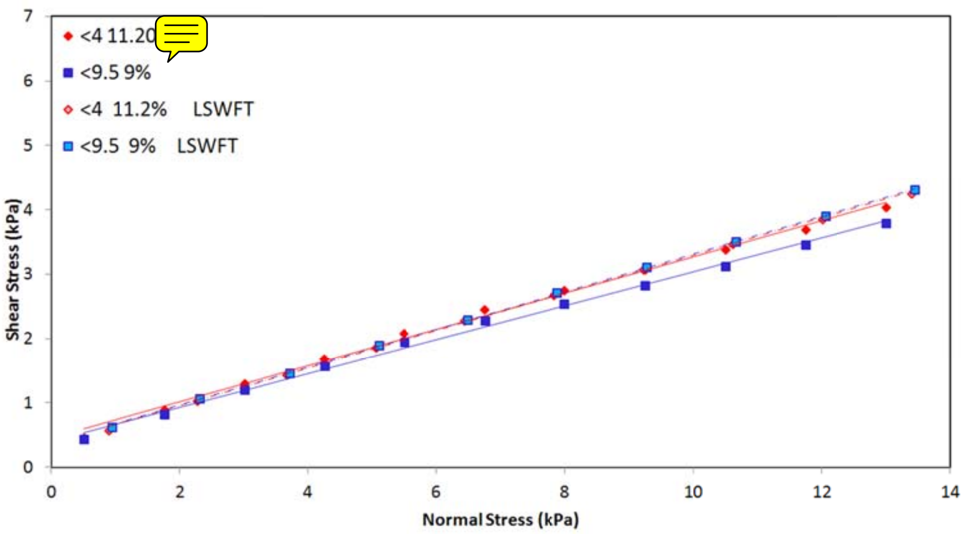

Figure 9 – Wall Yield Loci for various particle size distributions of moist coal on SS304-2B tested on JST and LSWFT

3.4 The Effects of Shear Rate

The standard shear rate of the shear cell on the JST is between 2.69 and 2.72mm/min [2]. The shear rate on the LSWFT is controlled by a servo-drive with velocity feedback that allows the machine to retain a smooth shear rate under varying load. Testing was conducted on the LSWFT using -4mm coal under dry and moist (11.2% wet basis) conditions at shear rates of 2.5, 25 and 50mm/min.

Figure 10 shows when the -4mm coal is dry, the variation of friction with shear rate is trivial where only a slightly higher friction is recorded at the higher normal stress.

When the moisture level is increased, Figure 11 clearly shows that shear rate has a notable influence on wall friction when the shear rate increased from 2.5 to 25mm/min. There was a minor increase in wall friction between 25 and 50mm/min. Further investigation is required to examine other wall materials and bulk materials at various moisture levels and size distributions. Generally, it is understood that greater friction is displayed under quasi-static conditions compared to kinetic conditions.

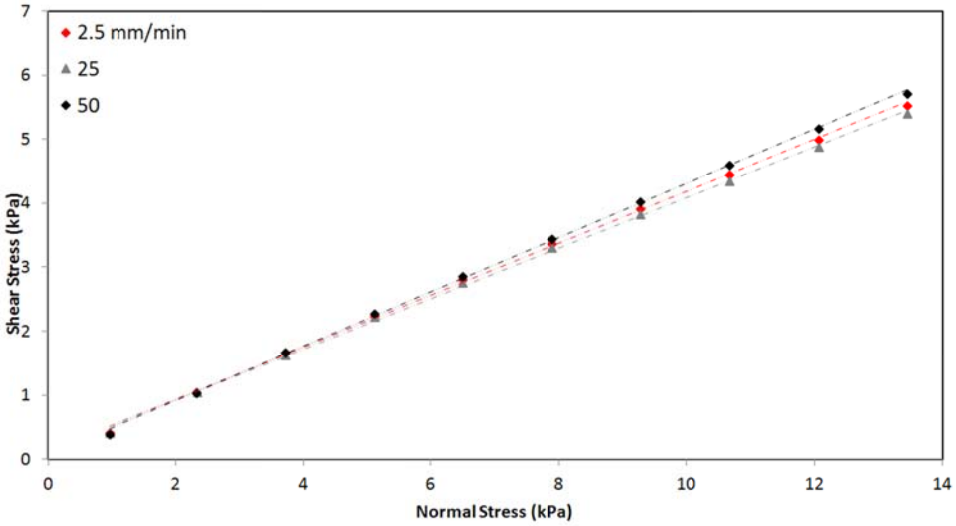

Figure 10 – Wall Yield Loci of dry coal on SS304-2B tested on LSWFT at various shear rates

