The effect of thermal drying on the mechanical strength of South African coals

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Transaction Paper

Synopsis

The dewatering of coal, and particularly fine coal, continues to challenge coal prepatration engineers to find a cost-effective solution. With known world oil reserves being depleted daily, it is envisaged that the future price of coal may justify the use of thermal drying to achieve lower coal product moisture levels. The effect of exposure of the coal to elevated toemperatures on the mechanical strength of the coal was investigated. It was found that temperature does not play a major role in determining the volume breakage of a particle and that other variables such as orientation during impact has a much greater influence.

A double breakage mechanism was reported during the grindability tests. Surface, as well as volume breakage, occurs for the first 4 minutes while only surface breakage takes place thereafter. Due to this double breakage action, it was found that exposure to temperature does play a role in the amount of breakage and breakage rates during grindability tests. It was also concluded that a particle will break to an optimum size due to impact, after which only its surface will grind away as it is subjected to breakage forces.

Introduction

Reducing the total moisture content of a final coal product remains one of the more frustrating areas in coal processing. An excessive amount of moisture leads to financial penalties[1] and can also cause handling difficulties. Conventional mechanical methods used to dewater coal do not seem to be able to do a complete job, while on the other hand, the value of coal does not justify the use of thermal drying methods. The presence of water in product coal continues to be an operational and economic problem, and while depleting oil reserves will eventually increase the value of coal, it is envisaged that thermal drying of coal will start to play a greater role in the future.

Apart from the removal of moisture from coal, thermal drying also has an effect on the coal's mechanical strength (from here referred to as strength)[2]. The strength of coal is an important property since it has a direct effect on the particle size of the coal. The particle size of the final coal product can then in turn affect the productivity and efficiency of downstream processes such as gasification. Studies have shown that the possibility of fragmentation of coal after thermal drying would increase with an increase in the applied temperature during the drying stage[3].

Background

Moisture exists in coal in three different states, as defined by Rong[4]. They are surface moisture, capillary moisture, and chemically bound moisture. Surface moisture refers to the inter-particle moisture and can be removed by mechanical methods such as filtration. However, studies on coal beneficiation plants showed that it is not uncommon for fine coal to have a final moisture percentage between 20 per cent to 30 per cent after filtration. The capillary moisture, commonly known as intra-particle moisture, can be removed only by using thermal methods. Chemically bound moisture is part of the structure of the ash fraction of the coal and cannot be removed, except by pyrolysis. Therefore, to produce a final coal product containing a single figure moisture percentage, thermal drying is inevitable. It is therefore important to understand what effect thermal drying has on the strength of a coal product.

In general, size degradation of coarse coal occurs at conveyor transfer points, in hopper bins, screening operations, during stockpiling and reclaiming, and even during more gentle operations such as conveying. The degree of size degradation depends on the cumulative energy imparted to the coal and on the inherent strength of the particle. Although the

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material strength of coal depends on its rank and composition[5], it is also depends ons its size[6]. Therefore, it can be concluded that the energy requirement for size reduction increases with decreasing particle size.

Two mechanisms of fracture occur when force is applied to coarse material. They are volume breakage (including cleavage and shatter) and surface breakage (abrasion)[7]. The two mechanisms of fracture are distinguished by the size distribution of the degraded product. Volume breakage usually gives a product that has a more progressive size distribution, while surface breakage will yield some fine material, and one particle that is closely related to the size of the original particle.

Experimental design

Two types of tests were used to determine the strength of the coal. The first is the drop shatter test, based on the ASTM D44-75 standard, and the second is a normal grindability test.

The drop shatter test is used to determine the relative size-stability of coal, and is normally an indication of the ability of coal to withstand breakage during handling and preparation. The test involves dropping coal fragments from a fixed height onto a solid surface. A size analysis is then performed on the product after the drop to determine the amount of material that has broken to finer size ranges.

Mathematical models of crushing and grinding processes have been used extensively for circuit design in the minerals process industry. An important concept of these models is that size degradation can be considered a first order rate process[7]. Therefore, for the drop shatter test:

$$M_1 - M_0 = -K_V M_0 \quad [1]$$

where M_0 is the initial mass of the size fraction, M_1 is the mass of the unbroken material after the first drop, and K_V is the breakage index.

