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DESKTOP STUDY ON THE HANDLEABILITY OF COAL

By

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Desktop study on the handleability of coal

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Abstract

This report is a desktop study on the handleability of coal and aims to define coal handleability, determine what issues are caused by poor handleability, what material properties influence the handleability of coal, what methods are used to test coal handleability, and what solutions exist for improving coal handleability. In addition to the literature survey, visits to coal preparation plants in the Witbank-Middelburg area were made and a questionnaire sent to stakeholders to assess the types of handleability issues that South African operations struggle with, is coal handleability tested on South African operations, and what solutions are implemented on South African plants to improve coal handleability.

Coal handleability is the behaviour of a coal in a handling and storage circuit. The handleability of coal is influenced by materials properties (particle size distribution, moisture content, coal wettability and mineral matter content) and by the processing circuit. Coals with good handleability characteristics usually contain low levels of fines, moisture, and clay. This was confirmed for South African coals by the plant visits and questionnaire.

There are various methods that have been used to test the handleability of coal and each method subjects the coal samples to conditions that simulate different stages in a transport and handling circuit. Tests simulate cohesion of coal to itself, cohesion to handleability equipment, flow from train trucks, and the flow of already moving coal. In addition to methods to directly test the handleability of coal, methods to estimate the coal handleability from laboratory data is also discussed.

Solutions that can be implemented to improve the handleability of coal or to reduce the impact of handleability related stoppages include drying the coal, dry processing the coal, converting the fine coal to coal-water fuel, agglomerating the fine coal, and making changes to existing equipment.

Finally, all the information on the definition, issues, causes, and solutions are collated and suggestions for future research made.

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Introduction

One of the most important aspects of a coal beneficiation operation is bulk materials handling. For coal beneficiation this consists mainly of transport on conveyor belts around the plant and for short distances between plant and customer; and for longer distances by either truck or rail. Many coal beneficiation operations experience some sort of issue while transporting coal. These issues are expensive to remediate and lead to reduced plant availability. In extreme cases these issues can lead to complete plant shutdown, translating into significant losses.[1-3] The issues caused during transport and handling includes bridging in bunkers, blocking of feeders, arching or rat-holing in hoppers, erratic flow from hoppers, accumulation on processing equipment (especially conveyors and conveyor transfer chutes), spillage from conveyors and chutes, gumming-up of comminution devices, and dusty coal on conveyors and stockpiles.[1-4] The occurrence of these issues depend on various materials characteristics and the characteristics of the materials handling facilities. The dependence on both material properties and the operation's properties results in one coal being able to pass through a specific plant with no issues, but another operation cannot process the same coal because of continuous handleability related stoppages.[3, 5] In addition to the difficulties experienced at the operations, transporting coal across long distances (as is the case for exported col in South Africa) allows the coal consolidate in the trucks and trains due to moisture migration, time consolidation, and vibration.[1]

Wibowo and Ng (2001) gives a summary of the various problems that can occur in solids processing units. They also give heuristics for identifying whether these problems are likely to occur in a solids processing plant, in which units the problems originate, and to suggest preventative measures.[4]

Definition

Brown (1998) highlighted the necessity of defining coal handleability in a universally accepted manner and to develop a universally accepted method to test coal handleability.[3]

There is no formal and widely accepted definition of handleability.[3, 6] But most authors define the handleability of a coal as either the ability of a specific coal feed to flow through the handling system unhindered, the flow properties of coal, or a coal's behaviour during transport and storage.[1, 6-8] Of these three broad definitions, the most appropriate is to define coal handleability as a coal's behaviour during transport and storage. A "well behaved" coal, or a coal with good handleability characteristics, will pass through a handling and transport facility at design capacity without causing significant handleability related stoppages. On the other hand, a "badly behaved" coal, or a coal with poor handleability characteristics, will not pass through a transport and handling circuit without causing significant stoppages.[6, 9]

Properties that influence coal handleability

All basic coal contracts include at least three or four quality parameters: net-as-received heating value, moisture content, ash yield, and sulphur content.[1] Although the coal sold into similar markets usually have similar analyses, the handleability of these coals can differ greatly depending on properties other than those stipulated in the coal specifications.[1] To illustrate this point, Table 1 below shows the typical specifications for coal delivered to Eskom and the Richards Bay Coal Terminal.[10] The specifications for a high-ash thermal coal will usually be similar to the Eskom specifications; two coals from different producers may both meet these specifications while behaving differently in the power station handling circuit.

Table 1: Typical specification for coal supplied to the Richards Bay Coal Terminal and Eskom.[†]

		Richards Bay Coal Terminal	Eskom
Calorific Value		> 5850 kcal/kg	21 MJ/kg
Total Moisture		< 12 %	< 10 %
Volatile Matter		> 22 % (RB1); > 25 % (RB2)	> 20 %
Ash Yield		< 15 %	< 30 %
Sulphur content		< 1 %	< 1 %
Particle size distribution	+50 mm	< 5 %	< 5 %
	-3 mm	-	< 30 %
	-1 mm	-	< 15 %

The difference in handleability characteristics is due to the various factors that influence the flow and packing of granular materials and the interdependence on oneanother.[1, 3, 8] These factors include the particle size, particle size distribution, particle shape, surface topography, surface moisture, and total moisture. Wibowo and Ng (2001) compiled the diagram given in Figure 1 below that shows some of the factors that can influence the handleability of granular materials and the interrelationships between these various properties.[4]

[†] These specifications are typical specifications. The specifications for each individual contract may differ significantly from these specifications.

According to Holuszko and Laskowski (2004) and Brown (1997) the factors that influence the handleability characteristics of coal has not been studied rigorously.[6, 9] This section will highlight what is known about some of the particle properties that influence the handleability characteristics of coal. Many of the properties that influence the handleability of a coal or coal blends are interrelated for some coal, but not others and no meaningful correlations has yet been found for the interdependence between properties.[7] An additional factor when determining the handleability of a coal is the specific handling operation and its products, as the handleability varies depending on the coal product i.e. what constitutes good handleability for thermal and metallurgical coal varies.[3] The determination of a property's influence on handleability and the interrelationships between the various properties are complicated by the fact that these properties constantly change during a handling and storage.[4, 11] This is especially true for a coal processing circuit.

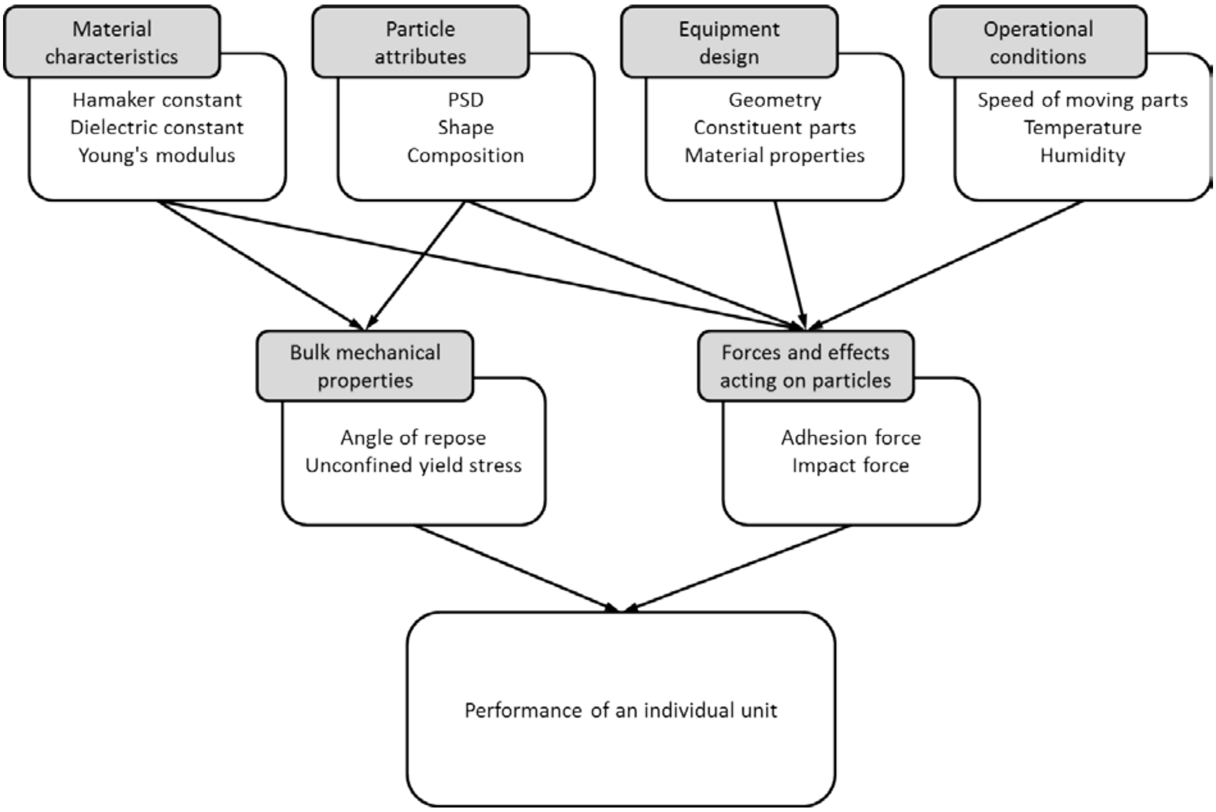

Figure 1: Interrelationship between factors affecting the performance of solids processing units (redrawn form Wibowo and Ng (2001))[4]

