Development of a Washability Monitor for Coal Utilizing Optical and X-Ray Analysis Techniques

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ABSTRACT: In coal washability, the objective is to establish the set of maximum possible separation performance criteria for a given coal feed. The method of choice for this has been the conventional sink-float analysis. Time, cost and safety aspects of the sink-float method have prompted the search for a new approach for establishing separation performance criteria, especially as performance levels of separator plants can be maximised if reliable information based on an analysis of washability in conjunction with particle size distribution, ash and elemental constituency becomes readily available.

It is proposed that the new method to establish washability and associated performance information utilise at least three measurement technologies concurrently: x-ray transmission, image processing, laser distance measurement, and, optionally, XRF elemental analysis of each coal particle. The value of the collected data would increase considerably if the washability data were additionally available in time to be considered in the control of the process plant. The incorporation of an automated washability monitor giving near real-time data would impinge positively on the profitability of the plant operation.

The basic measurement methods and first results are described. First tests with a prototype utilizing optical and X-ray analysis methods are encouraging.

DEFINITION OF WASHABILITY

The washability of coal or minerals is expressed by a curve or graph showing the results of a series of float-and-sink tests (Galvin, 2006). A number of these curves are drawn to illustrate different conditions or variables, usually on the same axes, thus presenting the information on one sheet of paper. Washability curves are essential when designing a new coal or mineral washery. There are four main types of washability curves: characteristic ash curve, cumulative float curve, cumulative sink curve, and densimetric or specific gravity curve (Singh, 2006). The different curves are based on the relation between ash or ore grade, mineral density and particle size distribution.

In determining the washability analysis, the particle density is the underlying feature of all washability curves. Conventionally, the particles were separated into density fractions by immersing them in fluids of a predetermined density, and skimming off those particles that remained afloat in the liquid. The particles remaining afloat thus had a density lower than that of the fluid they were subjected to. The particles that remained at the bottom of the fluid container thus had a density higher than that of the fluid. By progressively increasing, for example, the density of the fluid and immersing the remaining particles so as to be able to skim off the next density fraction, the particles would be fractioned into density groups. The liquids used range from aqueous solutions to organic liquids to suspensions. Unfortunately the liquids used for this separation process are often toxic or expensive. It stands to reason that a new method of determining washability is sought.

In addition to density, particle size distribution is also of importance to the topic of washability. Typically, the particle size distribution is based on sieve analyses. This technique is well introduced and proven in the laboratory. However, the size of a particle is not fully described by the mesh size of a sieve:

- sieve meshes may have different shapes (circular, hexagonal, square)
- particles may not necessarily be of cubic or spherical shape
- long but small particles may pass small meshes.

Using a model which describes the particle size by three measures (length*width*height), it can be stated that the sieve analysis characterizes the particle size by the second largest (or second smallest) of these measures. Although this method is the viable way for a sieve analysis in the laboratory it may be logical to regard the particle volume instead of the sieve size as a more appropriate characteristic feature to describe the size distribution.

Considering the issue around the liquids used in conventional float and sink analysis, as well as the requirement of a better volume determination of particles, this paper introduces a new method of determining washability curves that is suitable for daily use, and is deficient of the disadvantages of the conventional float and sink and sieve method.

Thus, the development of a washability monitor for coal particles has to determine at least some of the following characteristics of the coal to be measured:

- washability curve
- particle size distribution
- elemental constituency
- ash

In order for the development of such a washability analyser to be of interest to the coal preparation industry the monitor must bring with it at least these advantages:

- It must be relatively fast, reducing the usual manual effort of weeks into hours
- It must be reliable, working with minimal intervention of personnel
- It must work in an on-line fashion, and should demonstrate a high degree of mechanical integration into the process path at the point of measurement.

ONLINE COAL ANALYSIS

Different techniques of the online analysis of coal are in use for about 5 decades now (Bachmann, 1985&1991, Kirchner, 1991). Starting with gamma backscattering techniques in the fifties of the last century, more sophisticated techniques were developed later on. When these techniques were introduced to the industry the scope was to replace the sampling and sample analysis of the laboratory. Due to the fact that the chemistry of coal is quite complex this goal could not be achieved. Today the online analysis of coal is regarded as not to replace the laboratory but to supplement the laboratory.

