Predicting washability using a regression of ash content with controlled rock to coal mix ratio specimen used for calibration.

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Abstract Accurate information on coal washability characteristics is crucial for optimizing beneficiation processes. This study investigates the use of dual-energy X-ray transmission (DE-XRT) in predicting ash content and specific gravity (S.G.) by employing a structured calibration approach. A total of 36 coal samples from a British Columbia mine were analyzed using DE-XRT, S.G. measurements, and ash analysis. A controlled calibration method was developed by systematically varying rock-coal (rock-ash forming minerals) ratios to establish reliable DE-XRT response trends. Results demonstrated strong correlations between DE-XRT-derived relative density and rock mix ratios, confirming its capability in estimating coal quality. The generated washability curves closely followed traditional sink-and-float results, particularly at higher ash contents, validating DE-XRT's potential in coal sorting. These findings highlight DE-XRT as a viable tool for real-time coal quality assessment during its beneficiation. Future work should focus on refining calibration techniques and improving detection in extreme density ranges to enhance prediction accuracy and sorting efficiency.

1. Introduction

The use of X-ray transmission (XRT) sensors for coal sorting has been explored since the early 1970s, with initial studies by Jenkinson [1]. highlighting its potential for dry coal separation. This technique serves as an effective deshaling and destoning method, helping to remove unwanted material before coal reaches the processing plant. Additionally, XRT sorting can be applied in selective mining of shallow coal seams, reducing overburden contamination and dilution. While XRT technology has been integrated into commercial coal processing applications, primarily for coarse particle separation, its ability to predict washability characteristics has not been widely investigated.

A key challenge in coal processing is the accurate estimation of washability parameters, particularly ash content and specific gravity (S.G.), which are critical for efficient separation

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and quality control. Dual-energy X-ray transmission (DE-XRT) has shown promise in distinguishing between different coal lithotypes based on density differences which has been studied by our group previously and described [2], yet its predictive accuracy for washability characteristics requires further validation.

This study evaluates the regression analysis of ash content and specific gravity using DE-XRT through controlled calibration with mixed rock-coal samples. A total of 150 samples were collected from a British Columbia coal mine where 36 samples were analyzed using DE-XRT, S.G. measurements, and ash analysis. A structured calibration method was utilized, and these calibration curves were then used to analyze DE-XRT signals and assess their reliability in predicting washability characteristics.

By establishing a systematic calibration approach, this research provides valuable insights into the potential of DE-XRT for coal quality assessment. The findings contribute to improving the precision of DE-XRT in estimating coal ash content and S.G., thereby enhancing its applicability for real-time coal sorting and assessment of other beneficiation processes (gravity based).

2. Materials and methods

2.1. Material

2.1.1. Coal and rock samples

A total of 150 coal and rock samples were collected from a coal mine in British Columbia, with sample top sizes ranging from 5 to 30 cm. Surface dust and dirt were removed using water and a soft brush. After cleaning, the samples were placed in a dry, cool environment and allowed to air-dry naturally for 72 hours. Once fully dried, the coal and rock samples were sealed in polyethylene bags for future use.

Fig 1: Banded bright coal (Sample number 22)

2.1.2. Sample containers

As shown in Fig 2, the cylindrical containers are used for pulverized samples. These containers are made of low-density, thin-walled polypropylene to minimize any potential interference during the dual-energy X-ray transmission (DE-XRT) tests. To verify their suitability, the empty containers were scanned, and no detectable pixel density was observed.

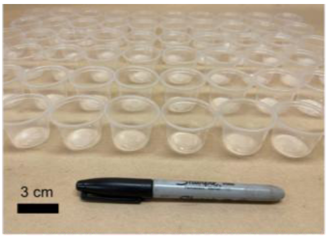

Fig 2: Cylindrical polypropylene container used in the experiment

2.2. Preparation of coal-rock mixed samples

2.2.1. Mass and specific gravity test

A tool for measuring the mass and specific gravity of coal and rock samples has been developed. This system was comprised of four essential components, including a metal support stand, a high-precision digital electronic scale, a beaker, water, and a nylon thread, as illustrated in Fig *3*3.

