Madencilik - Mining, 2023, 62(1), 7-15

BİLİMSEL MADENCİLİK DERGİSİ
SCIENTIFIC MINING JOURNAL

TMMOB Maden Mühendisleri Odası Yayını / The Publication of the Chamber of Mining Engineers of Turkey

www.mining.org.tr

Original Research

An investigation into the enrichment of coal wastes of Western Lignite Company (WLC) by physical and physico-chemical methods

Ali Ucar[a,*], Oktay Sahbaz[a,**], Nezahat Ediz[a,***], Sevgi Karaca[a,****], Ismail Goktay Ediz[a,*****]

[a] *Kütahya Dumlupınar University, Department of Mining Engineering, Kütahya, TÜRKİYE*

Received: 26 May 2022 • Accepted: 28 February 2023

A B S T R A C T

Mechanical excavation and the successive processes of coal production are the main reason for the occurrence of fine waste coals. These wastes are normally discharged without being processed from coal washing plants (-1 mm) which cause not only economic loses but also severe environmental problems. Therefore, it was attempted to enrich waste coals of WLC by using physical and physico-chemical methods and the results were compared.

From the tests, the optimum carbon content and the combustible recovery values were obtained as 85% and 97%, respectively, when sink-float method and the coarse particle size group were chosen. From the tests with the medium particle size group using spiral and Knelson separators, a combustible recovery of up to 90% was reached together with a carbon content of 80%. Moreover, a carbon content of 86.5% with a combustible recovery of 56.6% was obtained by using MGS. In the fine particle size group, the highest combustible recovery was obtained by using spiral and Knelson separators. The highest carbon content in the fine particle size group was reached through MGS and Jameson Cell.

Keywords: *Coal slimes, Flotation, Physical processing methods, Waste coal.*

Introduction

Coal is still the main fossil fuel that supplies 40% of total world energy demand (Xia et al., 2015; Meshram et al., 2015; Sivrikaya, 2014). On the other hand, coal comes out as the main energy resources in countries with limited energy resources because of high petroleum and natural gas prices. Therefore, maximum utilization of coal reserves in such countries is of utmost importance. Increased rate of mechanization and the successive processes used in coal production cause occurrence of a large amount of fine waste coals and decreases in plant performances. Hence, large amounts of coal waste are discharged to nearby waste ponds. This situation inevitably causes not only economic loses but also severe environmental problems (Chaurasia and Nikkam, 2016). Environmental effects caused by coal-related pollutants such as the acidic nature of pyrite within coal and new regulations about discharging coal wastes have recently caused mining companies and the researchers to focus on the possible enrichment of such wastes (Bahri and Karamoozian, 2012). Proper deposition or recycling of these fine coal wastes using effective methods or technologies are therefore, of highest importance for the mining industry in order to remove the environmental barriers for their growth and survival. For this purpose, alternative approaches such as partial or total enrichment of coals from the wastes or isolating the wastes after the dewatering process in suitable deposits to prevent environmental problems should be considered. This will enable the recycling of such coal wastes instead of discharging to the environment, which in turn, provide economic gains and environmental protection (GEM, 2019).

The universal problem with regard to fine waste coals also exists in Turkey. For example, fine coal bearing wastes of 2.5 million m^3 have been discharged yearly from the coal mine of the WLC for which the current research was carried out. Unfortunately, these wastes are not being used in the coal powered station nearby, mainly because of the high dewatering cost required. The other problem being faced with regard to the wastes of WLC is the cost of deposition is getting rather high for the company owing to strict legislation concerning the deposition of such wastes (Turkey, 2015). It is well known that most of the waste ponds are

* Corresponding author: ali.ucar@dpu.edu.tr • https://orcid.org/0000-0002-5220-8829
** oktay.sahbaz@dpu.edu.tr • https://orcid.org/0000-0003-0945-9048
*** nezahat.ediz@dpu.edu.tr • https://orcid.org/0000-0001-9619-7589
**** sevgi.karaca@dpu.edu.tr • https://orcid.org/0000-0001-7478-2437
***** goktay.ediz@dpu.edu.tr • https://orcid.org/0000-0003-0945-9048

https://doi.org/10.30797/madencilik.1111260

almost full with a total amount of wastes reaching up to 18 million m^3. Moreover, the newly created deposition areas such as the old open cast areas are being filled up rapidly. Therefore, the task of processing these fine waste coals is essential not only for economic reasons but also to comply with the legislation for the protection of environment.

From the literature reviewed, it was found out that some physical and physico-chemical methods were seen to be effective for the processing of fine coal wastes. As a matter of fact, various processing equipment ranging from jigs to heavy media separators and from cyclones to spiral separators have been successfully used in many coal processing plants in the world. New equipment such as Multi gravity separator (MGS), Knelson concentrator (KC), Falcon separator, spirals and heavy media cyclones based on the centrifugal forces have recently been employed for the separation and enrichment of fine waste coals.