This can be repeated several times on the same sample, which will yield for N drops that:

$$M_N = M_0(1 - K_V)^N \quad [2]$$

The numerical value of K_V is determined from the slope of a straight line plot of $\ln[M_N/M_0]$ versus N. A large K_V value means a greater extent of breakage and a lower resistance to shatter, which implies a lower strength[7].

The grinding test is used to measure the resistance of a coal particle to abrasion during transport and handling. The coal is subjected to standard autogenous grinding conditions and the amount of fines that are generated during fixed intervals is measured. For this process, the rate of surface breakage can be given by:

$$\frac{dM}{dt} = -K_s M \quad [3]$$

where M is the mass of coal remaining in the given size fraction and K_S is the breakage constant. Integrating this equation will give:

$$\ln\left(\frac{M}{M_0}\right) = -K_s t \quad [4]$$

The value of K_S can be determined from the slope of a straight line plot of $\ln[M/M_0]$ versus time. As with the drop shatter test, a large K_S implies a lower strength coal.

Experimental set-up

Three coal samples were obtained from Witbank Collieries (Witbank Number 4 seam coalfield in South Africa), New Vaal Collieries (Free State coalfield in South Africa) and Middelbult Collieries (Highveld coalfield in South Africa, adjacent to the Witbank coalfield). Table I shows the proximate analysis of the coal.

A quantity of sample was thermally dried at 25°C (which serves as the reference point for no drying), 105°C, 130°C, 160°C and 190°C in a nitrogen rich atmosphere for an hour. Thereafter it was split into size ranges of –19 mm + 13.2 mm for the drop shatter test and –13.2 mm + 6.6 mm for the grindability tests. A 200 g sample from each size range was used for each test.

Experiments were performed using the two different procedures for each one of the tests as described above. For the drop shatter tests, the coal sample was loaded into a hopper situated 8 metres above a solid steel surface. This steel surface was enclosed in a 2 metre high drum to prevent the coal from spilling after impact. The coal was dropped onto the steel surface and then the amount of +13.2 mm particles was weighed. The +13.2 mm particles were put through the test again. This was repeated four times.

For the grindability test, a standard 210 mm internal diameter laboratory steel mill was used. The mill was loaded with 200 g of the –13.2 mm + 6.6 mm sample without any grinding media. The mill was operated at 60 rpm, which is about 65 per cent of its critical speed. Every two minutes the mill was stopped and the amount of +6.6 mm coal was determined. Thereafter the whole sample was placed back in the mill and allowed to run for another two minutes. This was repeated 5 times.

The data obtained from both sets of experiments were reworked to produce the K_V and K_S values.

Results and discussion

Drop shatter tests

Drop shatter tests were done on the Witbank, New Vaal and Middelbult coals as described above, and selected results are shown in Figures 1–5. Figures 1–3 show the results for the different coal types. Each one of the graphs shows the mass fraction of coal remaining in the predetermined size rage after each drop. The legend of the graphs is an indication of the different drying temperatures in degrees Celsius.

From Figures 1–3 it is clear that the data are linear, but the influence of temperature on the strength of the coal was minimal. The data points on the graphs lie within acceptable

Table I

Proximate analysis of coal tested

	Witbank	New Vaal	Middelbult
% Moisture (SABS 924)	3.83	6.46	4.00
% Ash (ISO 1171)	11.62	35.79	31.34
% Volatile matter (ISO 562)	27.33	19.18	21.63
% Fixed carbon	57.22	38.56	43.03

error ranges, and there is no clear trend visible that would lead to a conclusion that the coal is more likely to shatter after it has been subjected to higher drying temperatures. This may indicate that insufficient time was given for the temperature effect to reach the core of the particle. Hence, there were only minor changes on the surface of the particles, which led to the constant volume breakage behaviour of the different particles.

Figure 4 shows the K_V values obtained for each coal type in relation to the drying temperature for the coal. From Figure 4 it can again be concluded that thermal drying has a minimal influence on the volume breakage of a coal particle. By following the trend of the graph, it does, however, appear as if there is a tendency for the K_V value to increase slightly towards the 190°C temperature range. Keeping in mind that a higher K_V value means a weaker coal, it can be stated that the tendency is for the coal to become only slightly weaker at elevated temperatures below 200°C.

