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Nomenclature

d_2	Diameter of adhesion interface	[m]
A	Area of adhesion interface	[m ²]
F_{a0}	Adhesive tensile force	[N]
F_C	Capillary force	[N]
F_{c0}	Cohesive tensile force	[N]
r_1	radius	[m]
S_{a0}	Adhesive shear force	[N]
γ	Surface tension	[N/s ²]
σ_{a0}	Adhesive tensile stress	[Pa]
σ_{c0}	Cohesive tensile force	[Pa]
τ_{a0}	Adhesive shear stress	[Pa]

Development of new Analysis Methods for the Characterization and Classification of Wet Sticky Ores

1. Introduction

Equipment used in bulk solids handling includes silos, hoppers, transfer chutes and feeders. In order to keep the running costs of this equipment low and to obtain maximum yield from investments, it is necessary to ensure a high degree of reliability regarding the continuous operation.

The ongoing exploitation and subsequent decrease of favourable ore bodies (in view of handleability) dictate the turn of mine sites towards formerly less attractive deposits. A multitude of these ore bodies are located close to or even beneath the water table and can cause handling issues due to their enhanced adhesive and cohesive characteristics. These materials can increase wear and cause expensive downtime by clogging up processing equipment. Especially transfer chutes, hoppers and screens are prone to clogging. The high propensity of material adhesion is also leading to increased carry back on belt conveyors.

The additional handling costs caused by downtime and sub-optimal running conditions for wet and sticky ores (WSO) range between 4-6 AUD per tonne (Long, 2009). This leads to a significant financial impact on the mineral industry. The underlying causes of WSO behaviour are still poorly understood and there is a lack of methods to predict their impact on mining operations. In order to gain a better understanding of the characteristics of these ores, to find a method of their classification, and ultimately to find ways of overcoming WSO handling issues, test methods for adhesion and cohesion within bulk material were developed.

2. Relevant mechanisms for handling problems

Macroscopic adhesion only occurs when a material is adhesive enough to adhere to equipment surfaces as well as cohesive enough to adhere to the first layers of material adhering to equipment surfaces (Burbaum, 2009). It is therefore necessary to consider both mechanisms, when investigating issues of clogging and build-up.

Adhesion is generally defined as the attraction forces between molecules of different matters. It can occur between solids, between solids and liquids or between gases and either of the formerly mentioned (Hering, 1989). In bulk material handling the adherence of bulk materials to handling equipment surfaces can be regarded as adhesion. Cohesion on the other hand is defined as the internal force of similar material adhering to itself. In bulk solids handling cohesion is defined as the bulk material adhering to itself. Bulk materials typically consist of a number of different minerals and organic substances, leaving this definition physically inaccurate. For bulk solid handling, however, this definition is advantageous.

The cohesive and adhesive forces can be categorised further by the direction of the applied forces, as shown in Figure 1. In a wall friction test, there are adhesive shear forces acting on the sample (in addition to the friction forces caused by the normal load). When a sample is pulled off a wall surface in vertical direction, the forces acting can be described as adhesive tensile forces. The same differentiation can be made for cohesive forces. An internal shear failure, as occurring during the Jenike shear test, has to overcome cohesive shear forces (next to the internal friction forces induced by the normal load). A sample's internal failure with the failure plane oriented perpendicular to the induced forces has to overcome cohesive tensile forces.

The mechanisms relevant for build-up on handling surfaces are adhesive tensile force, adhesive shear force and cohesive tensile force. Experimental determinations of these properties will allow the characterization of investigated samples as problematic or unproblematic regarding issues of build-up. Furthermore, these measurements allow to draw conclusions about the physical mechanisms underlying adhesion of bulk material to surfaces.

Habenicht (2006), showed that by solving the Young-Laplace equation for the capillary pressure between two steel surfaces connected by a liquid film as illustrated in Figure 2, it is admissible to substitute the meniscus radius of the capillary liquid r_2 with half the distance of the adhesions partners of $0.5 \cdot d_2$ leading to a simplified form for the adhesion force between the surfaces in form of

$$F_c = \gamma * \left(\frac{1}{r_1} + \frac{2}{d_2} \right) * \pi r_1^2, \quad (1)$$

where F_c is the force resulting from the capillary pressure, γ is the surface tension of the liquid and r_1 is the radius of the steel surfaces.