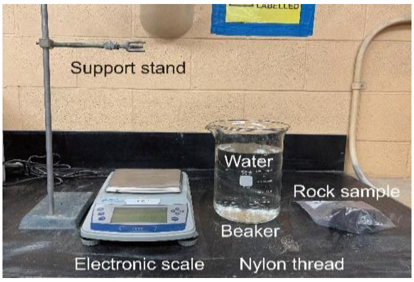

Fig 3: The equipment for mass and SG test

Fig *4*4 outlines the three-step process for conducting the method to determine the mass and specific gravity of coal and rock samples. The specific gravity of the sample can be calculated using Equation (1)

$$SG_i = \frac{m_{2,i} - m_{0,i}}{m_{1,i} - m_{0,i}} \tag{1}$$

The resulting where SG_i is the specific gravity of the coal and rock sample i. m_0, i is the mass of beaker and water when testing the coal and rock sample i. m_1, i is the mass of beaker, water, and suspended sample i. m_2,i is the mass of beaker, water, and bottom-touched sample i. The average specific gravity of all coal and rock samples belonging to a lithotype set can be calculated as

$$\overline{SG} = \frac{\sum_{i=1}^{n} m_{2,i} - m_{0,i}}{\sum_{i=1}^{n} m_{1,i} - m_{0,i}} \tag{2}$$

where n is the total number of coal and rock sample in a lithotype set.

After mass and specific gravity measurements, the wet coal and rock samples were gently dried using paper towels. They were then placed in a dry, cool environment and allowed to air-dry naturally for 24 hours. Once fully dried, the samples were sealed in polyethylene bags for future use.

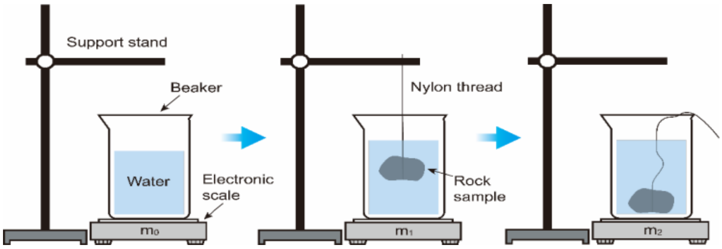

Fig 4: The workflow of mass and specific gravity test

2.2.2. Sample preparation

The crushing and pulverizing of coal and rock samples were carried out in four main steps. First, a hammer was used to break the samples down to approximately 10 cm in size. Next, half of the samples were randomly selected and further reduced using a jaw crusher with a small closed-side setting (less than 5 cm). To retain sufficient material with larger particle sizes for studying various size distributions, only a portion of the total samples underwent this secondary crushing. In the third step, the crushed samples were divided into two groups using a riffle splitter: approximately 80% were used to prepare a mixed particle-size sample, while the remaining 20% were further pulverized for 90 seconds using a pulverizer. Finally, the finely ground material was used to create a mixed pulverized sample.

2.2.3. Preparation of pulverized mixed sample

Three types of pulverized samples were prepared: pulverized banded bright coal sample, pulverized banded dull coal sample, and pulverized dull rock-like sample. In addition, two types of mixed pulverized samples were prepared: one combining banded bright coal with dull rock-like material, and the other combining banded dull coal with dull rock-like material.

To produce 20 groups of pulverized mixed samples with varying rock content, pulverized coal and rock samples were combined in different proportions. The rock mixing ratio, defined as the volume of rock relative to the total volume of coal and rock, is presented in Equation 3 [3]

$$R_M = \frac{V_{rock}}{V_{coal} + V_{rock}} \times 100\% \tag{3}$$

where R_M is the rock mixed ratio, V_{coal} and V_{rock} are the volume of coal and rock, respectively.

The preparation of pulverized mixed samples with specified rock mixing ratios was facilitated by the clearly defined average specific gravity values of each lithotype. Ten distinct rock mixing ratios, ranging from 0% to 100%, were selected for sample formulation. Each mixture was thoroughly homogenized and sealed in polyethylene bags for subsequent use.

The pulverized mixed samples were subsequently transferred into cylindrical polypropylene containers of consistent diameter but varying volumes, as illustrated in Fig ***5*** 5 (a). The use of uniform container geometry enabled precise control over sample thickness by adjusting the fill volume. Three sample volumes 5, 9, and 14 cm^3 were used, corresponding to distinct sample thicknesses. A total of sixty pulverized mixed samples were prepared, comprising ten rock mixing ratios at each of the three thickness levels. Upon preparation, all samples were sealed and stored under controlled conditions for subsequent analysis, as shown in Fig ***5***5 (b).