Taking into account the amount of scatter from the graph in Figure 4, it is safe to say that the type of coal has a very limited influence on the volume breakage. This statement can be quantified by taking the average fraction of coal remaining in the set size range after impact for every drying temperature per drop. This can be done for every coal type. A graph of this average fraction against the number of drops will give an indication of the influence of the coal type on the volume breakage strength of the sample.

From Figure 5 it can be seen that the influence of the type of coal on the breakage is minimal. It is, however, noteworthy that the Witbank and Middelbult coals, which have a higher carbon fraction, did break slightly more easily than the New Vaal coal (a high ash coal). Although not tested during this work, observations suggested that the orientation of a coal particle when making contact with the steel surface does play a significant role.

Grindability results

Selected results from the grindability tests are given in Figures 6–12. From Figures 6–8 it can be seen that there is a clear relationship between the applied drying temperature and the tendency for the particles to grind and chip away on the surface. More breakage occurs for all three coal types as the applied drying temperature increases. These results confirm the explanation given above that the influence of temperature has taken place only on the surface of the coal particles, and has not had time to reach the core.

Similarly, the rate of breakage increases as the applied

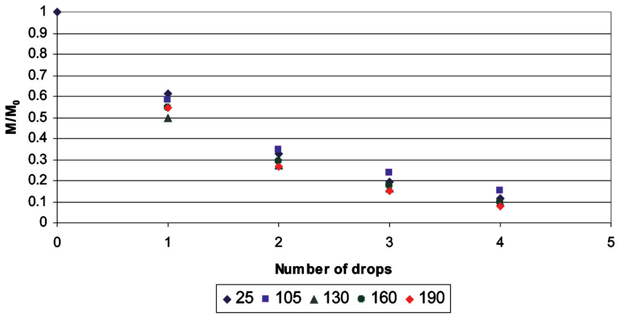

Figure 1—Drop shatter tests results for Witbank

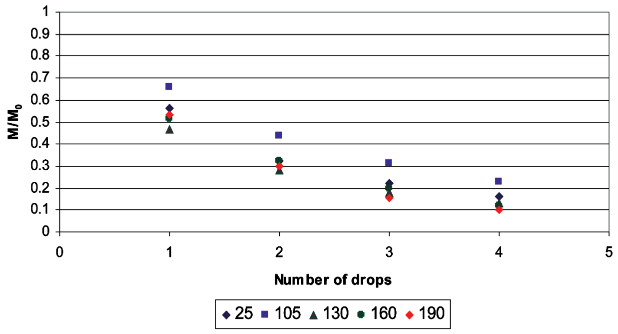

Figure 2—Drop shatter test results for New Vaal

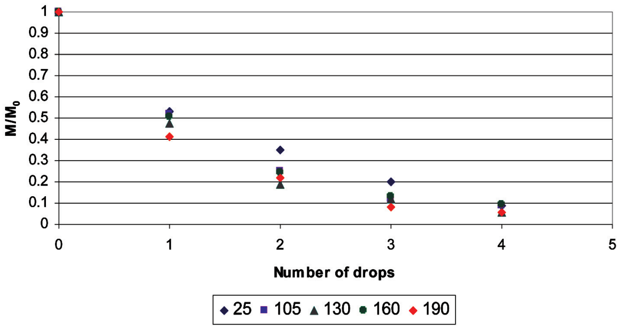

Figure 3—Drop shatter test results for Middelbult

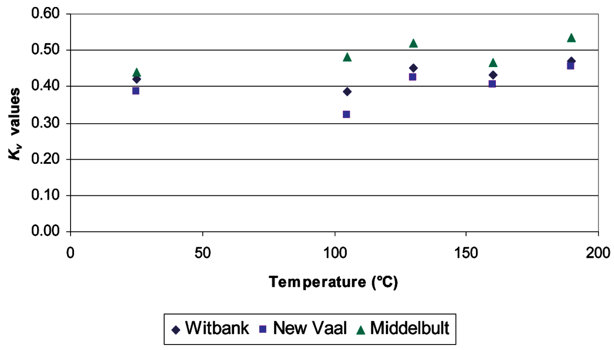

Figure 4—K_V values

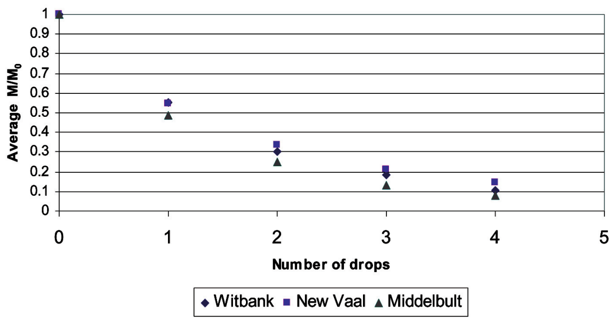

Figure 5—Average fraction breakage values

drying temperature increases. It is, however, interesting to note that there is a vast difference in the final amount of breakage and rate of breakage among the different types of coal.