Research attention has recently been drawn to spirals in removing the ash producing impurities within coal owing to the advantages they have, such as being economical, simple and solid in structure (no movable parts) (Honaker et al., 2006; Honaker, et al., 2013; Oney, 2013). While higher combustible recovery values have been obtained from the tests carried out using coal samples with low ash content, combustible recovery values typically decrease as ash content increases. Research interest has also increased on the use of KC for the processing of fine coals where spirals possess some difficulties. Honaker et al. (1996), obtained a clean coal of 8% ash content with a high combustible recovery from the tests on medium sized coals with low ash content. A clean coal with 16.28% ash content was obtained with a combustible recovery of 67.82% from a hard coal having an ash content of 34.30% by Öney and Tanrıverdi (2016). Uslu et al. (2012), reported that they had removed ash content with a high combustible recovery at a particle size group of -0.500+0.300 mm. A clean coal having 30.51% ash was obtained by Sabah and Koltka (2014) from the samples with high ash content taken from a waste pond.

Processing attempts using spirals on fine particle sizes have been very limited. Honaker et al. (2007) reached a clean coal of 11.71% ash content through a combustible recovery of 84% after processing by spirals on coals with a 33.5% ash content. Moreover, a clean coal of 8% ash content was obtained by 70% combustible recovery by Honaker and Das (2004) using KC on fine coals with a 22% ash content.

Although the MGS application is more common for the processing of chromium ores, there has also been a growing tendency for the use of MGS in coal enrichment. Many investigations have been carried out by using MGS on both run-of-mine coal with high ash content (Aslan et al., 1999; Oz Aksoy et al., 2012a; Oz Aksoy, et al., 2012b; Oz Aksoy et al., 2014) and on the medium and fine particle sized waste coals taken from waste ponds or coal processing plants (Altun et al., 2010; Cicek et al., 2008; Engin et al., 2006; Erdem et al., 2008; Erdem et al., 2012).

Physico-chemical methods have found increasing uses for the processing of finer coal wastes together with physical methods. Coal is typically known as an organic and naturally hydrophobic substance having some inorganic impurities. However, floatability of coal particles is a complex process determined by various factors owing to the complex chemical nature of coal. Although, presence of functional chemical groups within coal such as (carboxyl (-COOH), carbonyl (-C=O), and hydroxyl (phenolic –OH)) are thought to be the main reason for the floatability of coal surfaces, the other factors such as surface elemental composition, surface morphology and particle size also play important roles in the hydrophobicity of coal surfaces (Bunt, 1997; Piñeres et al., 2018; Polat et al., 2003; Sivrikaya, 2014; Sokolović et al., 2012; Tao et al., 2002; Wang and Tao, 2018; Xia etal., 2017). Since the hydrophobicity of coal samples taken from waste ponds is decreased because of the oxidation process, it is required to use an excessive amount of fuel oil (Tao et al., 2002). Therefore, ash content of most Turkish coals could not adequately be reduced by using the flotation method only (Sivrikaya, 2014; Oz Aksoy et al., 2010; Oz Aksoy et al., 2014). As a matter of fact, meaningful results were not obtained from many enrichment tests on highly oxidised coal wastes using mechanical flotation (Engin et al., 2008) and column flotation (Oteyaka et al., 2008). However, a clean coal of 18.3% ash content was obtained with a high combustible recovery by using the Jameson Cell (Ucar et al., 2006). Das et al. (2010), were able to reduce ash content by 50% by using the Jameson Cell in the processing of coking coals with an ash content of 26%; the combustible recovery was 54%.

In this research, enrichment possibilities of fine waste coals were investigated using various physical and physico-chemical methods which are commonly used for ore processing and the comparisons of the aforementioned methods were made. This research can, therefore, be stated as the first comprehensive study which compares the results of various enrichment methods for the wastes of a coal processing plant in Kütahya-Turkey. For this purpose, various methods such as sink-float, spiral separator, KC, MGS and different types of flotation cells were used. The waste pond material was also investigated in terms of their particle size distribution, mineralogy and fractional chemical composition. Effective enrichment performance for the processing of wastes ranging from coarse to fine was determined both by using the equipment working on centrifugal forces and flotation principles; more specifically by using classical and Jameson Cells. Finally, comparisons were made according to the particle size fractions and the equipment used.

