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Preliminary observations of the effect of plate roughness and particle size on the determination of wall friction

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Abstract

The determination of wall friction angle for bulk materials is vital in applications such as; bin and hopper design, conveyor transfer chutes, rail wagon unloading and any other use where bulk materials flow over a surface. It is generally accepted that the rougher the wall surface, the higher the wall friction angle. This paper will present an investigation of wall samples with various surface finishes using a translational shear tester (based on the design by Jenike). Five aluminium plates; one with a 'smooth' surface and the other four with milled grooves of varying spacing and depth to produce regular 'roughness' on the surface have been utilised. Glass beads of three size distributions have been used as the test products for this study to investigate the effect of particle size and plate roughness on the determination of wall friction. The results of this work have shown that it is not always the case that the 'rougher' wall surface generates the highest wall friction angle but there is also a dependence on the size of the particles as well.

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Preliminary Observations of the Effect of Plate Roughness and Particle Size on the Determination of Wall Friction

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ABSTRACT The determination of wall friction angle for bulk materials is vital in applications such as; bin and hopper design, conveyor transfer chutes, rail wagon unloading and any other use where bulk materials flow over a surface. It is generally accepted that the rougher the wall surface, the higher the wall friction angle.

This paper will present an investigation of wall samples with various surface finishes using a translational shear tester (based on the design by Jenike). Five aluminium plates; one with a 'smooth' surface and the other four with milled grooves of varying spacing and depth to produce regular 'roughness' on the surface have been utilised. Glass beads of three size distributions have been used as the test products for this study to investigate the effect of particle size and plate roughness on the determination of wall friction. The results of this work have shown that it is not always the case that the 'rougher' wall surface generates the highest wall friction angle but there is also a dependence on the size of the particles as well.

1. INTRODUCTION

One of the key parameters required to accurately determine the flow of bulk materials in bins or chutes is the wall friction angle. The measurement of wall friction angle for bulk materials applications has been performed for over 50 years. In a previous investigation on the influence of wall friction measurement by Halford et al. [1], the focus was placed on particle size distribution, moisture content, shear cell size and shear speed. One aspect that was not considered in this initial investigation was the effect of surface roughness of the wall plates.

Schulze [2] investigated the change in wall friction based on orientation of wall samples which had been pre-machined by surface grinding. One wall sample was prepared by cutting regular grooves into the surface to form a structured rough surface. The importance of wall orientation was highlighted and ideally the direction corresponding to minimum wall friction should be aligned to the direction of flow whenever possible. To provide some safety in design, the minimum wall friction angle should not be used, but rather a higher tested wall friction angle. There was no specific mention of the impact particle size had on the variation in wall friction angle. Han [3] also measured wall surfaces in different orientations after highlighting that roughness will vary directionally due to manufacturing process. Han [3] performed wall friction testing on both rotational and translational shear testers and in all cases found that as surface roughness increased, so too did the wall friction. Wu et al. [4] also concluded from their testing program that wall friction increases as surface roughness increases. A different finding by Bernache [5] showed that the testing of a material on a rough surface such as carbon steel can in fact have the same wall friction angle as a smooth surface wall such as cold rolled stainless steel with a milled finish. McGee et al. [6] make the comment that there is no such thing as a 'low friction' material as the frictional properties of the wall are very dependent on the bulk solid being considered.

Roberts et al. [7] comment that the average roughness measurement, R_a , is useful as an indicator for providing comparisons of wall materials but cannot sufficiently quantify the interaction of the particle size and the surface roughness. They instead measured surface spectral density to provide a more useful measure. Additionally, they comment that with tests of black coal on polished and rusted mild steel, there was a clear indication that the

rougher surface of the rusted mild steel causes particles to interlock with the wall surface, resulting in higher friction.

In most instances, it is advantageous to have bins which promote mass flow of material, which normally requires steep angled hopper walls to avoid issues such as ratholing, mechanical and/or cohesive arching. For wall materials which yield lower wall friction values, this allows for the design of hopper wall angles which are shallower while still promoting mass flow. This in turn means that less head room is required for the installation [8]. As a general rule bins are designed symmetrically to ensure even pressure distribution on the walls, to minimise the possibility of a failure. The flow patterns of the material will then be symmetrical provided that the roughness of the wall surface remains consistent. Rotter et al. [9] discuss how the wall friction can change in a silo as a result of abrasion or polishing when a bulk material slides against the wall. If this wear is relatively uniform, then this should not impose too much of a concern, which links back to the comments by Schulze [2]. However, if this wear is localised due to non-symmetrical loading for example, the result can alter the material flow pattern [7] or at worst the uneven stresses forming in the silo could lead to a failure occurring.