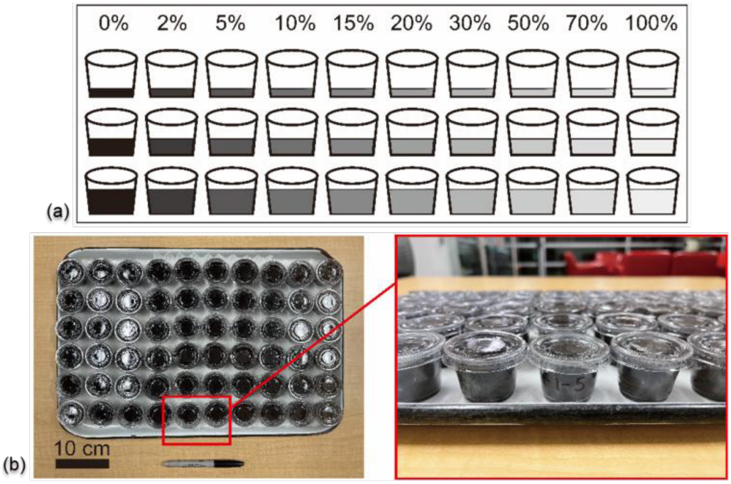

Fig 5: The preparation of the pulverized mixed sample. (a) the mixing of the pulverized coal sample and pulverized rock sample; and (b) the pulverized mixed sample

2.3. Dual energy X-ray transmission test

Dual-energy X-ray transmission (DE-XRT) testing was conducted using the COMEX MSX-400-VL-XR system located in the Coal and Mineral Processing Laboratory at UBC as shown in Fig *6*6. The system comprises seven main components: X-ray unit, optical camera, visible light source, processor, material inlet, conveyor belt, product box, and reject box. Samples were fed onto the belt via the material inlet and conveyed at a speed of 0.2 m/s. As each sample passed through the system, it was analyzed by both the optical and X-ray sensors, generating three images per scan: an optical image, a low-energy X-ray image, and a high-energy X-ray image. Based on predefined identification criteria, samples were typically sorted into either the product or reject box. However, to prevent breakage upon impact, the belt was reversed at the end of the scan in this study, avoiding sample drop.

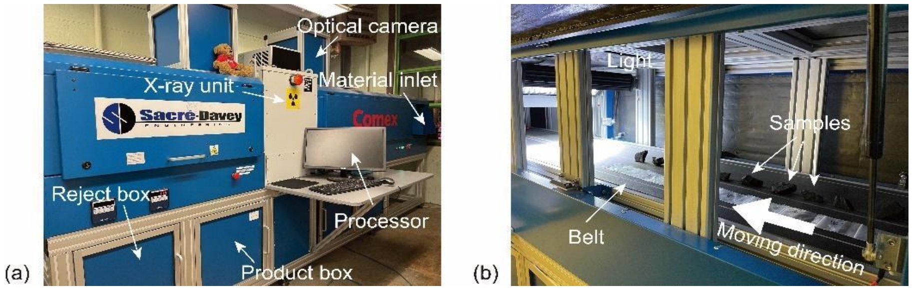

Fig 6: The equipment of the DE-XRT test. (a) the main parts of the DE-XRT equipment; and (b) the inner of the equipment

The intensity of each pixel of the low energy X-ray image and the high energy X-ray image is dependent on the mass attenuation coefficients, which are related to radiation and the material properties such as atomic number [4]. The X-ray is attenuated when it penetrates the material, and the X-ray transparencies follow the Lambert-Beer's law for monochromatic narrow X-ray beam as [5].

3. Results and discussion

3.1. Relative density of the pulverized mixed sample

The experiment involved pulverizing rock samples in ten varying mix ratios across three distinct thicknesses. Fig7 illustrates the processed images of the thirty samples of banded bright coal and dull rock mixture. The pixel values within these images have been assigned a range between 0 (blue) to 200 (yellow), where the lower values indicate lower-density material and higher values represent higher-density material.