Provided that a reliable and representative sampling device is used, laboratory analysis can determine the properties very precisely, but this analysis process is slow. Results are available after many hours or even days. If an external laboratory is involved then sample turnaround times of one to two weeks are not unusual.

Compared to the laboratory analysis the online analysis delivers instantaneous results. The control room staff can act on the information directly while the laboratory results give only an explanation what occurred in the past.

Various coal characteristics are measured online today. Dual or triple energy ash meters combined with moisture meters are commonly used. Ash and sulphur content can be measured precisely using methods like PGNAA and X-ray fluorescence which are the state-of-the-art measuring methods today. These methods are described in various recent papers.

Density determination

Before X-ray fluorescence and PGNAA became available ash content was determined using the so called dual energy transmission method. With this method the coal is irradiated by gamma radiation with two different energies; the radiation is partly absorbed by the coal. While the absorption of the high energy radiation is caused mainly by the weight per area of the coal, the absorption of the low energy radiation is caused by the weight per area and the composition of the coal which correlates more or less with the ash content.

The weight per area itself is correlated to the (bulk) density of the coal. If the thickness of the coal layer is known then the density can be derived from the weight per area as the result of the weight per area divided by the layer thickness.

Therefore, a transmission measurement that gives the mass per area combined with an optical measurement of the layer thickness leads to the determination of coal density on the belt. If this method is applied to a normal loaded belt then it is still not sufficient to determine the washability of the coal since single particles cannot be isolated and therefore the size distribution cannot be derived.

Single path setup

Dual ash analysers are equipped with two nuclear sources. Americium^{241} is used as the low energy source and Caesium^{137} as the high energy source. The non-absorbed but transmitted radiation is detected by a scintillation counter. A typical dual energy installation is shown below.

Figure 1. Dual energy ash meter (Berthold 2009)

Since the purpose of these devices is the measurement of ash, the sources are optimized to transmit typical layers of coal belts. Characteristic for this measurement is the fact that a narrow beam irradiates the coal in the centre of the belt. The second and, if available, the third beam are installed accordingly so that all measurements irradiate the same coal in the centre. In specific arrangements three sets of measuring beams may be installed across a belt in order to compensate for coal segregation on the belt.

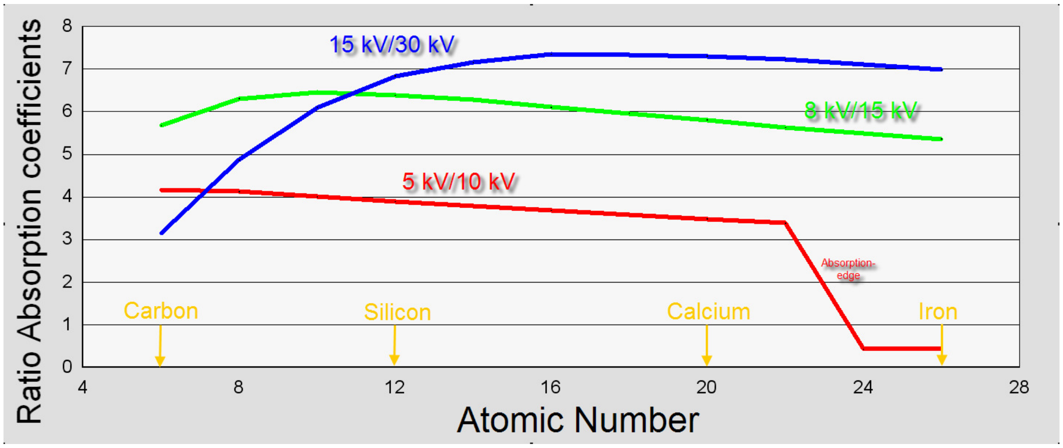

Figure 2. Quotient of the X ray absorption coefficients for different energies versus atomic number of absorbing material (Berger et al 2008)

A washability meter can be derived from this setup. For washability, single particles have to be analysed individually. That means that the particles have to be positioned as single particle stream centred on the belt. Just a high energy measuring path is required. Unfortunately the absorption of Caesium^{137} gamma radiation by single particles is quite low so that this standard measurement setup cannot be used. The measurement can be performed only with low energy radiation.