In all of the literature considered, there was no specific investigation found focusing on the specific influence of the particle size coupled with the surface roughness of walls and the influence of wall friction. The general consensus is that wall friction increases with increased surface roughness, but as there are no definitive findings based on particle size effects, the preliminary investigation presented in this paper aim to begin that process.

2. WALL PLATES AND SURFACE ROUGHNESS MEASUREMENT

To investigate the effect of surface roughness on the wall friction angle, five aluminium wall samples were prepared, as shown in Figure 1. Plate A has had no machining applied and is an as received condition. Plate B has been omitted as it is the same surface finish as plate C. Plates C, D, E and F have all been machined using a milling machine set to different cut rates to mimic different wall roughness in an ordered way. Each plate (C, D, E and F) were first machined identically to the plate C surface finish shown in Figure 1. After this, further milling was performed to produce the final cuts for plates D, E and F. The depth of cuts varies also due to the way in which the milling machine performs the cutting action. Due to the speed of the cutting acting for plate F, the gaps between the deeper cuts remain with the same surface finish as plate C, as can be seen in Figure 1(b) and Figure 1(e). The photos shown in Figure 1 have been taken at a 45 degree angle to allow the machining to be visible and the primary direction of testing wall friction is across the cuts, i.e. from the bottom to the top of the images. A Hommel T1000 surface roughness tester, see Figure 2, was used to measure the average surface roughness, R_a , of each plate and is provided in Table 1. The surface roughness tester was also capable of profiling the surface of each of the five wall plates. The detail of each plate profile is shown in Figure 3. Each test was performed over 15 mm of travel and the y-axis scale has been kept the same for each graph to allow a direct visual comparison between the surface profiles of each plate.

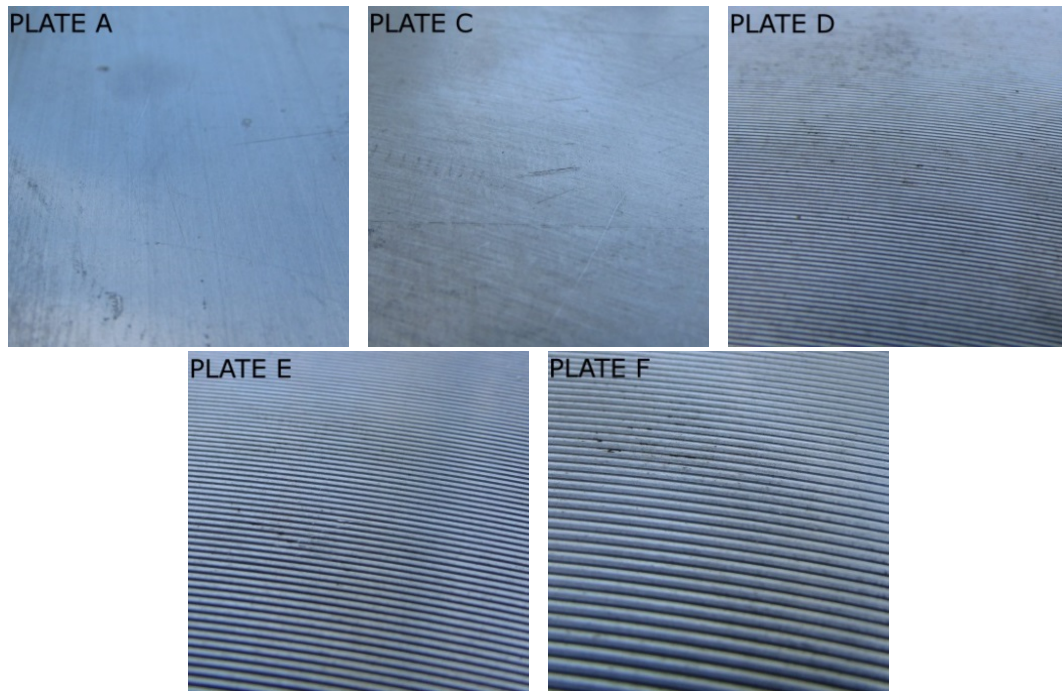


Figure 1 The five aluminium tests plates showing their surface finish
Photos taken at the same distance from the plates at a 45 degree angle