Particle size, particle size distribution and particle shape

Some authors consider the particle size distribution to be the most important influence on the handleability of coal,[1, 6, 8] while other authors consider the combined effect of fines and moisture content to be the most important influence on coal handleability.[2, 9] Generally, an increase in the amount of fines in a coal stream leads to a decrease in the handleability of coal.[1, 6-9] In a coal handleability context, fines are considered particles smaller than 2.36 mm.[2] It is not only the amount of fines present in a coal stream, but also the particle size distribution and particle shape that impacts the flow and packing of coal.[1, 7] By widening the particle size distribution of a coal feed, the effect of fine coal on the handleability characteristics become less pronounced. More fines can be tolerated before handleability issues start occurring compared to the same coal with a narrow particle size distribution.[6, 7] A wide particle size distribution can, however, cause other problems such as the segregation of well-mixed streams.[1] The particle size and shape of a coal is one of the properties that can change significantly during the process due to impact during feeding, abrasion during transport, compression during storage, and shear during unloading.[1]

Since the fines has the biggest influence on the handleability of coal, Holuszko and Laskowski (2004) stated the importance of keeping the particle size distributions as constant as possible when comparing the handleability of coals or the influence of other properties on the handleability of coals.[6]

Moisture

Moisture is the other property that some authors consider very important to the handleability characteristics of coal, especially in combination with the fines content.[2, 9] The handleability of coal is strongly affected by its moisture content, with the handleability decreasing as the moisture content increases.[1, 6-9] The moisture content at which a specific coal starts to experience reduced handleability differs for different coals and depends on factors such as the equilibrium moisture (moisture holding capacity), fines content, moisture history, and composition of the coal.[6-8, 12] As an illustration: Holuszko et al. (2004) found that any moisture content higher than 10 % influenced the handleability of the coal they tested and above 17 % no-flow conditions started forming;[7] while Abou-Chakra and Tuzun (2000) found that for a moisture content above 12 % problems such as bridging in bunkers and blocking of feeders could be expected for the coal they studied.[1]

The type of moisture that is relevant to the handleability characteristics of coal is the surface moisture (sometimes referred to as the free moisture).[1, 13, 14] It is the free moisture that forms liquid bridges between coal particles and is responsible for the cohesion between coal particles.[1] Equilibrium moisture indicates the amount of water that a coal can hold and increases as coal becomes more hydrophilic, coals with a high equilibrium moisture can tolerate a higher moisture content before their handleability begins to deteriorate.[6] The amount of moisture present in coal and the particles size of that coal are intimately interdependent. As the size of the particles decrease the amount of free moisture increase.[6, 8, 14] Scholtz et al. (2015) gives an example of a coal that contains 4 % inherent moisture and 3 % free moisture in the 150 mm x 100 mm fraction. The inherent moisture stays constant in all of the size fractions, but the free moisture content increases to 6-11 % for the 12 mm x 0.5 mm fraction and to 21 % for the -0.5 mm fraction.[14] Particles that contain a lower amount of clay minerals can tolerate a higher moisture content.[8] Because so many factors influence the effect of moisture content on handleability characteristics, moisture content cannot be used as the only indication of handleability if any of the other factors differ.[8]

The moisture content of a coal is not only important for the handleability but influences all downstream activities especially the long distance transport and saleability of the coal.[13, 15] According to Parekh (2009), every 1 % increase in moisture decreases the calorific value of a coal the equivalent of 4 % mineral matter,[13] an increase in moisture also increase the transport cost.[16] However, it is currently very difficult to prevent the addition of water to coal during processing as gravity based separation technologies usually require large amounts of water and dry beneficiation technologies are ineffective.[14, 17]

Wettability

The wettability of a coal is influenced by its hydrophobicity, porosity, as well as the coal's mineral matter content and nature.[6] The hydrophobicity of a coal influences not only the wettability of the coal surface, but also the equilibrium moisture content, the absorption of water into pores, and the formation of stable liquid bridges between coal particles.[6, 7] Lower rank coals and highly oxidised coals tend to be more hydrophilic; these coals can be easily wetted, has higher equilibrium moisture content, and forms liquid bridges that are more stable than those formed between hydrophobic coal particles.[6] Figure 2 shows an example of an unstable and a stable water bridge between coal particles.[18]

Although hydrophilic coals can tolerate higher moisture content before its handleability is negatively impacted, when the moisture contents reaches the coal's critical moisture content, no-flow conditions are likely to develop.[6, 7] Hydrophobic coals, on the other hand, do not have good handleability characteristics but tend not to develop no-flow conditions even above the critical moisture content.[6, 7]

Particle composition

The ash yield and the nature of the mineral matter of coal contributes to the handleability characteristics of the coal.[9] Coal that has a low ash yield generally has better handleability characteristics when compared to coal with a higher ash yield.[9] The influence of increasing ash content is more pronounced on coals that has a low ash content compared to a similar increase in higher ash coals.[9] If the coal contains a high proportion of clay minerals, the effect of the ash yield on the handleability is more pronounced;[6] the effect of an increasing proportion of clay minerals is also more pronounced if the coal is hydrophobic compared to hydrophilic coals.[6] This is because the clays tend to swell and become sticky when wet, increasing the yield strength of the coal.[6, 8]

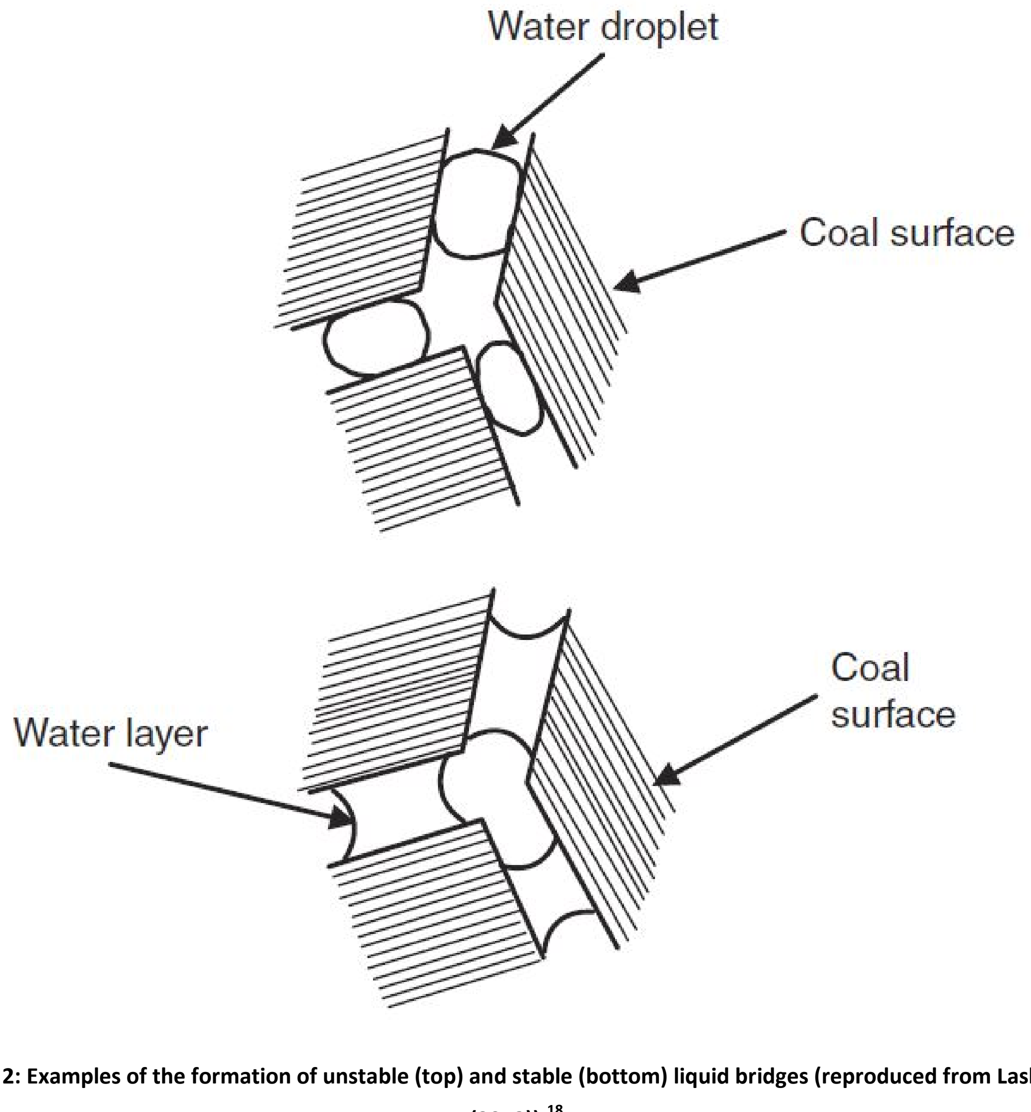

Figure 2: Examples of the formation of unstable (top) and stable (bottom) liquid bridges (reproduced from Laskowski (2013)).[18]

Handleability testing

Handleability testing is done to assess the behaviour of a coal in a handling operation.[11] There is a variety of methods developed to assess coal handleability, but no method that is widely accepted as the standard method to assess coal handleability. The method that is most commonly used to assess the handleability of coal is by visual inspection. But, visual inspection is dependent only on the operators experience of what constitutes good or bad handling at the specific site and no quantitative analyses can be done.[3, 11]

Among the other methods that are used to test the handleability, each method was designed to determine the flow and handleability of the coal when subjected to specific conditions or processing scenario.[7] A contributory factor to the number of testing methods available is that each unit process' conditions differ, although tests that determine the handleability under similar conditions give similar results.[9] Zhong et al. (2005) stated that the majority of the handleability issues caused is due to the cohesion of coal, this cohesion is controlled by the cohesive strength of the coal and is most easily tested using unconfined compression strength testing.[5]

Shear cell

One of the most familiar tests to calculate the flow properties of coal is a shear cell that measures the shear properties of fine powders.[2, 11] A sample of sized coal is placed in the apparatus, and a known force is applied to consolidate the sample. After consolidation the coal is sheared with a lateral force and this force recorded. The tests are repeated for various loads, moisture contents and consolidation times. The data generated is used to calculate flow functions and the shear strength of the coal.[2] In order for a coal to flow the stresses in the bulk material must exceed the shear strength of the coal.[2] Although this test is a widely used test, it requires a high level of expertise to conduct repeatably and the tests can only be conducted on the fine fraction of the coal.[2, 9, 11] A schematic showing the constituent parts and the various forces involved in a Jenike shear cell is shown in Figure 3.