1. Materials and methods

1.1. Materials

The samples used during the tests were collected from the waste pond of WLC called Number-4. The pond covers an area of 163637 m^2 with a waste capacity of 3960000 tons. Samples were collected by WLC personnel using an excavator, however, sampling points were determined by the researchers. Samples were collected by 50 m intervals and from the deepest part of the pond that the excavator arm could reach. Two buckets of samples (approximately 2 tons) were excavated from each excavation point. The samples obtained were first mixed-homogenized and later the amount of samples were reduced, near the pond, for delivery to the Mining Laboratory of Dumlupınar University. Approximately 400 kg of the material was taken to the laboratory and then they were re-mixed and homogenised. Homogenized materials were stored after being divided by the coning-and-quartering procedure for use in the following experiments. A Russel-Sieve was used for the proper classification of the material such as in 1, 0.212 and 0.038 mm particle sizes. -0.038 mm sized material was separated by sieving.

1.2. Characterisation

Particle size, chemical (elements, humidity, ash, sulphur and calorific value) and mineralogical analyses were made for the characterisation of the material used. Sieve analysis of the waste material taken from the pond was made in order to determine the cumulative amount of material for any particle fraction chosen and the results are summarised in Figure 1. As seen from Figure 1, waste material taken from the pond exhibits homogeneous distribution at fine particle fractions. Although, the largest particle size is 4 mm, 80% of the samples are finer than 0.150 mm. Under-sieve rate of 0.038 mm is seen to be 69.55%.

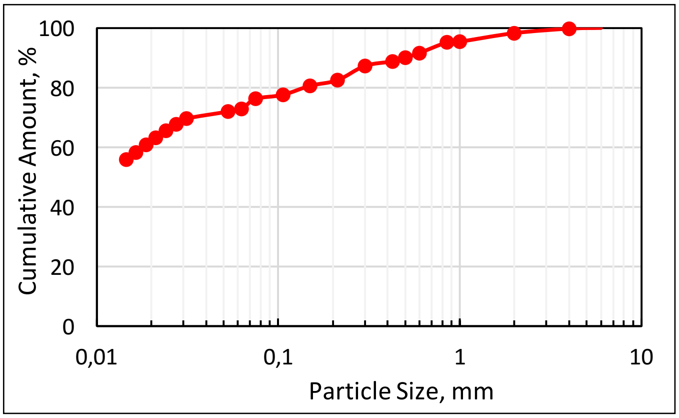

Figure 1. *Particle size distribution of the sample*

Elemental analysis of the material was made using an XRF instrument-of Panalytical brand (Axios Max model). Results of the elemental analysis for the samples taken from the waste pond are given in Table 1.

When Table 1 is examined, it is seen that major oxides are comprised of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O and SO_3. Total amount of Na_2O and TiO_2 compounds within the sample is less than 1%. The reason for the high concentration of SiO_2, Al_2O_3 and Fe_2O_3 are explained by the existence of silica and clay minerals as gang (waste) or neighbouring minerals within the coal.

Coal wastes were classified into various particle size groups through sieving. The results for moisture, ash and sulphur contents, lower calorific value (LCV) and upper calorific value (UCV) of these particle size groups are given in Table 2.

As seen from Table 2, calorific values typically decrease while ash content increases as the particle size decreases. This result can be explained by the fact that clay minerals have fine particles and, therefore, they mostly pass into finer particle size groups. This result is even more noticeable in the materials under 38 microns.

Mineralogical analysis of the samples was made using an XRD instrument called PANalytical-Empyrean series using CuKαX-rays (λ=1.54 Å) in the range of 2θ=5–70° and at a rate of 2°/min. When XRD patterns of the samples are examined (Figure 2), it is seen that the dominant minerals are composed of quartz, muscovite/illite, montmorillonite, kristobalite, kaolinite, gypsum and pyrite.

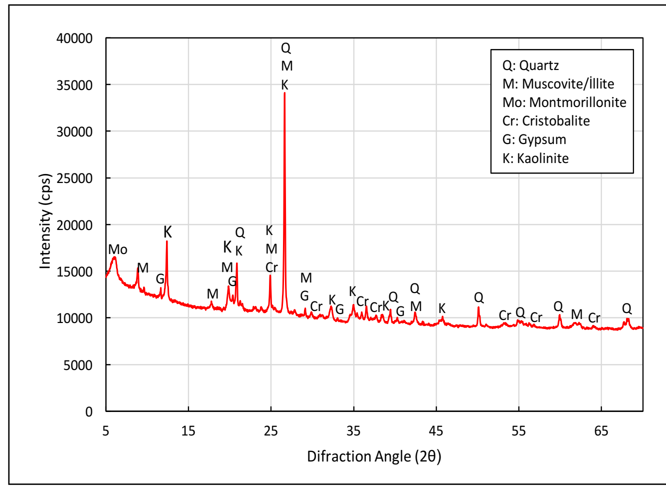

Figure 2. *XRD pattern of the sample*

Table 1. *Results of elemental analysis of the sample*

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	SO_3	LOI
Amount (%)	37.40	14.06	7.07	1.05	2.42	1.73	0.16	0.70	2.01	33.3