Figure 2 Hommel T1000 surface roughness tester

Table 1 Summary of cutting details for the aluminium wall samples and their measured Ra roughness values

Plate	Cut Rate (mm/min)	Depth of Cut (μm)	Width of Cut* (μm)	Ra (μm)
A	As received (smooth)	0	-	0.13
C	18	3	96	1.12
D	63	25	320	10.30
E	108	70	555	17.53
F	167	70	833	25.67

* estimated from the cuts shown in Figure 3

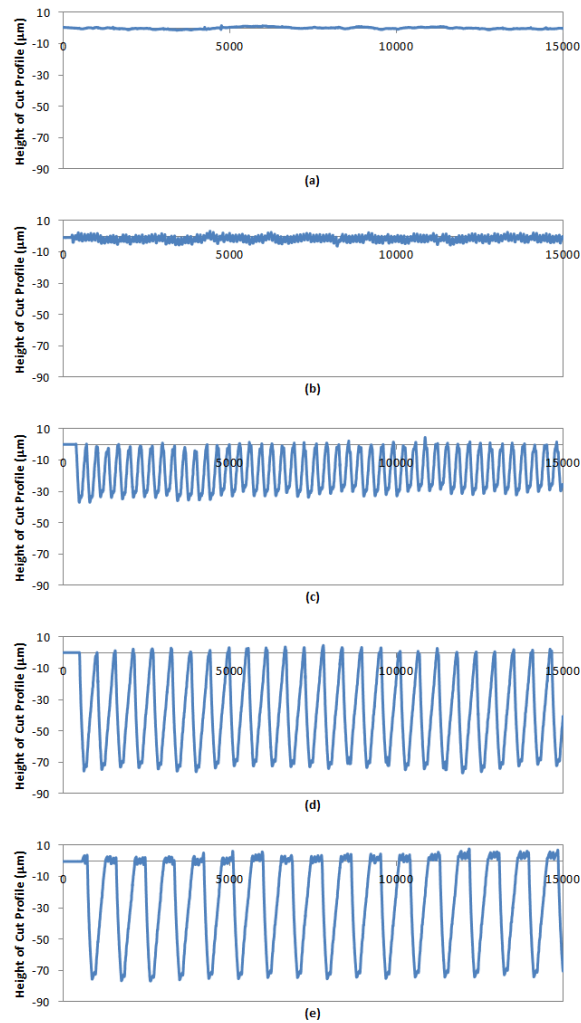


Figure 3 The cut profile of the five plates with the horizontal axes showing the distance in μm the profiler travelled for (a) plate A, (b) plate C, (c) plate D, (d) plate E and (e) plate F

3. TEST MATERIALS

The purpose of this investigation was to investigate the effect of surface roughness and the way in which particle size influences the determination of wall friction. Glass beads were chosen as the test material in three size ranges prepared by mechanical sieving; 106 – 150 μm , 425 – 500 μm and 850 – 1000 μm , as shown in Figure 4. It should also be noted that the glass bead are dry and as such have no cohesive properties which might add to variability of results.