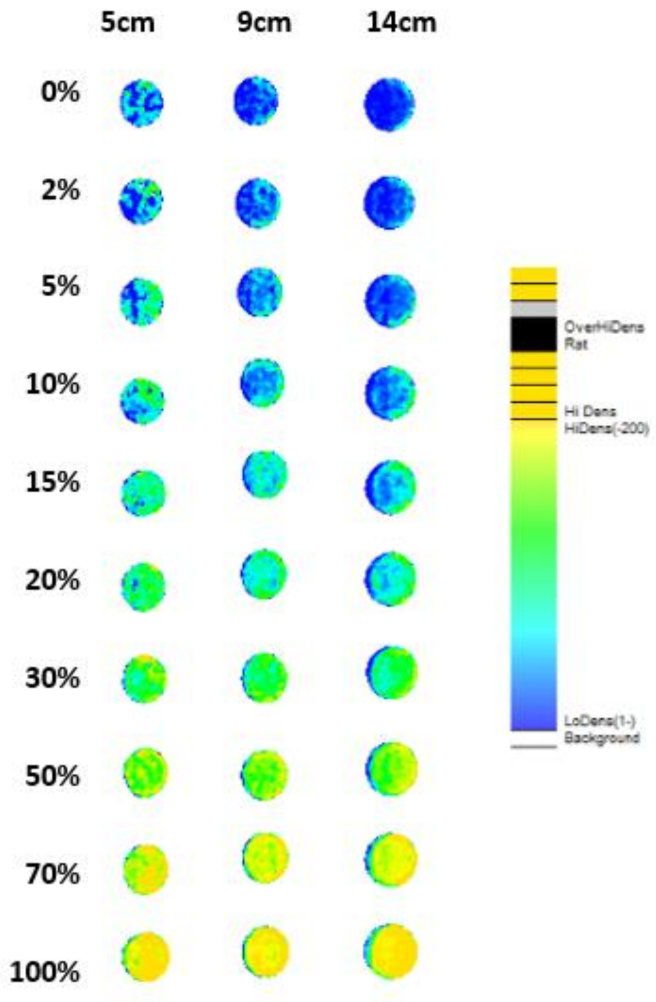

Fig 7: Banded bright coal pulverized samples rock mix ratio

Fig6 illustrates a clear trend in pixel coloration, with values transitioning from blue at 0% to yellow at 100% as the rock mixing ratio increases. This pattern is consistently observed across all sample thicknesses, as indicated by the similar color distributions within each corresponding image.

To quantify this relationship, the average pixel value for each sample was calculated and converted to the corresponding average relative density. These values were then plotted against the rock mixing ratio in a scatter plot, as shown in Fig8. Sample thickness is represented by color: blue for 5 cm, orange for 9 cm, and gray for 14 cm.

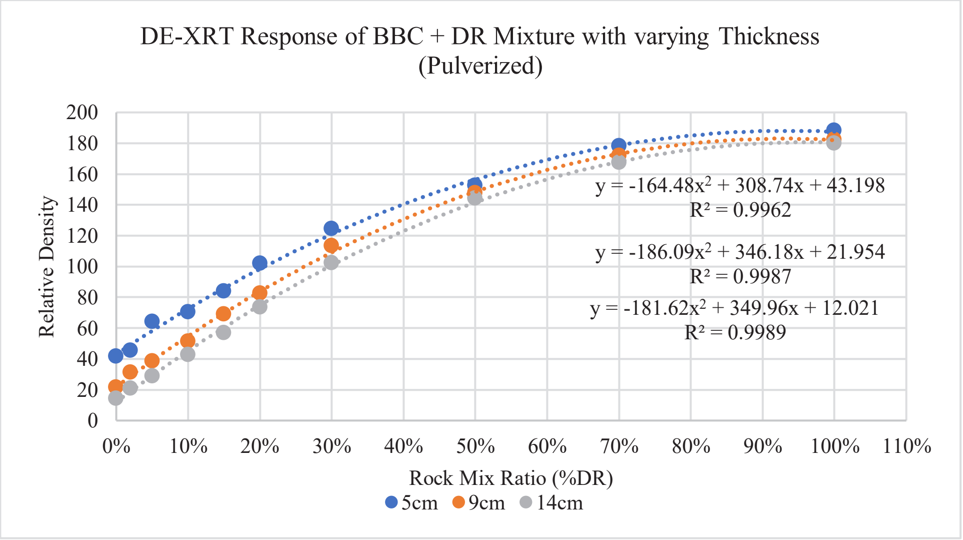

Fig 8: Scatter plot of DE-XRT response versus rock mix ratio of pulverized BBC and DR mixture with varying thickness

A second-order polynomial function was employed to model the relationship between rock mixing ratio and relative density. As shown in Fig8. the fitted curves exhibit a strong correlation across all sample groups, with R^2 values approaching 1, indicating the suitability of the polynomial function for approximating the rock mixing ratio.