The absorption coefficients are dependent on the atomic number of the absorbing material. Nevertheless, the ratio of the high energy and low energy absorption coefficients is more or less constant at certain energy ranges as can be seen in Figure 2. Therefore, an absorption measurement independent of the atomic number, but dependent on the density can also be performed with two low energy X-ray measurements. Thus the setup chosen for the particle density measurement consists of two subsequent X-ray measurements as can be seen in Figure 3.

Figure 3. X ray measuring path mounted on a small conveyor

The setup was tested using ore particles with different shapes. Although the shape of the particles which have the same density varies (Figure 8) the measured density is quite uniform.

Multiple path setup

Although the basic approach of this density determination is quite promising, the measurement is limited by the fact that one particle after the other has to be measured. Therefore, specific measurement arrangements have to be considered.

Today the “dual energy ash measurement” is widely used in a field which has nothing to do with coal. Equipped with X-ray tubes, bone scanners, which utilise two different energies, are used to determine the bone density in human bodies. This so called *Dual energy X-ray absorptiometry* is an effective way to detect Osteoporosis in humans. An X-ray image is derived using a line detector which scans the human body. From there the bone density is calculated.

The same method may be applied to coal particles. It is no longer required that the particles be placed in the centre of the belt and measured one by one, but the whole area which is spanned by the line detector can be considered for the measurement. However, it must still be a single layer of coal.

Although the throughput of the system can be multiplied by using this arrangement, one problem remains unsolved: the method is limited to a particle size of about 125 mm³.

VOLUME MEASUREMENT

Spatial reconstruction using laser line scanning

Optical distance measurement in the range of 10 – 100 cm is mostly done using lasers. This technique has been available for more than ten years and is widely accepted. The basic principle can be seen in Figure 4. A laser projects a well focused dot onto a surface. The laser image is then projected via a lens onto a detector which can be a CCD line or a position sensing device to measure the distance through the lens. The lens which “sees” the dot needs to be mounted at an angle to the surface where the laser dot is projected. The position of the projected laser dot on the detector depends on the distance of the detected object to the detector and on the distance between laser and sensor.

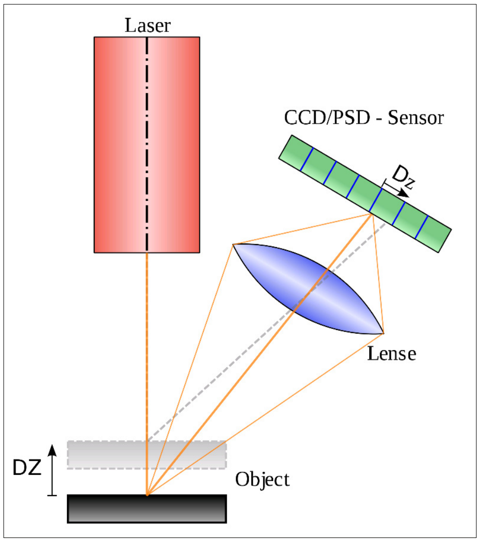

Figure 4. Principle of laser triangulation (Wikimedia, 2009)

Using the one-dimensional approach will give only very little information about each particle on a conveyor belt. In the best case the length and a height profile at one single line of the particle can be obtained. In the worst case no particle can be seen at all because it is not exactly centered. If the particle is scanned a second time and the orientation does not exactly match the previous one, the measurement will show a totally different result.

This principle can easily be expanded to a two dimensional measurement by replacing the laser by a line laser and the single detector by a camera. The same effect could be achieved by using a fast distance sensor and a rotating mirror. The mechanical complexity of the rotating mirror is much higher than using a standard industrial camera, so the approach is to use a camera. Another advantage of using a camera is that the initial cost and time required to set up a test device is lower than using highly specialized laser scanners or to build one. The camera can be connected to a PC which provides a fast and easy-configurable evaluation device.

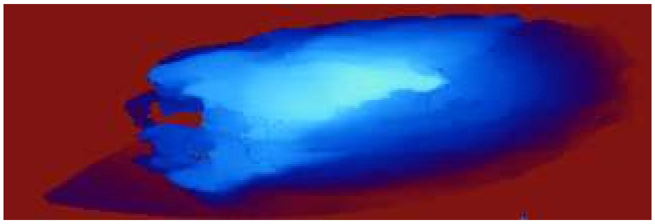

Figure 5. False color display of a scanned particle

Using a standard camera is an economic and easy way to realize the measurement. No special low-level camera programming is required and the options for debugging and realizing software changes are powerful. Various specialized imaging toolkits are available as well as interfaces. Almost every programming language can be used. For testing purposes the software can be tested easily using prerecorded images, and each step of the software can be understood directly.