Table 2. *The results of humidity, ash content, LCV and UCV of the sample*

Particle Size (mm)	Weight (%)	Ash (%)	UCV (kcal/kg)	LCV, (kcal/kg)	Sulphur, (%)	Moisture, (%)
+4	0.24	27.25	5191	4763	1.07	3.80
-4+2	1.50	24.83	5441	4944	1.16	4.70
-2+1	2.87	20.41	5731	5233	1.19	4.30
-1+0.85	0.24	25.45	5170	4710	1.23	4.30
-0.85+0.6	3.55	22.31	5468	4980	1.24	4.40
-0.6+0.5	1.61	26.00	5260	4803	1.28	4.20
-0.5+0.425	1.23	26.66	5031	4564	1.26	4.60
-0.425+0.3	1.52	33.64	4859	4451	1.20	4.00
-0.3+0.212	4.78	40.04	4519	4133	1.33	4.20
-0.212+0.150	1.86	40.78	4670	4251	1.33	4.60
-0.150+0.106	3.06	47.1	3933	3680	1.43	2.20
-0.106+0.075	1.35	48.03	3358	3086	1.39	3.10
-0.075+0.063	3.33	49.07	3598	3263	1.31	3.90
-0.063+0.053	0.93	50.69	3127	2870	1.12	3.10
-0.053+0.038	2.37	58.81	2531	2333	1.11	2.50
-0.038	69.55	81.91	-	-	0.34	1.70
Total	100.00	68.01	-	-	0.62	2.35

1.3. Methods

The enrichment possibility of the samples taken from the waste pond called Number-4 was investigated in terms of their particle size distribution. Enrichment process was carried out in two stages, namely, the -0.038 mm sized materials with almost no coal content were first removed and the remaining materials were then processed. Samples were classified as coarse (+1 mm), medium (-1+0.212 mm) and fine (-0.212+0.038 mm) and the tests were carried out using these fraction groups of the samples. However, the ultra-fine fraction of the samples (-0.038 mm) being the largest portion (69.55%) but with high ash content (81.91%) and low calorific value was not used during the investigation. Two different enrichment methods, namely physical and physico-chemical methods, were employed throughout the research. Gravity based methods such as sink-float, spiral, KC and MGS were used for the physical processing. On the other hand, flotation method was employed with the mechanical and Jameson type of flotation cells for the physico-chemical processing of fine fraction group only. Sink-float processing method was preferred for the coarse fraction of the samples; the other gravity methods were used for both fine and medium size groups.

The most important performance assessment methods for processing are upgrading curves such as Halbich and Fuerstenau Curves (Duchnowska and Drzymala, 2012). In this research, Halbich Curves were used for the performance assessments or for the comparison of various processing methods employed.

1.3.1. Physical enrichment

In this research, the coarse fraction of the samples was processed by using sink-float method while the gravity based equipment such as Spiral, KC and MGS were used for the processing of other size groups.

1.3.1.1. Sink-float tests

In ASTM method D4371-06, sink-float processing method is fully described. Standard float-sink processes include adding predetermined amounts of representative coal samples into liquids with known densities or a range of densities, after classifying the samples to a specific particle size. Compared to clay, coal has relatively lower specific gravity (1.2 to 1.5). As a result, float-sink tests are typically conducted in liquids with densities ranging from 1.3 to 2.0. These densities were prepared by using $ZnCl_2$. Because coal has a lower density than the mass of clay, it floats in liquids with densities that are equivalent to or higher than coal, while clay sink.

The floating material is evaluated by scraping it off the top of the test tank, drying it, and weighing it to determine the float fraction based on the density of the liquid. The float fraction's ash content is also measured. Then, the graphs are drawn. In such an evaluation, various methods such as Henry Rheinhard Curves, Mayer Curve, Washability Index and MCM Curve are typically utilized (Arslan and Kemal, 2006; Meyers, 2012; Subba Rao and Gouricharan, 2016; Unlu, 1990). More specifically, these methods indicate maximum coal quality to be reached after coal washing processes. Henry Rheinhard Curves were used to evaluate coal washing performance after the float-sink tests during this investigation.

1.3.1.2. Spiral

A laboratory type of Spiral having 5 curvatures and a diameter of 12.5 cm was used. The effects of feeding rate and solid rate to carbon content and combustible recovery values were determined for the fine and medium size fractions during the tests. Samples were collected by intervals both from the concentrate and the waste during testing without changing the descent angle of the equipment. The Spiral was used for the processing of the fine and medium size fractions. The spiral experimental conditions were (Table 3):

Table 3. *Spiral experimental operating conditions*

Parameters	Values
Descent angle (°)	90
Feeding rate (l/min)	5, 10, 15
Solid ratio (%)	10, 20, 30

The optimum results from the tests with medium size fraction were obtained as 30% and 10 l/min for the solid ratio and feeding rate, respectively. However, the optimum results from the tests with the fine fraction were obtained as 20% and 15 l/min for the solid ratio and feeding rate, respectively.