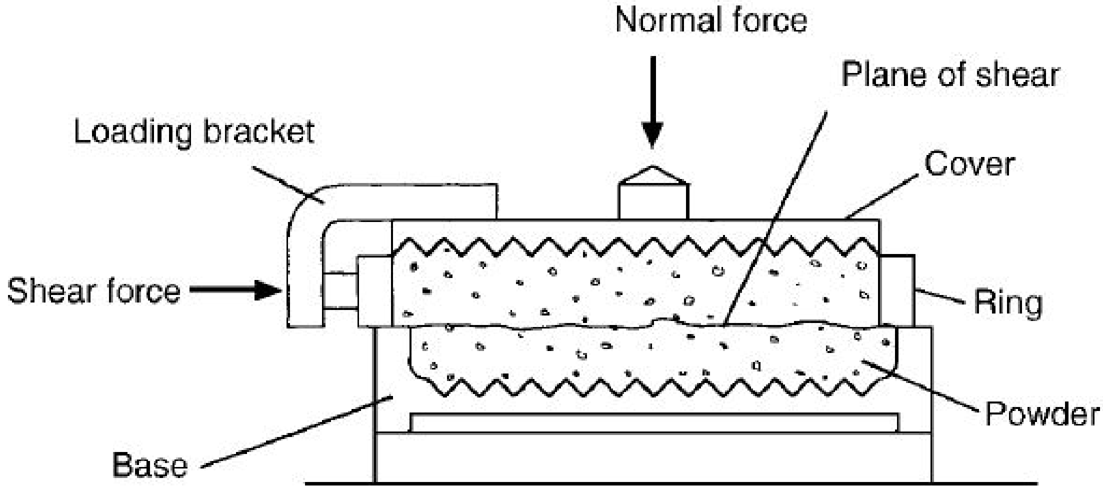

Figure 3: Schematic of a Jenike shear cell (reproduced from Rhodes (2008))[19]

Durham cone

The Durham cone was developed to assess the discharge of a coal from merry-go-round rail wagons and imitates gravity flow of a consolidated coal sample.[6, 7] A sample of the as-received coal is placed in the device and vibrated for 30 seconds to consolidate the sample. After consolidation, the bottom of the cone is opened and the time is takes for the cone to empty recorded.[2, 6, 7] The Durham cone is a simple and fast method to determine the flowability of a coal.[3, 7, 9, 11] However, the Durham cone is neither reliable nor repeatable and sample preparation greatly influences the results.[3, 7, 9, 11] Figure 4 shows a schematic of a Durham cone.

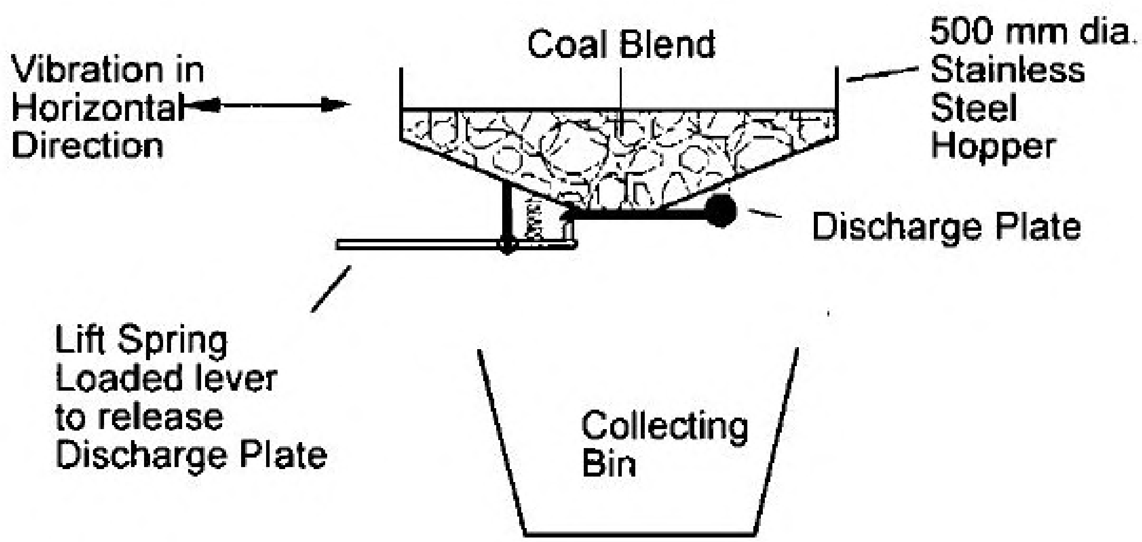

Figure 4: Schematic of a Durham cone (reproduced from Brown and Atkin (2000))[11]

Nottingham handleability monitor

The Nottingham handleability monitor, also known as an extrusion trough tester, was developed to measure the cohesive strength of a bulk coal sample due to compression.[6, 7] A 50 kg sample of coal is fed into the device via a hopper at the top and a subsample is forced through a venturi by a hydraulic ram while the pressure and time trace is recorded.[7, 11] The time-pressure traces are recorded for five consecutive subsamples and data used to calculate the average maximum pressure and the average maximum gradient, which is used to rapidly assess a coal's handleability.[7, 9, 11] Increased average maximum pressures indicated worsening handleability.[11] The Nottingham handleability monitor is a rapid testing method that can be used continuously and can accommodate large samples, care must be taken to ensure that representative samples are tested. [7, 11]

Holuszko et al. (2004) made a comparison of the handleability characteristics determined by the Durham cone and the Nottingham handleability monitor.[7] They found that despite the differences in the conditions tested the two methods are comparable, but that the Durham cone is more sensitive to changes in particle conditions.[7] Figure 5 shows a schematic of a Nottingham handleability monitor.

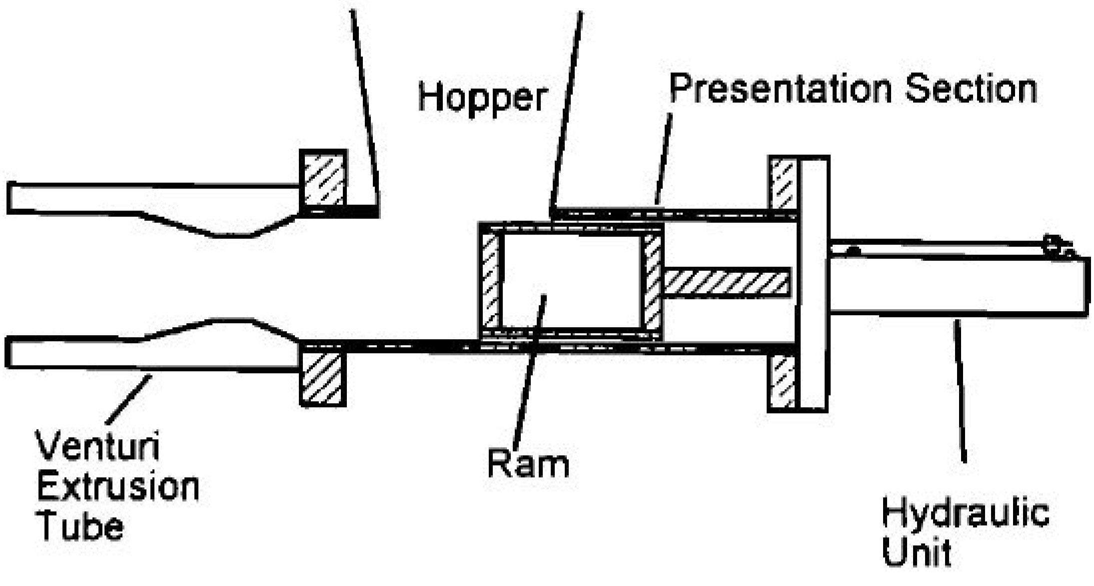

Figure 5: Schematic of a Nottingham handleability monitor (reproduced from Brown and Atkin (2000)).[11]

Pelletisation

The same surface properties that determine the agglomeration of fine coal particles during handling and transport also determines aggregation during the pelletisation of fine coal particles. As a result there are apparent similarities between the behaviour of fine coal particles during pelletisation and the behaviour of the coal during transport.[6] In order to form a pellet from fine coal particles, the coal surface is wetted and liquid bridges form between individual particles binding them together.[6] A pellet's strength is dependent on the capillary forces between the particles, which is influenced by the hydrophobicity of the coal.[6] Holuszko and Laskowski (2004) used pelletisation tests to determine the surface properties and particle-particle interactions of -0.5 mm coal particles.[6] They found that coal with poor handleability characteristics generally had higher equilibrium moistures and produced stronger pellets, while coal with better handleability characteristics had lower equilibrium moistures and produced weaker pellets.[6]