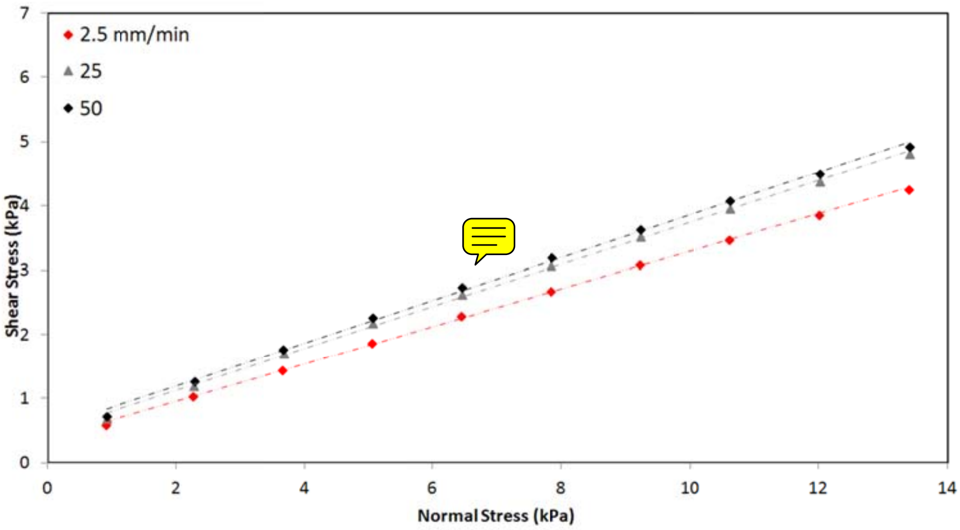

Figure 11 – Wall Yield Loci of coal at 11.2% moisture content on SS304-2B tested on LSWFT at various shear rates

4. Wall Friction Characteristics of Iron Ore Fines

A comparison of the wall friction characteristics for moist iron ore fines was undertaken using the JST and LSWFT. The moist sample of iron ore tested on the JST was sieved to -4mm while the bulk size distribution (-9.5mm) was tested on the LSWFT at the “as received” moisture content. SS304-2B and a polished sample of Arcoplate (tested with shear direction and grain aligned) were examined.

Figure 12 shows that higher wall friction is displayed when the iron ore is tested with the bulk size distribution on the LSWFT for both the SS304-2B and Arcoplate. On the LSWFT, the variation of friction between the SS304-2B and Arcoplate is minor where slightly greater friction was measured on the Arcoplate. The JST also shows that higher friction was measured on the Arcoplate but there is a significant increase in friction on the Arcoplate at higher normal stress. Reviewing the wall friction angles in Figure 12, the friction on the LSWFT is constant indicating negligible cohesion while the JST indicates greater cohesion based on linear extrapolation. However, the lowest normal stress data points on the WYL for the JST lie below the linear line of best fit indicating that the cohesive stress measured on the JST is overestimated. The difference between the WYL measured on the JST and LSWFT will have a noteworthy effect on the design parameters for a mass-flow hopper, bin wall loads and feeder loads.