The disadvantage is the limited continuous speed of normal cameras. The USB 2.0 interface allows a maximum data rate of about 480 Mbit/s. A USB connected black/white industrial camera currently provides around 30 frames per second at a resolution of 1.3 megapixels. Higher data rates are not possible due to the limited bandwidth of USB.

Another option is to use an Ethernet-connected camera. Ethernet provides a usable bandwidth of 1000 Mbit/s and thus offers the double frame rate of the USB camera. Therefore the use of Ethernet as interface allows running a fast particle analysis without being limited by the available hardware.

Resolution vs. being able to scan every special particle

In theory the best resolution will be achieved if the camera angle to the belt approaches zero. This maximizes the distance the camera monitors between the projection of the laser without a particle and with a particle of a given height. But in this configuration the back of the particle (as seen from the camera) cannot be seen at all. The larger the angle alpha becomes the lower the maximum possible resolution gets with a given camera. Alpha is also the angle of the maximum (negative) slope of the particle where the measurement is still working.

In the experimental setup an angle of around 30-40° was chosen as a reasonable tradeoff between resolution and maximum slope. Another reason for this range is that it allows the use of a mirror to see the back of the particles.

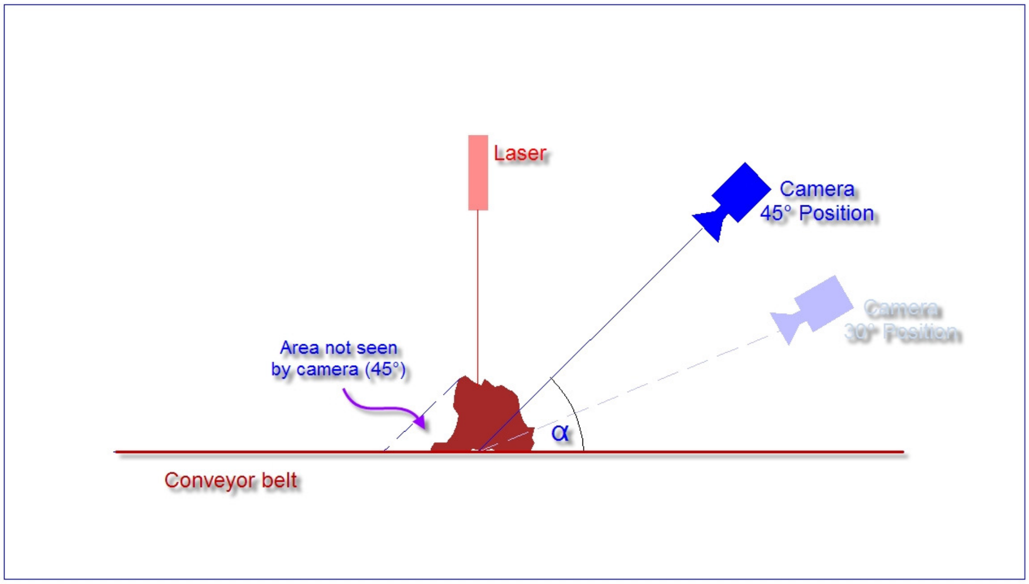

Figure 6. Laser and camera alignment

Unsolved and potential issues

In the current setup the base of all particles is regarded as flat. However, this assumption has to be proven in a continuous arrangement. To look at the base of the particles can either be done using turning the particles around or by measuring through a clear belt. Turning the particles around requires a high amount of mechanics of a similarly complicated construction of two flexible belts.

In conclusion, an industrial proof solution for "looking" at the bottom of the particles is very complex compared to the current setup. For this reason the need for the measurement of the bottom should be avoided. Another problem is the use of just one line laser centered above the belt. Any particle where the sides fall off faster than the laser can "see" it will not be recognized and thus averaged (Figure 6).

Further improvements

Even with a 45 degree angle between the belt and the camera many particles can be found where some part of the surface cannot be seen because it is too steep. The only chance to avoid this is to look at the back of the particle at the same time. Basically, there are two different ways of doing this. This can be done either with a second camera or with a mirror which enables the same camera to see the front and the back side simultaneously. This is shown in fig. 7. Unfortunately this decreases the usable resolution of the camera because a wider field of view is required.