Avalanching

Avalanching is one of the mechanisms by which the particles in a well-mixed coal stream can segregate and stratify.[3] According to Brown (1998) the avalanching behaviour of a powder may be related to their flowability and gives similar results to the Durham cone; while the results from the Durham cone gives the flowability of consolidated coal that flows under gravity, avalanching gives an indication of the handleability of coal that is already in motion.[3]

To test the avalanching behaviour of a coal, a sample of coal is continually fed onto an inclined ramp. The material forms a pile of coal on top of the ramp while some of the material avalanche from the top of the pile to the bottom of the ramp onto a balance.[3] Any small avalanche that has insufficient energy to reach the bottom of the ramp has to be disregarded.[3] The data gathered by avalanching testing can be used along with other shear methods to give a fuller description of the handleability taking into account the various flow regimes.[3] The time and regularity between avalanching events were indicative of the handleability of fine powders, with short regular intervals (high degree of deterministic chaos) indicating good handleability characteristics.[3, 20]

Edinburgh cohesion tester

The Edinburgh cohesion tester was developed to be a simple inexpensive manually-operated handleability tester that determines the unconfined compression strength of the coal.[5, 21, 22] A sized coal sample is placed in the tester mould and consolidated with 100 kPa of force for 1 minute. After consolidation, the mould is removed and the unconfined sample compressed until failure while the force required to break the particle is recorded. Because the Edinburgh cohesion tester could not accommodate particles any larger than 25mm, the tester was enlarged and automation added to ensure that particles up to -50mm could be accommodated.[21] The enlarged Automated Edinburgh cohesion tester uses the same basic operating principle as that of the Edinburg cohesion tester but without the necessity of screening the larger sample.[21, 23] The automated Edinburgh cohesion tester was field tested by Ooi et al. (2005) who found that the automated Edinburgh cohesion tester gave repeatable data that correlated well with discharge times from trains at the collieries.[21, 23]

Figure 6 shows the operating steps of the Automated Edinburgh cohesion tester: (a) filling the mould, (b) determining the bed height, (c) consolidation of the sample, (d) removal of the mould, and (e) compressing the sample to failure.[21]

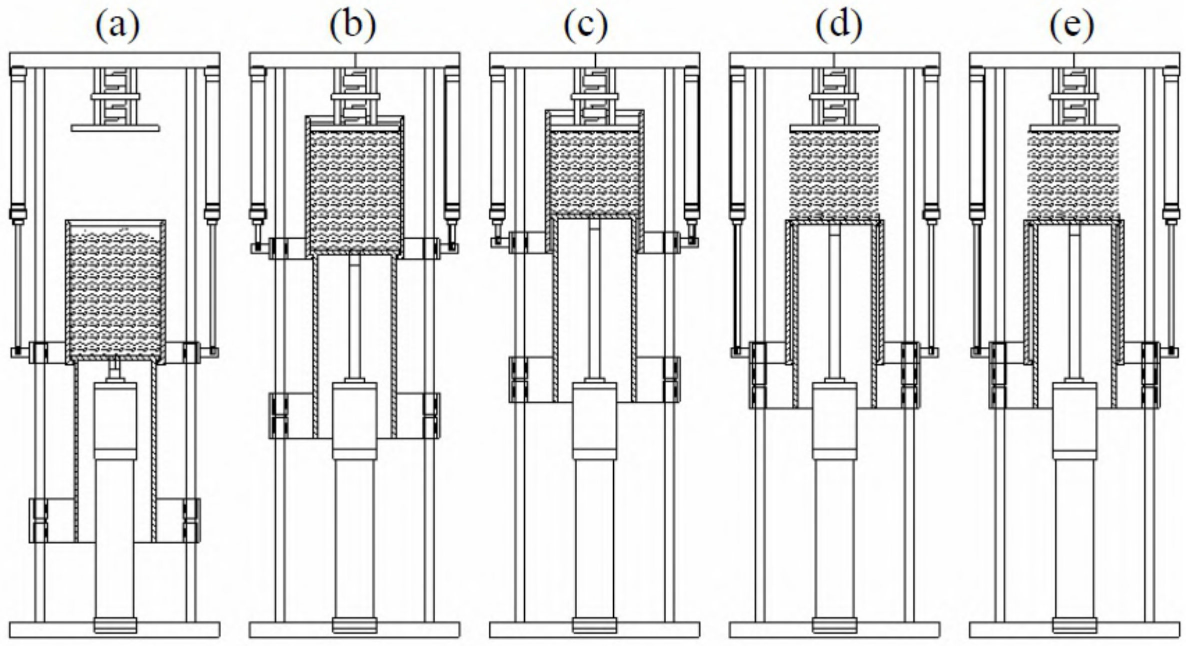

Figure 6: Operating stages of the Automated Edinburgh cohesion tester (reproduced from Ooi et al. (2005))[21]

Handleability index

Because the handleability characteristics is hard to determine experimentally and the various properties that influence coal handleability are also influenced by one another, authors such as Arnold (2004) and Brown (1997) suggested that combinations of easily determined properties can be used to determine if a coal can be easily handled in a handling operation.[2, 9] This combined property assessment is referred to as a coal's handleability index (HI).

The HI developed by Arnold (2004) was developed to aid coal buyers to develop coal specifications for thermal coal. In order to assess the HI they required a device that does not require the same expertise as a shear cell but can directly measure the HI.[2] They developed a device, very similar in design and operation to an Edinburgh cohesion cester, to determine the handleability index. The device consisted of a three-piece mould, consolidating arm, consolidating weights, and a loading pin. The consolidating arm was counter balanced to enable direct calculation of the consolidation pressures and the force required to break the consolidated coal column. A coal sample is placed into the mould and consolidated for 5 minutes from both ends of the mould. After consolidation the mould is removed and the sample's bulk density and unconfined strength determined. In order to determine the sample strength, weight is added in small increments until the sample fails.[2] The HI values are the ratio between the unconfined yield strength and the bulk density of the consolidated sample. These values range from 0 m for free-flowing coal and 1 m for samples that require significant force to break a consolidated sample.[2] Figure 7 shows the schematic of the HI tester developed by Arnold (2004).

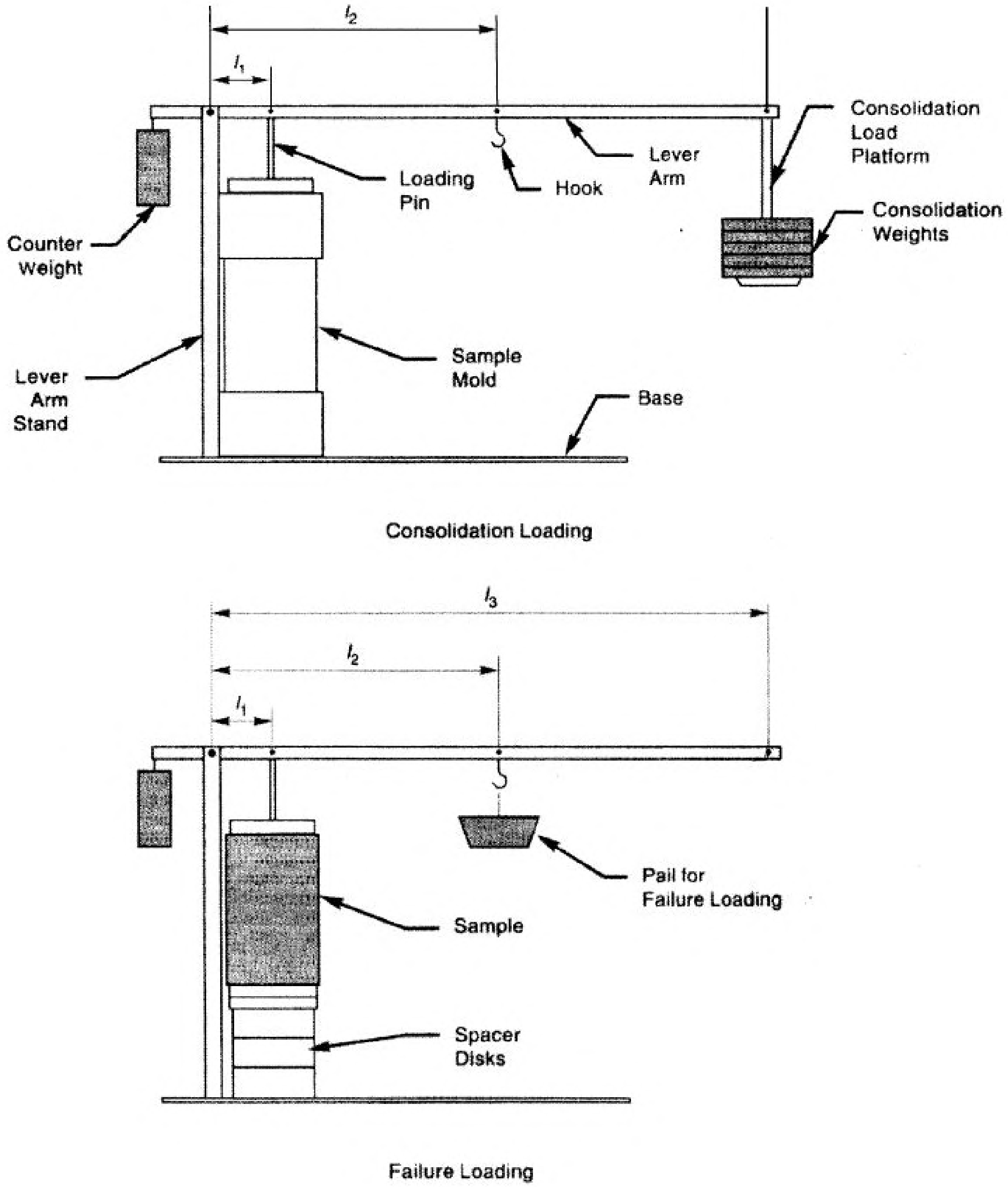

Figure 7: HI tester (Reproduced from Arnold (2004)).[2]