In this case, the capillary force is only dependent on the thickness of the liquid film between the adhesion partners. The theoretical adhesive tensile stress as a function of the thickness of the liquid bridge is shown in Figure 3.

Burbaum (2009) determined the adhesive tensile stress between two stainless steel surfaces experimentally and validated Habenicht's theory. He was able to apply this model to a similar adhesion test between clay samples and stainless steel surfaces. Comparing simultaneous measurements of the adhesive tensile forces and the thickness of the liquid bridge on the interface with the mathematical predictions from Equation 1 he was able to prove that for this case the capillary forces are the main source of adhesion.

3. Testers

In order to measure the bulk material properties identified as significant for problematic handleability in section 2, three new testers were developed that are described in the following sections.

3.1 Adhesive tensile tester

With the adhesive tensile tester the tensile force required to pull off a bulk solid sample from a material surface in vertical direction can be measured. Adhesive tensile stress can be defined as

$$\sigma_{a0} = \frac{F_{a0}}{A}, \quad (2)$$

where F_{a0} is the force needed to separate the bulk material from the surface and A is the contact area of the adhesion partners.

The measurement of the adhesive tensile strength comprises of two steps. First the sample is consolidated within a tensile ring onto the wall sample surface. As illustrated in Figure 4, the tensile ring is a circular mould that holds the bulk material. In the next step the sample is lifted off via the tensile ring with a velocity of 8 mm/min and the tensile force necessary to pull the sample from the wall surface is measured.

he consolidation process follows the standard wall friction testing technique, as described in (*Standard Shear Testing Technique for Particulate Solids Using the Jenike Shear Cell*, 1989). It has to be noted, that with an inner diameter of 65 mm and a height of 16 mm the tensile ring has a larger ratio of height over diameter than the Jenike shear tester to allow for sufficient internal strength of the sample. It is also tapered at an angle of 10 degrees to facilitate the application of a vertical tensile force on the sample. A typical measurement for an adhesive material will result in a curve as depicted in Figure 5, where the course of the can be divided into four sections:

- I. Constant datum value resulting from the weight of the tensile mechanism
- II. The tensile force increases until failure occurs at peak force
- III. The tensile force decreases until all adhesive bonds are broken
- IV. The remaining tensile force results from the material's bodyweight and the weight of the tensile mechanism

3.2 Adhesive shear tester

The adhesive shear force is the portion of the force required to shear a bulk material along a wall surface, which is caused by adhesion. Shear forces can be measured using the standard wall friction test as defined by *ASTM Standard D6128 (2014)*. The wall friction test includes shear forces generated by friction as a result of a normal force on the bulk solid sample. In order to eliminate forces of friction, any normal force acting on the sample is eliminated by tilting the setup in the vertical position and shearing vertically as depicted in Figure 6.

A typical measurement for an adhesive material will result in a stress progression curve as shown in Figure 7. The measurement can be divided into four sections:

- I. The tensile force is not yet applied
- II. The tensile force increases until failure occurs at the peak force
- III. The tensile force decreases until all adhesive bonds are broken and the adhesion partners are separated
- IV. The remaining tensile force results from the material's bodyweight

3.3 Cohesive tensile tester

To suit the demands of wet and sticky ores, a split cell tensile tester (Ajax Tensile Tester, GB) was adapted. It allows the measurement of the maximum force required to fracture a sample contained in a cylindrical split cell. One half of the cell is fixed on the main body of the tester, while the matching section is movable and driven by a set of tensile springs. The schematic design of the tester is shown in Figure 8.

3.4. Repeatability of the tests

To determine the repeatability of the tests, a number of measurements were repeated. The repeatability was found to be in the range of a Jenike shear tester and therefore sufficient for bulk solids testing.