1.3.1.3. Knelson concentrator (KC)

Fine and medium size fractions of the samples were processed by using a laboratory type of KC (KC-MD3). Test were accomplished by changing water flow rates and the rotational speed of conical bowl on both fractions. The KC experimental conditions were (Table 4):

Table 4. *KC experimental operating conditions*

Parameters	Values
Solid ratio (%)	10
Rotational speed (rpm)	20, 30, 40, 50
Water flow rate (l/min)	2, 3, 4

Samples were fed to the KC at a solid ratio of 10% and the overflow (clean coal) was collected in a concentrate bowl while the underflow (waste) was retained by the KC chamber. Clean coal was then washed and dewatered by filtration. Afterwards they were dried, weighed and analysed for their ash content. The optimum operational parameters such as rotational speed and water flow rate for the KC were determined as 150 rpm and 2 l/min, respectively, for the medium and fine particle size groups.

1.3.1.4. Multi gravity separator (MGS)

A laboratory type of MGS called Mozley C900 with a length of 0.6 m and a diameter of 0.5 m was used throughout the experiments. A series of tests were conducted in order to determine the optimum working parameters given below for a maximum concentrate grade and a recovery when using the MGS (Table 5):

Table 5. *MGS experimental operating conditions*

Parameters	Values
Rotational speed (rpm)	230
Drum slope (°)	0, 2, 4
Wash water rate (l/min)	2, 3, 4
Pulp density (% w/w)	20
Feeding rate (l/min)	2
Shaking amplitude (mm)	15
Shaking frequency (cps)	4

Samples which were prepared to be in medium and fine particles sizes were fed to the inner surface of the equipment continuously. The heaviest particles were placed on the inner surface of the drum by infiltrating through the thin layer caused by the pulp under centrifugal forces. These were then transferred upwardly by the scrapers which rotate faster than the drum itself rotating in the same direction. The samples were reverse flow washed before they were discharged from the open end. The low density particles (coal) were transferred to the other exit behind the lower drum by the washing water. Consequently, the products were separately obtained after the steady-state conditions reached; they were then drained, dried, weighed and analysed to determine the optimum parameters given below:

The optimum conditions for medium sized material using MGS were determined as 2° and 2 l/min for the drum slope and feeding rate, respectively. On the other hand, the feeding rate for the fine sized material using MGS was determined as 4 l/min, when the drum slope was chosen as 0°.

1.3.2. Flotation methods

Coal is a solid matter having a heteropolar surface owing to the hydrophobic carbon structure and hydrophilic mineral matter content. Therefore, the flotation method has been used for the recovery of fine coal particles (hydrophobic part) for a long time. In this research, a Denver mechanical flotation cell which is commonly used worldwide and a Jameson Flotation Cell which is mainly used for the processing of fine coals were preferred. A series of flotation tests were conducted in order to float coal particles and to depress ash containing minerals under various operational parameters such as the dosages of collector, depressant and frothing agents. Flotation tests were carried out on the fine sized materials.

1.3.2.1. Mechanic flotation cell

A laboratory type of flotation cell with a capacity of 2 l and self-aerating character was used during the tests. Several tests were conducted to determine the optimum flotation parameters given below (Table 6):

Table 6. *Mechanical flotation cell experimental operating conditions*

Parameters	Values
Collector (kerosene) dosage (g/t)	7000, 8500, 10 000
Frother (AF65) dosage (ppm)	8, 16.5, 25
Depressant (Na_2SiO_3) dosage (g/t)	100, 550, 1000
Mixing rate (rpm)	1200
pH	Natural (7.3)
Pulp solid ratio (%)	10
Conditioning time (min)	8
Flotation time (min)	2

1.3.2.2. Experiments with the Jameson flotation cell

The Jameson Flotation cell, having a worldwide use of more than 250, has been successfully used for coal flotation, especially in Australia. The Jameson Cell whose operational parameters have been explained by various research, Jameson (Jameson, 1988), Sahbaz et al. (2008), was also chosen for this research under the given conditions (Table 7):

Table 7. *Jameson flotation cell experimental operating conditions*

Parameters	Values
Collector (kerosene) dosage (g/t)	700, 5900, 11 000
Frother (AF65) dosage (ppm)	8, 16.5, 25
Depressant (Na_2SiO_3) dosage (g/t)	100, 550, 1000
pH	Natural (7.3)
Pulp solid ratio (%)	5
Conditioning time (min)	8
Feeding rate (l/min)	12
Flow rate for washing water (l/min)	3.2
Tailing flow rate (l/min)	14.5
Bias factor rate	0.78
Air to pulp ratio	0.9
Cell (transparent plexiglas) diameter (d_H) (cm)	20
Vertical shaft (transparent plexiglas) diameter (d_D) and the length (L_C) (cm)	2 and 180
Nozzle (stainless casting steel) diameter (D_N) (cm)	0.4