Wawrzynkiewicz (2004) developed a "looseness counter" to determine the handleability characteristics of a coal. The looseness counter determines the tensile strength of the sample while the HI tester tests the compressive strength of the sample.[2, 8] In the looseness counter, a column of sized coal particles are consolidated; after consolidation the sample is pulled apart from both ends and the tensile strength of the column recorded.[8] The tensile strength data is used to determine a handleability index for the coal: as the value of the index increases the coal becomes more difficult to transport. The HI tester and the looseness counter both uses a low sample mass but cannot test a coal sample as is, the top size must be reduced to -2.36 mm for the HI tester and -14 mm for the looseness counter.[2, 8] By crushing the sample the particle size distribution of the sample is changed, thereby changing the handleability.[8]

Arnold (2004) tested the flow of large samples in pilot-scale storage bins and found that for HI values below 0.35 m flowability was maintained, and in industrial bins flowability was maintained below HI values of 0.2 m.[2]

Arnold (2004) also tested various bituminous coals from the Eastern United States and found that the HI of the various coals can be correlated to the particle size distribution (PSD) and moisture content of the various coals. Figure 8 shows how the fines content (percentage passing 0.5 mm) and moisture content of the various coals influences the handleability of the coals.[2]

Handleability threshold

Every coal handling circuit is different; the circuits process different coals and, even if the exact same equipment is used, the operation of each circuit is different. As a result, a coal that has good handleability characteristics at one operation might behave poorly in another.[11] Some authors have suggested the use of the techniques mentioned above in combination with threshold values that will indicate whether a coal is likely to cause handleability related issues.[2, 11]

In addition to the use of handleability tests, Brown (1997) and Arnold (2004) used combinations of easily determined material properties to estimate the behaviour of a coal.[2, 9] Brown (1997) used a combination of the moisture content, the amount of fines (in this case particle smaller than 0.038 mm), and the ash yield; the combined factor was named the Moisture x Ash fraction. They compared this value to the perception of plant operators, and found that coal characterised as poor handling coals had higher Moisture x Ash fraction values.[9] The Moisture x Ash fraction values also increased linearly as the extrusion through index increased (see Nottingham handleability monitor). Arnold (2004) compared a combination of the moisture and fines content of a sample to the perceptions of plant operators to generate the handleability classification in Figure 8 (Figure 8 was compiled for 22 coals from the Eastern USA). They suggested that plant operators can estimate the behaviour of a coal by using data from moisture and particle size distribution laboratory tests.

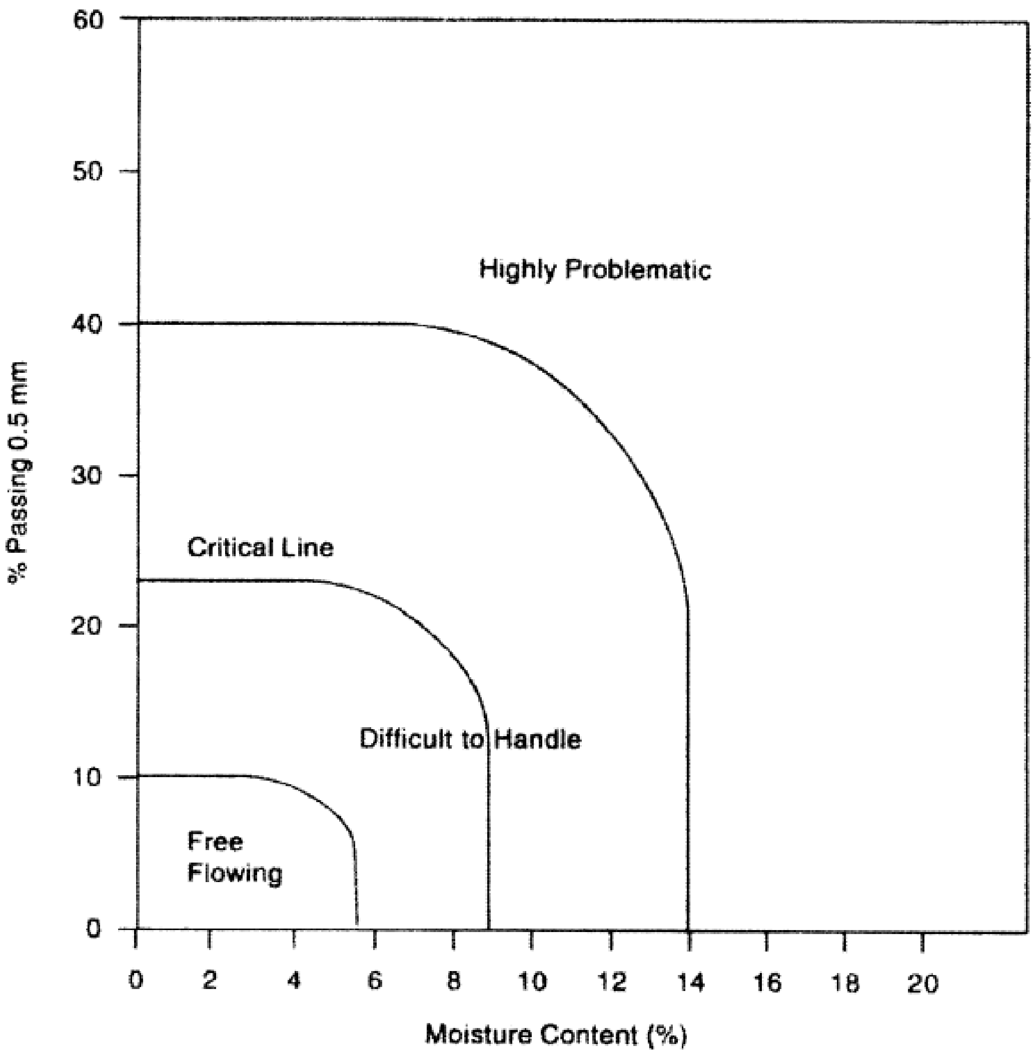

Figure 8: Handleability classification (reproduced from Arnold (2004)).[2]

Possible Solutions

Wibowo and Ng (2001) proposed a three step approach to determine what solids processing issues are likely to occur at an operation and to propose possible solutions for the issues based on the main property causing the handleability issue.[4] Step 1 is the identification of the various potential problems; step 2 is to determine which properties are responsible for the issue and which properties will counteract the problems; finally, in step 3 possible alternatives are proposed.[4] The possible solutions to the problems caused by poor coal handleability characteristics are mostly aimed at changing the material properties responsible for the poor handleability, thereby reducing the negative impact of the material properties on coal handleability. Many of the solutions suggested here may already be implemented on various plants, but not necessarily with the aim of increasing handleability; rather the aim is usually to increase processing efficiency and to ensure products meet specifications.

Dewatering, drying, and dry processing the coal reduces or avoids moisture in the coal and increases the handleability. Dewatering is done using screens if the particles are bigger than 5 mm or using centrifuges and filters if the particles are smaller than 5 mm.[15] Dewatering screens are able to reduce the moisture of +25 mm coal to 15 % and the moisture of -12 mm coal to no less than 18 %.[14] Filters are able to reduce the moisture content of a product to between 20-35 % depending on the type of filter and the particle size distribution.[14, 15] Centrifuges are able to reduce the moisture content to between 4.5-15 %, again depending on the type of centrifuge and particle size distribution.[14] However, considering that moisture related handleability issues can start from as low as 10 % moisture, mechanical dewatering is often not sufficient and costly thermal drying must be used to achieve target moistures.[13, 15] Dry processing the coal avoids the adding water to the coal but dry processing is not as efficient as wet processing, especially for processing coal fines.[17]

Because of the relationship between the amount of fines and the moisture content of the coal, the fines can be removed and discarded or processed separately and recombined with the product before sale. Removing the fines reduces the shear strength of the coal by reducing the surface area, free moisture, and the number of stable water bridges that can form in a coal stream. Neither discarding the fines nor recombining the fines with the product is without its sacrifices. If the fines are recombined with the product before sale, the improvements to handleability gained by the initial removal is lost when the fines (and the accompanying moisture) is added back.[5] If the fines are discarded some of the higher quality coal is discarded. This is because the higher quality coal is usually the weaker fraction of a coal stream.[24, 25] Additionally, slimes impoundments can cause significant environmental damage if spills occur and it is becoming increasingly difficult to obtain permission to build slimes impoundments.[13]

Agglomeration of the fine coal by briquetting, pelletisation, or oil agglomeration has been proposed as solutions to increase the particle size of the fine coal's high quality constituents. Agglomeration reduces the shear strength of the coal without reintroducing handleability issues or losing the high quality coal, but all agglomeration solutions are currently economically unviable due to the high costs of binders and fuel oil.[8, 14, 26] Another alternative for utilising the fine coal without adding the fine coal back into the product stream, is to use the fine coal in coal-water fuel. Coal-water fuel is a highly loaded slurry of coal and water that can be burned like a fuel oil or can be used as a diesel alternative in large diesel engines.[18] Although there is an energy loss due to the evaporation of water (±4-12 % depending on the energy content of the coal), the reactivity of the coal is increased.[18, 27] The handleability of the coarse fraction is improved and the fine coal is transported as a slurry.[18] In addition to increasing handleability, excessive dust and spontaneous combustion during storage is also decreased with the use of coal-water fuel.[18]

In plants that process different coals it is often possible to blend coals from various sources to improve the handleability characteristics.[1, 5] When blending different coals, some of the materials properties change linearly depending on the proportions of the different constituents; however, the handleability of a coal blend changes non-linearly.[5, 28] The interaction between some properties (moisture and particle size for instance) can negate the positive effect of blending, making the property estimation of the new coal blend difficult.[1]

When a modification of the coal properties is not a viable option, the handling and transport equipment can also be modified. Installing low friction liners, vibrating or apron feeders, and air cannons can reduce handleability related stoppages.