4. Investigations and characterization of WSM

The adhesive and cohesive characteristics of two materials, generally characterized as WSO during mining operations, because of frequently occurring handling problems, were investigated. One sample was bauxite, the other one a nickel ore.

Adhesion tests were conducted on a stainless steel sample with a 2B finish and an Arcoplate sample. These two samples were chosen because they represent opposite ends of the spectrum of wall materials likely to be encountered in bulk solids handling, with roughness values of:

1. Stainless steel	Ra=0.8
2. Arcoplate	Ra=19.3

For any of the supporting points of the graphs presented in section 4, a minimum of three repetitions have been carried out. The mean value of these measurements can be found in the subsequent plots. Additionally the 95 % confidence interval (C.I.) was determined from the measurements.

4.1 Adhesive tensile stress

The adhesive tensile stress of the nickel ore is highly dependent on the moisture content (MC). At 29 % MC an influence of the consolidation pressure is visible, but not very pronounced, as shown in Figure 9. At 34.7 % MC there is a significant increase of adhesive tensile stress with increasing consolidation pressure. The wall material does not have any significant influence on the adhesion force.

Figure 10 shows the adhesive tensile stress measured for the bauxite, paired with the stainless steel wall sample. For visibility the 95 % C.I. is left out in the plot. It is relatively low with a mean value of 0.17 kPa. Figure 11 is the equivalent measurement using Arcoplate as the adhesion partner. Here the mean of the 95 % C.I. is 0.23 kPa.

As for the nickel ore, an influence of moisture content can be determined. From 12 % to 15 % MC the adhesive tensile stress increases. At higher moisture content it decreases again. The wall sample does not show any significant influence on the adhesive tensile stress. This supports the theory that the adhesion is a result of capillary effects.

4.2 Adhesive shear stress

Figure 12 contains the adhesive shear stress of the nickel ore at 34.7 % moisture content for both wall samples tested. The mean 95 % confidence interval is 0.3 kPa. The test results do not show any influence of the wall material. This is an indicator that the failure mechanism is similar to that described in section 2. The material is torn off the wall sample, but no actual shear movement between the bulk solid and the wall sample occurs while adhesive bonds are still in place.

Figure 13 shows the results of the adhesive tensile measurements of the bauxite sample. The mean 95 % C.I. is 0.1 kPa. In contrast to the behaviour of the nickel ore, the adhesive shear stress of the bauxite shows sensitive regarding the wall sample. When paired with Arcoplate the bauxite behaves similar to the nickel ore, the adhesive shear stress increases with increasing consolidation pressure, as well as with increasing moisture content. For 18 % moisture content the adhesive shear stress at 14 kPa consolidation pressure could not be determined, because the variance of the measurements was too high. Paired with the stainless steel sample, the adhesive shear stress seems to be independent on both consolidation pressure and moisture content.

The failure of the bauxite bulk sample on the two wall surfaces followed different mechanisms, which explains the different shape of the adhesive shear functions for the respective wall samples in Figure 13. The nickel ore behaved as predicted in section 1. During the measurement the tensile force increased until the material was pulled off the wall samples. The bauxite behaved in a similar way when paired with the Arcoplate sample. Paired with the stainless steel sample, however, the bauxite remained attached to the wall sample permitting relative movement of the adhesion partners, while sustaining constant adhesion. The force measurements resulting from the bauxite testing therefore have a rather different shape for the two wall materials, as shown in Figure 14. Paired with Arcoplate, the tensile force increases to a maximum, from where it is decreasing again when the bulk solid detaches from the wall material. In the stainless steel the tensile force increases towards a constant maximum.

The difference in behaviour can be explained with the thickness of the liquid film on the interface between bulk material and wall sample. The nickel ore with a relatively high saturated moisture content of 57.0 % is able to bind a lot of moisture. The tested absolute moisture content of 34.7 % represents 61 % of the saturated moisture content. The bauxite has a lower ability to bind water, the tested moisture content of 18 % represents 87 % of its saturated moisture content. Therefore there is more free water within the nickel ore and the liquid film on the interface of the adhesion partner is thicker. The thicker water film forms

a flexible liquid bridge that permits some relative movement while maintaining adhesion caused by capillary pressure following the model of Figure 2. However, the liquid film is not flexible enough, to permit relative movement across the rough surface of the Arcoplate. The overall adhesive shear stress of the bauxite is much smaller than that of the nickel ore, which can be confirmed by applying the Young-Laplace equation (section 2).