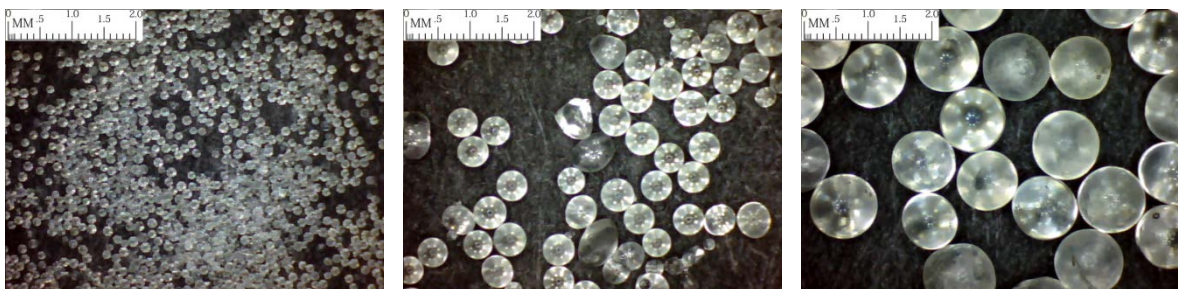


Figure 4 The three size ranges of glass beads used in wall friction tests

4. WALL FRICTION TESTS

A translational shear tester (TST) similar in design to those originally developed by Jenike (JST) was used to perform the testing in this research, see Figure 5. The cube shown positioned above the shear ring in Figure 5 is a calibrated mass, allowing the round masses to clear the main body of the shear tester. The main difference of the TST over the traditional JST is that this apparatus allows for substantially longer translational travel. The operation of the JST allows for only one complete cycle of shear testing, after which the machine must be reset before commencing further runs (i.e. push – return (PR) method). The TST was purposely designed such that approximately seven times the travel could be obtained. This comfortably allows for four to five tests to be run one after the other, without the need for the machine to be reset each time (i.e. push – push (PP) method). However, to allow direct comparison to the traditional JST style machines, the push – return method can still be employed.

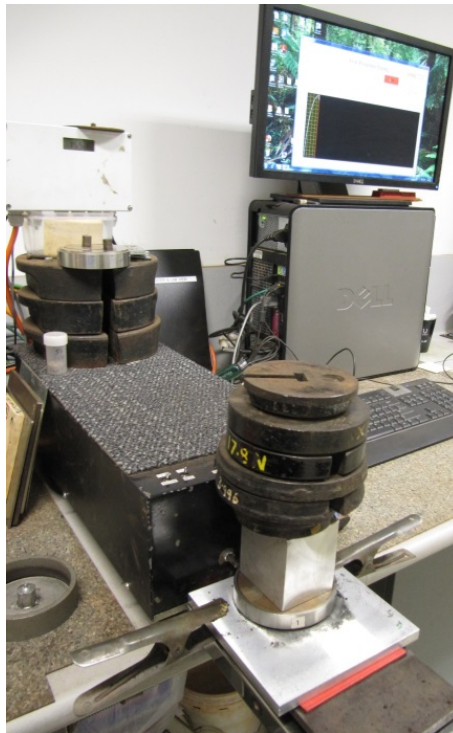


Figure 5 The translational shear tester (TST) used in this test program

4.1 Wall Yield Loci

Each of the three size ranges of glass beads were tested on each of the five wall surfaces using both the PP and the PR methods. This step was performed primarily to investigate whether there were any differences in results between the two methods. A discussion on the comparison of testing using the PP and PR methods on the TST will be provided in Section 5. Testing was performed following the method outlined in both the SSTT [10] and AS3880 [11] with a push rate of 2.5 mm/min. Standard practice is to pre-prepare a wall surface by ‘rubbing in’ a sample of the wall material before commencing testing, to ensure it is in a relatively steady-state condition. The wall yield loci are produced by applying a normal load and then reducing the load in incremental steps all while determining the corresponding shear stress required to shear the material across the wall plate. Two sets of PP tests were performed to check for repeatability and a single PR test was completed to allow a comparison to the normal SSTT method. The resulting wall yield loci results are presented in Figure 6 to Figure 8.

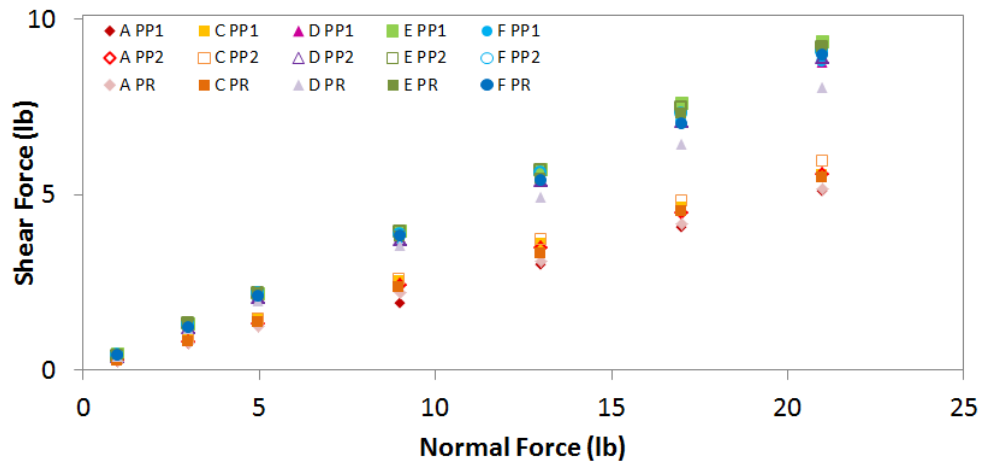


Figure 6 Wall yield loci results for the 106 – 150 μm glass beads on the five wall plates