Site visits to assess the need for handleability testing

During the initial phases of the project, a number of coal processing plants in the Witbank and Middelburg area were visited. The visits were to determine what handleability issues the processing plants face, how relevant the available literature is to South African coal processing plants, if the handleability is routinely tested, and if there are any implemented solutions specifically aimed at increasing the handleability. From these visits the following general observations were made:

- Most of the visited plants experience handleability issues, but there are measures in place to minimise the effect of the blockages that occur. The solutions implemented on the plants visited where air cannons (pneumatic accumulation control systems) to clear blockages in coal bunkers or transfer chutes and periodic housekeeping to clear excessive build-up of coal sticking to conveyors and transfer chutes. When blockages do occur, despite the air cannons or where there are no air cannons installed the, blockages are cleared manually.
- The air cannons do not meet the expectations of some of the plant operating personnel.
- None of the plants tested the handleability of the coal.
- Excessive moisture, excessive fines, high clay content, and weathered coal (hydrophilic coal) all results in poor handleability. This confirms what is found in literature for South African operations.
- The addition of the filter cake to the product stream negatively impacts the handleability of the product. This is especially true if the added filter cake exceeds 30% of the product stream.
- The blending choices made at the plant will influence the downstream handleability. For example: if the small blockages at the rapid load-out terminals are not cleared quickly a small blockage can result in blockages that take up to 5 days to clear. The suspected cause is migration of moisture to the bottom of the silos and the subsequent increased compressive strength of the coal.

Results of the handleability questionnaire

Various stakeholders were asked to complete an electronic questionnaire; eight respondents started the questionnaire but only six completed it. A complete list of questions and responses are given in Appendix: Questionnaire and responses. All of the respondents were either metallurgists or high level managers. Coal processed were from the Witbank, Highveld, Vereeniging-Sasolburg, and Free State coalfields. The following is a summary of the responses:

- Figure 9 shows the issues experienced at respondents' operations. The handleability issues mentioned under "Other" were fine material blinding the screens.

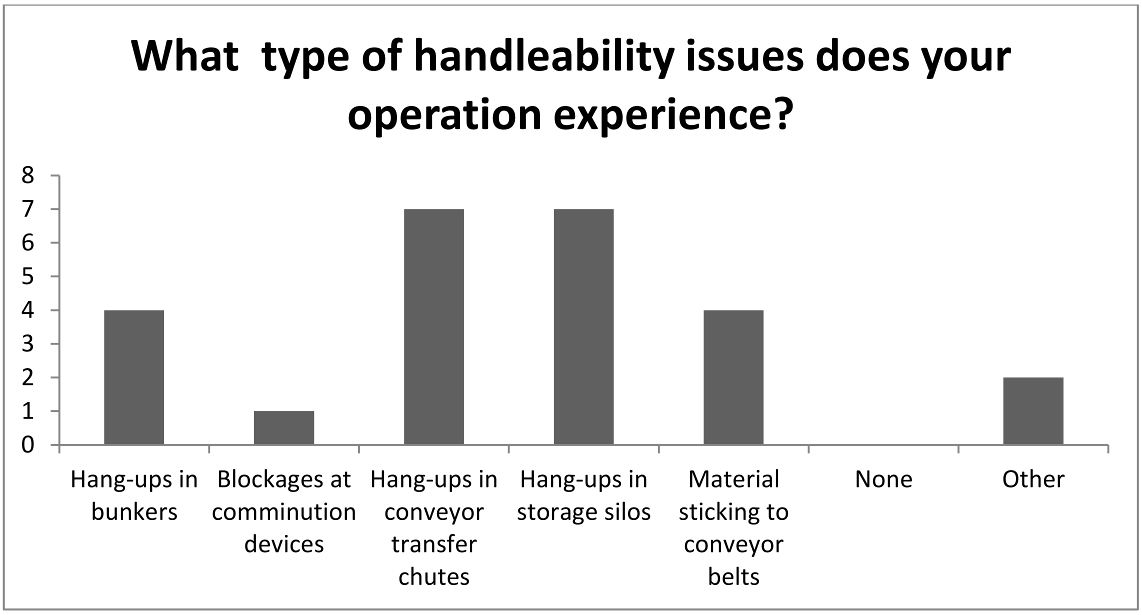

Figure 9: Responses to the question: What type of handleability issues does your operation experience?

- Figure 10 shows that all plants experience hang-ups or blockages but the frequency varies between the plants. When blockages do occur all but one respondent indicated that there are procedures in place to clear the blockage and that blockages are cleared in less than 2 hours.

- Only a single respondent indicated that handleability testing is done prior to processing. But only coal which has high moisture and/or high fines concentration is sent to be tested by an external laboratory.

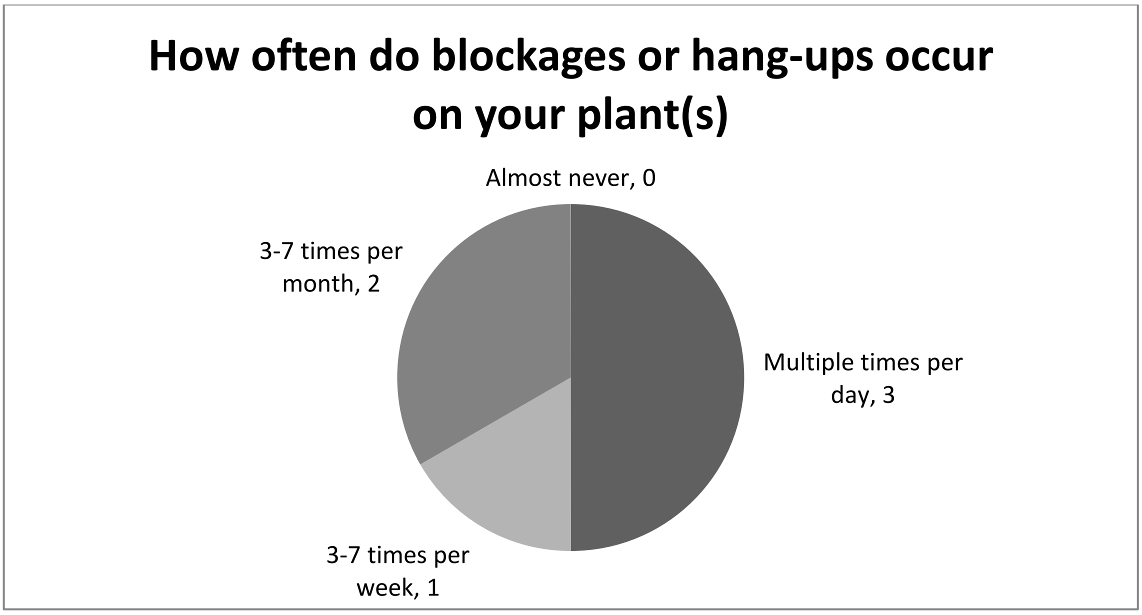

Figure 10: Responses to the question: How often do blockages of hang-ups occur on your plant(s)

- All but one respondent indicated that it is possible to assess the handleability of a coal by visual observation. Figure 11 shows which material properties are observed and also show that previous knowledge such as the weathering of the coal is beneficial to the assessment of coal handleability.

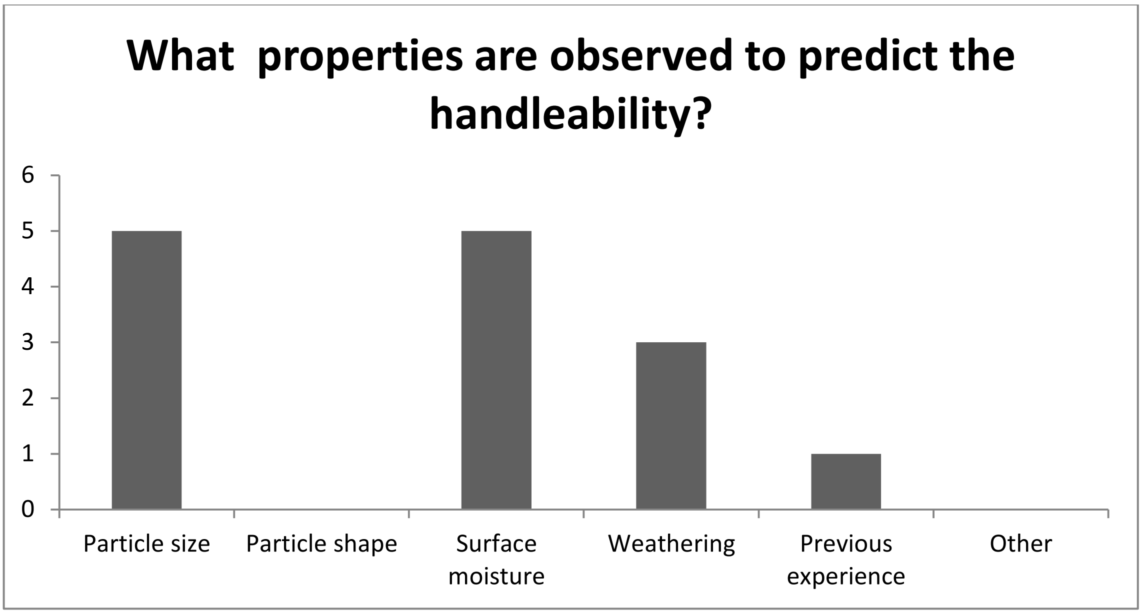

Figure 11: Responses to the question: What properties are observed to predict the handleability?