4.3 Cohesive tensile test

The nickel ore was tested at three different moisture contents regarding the cohesive tensile strength, as shown in Figure 15. The stress necessary for failure increases with increasing moisture content of the sample as well as with increasing consolidation load. The standard deviation of the test conducted at 34.7 % moisture is quite high for the last point of consolidation, leading to a large confidence interval. The trend of the curve, however, fits a linear function very well.

Figure 16 shows a plot of the cohesive tensile measurements of the bauxite ore. Only two moisture contents were investigated. A measurement at moisture contents lower than 10 % was not possible, as the sample was not cohesive enough at low moisture contents for the measurement range of the test setup. At 10 % moisture the determination of supporting points for the curve was not possible for consolidation levels below 25 kPa, since the resulting cohesion of the sample was not sufficient for testing. At moisture contents above 12 % the determination of cohesive tensile stress was not possible either, because the ratio of the cohesion within the sample to the adhesion of the material to the split cell walls was too high, leading to a detachment of the sample from the split cell walls, instead of internal failure. The ratio becomes unfavourable due to both the increase in cohesion with increasing moisture content, as well as to the decrease in adhesion as a result of the abundance of more free water and the therefore increased thickness of the liquid bridges.

The measurements conducted show a large influence of the moisture content. At 12 % moisture the overall cohesive tensile strength is a lot higher than at 10 % moisture. It is also much more dependent on the consolidation stress at the higher moisture content, as the higher linear slope of the graph suggests.

5. Classification of WSM

In search of a straightforward method to classify problematic bulk solids it is beneficial to combine the adhesive tensile test results with those of the cohesive tensile test. Macroscopic adhesion will only occur when a material is adhesive enough to adhere to equipment surfaces as well as cohesive enough to cohere to the first layers of material adhering to equipment surfaces (Burbaum, 2009). Therefore a material can be classified as wet and sticky based on the weaker of the two mechanisms, since the weaker mechanism will determine failure of build-up on the wall.

During the course of this work the cohesive forces within a material were found to be significantly larger than the adhesive forces. Therefore it is suggested to define a minimum value of adhesion as the threshold for a material to be classified as wet and sticky.

The minimum adhesion threshold is set at 500 Pa, which is twice the minimum measurable adhesion value of the current adhesive tensile tester. This adhesion value ensures for the common bulk density of $\sim 2000 \text{ kg/m}^3$ that the adhesion stress is sufficient to support an adhesion layer of 2.5 cm thickness. Since the materials tested are known for handling problems in industrial applications, they exceed the proposed adhesive threshold at any given moisture content for at least one of the wall samples. In the following two sections the two tested bulk materials will be classified according to the introduced criteria.

5.1 Classification of the nickel ore

Figure 17 summarizes the information gathered for the classification of the nickel ore at 29.1 % moisture content. The cohesive tensile strength is larger than the adhesive tensile strength throughout the whole consolidation range tested. Therefore it is valid to base the classification of this material on the proposed adhesive threshold. As the graph shows, the adhesive threshold is only exceeded in combination with the Arcoplate wall material for high consolidation pressures. At this moisture content, therefore, the material is not yet classified as wet and sticky.

Figure 18 shows the corresponding information for the nickel ore at the increased moisture content of 34.7 %. The material has gained adhesive and cohesive tensile strength. The adhesive threshold is exceeded for both material combinations at around 8 kPa consolidation pressure. At this moisture content the nickel ore can be considered as a problematic wet and sticky ore.