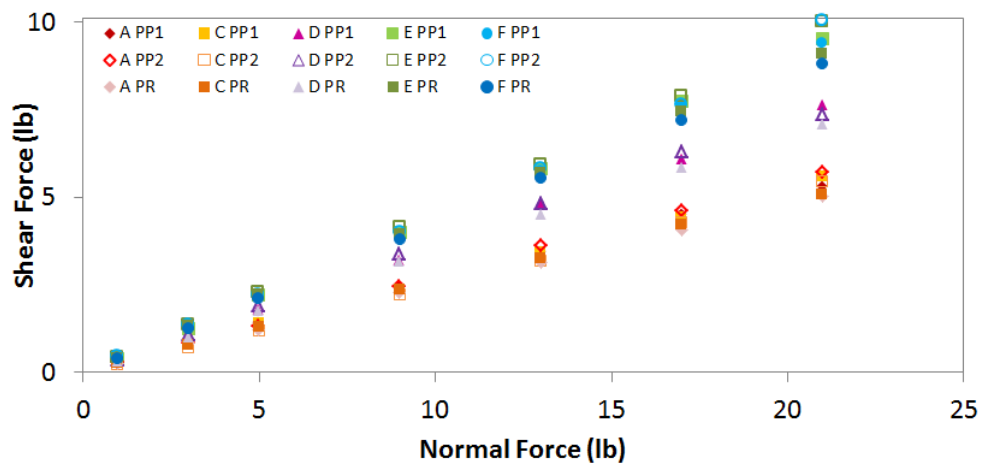


Figure 7 Wall yield loci results for the 425 – 500 μm glass beads on the five wall plates

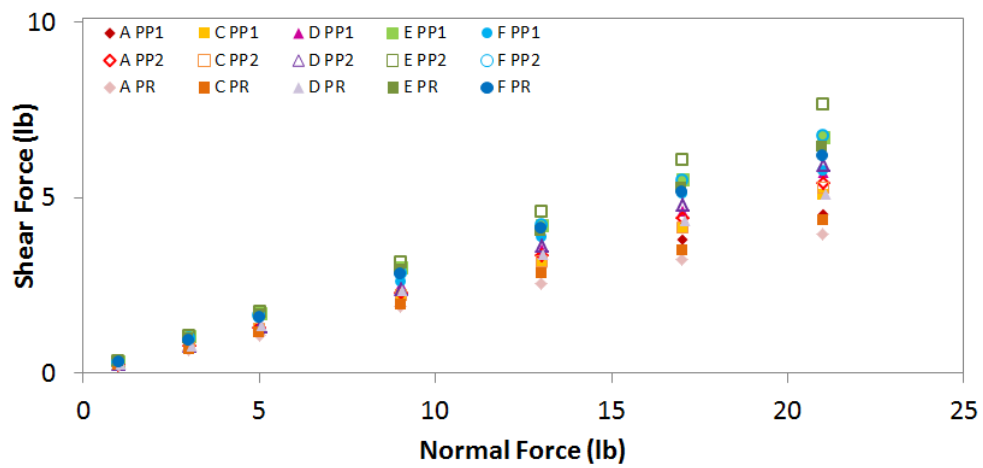


Figure 8 Wall yield loci results for the 850 – 1000 μm glass beads on the five wall plates

The 45 wall yield loci presented above all pass very close to or through the origin, confirming the glass beads contain little to no cohesive properties in their tested state. Using a line of best fit through each set of loci data, the angle each wall yield locus makes with respect to the horizontal axis can therefore be assumed to be constant, which also implies that a constant wall friction angle results. These are shown in Table 2 below.