2. Results and discussion

After the characterisation studies on the wastes of Number-4 pond, it can be said that increased ash content and decreased calorific value owing to the decrease in particle size is an expected result. Total sulphur content of the sample was increased up to the particle size of 0.106 mm, from which it decreased with a decrease in particle size. The reason why sulphur content is relatively lower at -0.038 mm is explained by the fact that sulphur is dominantly contained by the coal material (Table 2). In fact, when Table 1 and 2 is reviewed together, it is seen that total ash content and the loss of ignition values of the waste materials obtained from the elemental analysis show a good conformity. Likewise, total ash content of the waste materials is in good agreement with the ash values obtained from the elemental analysis. As seen from the characterization results, it can conveniently be said that materials under 0.038 mm should not be enriched because of its low carbon content while the other size groups could properly be enriched by using physical and physico-chemical methods.

Experimental parameters were also optimised by evaluating the results obtained from each tests on the various size groups. Ideal beneficiation curves were drawn using the results of combustible recovery and carbon content values experimentally obtained from the fine, medium and coarse size groups of the waste materials under the optimum conditions as well as using the theoretical results of the combined size groups concerned, comparisons were also made.

2.1. Enrichment tests on the coarse size group

The float-sink test results for the coarse size group is given in Figure 3. As seen from the ±0.1 density curve, it can be said that the washing process is made as “very easy”, “easy” and “difficult” at the densities of 1.8 gr/cm^3, 1.6-1.7 gr/cm^3 and at <1.6 gr/cm^3, respectively. A clean coal was obtained with an ash content of 15%, by weight of 88% and a recovery rate of 96.4%, using the optimum density of 1.7 gr/cm^3.

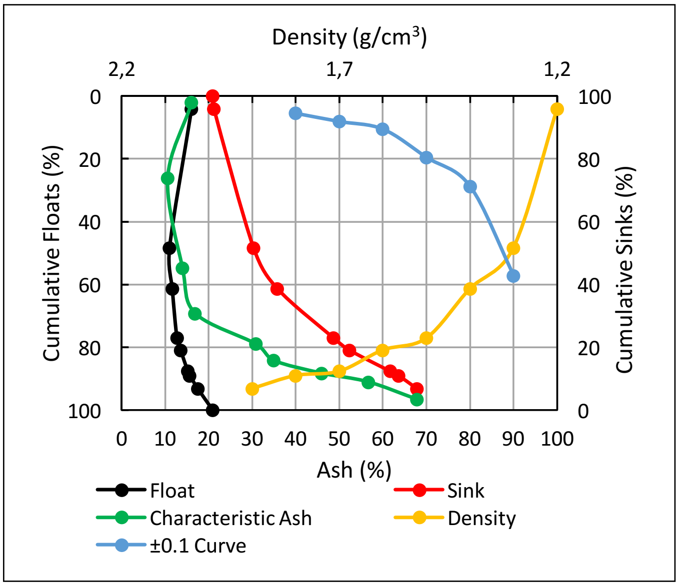

Figure 3. *Float-Sink test results for the coarse particles*

2.2. Enrichment tests on the medium size group

Four different methods were used in order to enrich waste coals in the medium size group (ash content is 31.13%) which are namely; classification, classification + Spiral, MGS and KC. Recovery performance curves obtained from the results are given in Figure 4.

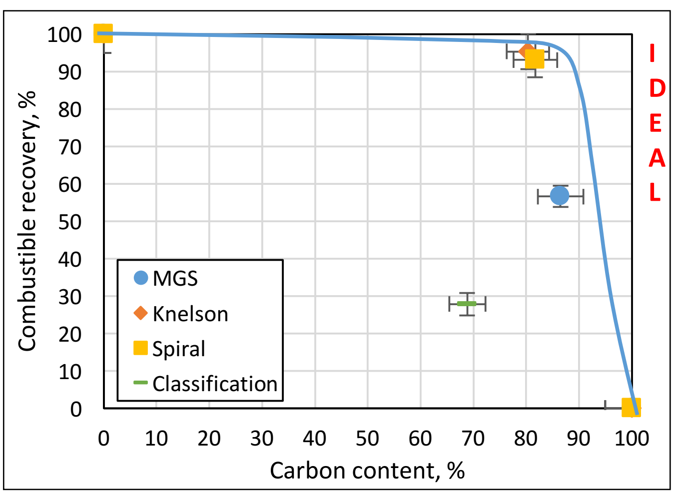

Figure 4. *Comparisons for the recovery performances of various gravity methods on the medium size group*

The best results were obtained by using Spiral and KC at optimum conditions with regard to the carbon content and combustible recovery results, while carbon content of the clean coal produced by classification was found to be 68.87%. The best combustible recovery value was obtained as 95.29% when using the KC; the carbon content was found to be 80.37% in these tests. On the other hand, the best carbon content value was reached by MGS as approximately 85%. However, the combustible recovery could only reach a value of 55% by MGS.