- The majority of respondents indicated that material properties such as the surface moisture, mineral matter content, and weathering of the coal influence the handleability of the coal. The surface moisture values that were indicated as troublesome were between 10 and 30 %. Mineral matter content of higher than 30 % were indicated as troublesome by three of the respondents, while one respondent indicated that mineral matter content as low as 10 to 20 % caused trouble. This discrepancy is probably dependent on the type of minerals present in the coal. Figure 12 shows which of the minerals in coal negatively impacts coal handleability. Clay minerals and silicates were the only minerals to be indicated as having a negative impact. The minerals classified as “Other” in Figure 12 reiterated the negative impact of weathered coal on handleability characteristics. This confirmed what was found in literature for South African operations.

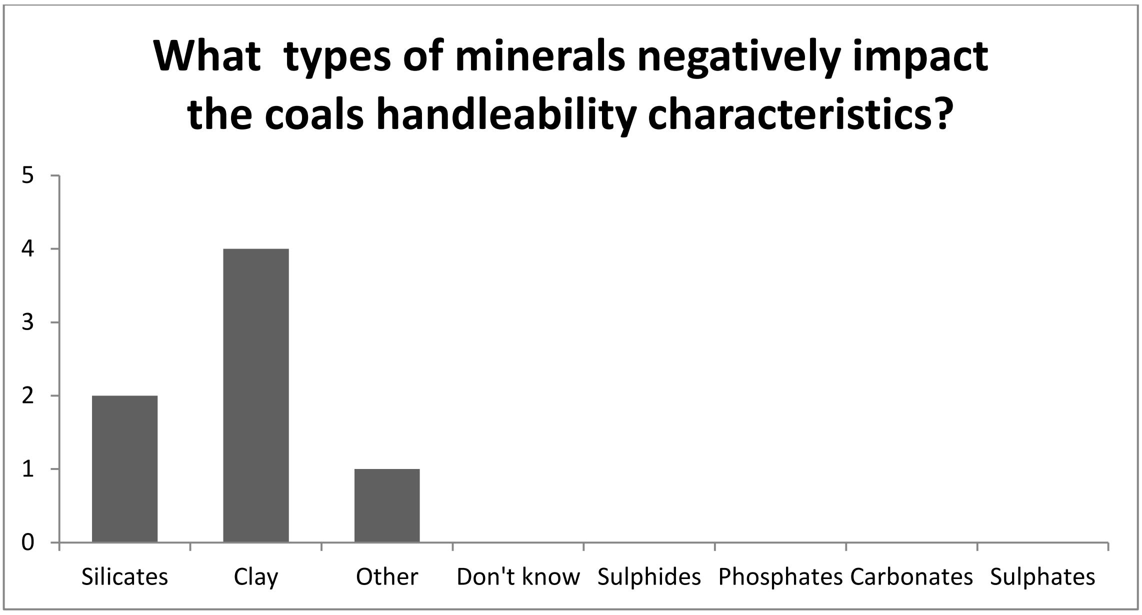

Figure 12: Responses to the question: What types of minerals negatively impact the coals handleability characteristics?

- All of the respondents who indicated that coal from different sources are combined before processing also indicated that the blending increased the handleability of the coal.
- Figure 13 shows which preventative actions are taken at the various operations to try to minimise the negative impact of poor handling coals. Blending and feed rate adjustments were indicated as the most widely used solutions employed. The “Other” actions given by the respondents were to increase the water addition to the screens, activate the pneumatic accumulation control systems, and follow procedures similar to those used during wet weather.
- The equipment modifications suggested by the respondents to alleviate the impact of poor handling coals were mostly modifications of the transfer chutes and discharges from silos by installing low friction liners and vibratory or apron feeders.

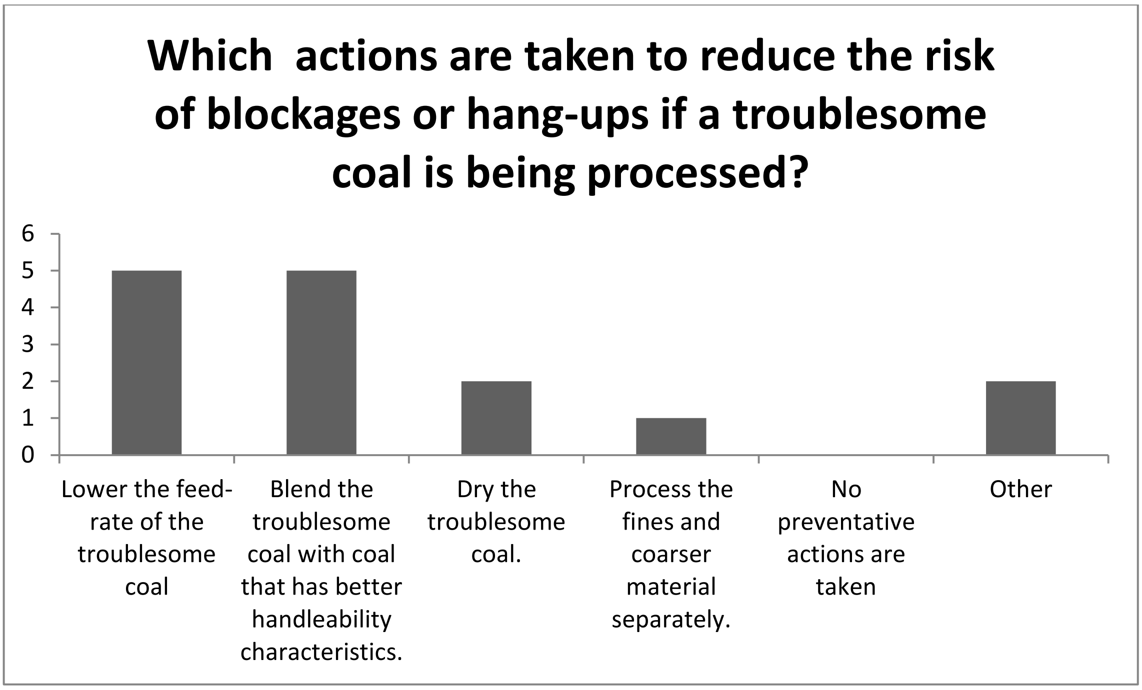

Figure 13: Responses to the question: Which actions are taken to reduce the risk of blockages or hang-ups if a troublesome coal is being processed?

Summary

This report discussed the definition of handleability, the problems caused by poor handling coal, the material properties that influence the handleability characteristics of coal, the methods that can be used to test the handleability, and the possible solutions to remediate handleability related issues. The report also lists a number of observations made on coal processing plants in the Witbank-Middelburg area and the results of six complete replies to a questionnaire on the handleability of coal sent to coal processors.

Handleability is the behaviour of a coal in a transport and handling circuit. The handleability of coal is dependent on the material properties of the coal and on the circuit that is used to process the coal. The material properties that influence coal handleability are particle size distribution, free moisture, wettability, and the composition of the coal; with fines content and moisture content being the biggest factors.

There are various methods that have been used to test the handleability of coal. Each method subjects the coal samples to conditions that simulate different stages in a transport and handling circuit:

- A shear cell tests the shear stress of coal when sheared across hopper construction materials or a bed of coal.
- The Nottingham handleability monitor, Edinburgh cohesion tester, and handleability tester determines the compressive strength of a consolidated coal sample. As the compressive strength increase the handleability deteriorates.
- Pelletisation tests determine the surface properties of a coal, specifically the wettability, and relate this to the handleability of a coal.
- A Durham cone and avalanching tests assess the flow of a coal sample. The Durham cone for a stationary consolidated coal and the avalanching test for coal that is already in motion.

The cohesion of a coal to itself or to the processing equipment is the cause of most of the handleability related issues. As a result, one of the methods that test the unconfined compressive strength (ex. Edinburgh cohesion tester) of a consolidated coal sample would be the better initial choice to determine the handleability of South African coal.

The possible solutions to alleviate handleability issues modify either the material property responsible for causing the issue or modify existing processing equipment. Solutions suggested in literature include dewatering, drying, dry processing, fines removal, pelletisation, briquetting, oil agglomeration, coal-water liquids, and blending. Solutions that rely on the modification of

processing equipment include the use of low friction liners, mechanical feeders, and air cannons. Many of these solutions are already implemented on various plants as part of the normal processing circuit, but they were not necessarily implemented to control handleability.

Suggestions for future research

In order to determine the effect of coal handleability on South African operations it is suggested that the following four research questions are answered:

- What is the quantitative effect of coal material properties on the handleability of South African coal and what is the interdependence of these material properties?