Table 2 Approximate wall friction angles from each wall yield loci

Plate/Test Method	Glass Beads 106-150 μm	Glass Beads 425-500 μm	Glass Beads 850-1000 μm
A PP1	14.9	14.2	12.0
C PP1	14.7	14.7	13.4
D PP1	22.6	20.0	15.1
E PP1	24.0	24.3	17.6
F PP1	22.6	24.0	15.6
A PP2	14.8	15.3	14.4
C PP2	15.7	14.1	13.8
D PP2	22.8	19.6	15.5
E PP2	23.6	25.0	19.6
F PP2	23.3	24.7	17.8
A PR	13.7	13.3	10.5
C PR	14.6	13.5	11.5
D PR	20.8	18.7	13.8
E PR	23.1	23.5	17.0
F PR	22.8	22.8	16.5

The results for the 106 – 150 μm glass beads are shown in Figure 6 and it can be seen that plates A and C produce very similar wall yield loci results, which are lower than the grouping of results for plates D, E and F. Plates A and C have the smoothest wall finishes and it would seem that coupled with the small glass beads, this combination generates the lowest wall friction with the particles sliding across the surface of plate A or only partially entering the grooves of Plate C. On the other hand, for plates D, E and F, the wider cuts in the wall plate surfaces allow the small glass beads to fully enter the cuts, creating a higher friction as the particles are pushed across other particles captured in the cuts. This seems to imply that for these three plates, the particle/particle interaction is more dominant. Although difficult to see, the results for plate F for all three sets of tests are marginally lower than the results for plate E.

Figure 7 shows the wall yield loci results for the 425 – 500 μm glass beads. Again plates A and C show very similar results, requiring the lowest shear stress to shear the product across the wall plates. The particle size is substantially larger than the width of the cuts for plate C so the particles tend to slide across the cuts without much effort. The particle size distribution is close to the width of the cuts for plate D and it can be seen that the results D show a higher required shear stress than plates A and C. The glass beads are smaller in diameter than the cuts in both plates E and F and as a result, some particles work their way into the cuts and then during the shearing process, particles shear across other particles. Again, the results for plate F are slightly lower than those for plate E.

Figure 8 shows the results for the 850 – 1000 μm glass beads. There is a less defined distinction between the wall yield loci for all the testing completed in this section. Although hard to discern from the graph, the general trend shows that the wall yield loci increases for plates A, C, D and E and then plate F drops to a value between those of plates D and E. This implies that even though the surface roughness of plate F is highest, the testing of this particular particle size range of glass beads results in a slightly better wall friction result than plate E. This will be explained further in the following section. Referring to the cut widths of plates C, D, E and F, they are all narrower than the glass bead particle size range and so for this set of tests, particles can never fully enter the cuts to result in a dominance of particle/particle friction.

4.2 Trends of Wall Yield Loci Gradient

In an attempt to present the variation of the wall yield loci results presented in Figure 6 to Figure 8 with more clarity, the gradient of each wall yield loci has been extracted and plotted in Figure 9. The similarity in results for plates A and C shown above has also been confirmed in Figure 9, showing very similar gradients for the PP and PR test methods and glass bead particle size ranges. There is a noticeable step jump in gradient values as the plate surface roughness increases, as seen for plates D, E and F.

In terms of particle size, the two smaller ranges produce a noticeably higher wall yield loci gradients, especially for plates D, E and F. It is reasoned that the glass beads in these two size ranges are filling the cuts and as a result there is less particle/wall interaction but instead there tends to be more particle/particle interaction as particles shear over other trapped particles. Also of note is that regardless of shear method, plate E consistently produces the highest gradient of wall yield loci and thus wall friction angle for all size ranges. Plate E does not have the highest roughness as the Ra value shows (Table 1); however, on further inspection of the wall surfaces for plates E and F, a likely reasoning for the higher value can be deduced. For plate E, the cuts in the surface have been made at a cutting rate that produces a sawtooth like profile, that is, a sharp peak is present between each cut, refer back to Figure 3(d). This is different to the profile formed for plate F. The cutting rate is at a sufficient speed that some of the original surface of the wall material remains in between cuts. From Figure 3(e) it is estimated that each flat zone is approximately 350 μm in width. The repeated combination of this flat zone followed by the cut is likely producing a net reduced friction due to some of the shearing of the particles travelling over a surface which mimics that of plate C, as mentioned in Section 2, which has a relatively small surface roughness value in comparison.

Additional inclusions in Figure 9 are the three dashed lines representing the static angle of internal friction values for each of the glass bead particle size ranges used in the wall friction test program. These static angle of internal friction values are determined from the slope of the instantaneous yield loci (which for these free flowing glass beads is nearly identical to the effective angle of internal friction, δ). The method for this testing will not be explained in detail here, except to say that the TST was again used, where two cells of material are stacked on top of each other and under normal load, the top cell is sheared across the other stationary cell to create particle shear. The data obtained is then processed to determine the internal friction of a material. Full details of this testing method are explained in AS 3880 [11].