Similar carbon values were obtained (~34% ash) by Altun et al. (2010) and Erdem, et al. (2012) from the beneficiation tests on waste coals using MGS. However, combustible recovery values were relatively higher than those of this research. Aslan (2007), reached a clean coal with a combustible recovery of 60% and an ash content of 36.1% in his research. In all these beneficiation tests using waste coals and MGS, both combustible recovery and ash content values were found to be high. However, high combustible recovery values were obtained together with relatively lower ash contents in this research.

As seen from Figure 4, a clean coal with an ash content of 81.73% was obtained with a combustible recovery of 81.73% by using Spiral. In research done by Sivrikaya (2014), a clean coal with a similar ash content was obtained by a combustible recovery of 57% on coals at -1.5 mm particle size.

2.3. Enrichment tests on the fine size group

The flotation method was also used together with physical methods for the beneficiation of fine sized waste coals. The results of optimum combustible recovery and carbon content obtained by using the classification method and other beneficiation methods after classification are summarized in Figure 5.

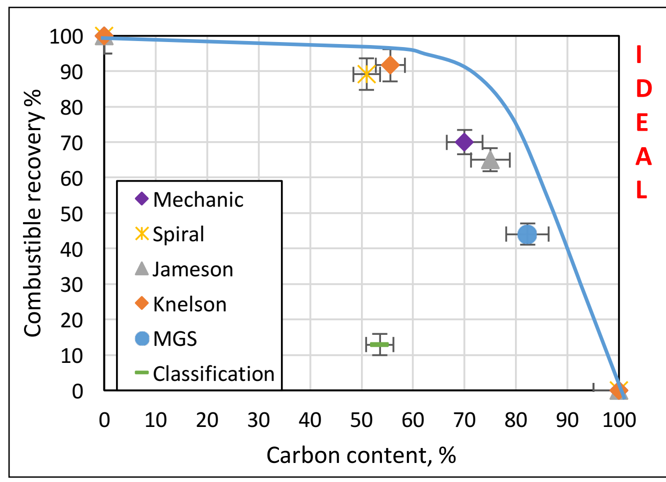

Figure 5. *Performance comparisons for the methods used in the beneficiation of the fine sized group*

A clean coal with a carbon content of 50.8% was obtained by a combustible recovery of 12.9% when the classification method was used on the fine size group. It is well known that methods with higher recovery performances such as MGS, KC and Flotation have become more important for the beneficiation of fine waste coals. As a matter of fact, the highest recoveries were obtained by using Spiral and KC for the fine sized coals as well as for the medium size group. Combustible recoveries of 89.12% and 91.66% were obtained when Spiral and KC were used, respectively. However, carbon contents still remained low with these equipment (around 55%).

The highest carbon content (82.24%) was obtained by MGS in this group of tests. From the tests, it was realised that MGS was more selective but the recovery rate was still low with MGS. In fact, Falconer (2003) reported that MGS provided better selection for fine size groups (75~10 micron). Moreover, similar results were obtained by Ozgen et al. (2011) and Sabah et al. (2007) in their research they achieved clean coals with 20-23% ash contents from the waste of Tunçbilek/Kütahya washery by combustible recoveries of 50-55%. Sonmez and Koca (1997) also gained clean coals with an ash content of 17.62% from the wastes of Tunçbilek/Ömerler washery (41% ash content) by a combustible recovery of 70.66%. In a research done by Koca et al. (2000), a clean coal with an ash content of 17.39 and a lower calorific value of 5082 kcal/kg was obtained by a combustible recovery of 63.08% using MGS from the wastes of Alpagut-Dodurga washery whose ash content, total sulphur and lower caloric values were originally 49.19%, 1.37% and 2650 kcal/kg, respectively. It could properly be concluded that several researches have been carried out on the beneficiation of waste coals using MGS and the results of those studies show similarity with the results of this research.

Meaningful results for carbon content and combustible recovery were not obtained by using the two different types of flotation equipment on the fine size group. In other words, clean coals were obtained with carbon contents of 70% and 75% and combustible recoveries of 70% and 65% from the mechanical flotation and Jameson floatation tests, respectively (Figure 5).

The result can be explained by the oxidation of coal and also by the fact that oxidation process can alter the properties of the coal surface and coal structures. It is well known that low rank coals and oxidised coal surfaces are difficult to float and they require excessive use of kerosene since high oxygen containing functional groups on coal surface cause coal surfaces to become even further hydrophilic (Bunt, 1997; Piñeres et al., 2018; Polat et al., 2003; Sivrikaya, 2014; Sokolović et al., 2012; Tao et al., 2002; Wang and Tao 2018; Xia et al., 2017). Tao et al. (2002) reported that they obtained relatively better results from the mechanical floatation tests using special reactive agents on the oxidised waste coal, however, they were not able to gain successful results from the column floatation tests.