Notably, the 5 cm thick samples show a tendency toward higher relative density values, suggesting a potential bias. This may result from the convergence of low- and high-energy attenuation values as overall attenuation decreases, which increases the likelihood of measurement errors in thinner samples. Consequently, the 5 cm samples may be more susceptible to bias compared to the thicker counterparts. The same approach used to generate correlation and was applied to produce the plot as shown in Fig9. Sample thickness is represented by color in the plot: blue for 5 cm, orange for 9 cm, and gray for 14 cm.

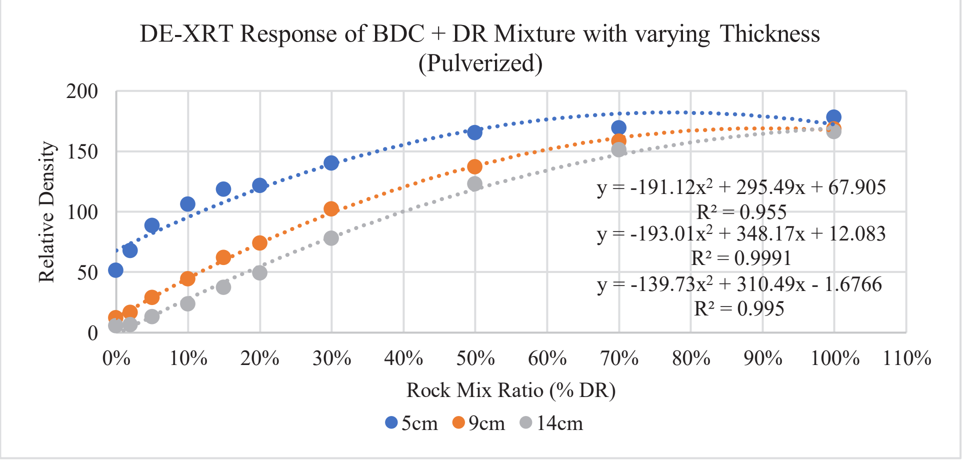

Fig 9: Scatter plot of DE-XRT response versus rock mix ratio of pulverized BDC and DR mixture with varying thickness

A second-order polynomial function was also applied to model the relationship between rock mixing ratio and relative density for pulverized banded dull coal (BDC) samples. As shown in Fig9, strong correlations were observed for the 9 cm and 14 cm thick samples, with R^2 values approaching 1. However, the 5 cm samples, as illustrated in **Fig**9 , exhibited a bias toward higher relative density values and demonstrated a comparatively weaker correlation.

Furthermore, using density calibration curves derived from two known materials of different thicknesses, the results confirmed a strong correlation between rock mixing ratio and relative density. This finding suggests that selecting reference materials with distinct ore characteristics can enhance the reliability of density-based estimations of material composition.

3.2. Coal washability analysis

Using the density curve derived from the pulverized samples, the relative density values of the 36 samples were analyzed to identify correlations. To develop the washability curve and replicate the sink-and-float test based on individual particle S.G., the samples were arranged in ascending order of S.G. The orange marker and line in **Fig 10** represents the washability curve, generated by ranking each particle from lowest to highest S.G.

To construct a washability curve using DE-XRT data, the linear equation obtained from correlation analysis was applied to predict the specific gravity and ash content of each sample. Instead of ranking coal based on direct S.G. measurements, the DE-XRT model ranks samples according to their predicted specific gravity, derived from the average relative density obtained through XRT analysis. This approach allows for a direct comparison between traditional sink-and-float results and DE-XRT predictions.

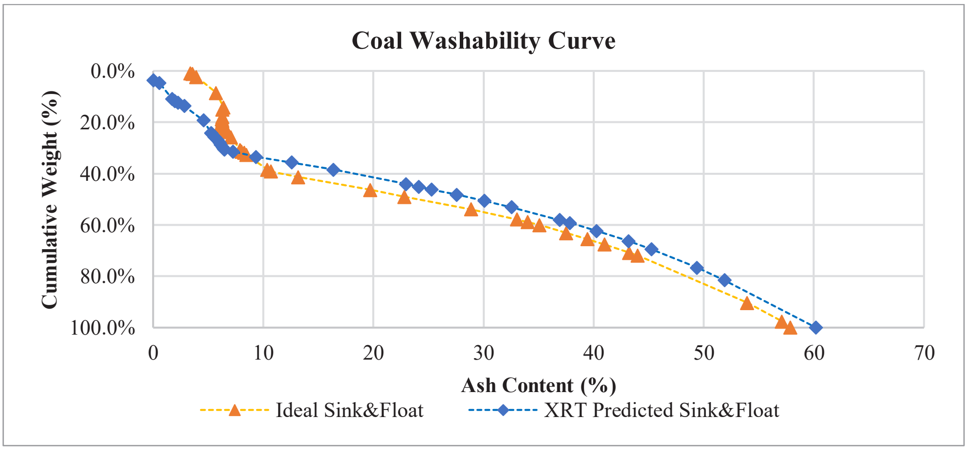

Fig 10: Coal washability curve (ideal versus XRT predicted)