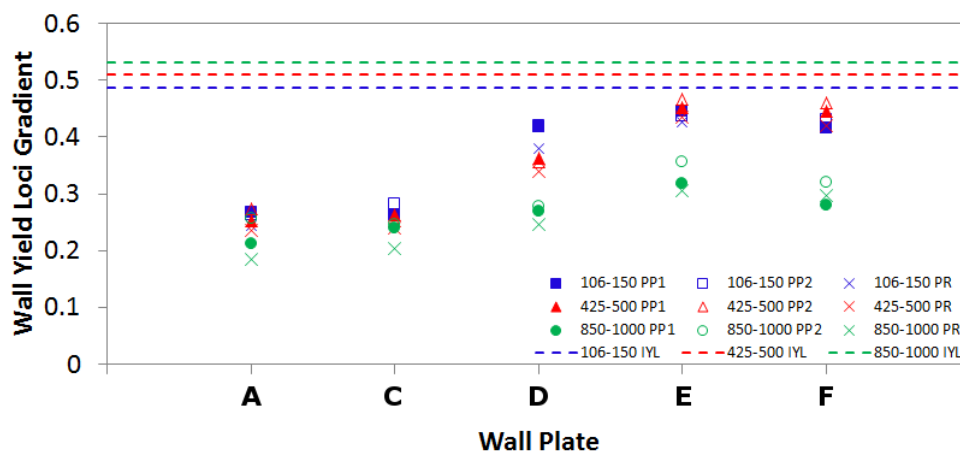


Figure 9 The wall yield loci gradient plots of all PP and PR tests for the three glass bead size ranges. Also included are the corresponding IYL gradient values for each glass bead size range

It is clear that for plates D, E and F, the roughness of the wall surfaces and the widths of the cuts in the surface are creating wall friction results which are tending towards the internal friction values for the two smaller glass bead size ranges. The main reason for this is as previously mentioned; that the particles are able to enter the cuts of the three rougher plates and the shear behaviour is more akin to particle/particle interactions than particle/wall interactions. For the larger glass bead size range, the results are still being dominated by the particle/wall interactions as the shearing process occurs.

5. COMPARISON OF PUSH-PUSH AND PUSH-RETURN METHODS

In Figure 6 to Figure 8 it was hard to identify if there was any noticeable difference between the push-push and the push-return methods for determining the wall yield loci. It became clearer when reviewing the wall friction angles in Table 2 and the data plotted in Figure 9. There is a small amount of experimental scatter, which is to be expected when testing any bulk material; however, the results of the PP and PR are close enough to imply that the push-push method is capable of generating as accurate results as the more traditional push-return method.

6. CONCLUSION

From the available literature, there is a general consensus that as plate roughness increases, so does the wall friction. This statement is made by numerous researchers, who combined have tested many product/wall combinations. However, there was no specific indication provided on the influence of particle size with reference to this statement in these previous investigations. As a result, this paper provides a preliminary investigation into the combined effect of plate roughness and particle size and the effect on wall friction.

Five wall plates were used, four of which were milled to provide varying degrees of roughness. Glass beads of three size fractions were also used to investigate the interaction of particle size with surface roughness. It was found that there is a trend where wall friction increases as roughness increases, however, this is also not true under certain circumstances. If the particles are sufficiently small as to fill the grooves of a milled wall plate, the friction increases, in part due to particle/particle interaction rather than particle/wall interaction. This is akin to the internal friction angle, which can also be measured in a different configuration of the translational shear tester.

Results of testing one material of three size ranges on five wall plates have produced preliminary findings which of course need to be investigated further. The use of additional materials of similar sizes as well as smaller and larger will help to generate a better picture of the findings here.

As a side issue to the research presented in this paper, a comparison of the traditional push – return method of shear testing on a translational Jenike type shear tester has been compared to the push – push method of shear testing possible with the translational shear tester developed by Bulk Materials Engineering Australia. A comparison of the results has shown that there is very little difference between the two methods, except for that which is normally expected when testing bulk materials in general. Of course, a limited range of test products and wall materials was tested in undertaking this research and further results on a much wider range of combinations will be completed in the future to verify this further.

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