As described earlier, the breakage rate constant, K_S, is determined from the slope of the graph of $\ln[M/M_0]$ vs. time. This graph is shown in Figure 9.

The graph in Figure 9 shows that the rate of breakage of the Middelbult coal is much lower than the rate of breakage of the New Vaal coal (keep in mind that a lower K_S value means a lower tendency to break). In general, the Free State coalfields are predominantly dull coal, interlaminated with sandstone and mudstone, whereas the Witbank coal field has high coal zones with mudstone and siltstone partings. The Highveld coalfield on the other hand, consists more of very thin discontinuous layers[8], giving a coal sample that looks like shale. Therefore, for the New Vaal coal, there is a more homogeneous distribution of interfaces between the macerals and the minerals close to the surface than is the case with the Middelbult coal, meaning more potential weak spots. The number of weak spots is exaggerated when exposed to the higher temperature and will give rise to greater breakage rates.

An interesting trend arose during the determination of the K_S values. The graphs of $\ln[M/M_0]$ vs. time did not yield a linear relationship as was expected from the relevant literature. An example of the Witbank coals is shown in Figure 10.

Figure 10 shows a graph where there is a clear discontinuity in each of the tests between 2 and 4 minutes. It yields a curve with two different slopes, indicating two different breakage rates. Since the grindability was carried out in a laboratory-scale mill, the path each particle travels leaves space for a 200 mm freefall, which will include some degree of volume breakage, especially on an already weakened surface. It means that for the first few minutes both surface and volume breakage may occur. Similar findings were documented in the paper of Sahoo and Roach[7].

To determine the significance of the impact on the surface breakage of the particle, the slope of the curves for the first 4 minutes and the remaining 6 minutes were drawn separately. From the slope, the K_S values were determined for the different breakage mechanisms. The results are given in Figures 11 and 12.

Figure 11 (which is the K_S values for the first 4 minutes of grinding) shows a distinct relationship to the graph in Figure 9, whereas Figure 12 has yielded a near horizontal line. These results are very significant. It means that most of the breakage of the particles takes place in the first 4 minutes of grinding, whereas very little breakage occurs in the remaining time. It seems as if there is an optimum size to