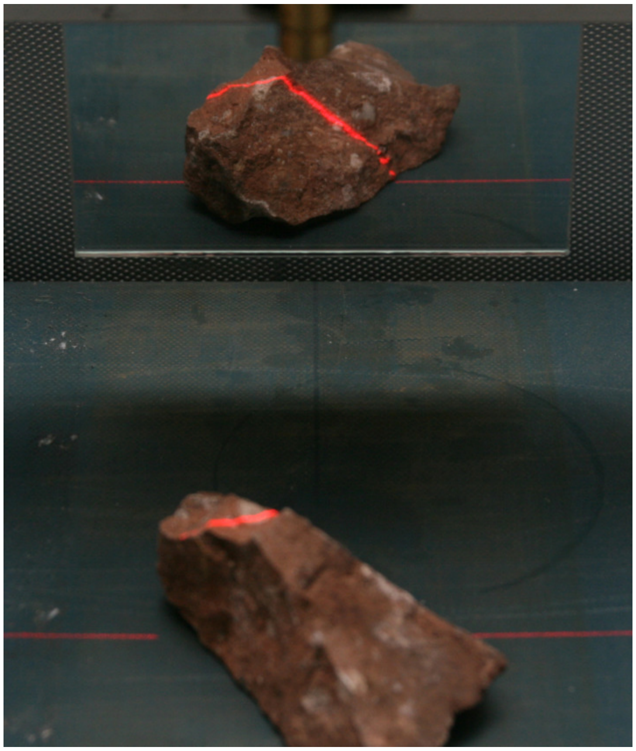

Figure 7. Improved evaluation using a mirror

Using a second camera will increase the load on the computer and possibly require additional USB or Ethernet hardware. Since today most industrial PCs provide two Gbit Ethernet controllers and also several USB host controllers this is usually not a problem.

To project a laser line on particles with very steep edges, 2 more lasers situated left and right from the belt should be installed. Furthermore, the recognition of particles can be improved by using an additional camera at a very flat angle.

Software

The software is continuously reading out the camera(s) and scanning the images for the laser line. If a mirror is provided to see the back of the particles the software scans two areas of the image for the laser line. To decrease the sensitivity to vibration the software only calculates the difference between the laser line seen on the belt and the line seen on the particle within one image. Thus small changes in the camera angle or vibrations of the camera do not affect the readout. This is done for the front and back view using a mirror or using two cameras. In both cases a calibration between the front and back view is required to correct for perspective distortion.

The software uses the corrected camera data to calculate a height map. The height map is used to calculate the dimensions of the particle. The volume is the integral of all heights of the particle. Also, the maximum height/width/length of the particle can be calculated thus giving a measure about the mesh size this particle would fit through. The height map and the characteristic data are then saved into a SQL database.

Other optical methods for online volume determination

Spatial reconstruction using laser line scanning

Although the presented concept of the particle volume determination works quite well it is a slow measuring method. Several images have to be processed for each single particle which limits the analyzing time. Therefore other optical methods have to be considered although these methods are not yet developed for this application.

Spatial reconstruction using hue information

One method for determining the surface topology using a single still frame captured by a color camera uses differently colored light sources which illuminate the sample from opposite directions, resulting in a mixed color varying with the surface normal direction in regard to the viewport direction. The hue value translates into a local derivation that determines the surface topology that is obtained by numerical integration. Colored and textured surfaces may cause higher standard deviation or misinterpretation of the given information. Although very fast, this method needs to be tested extensively with ore and coal samples. This method also requires reasonably priced hardware.

Spatial reconstruction using stripe light projection

A very common approach in biometrics and forensics is the use of projected stripes of colored light, increasing in spatial density in a multi-pass scanning procedure. After scanning, a multi-scale height map is computed. Alternating projections can be used to scan both sides of an object at once. Evidently, this method can, by its nature, not be designed to run in real time.

Spatial reconstruction using cast shadows in multiple directions

A first approach was to consider the possibility of reconstructing the sample geometry using cast shadows. Therefore, a polygonal, circularly closed screen with point light sources on each edge all mounted at the same height is envisioned. This way a polygonal approximation can be calculated by combining pyramidal volumes given by the known corresponding light source coordinates and the base area which is derived from the shadow on the respective screen through perspective correction. This method has significant drawbacks:

- large errors when scanning concave surfaces,
- bad approximation of geometrical detail,
- reduced resolution when scanning complex geometries that may feature occlusions,
- slowly improving non converging approximation behavior with increasing number of light sources.