    - From literature and operator experience it is clear that the moisture, particle size distribution, wettability, and particle composition influence the handleability characteristics of coal. However, no quantitative data is available on how a change in one of these properties will influence the handleability of South African coals. The interdependence between these properties, which can differ between different coals, is also not documented.

- Is the handleability threshold classification (see Figure 8) suggested by Arnold (2004) appropriate for South African coal operations?

    - The handleability threshold classification uses moisture and particle size distribution data generated on the plant to estimate the handleability of a coal without the need for additional laboratory tests. The drawback of using current laboratory tests is the time between sending the coal sample to the laboratory and getting the results.

- Is it possible to rapidly asses the handleability of a coal using one of the handleability testing devices described above (see Handleability testing)?

    - Some of these tests were designed to be used by the plant operators to ensure that the handleability characteristics of a coal can be assessed with minimum delays.

- Will the availability and use of a handleability threshold classification or rapid handleability assessments improve the operability of South African coal operations?

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Appendix: Questionnaire and responses

Below are all the questions in the questionnaire and all the complete responses received. All responses are given exactly as they were received only information that could compromise the individual respondents' identity was blacked out or removed. The authors would like to thank the respondents for the valuable information they supplied.

Question	Responses	Comments
What is your position in your organisation?		One plant manager, one head of coal processing, two metallurgical managers, one trainee metallurgist and one plant metallurgist responded to the questionnaire
What is the name of your operation?		These responses were removed for the sake of anonymity.

From which sources do the coals you process come (ex. Highveld No. 2 seam, Waterberg Zone 3, or Tuli coalfield)?	• Highveld 4 Seam • Witbank 1,2,4 & 5 and Free State Coals • Springboklaagte 2 Seam • Highveld No. 4 Seam • Vereeniging-Sasolburg Coalfield. No. 1 Seam (Bottom seam); No. 2, No. 2A and B (Middle, Lower Middle and Upper Middle Seam); No.3 (Top Seam) Seam • Vereeniging-Sasolburg Coalfield: No1 Seam(Bottom),No2 Seam (Middle),No2A Seam (Lower Middle), No2B Seam (Upper Middle), No 3 Seam (Top)	
What type of handleability issues does your operation experience? a. Hang-ups in bunkers. b. Blockages at comminution devices. c. Hang-ups in conveyor transfer chutes. d. Hang-ups in storage silos e. Material sticking to conveyor belts. f. None. g. Other. Please specify.	a. 4 b. 1 c. 7 d. 7 e. 4 f. 0 g. 2	

How often do blockages or hang-ups occur on your plant(s)? a. Multiple times per day. b. 3-7 times per week. c. 3-7 times per month. d. Almost never.	a. 3 b. 1 c. 2 d. 0	
Are there standard operating procedures to clear blockages or hang-ups? a. Yes. Please describe the procedure briefly. b. No.	a. 5 b. 1 • Dependent on the type of blockage, where it is and what it is blocked with? • Standard [redacted] Operating Procedure for clearing blockages • Lockout conveyor. Wash-out chute with water. • There are procedures. Please email [redacted] for documents • Unblocking Chute Procedure	
How long does it take (on average) to clear a blockage or hang-up? a. Less than an hour. b. Between 1 and 2 hours. c. Between 2 and 5 hours. d. More than 5 hours. e. I don't know.	a. 3 b. 2 c. 0 d. 0 e. 1	

Is coal handleability tested on your plant(s)? a. Yes. Please describe the method used to determine the handleability characteristics of coal briefly. b. No. c. I don’t know.	a. 1 b. 5 c. 0	
Is it possible to predict what a coal’s handleability characteristics are going to be by observation and without testing? a. Yes. b. No. c. I don’t know.	a. 5 b. 0 c. 1	
What properties are observed to predict the handleability? a. Particle size. b. Particle shape c. Surface moisture. d. Weathering. e. I know what the handleability characteristics are from previous experience. f. Other. Please specify.	a. 4 b. 0 c. 5 d. 3 e. 1 f. 1 • Conveying of ultra-fine coal (-150 micron)	For Figure 11 the single response at “f. Other” was counted along with “a. particle size”.

Does the surface moisture of the run-of-mine coal influence the handleability of the coal? a. Yes. b. No. c. I don't know	a. 5 b. 1 c. 0	
What surface moisture contents are the most troublesome? a. Below 10% b. Between 10 and 20% c. Between 20 and 30% d. Greater than 30% e. I don't know.	a. 0 b. 3 c. 2 d. 0 e. 0	
Does the ash content of the coal influence the handleability? a. Yes. b. No. c. I don't know.	a. 4 b. 2 c. 0	

Which ash contents are the most troublesome? a. Below 10 % b. Between 10 and 20 % c. Between 20 and 30 % d. Above 30 % e. I don't know.	a. 0 b. 1 c. 0 d. 3 e. 0	
What types of minerals negatively impact the coals handleability characteristics? a. I don't know. b. Sulphide minerals (Ex. Pyrite). c. Silicate minerals (other than clays. Ex. Quartz). d. Clay minerals (Ex. Kaolinite, Illite). e. Phosphate minerals (Ex. Goyazite). f. Carbonate minerals (Ex. Calcite, Dolomite). g. Sulphate minerals (Ex. Gypsum, Bassanite). h. Other. Please specify.	a. 0 b. 0 c. 2 d. 4 e. 0 f. 0 g. 0 h. 1 • Weathered materials are also very troublesome	
Does the weathering of the coal influence the handleability of the coal? a. Yes b. No c. I don't know.	a. 5 b. 1 c. 0	

Is coal from different sources combined before processing? a. Yes. b. No. c. I don't know.	a. 4 b. 1 c. 1	
Does blending affect the handleability of the feed? a. Yes. It improves the handleability. b. Yes. It reduces the handleability. c. No. d. I don't know.	a. 4 b. 0 c. 0 d. 0	

Which actions are taken to reduce the risk of blockages or hang-ups if a troublesome coal is being processed? a. Lower the feed-rate of the troublesome coal b. Blend the troublesome coal with coal that has better handleability characteristics. c. Dry the troublesome coal. d. Process the fines and coarser material separately. e. No preventative actions are taken f. Other. Please specify.	a. 5 b. 5 c. 2 d. 1 e. 0 f. 1 • Open appertures on screen & add more water • Use Pneumatic Accumulation Control System, Follow Wet Weather Preparedness Procedure	

Are there any design changes that can be made to increase the handleability of coal on your plant(s)? Please specify.	• Use low friction material & angles of under pans to increase • I am going to be honest with you the design of the questionaire is a problem in that some of the preceding questions do not provide optionality to the "it depends type answer". The answer to this question is that in all cases the answer is yes BUT it depends on how long you are going to experience the problem for etc - if it is for isolated periods then it may not be worth doing - you slow doen the plant etc but in all cases you need to have a fundamental understanding from your mining technical team whe you are going to encounter these difficult conditions so that you can set up the plant accordingly • At [redacted] we dont experience blockages on the ROM side. However conveying fine coal product do render blockages from time to time. We have modified the transfer chutes, using non stick liners & installed vibrating motors on the transfer chutes (product). • Chute design • Chute Modifications: Low friction co-efficient surface for ease of flow. Pneumatic Accumulation Control System • Chute Design, Low Friction Coefficient Surfaces	

What percentage of the run-of-mine coal are fines (1 x 0.1 mm) or ultra-fines (-0.1 mm)? a. Less than 5 % b. Between 5 and 10 % c. Between 10 and 15 % d. Between 15 and 20% e. More than 20% f. I don't know.	a. 2 b. 1 c. 1 d. 2 e. 0 f. 0	
Are the fines or ultra-fines separated from the rest of the feed and processed separately? a. Yes. b. No. c. I don't know.	a. 4 b. 2 c. 0	
What methods are used to dewater / dry the fines before disposal or sale? a. Filters. b. Centrifuges. c. Thickeners. d. Thermal drying. e. Dewatering screens. a. Other. Please specify.	a. 3 b. 3 c. 3 d. 0 e. 3 0	

How much of the fines or ultra-fines goes to product? a. Less than 25 % b. Between 25 and 50% c. Between 50 and 75% d. Between 75 and 100% e. All of the fines. f. I don't know.	a. 1 b. 0 c. 2 d. 0 e. 1 f. 0	
Are the fine and ultra-fine coal recombined with the rest of the feed before sale, storage or disposal? a. Yes. b. No. f. I don't know.	a. 3 b. 1 c. 0	

To which markets is the fine coal supplied? a. Local thermal industry. b. Local petrochemical industry. c. Local metallurgical industry. d. Export thermal industry. e. Export petrochemical industry. f. Export metallurgical industry. g. None of the fines are sold. c. Other. Please specify.	a. 0 b. 0 c. 0 d. 2 e. 0 f. 0 g. 0 h. 2 • The preceding 2 questions for me are another case of bad design (for me with multiple plants) - the correct answer is that it depends • I am not in a position to tell ([redacted])	
How are the fines discarded? a. Discard dump. b. Slurry pond. c. None of the fines are discarded. h. Other. Please specify.	a. 2 b. 1 c. 0 d. 2 • Both slurry pond and discard dump dependent if there is filtration • Placed on a open air stockpile to dry. It is not discarded & sold as is and also used to make briquettes	

What is the approximate CV of the discarded fines or ultra-fines? a. Below 21 MJ/kg (±5000 kcal/kg). b. Between 21 and 27 MJ/kg (±5000 to ±6500 kcal/kg). c. Above 27 MJ/kg (±6500 kcal/kg). d. I don't know.	a. 3 b. 1 c. 0 d. 0	