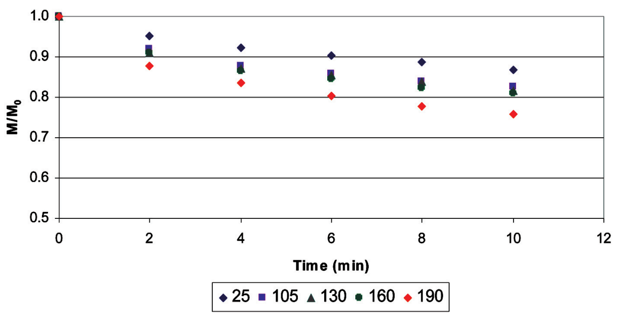

Figure 6—Witbank grindability results

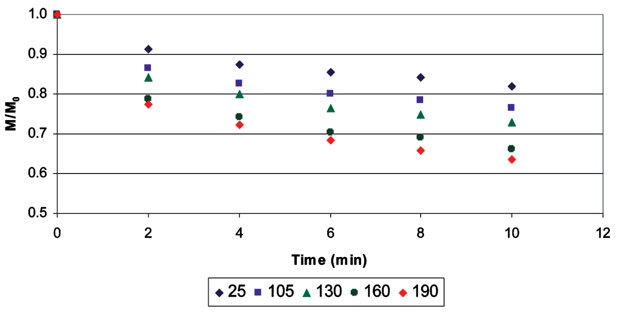

Figure 7—New Vaal grindability results

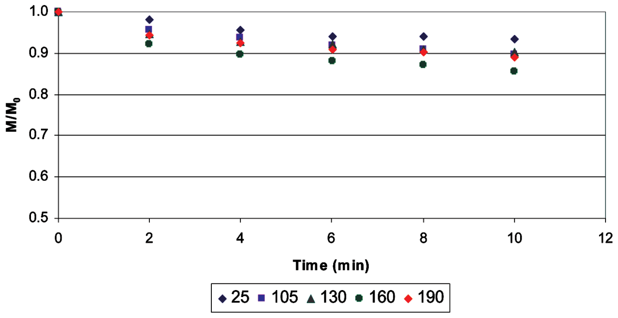

Figure 8—Middelbult grindability results

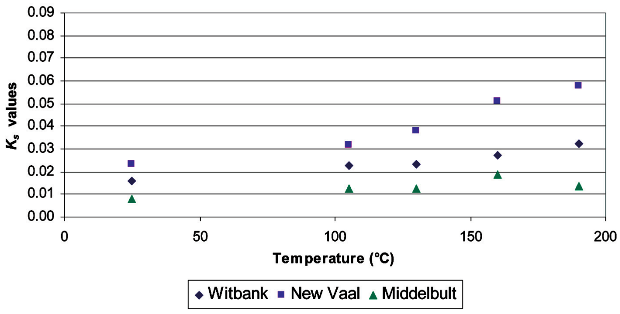

Figure 9—K_S values

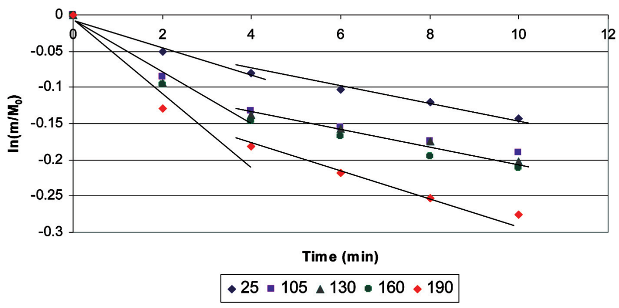

Figure 10—Example of Witbank reworked grindability data

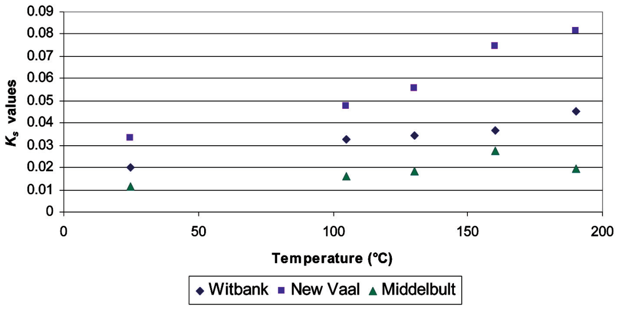

Figure 11—K_S values for the first 4 minutes

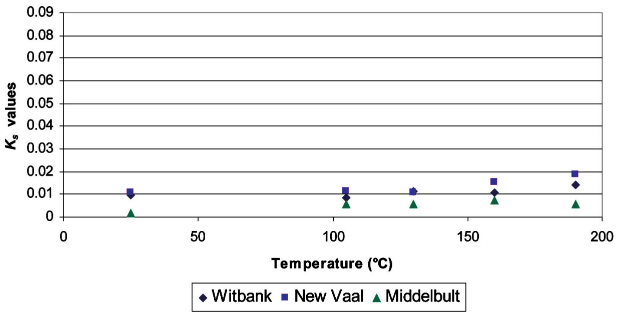

Figure 12—K_S values for the final 6 minutes

which a particle will tend to reduce during handling operations, together with an amount of fines generated from these breakages. Only when the applied forces to the particles are increased will they tend to break beyond this optimum size.

Conclusions

From the results above, the following can be concluded:

- Thermal drying for a time less than 1 hour does not have a significant influence on the mechanical strength of a particle greater than 13.2 mm, and the tendency is for volume breakage to occur. It does, however, show some influence on the strength of the surface of the particles, which will cause more breakage to occur if no drying takes place.
- The orientation of the particle during impact, rather than the type of coal, has an influence on the volume breakage.
- For the first 2 to 4 minutes of a grindability test, both surface and volume breakage take place. It is during this time that most of the breakage occurs. For the remaining time, only surface grindability takes place.
- Although not proven, it does seem that coal tends to break easily to a certain size, whereafter it takes a definite input of energy to break the coal more finely.

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