However, this method is not overly demanding in regard to image capturing devices. Fast pulsed LED light sources are also readily available. This method can nevertheless be applied to fields where partially transparent or refractive samples are being analyzed such as droplet formation monitoring at outlets.

COMBINATION DENSITY / VOLUME

Based on the measurement of the density using X ray attenuation and the optical volume measurement the distribution function of particle size versus density can be obtained. The quality of the measurement depends strongly on the fact that the density measurement has to be independent on the volume of the particle.

Figure 8 shows measurements obtained on particles with constant density (2,4 to 2,6) but different volumes. The first graph shows the single measurements on the particles while moving through the measurement. The ▲ indicate the X ray absorption measurements (arbitrary units) while the ▼ indicate the volume of the particles, measured in incremental pixels on the camera screen.

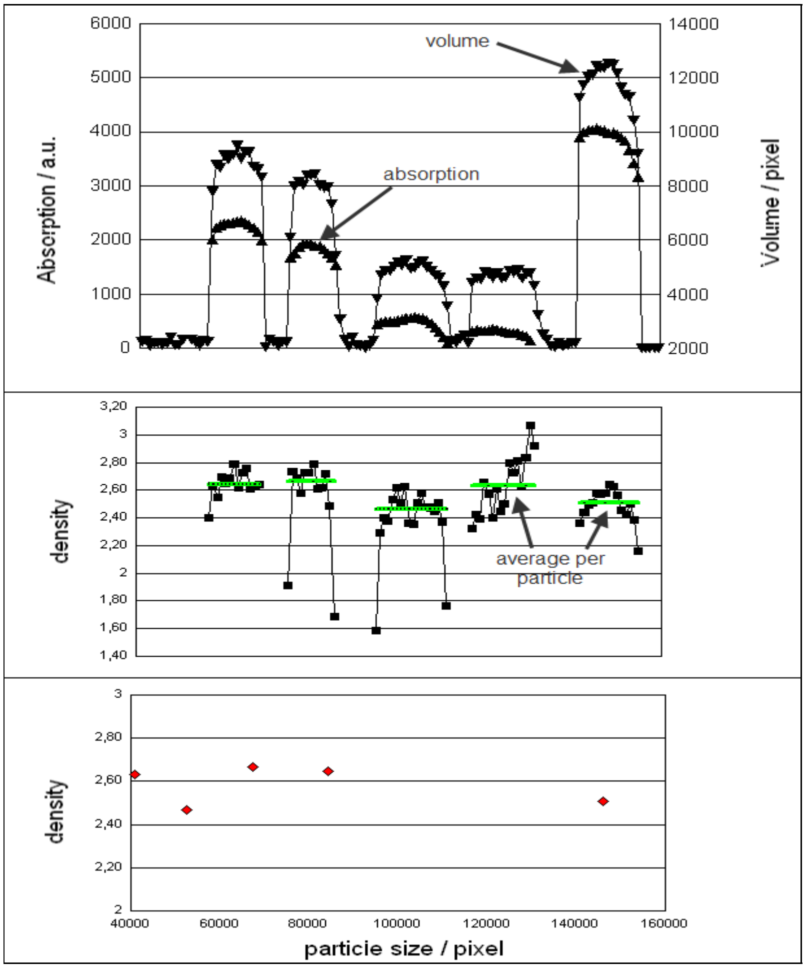

Figure 8. Density versus particle size curve

The second graph shows the density values derived from the previous measurement. As can be seen, the density varies inside of the particles. This is quite strong in the fourth particle; it becomes more dense to the end. However, the arithmetic average does not vary strongly and represents the values measured with laboratory methods.

The last graph shows the total volume of the particles versus density. The largest particle has a 3,5 times larger volume than the smallest.

CONCLUSION

Cost and safety aspects of the sink-float method in determining washability have prompted the search for a new approach for establishing separation performance criteria. The proposed method of using x-ray and optical methods promises to deliver results fast enough to use the information for plant control. These results obtained with particles of constant density show that the method is suitable in principle to determine the washability of coal or ore. However, further development needs to be done in order to use this method practically in a preparation plant.

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