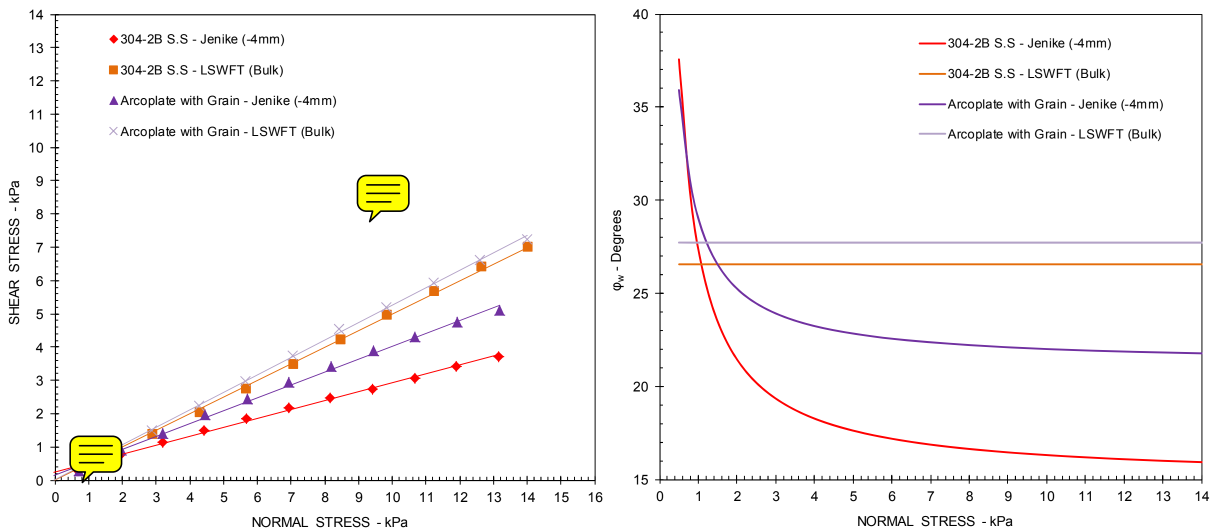

Figure 12 – Wall Yield Loci (left) and wall friction angle, ϕ_w, (right) of -4mm (4.1% moisture content) and bulk (3.6% moisture content) iron ore fines on SS304-2B and Arcoplate tested on JST and LSWFT

5. Concluding Remarks

While the measurement of wall friction for a bulk solid is conceptually simple, the influences various parameters have on the outcome remains unclear. While certain generalisations may be proposed there remains considerable ‘exceptions to the rule’. Although it is generally considered to be quicker and easier to test the -4mm size fraction of a bulk material for design purposes, this paper has emphasised the potential risks of following international standards. The developed LSWFT has shown to be a valuable machine to compare results with those obtained with the JST. The wall friction comparison of the wall friction variations assist in making informed decisions for the design of reliable storage and handling equipment.

This study has shown that retaining a low aspect ratio of the particle top size to the shear cell diameter is ideal to obtain reliable and repeatable results. Considerable further research is required to examine variables such as particle size, moisture level and shear rate on the wall friction characteristics and also to have a better appreciation of the advantages and limitations of the of the LSWFT and JST for wall friction measurements.

In the meantime the authors' retain the belief that with the present state of knowledge about wall friction it is dangerous to estimate appropriate wall friction values to use in design without undertaking measurements designed to duplicate field conditions as closely as possible.

6. References

[1] Schwedes, J., Review on Testers for Measuring Flow Properties of Bulk Solids, Granular Matter, Vol. 5, No. 1, 2003, pp. 1-43.

[2] Institution of Chemical Engineers, Standard Shear Testing Technique for Particulate Solids Using the Jenike Shear Cell: A report of the EFCE Working Party on the Mechanics of Particulate Solids, Rugby, England, Institution of Chemical Engineers, 1989.

[3] van den Bergh, W. J. B. & Scarlett, B. Influence of Particle Breakage on the Wall Friction Coefficient of Brittle Particulate Solids: Part 1. Influence of Wall Inclination, Normal Load and Displacement, Powder Technology, Vol. 67, No. 3, 1991, pp. 237-47.

[4] Scott, O.J. and Keys, S., The Variation of Boundary Friction for Granular Products, Intl. Conf. on Bulk Materials Handling and Transportation, Wollongong, 6-8 July, 1992, pp. 279-286.

[5] Haaker, G., Wall Friction Measurements on Bulk Solids, Powder Handling & Processing, Vol. 11, No. 1, 1999, pp. 19-25.

[6] Iqbal, T. and Fitzpatrick, J.J., Effect of Storage Conditions on the Wall Friction Characteristics of Three Food Powders, Journal of Food Engineering, Vol. 72, No. 1, 2006, pp. 273-280.

[7] Pillai, J.R., Bradley, M.S.A. and Berry, R.J., Comparison Between the Angles of Wall Friction Measured on an In-Line Wall Friction Tester and on The Jenike Wall Friction Tester, Powder Technology, Vol. 174, 2007, pp. 64-70.

[8] Han, T., Comparison Between Wall Friction Measurements by Jenike Shear Tester and Ring Shear Tester, Kona Powder & Particle Journal, Vol. 29, 2011, pp. 118-124.

[9] McGee, E., Report on WPMPS Technical Project - Wall Friction, September 2012, 25 pages.

[10] Lawler, C., Investigations into the Wall Friction of Bulk Materials Using a Large Scale Wall Friction Tester, BE Thesis, University of Wollongong, November 2012, 69 pages.

[11] Grima, A. P., Mills, B.P.et al., Investigation of Measuring Wall Friction on a LSWFT and Jenike Tester, in Proceedings of BulkSolids Europe 2010, Glasgow, Scotland, 9-10 September 2010, Proc on USB.