The washability curve compares ideal Sink & Float separation with XRT Predicted Sink & Float, demonstrating the effectiveness of DE-XRT in coal sorting. The XRT-predicted values closely follow the ideal separation curve, particularly at higher ash contents (30-60%), indicating strong predictive accuracy. However, deviations are observed at lower ash contents (0-10%), where XRT overestimates cumulative weight, suggesting challenges in distinguishing clean coal fractions.

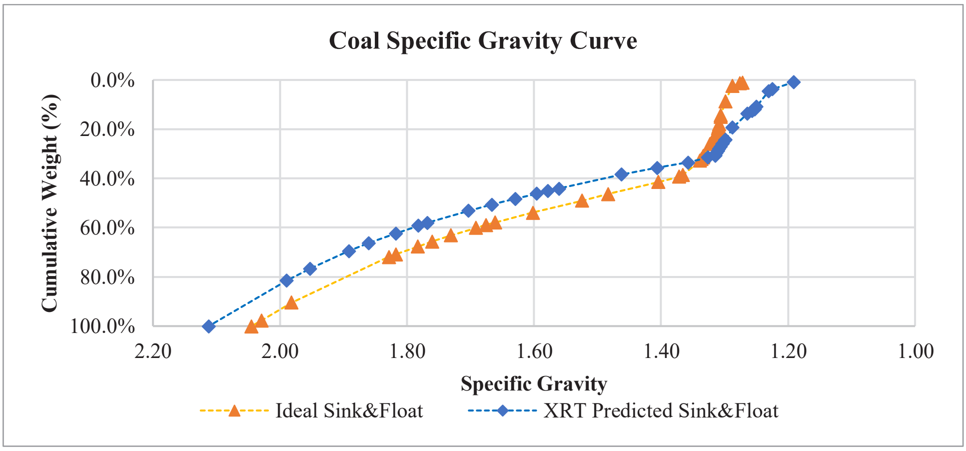

Fig 11: Coal specific gravity curve (ideal versus XRT predicted)

From the Coal Specific Gravity Curve, we see that XRT Predicted Sink & Float follows the Ideal Sink & Float trend well in the mid-range specific gravity values (1.40–2.00 S.G.), indicating that DE-XRT can reasonably estimate coal separability in this range. However, at low specific gravity (<1.40), XRT underestimates cumulative weight, and at high specific gravity (>2.00), it overestimates it. This suggests some limitations in accurately predicting extreme values, likely due to sensor resolution, calibration differences, or variations in material response.

Given this, XRT should be able to estimate the specific gravity range needed for operational separation, particularly in the mid-density range, which is most relevant for coal processing. However, fine-tuning the calibration and improving detection in extreme density ranges would enhance its accuracy for more precise operational control.

4. Conclusion

This study evaluated the effectiveness of dual-energy X-ray transmission (DE-XRT) in predicting washability characteristics of coal through the correlation of ash content and specific gravity (S.G.). By analyzing 36 samples from a coal mine in British Columbia, a structured calibration method using controlled rock-coal ratios was developed to establish DE-XRT response trends. The results demonstrated strong correlations between DE-XRT relative density and rock mix ratio, confirming that DE-XRT can be a viable tool for coal sorting.

The generated washability curves revealed that DE-XRT closely follows the ideal sink-and-float separation, particularly at higher ash contents (30–60%), while minor deviations at lower ash contents (0–10%) suggest challenges in distinguishing cleaner coal fractions. Similarly, the specific gravity curve indicated that DE-XRT accurately estimates separability in the mid-density range (1.40–2.00 S.G.), though some discrepancies were observed at extreme density values. These deviations likely stem from sensor resolution limitations, calibration differences, or material heterogeneity.

Overall, DE-XRT shows promise in determining the specific gravity range needed for operational coal separation, particularly in the mid-density range. Future research should focus on refining calibration methods and improving detection at extreme density levels to enhance prediction accuracy and ensure optimal coal processing efficiency.

Reference

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