5.2 Classification of the bauxite sample

The bauxite material is classified in a similar manner. The measurements taken at 10 % moisture show, that the bauxite's cohesive and adhesive properties are comparable in magnitude, as shown in Figure 19. They exceed the adhesive threshold at 25 kPa consolidation pressure. At 12 % moisture content the cohesive tensile stress is much higher while the adhesive tensile

stress increases only about 0.2 kPa (Fig.20). At this moisture content the material behaviour in handling applications will be much more critical than at 10 %, due to the increase of cohesive strength and the ore can be considered wet and sticky.

At 15 % and 18 % moisture content the cohesive tensile stress was too large to be measured with the current test set-up and therefore exceeds the threshold. 1 shows that the adhesive tensile stress at 15 % moisture exceeds the threshold throughout the whole consolidation range. At 18 % moisture the adhesive tensile strength has decreased again, but the threshold is still exceeded for the stainless steel wall material, as shown in Figure 22. In combination with the Arcoplate the material's adhesive tensile stress breaks the threshold at 25 kPa consolidation pressure.

6. Conclusion

This paper presented measurements on adhesive and cohesive stresses on wet and sticky bulk material. The accuracy and repeatability were found to be in the range of tests commonly used for bulk material testing.

The adhesive tensile stress was found to be mainly dependent on capillary forces and can therefore be described using the Young-Laplace equation. The capillary forces are governed by the thickness of the liquid film in the contact interface. Therefore the adhesive tensile stress is independent on the wall material, but rather a function of the moisture content, permeability and matric pressure of a bulk solid, as these properties govern the thickness of the liquid film.

The adhesive shear stress, on the other hand, was found to be dependent on the bulk material's adhesive properties, as well as on the roughness of the wall samples used for testing. The mechanisms of failure of the adhesive bonds followed two different mechanisms. This leads to the conclusion, that the adhesive shear force is in fact rather the result of adhesive tensile force. When failure of the adhesive bond occurs without relative movement of the adhesion partners, the measured force is simply a result of breaking adhesive bonds via shear. If the adhesive bond is sustained during relative movement of the adhesion partners, the measured force is rather a friction force introduced by adhesive tensile force acting as the normal force introducing friction to the relative movement between the adhesion partners.

Next to adhesive stresses the cohesive tensile stresses within bulk materials were measured in order to gain an understanding of the ratio of internal to external forces. No investigations regarding the physical causes of cohesion were conducted. The relevant mechanisms are expected to be surface charges, particle size distribution, matric pressure and permeability. These characteristics are closely linked to each other and also related to the adhesive characteristics. Further investigations regarding these parameters can therefore give an insight on both cohesion and adhesion.

Based on the measured material characteristics, a method to assess the potential of bulk materials to cause handling problems has been developed. An adhesive threshold value has been introduced which has to be exceeded by a material to be characterized as wet and sticky. Additionally, the internal cohesion of a sample has to be larger than the adhesion for a material to be characterized as wet and sticky. The threshold is somewhat preliminary and has to be adapted according to future experiences in the industry.

To gain a better understanding of the adhesive and cohesive forces to be expected from a bulk material further measurements of the respective forces have to be conducted. These will have to be linked to the main influencing parameters like moisture content, matric pressure and permeability on the one hand and particle size distribution, surface charge and mineralogy content on the other.

References

- ASTM Standard D6128-06. Standard Test Method for Shear Testing of Bulk Solids Using the Jenike Shear Cell
ASTM International, West Conshohocken, PA, 2014
- Burbaum, U., 2009. Adhäsion bindiger Böden an Werkstoffoberflächen von Tunnelbohrmaschinen (phd). TU Darmstadt, Fachbereich Material- und Geowissenschaften, FG Ingenieurgeologie.
- Habenicht, G. 2006. Kleben (5th ed.). Berlin, Heidelberg
- Hering, E.; Martin, R.; Stohrer, M. 1989. Physik für Ingenieure (2nd ed.). Düsseldorf
- Long, J., 2009. Wet and sticky ore mystery... a thing of the past? [WWW Document]. News Events. URL <http://news.curtin.edu.au/stories/wet-and-sticky-ore-mystery-a-thing-of-the-past/> (accessed 1.8.15).
- Standard Shear Testing Technique for Particulate Solids Using the Jenike Shear Cell, 1989. . IChemE.