During the optimisation tests, it was found that each size group required different beneficiation methods for better results. Figure 6 summarises the performances of each method used for the size groups used. As seen from Figure 6, spirals become more advantageous with key properties such as being economical, simple and solid (requiring less maintenance and having no movable part) as well as they do not demand chemical use while processing. Almost ideal values were obtained in the medium size group, however, the results for carbon content could not be regarded as ideal in the fine size group. This result was explained by the fact that fine clay particles were mixed up with coal particles through secondary flows when testing with the fine size group. Therefore, equipment such as MGS which applies higher centrifugal forces, should be more meaningful for fine size groups. It was also realised that better results could be gained if the secondary beneficiation process was applied by reducing the solid ratio and water flow rate after preliminary beneficiation by the spiral.

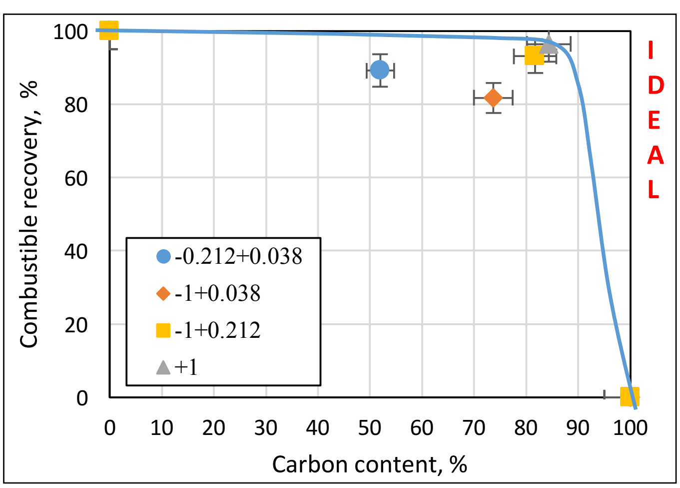

Figure 6. *Comparison of the beneficiation methods used on the various particle size groups*

Centrifugal separators such as KC and MGS concentrators still have limited industrial use although they have been developed for the beneficiation of finely sized coals or minerals. From the test results, it can also be concluded that spirals are good at medium size groups, however, MGS concentrators should be used for fine sized coals to obtain higher carbon content; and KC should be preferred for higher combustible recoveries. The Jameson flotation cell can also be considered for fine sized coals. However, the flotation method should be taken into account only for fresh waste coals which means that it should be used before oxidation occurs to get higher performances.

Conclusion

This research was carried out to determine enrichment possibilities for fine waste coals of WLC by using various physical and physico-chemical methods. The other purpose of the research was to provide a sustainable solution for the environmental problems caused by the deposition of these wastes and to compare the results of various methods for the beneficiation of such waste coals with different size fractions. During the investigation, various physical processing equipment such as sink-float tank, spiral separator, KC, MGS and equipment using physico-chemical methods such as a mechanical cell and the Jameson cell were used.

From the tests carried out, a clean coal with a carbon content and a combustible recovery of 85% and 97% were obtained, respectively, when sink-float method and coarse particle size group (+1 mm) were chosen. Therefore, it was concluded that there was no other equipment needed for the beneficiation of this size group. From the tests with the medium particle size group (-1+0.212 mm) using spiral and KC, combustible recovery of up to 94% was reached together with a carbon content of 81%. A carbon content of 86.49% with a low combustible recovery of 56.58% was obtained by using MGS. In the fine particle size group (-0.212+0.038 mm), the highest combustible recovery values were obtained by using spiral and KC (approximately 90%). Almost ideal carbon content was reached as 82.24% when MGS was used. In the flotation tests, however, a clean coal with carbon contents of 70-75% was obtained through a combustible recovery of 70% by using both mechanical and Jameson Cells.

From the tests results obtained, it was understood that Spirals could efficiently be used for the processing of coal slimes in order to prevent environmental problems and economic loses. The use of MGS, on the other hand, could also be considered as an alternative to spirals whose selectivity is relatively reduced in fine particle sizes. However, more experiments are needed to investigate the reasons of low combustible recovery they produce. Moreover, flotation methods should be considered as an alternative owing to its moderate high carbon content and combustible recovery values over 70%, especially in fine particle size groups. It was also found that the Jameson flotation cell had better selectivity over the mechanical cell and, therefore, it possesses a potential of producing higher carbon content and combustible recovery values on non-oxidised coal surfaces.

Acknowledgement

The authors would like to express their gratitude to the administration of Western Lignite Company for their help in conducting the research.

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