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COMBINED HEAVY MEDIUM-FLOTATION APPROACH FOR RECOVERY OF UNBURNED CARBON FROM THERMAL POWER PLANT SLAG

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Abstract: This study aimed to study unburned carbon recovery from thermal power plant slag using heavy-medium separation and flotation methods. In this context, firstly, the chemical, physical, and mineralogical properties of the slag sample were determined. Based on the data obtained from the chemical, physical, and mineralogical properties of the slag, heavy-medium separation and flotation experiments were carried out. Extensive mineralogical, physical, and microscopic characterization revealed that the slag contains quartz, cristobalite, mullite, hematite, and graphite, and had a porous structure rich in cenospheres and partially unburned coal fragments. The heavy medium separation process showed limited selectivity due to the presence of hollow spherical particles and mineral intergrowth. Thus, the lowest ash content was obtained from the -0.5+0.074 mm fraction with a density of 1.3 g/cm^3 in heavy medium separation experiments. Flotation experiments showed that increasing collector dosage improved combustible recovery and reduced ash content, while decreasing pH increased the recovery but also increased the ash levels. The best flotation performance was obtained with 55.0% ash content and 14.4% combustible recovery using 600 g/t of montanol at natural pH (10.1). Overall, the complex mineralogical structure of the slag, particularly the abundance of cenospheres and the intimate association of carbon with inorganic phases, had significantly limited the efficiency of physical separation methods. In conclusion, the combined mineral processing and beneficiation processes, particularly the combination of fine-sized separation methods, are necessary for recovering unburned carbon with higher purity.

Keywords: Mineral processing, Thermal power plant slag, Unburned carbon, Heavy medium separation, Flotation

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1. Introduction

As a result of 70-80% of the energy demand is supplied by fossil sources, coal consumption was reached to 8.85 billion tonnes in several major markets, and millions of tons of slag, bottom ash, and fly ash are produced as solid byproducts in thermal power plants around the world (IEA, 2025). Since these byproducts were initially considered waste and stocked without being used, the problem of space for the stocking of these waste materials began to arise, and the necessity to evaluate such materials appeared due to environmental effects (EPA, 2020). Studies have shown that due to their pozzolanic properties, these types of materials are used in the cement industry, as a filler material in mines, and as aggregates in road construction, and are beginning to be valued as by-products rather than waste (Kumar et al., 2010; Behera et al., 2021; Mohsen et al., 2023).

Low-calorie coals such as lignite, which cannot be used for heating purposes, are mostly burned in pulverized form to heat the boilers that generate steam in thermal power plants (Deniz et al., 2021). For electricity generation, coal that is crushed and ground so that 80% passes through a 75 µm sieve is mixed with preheated air for drying and blown into a thermal power plant boiler to be burned (Williams et al., 2016). As a result of the combustion process, depending on the type of coal, various gases and solid wastes (such as coal ash and unburned residues) in the form of slag, ash, and gas are released into the atmosphere, soil, and water as pollutants (Oktay, 2009; Guttikunda and Jawahar, 2014). Due to energy demand, there is a strong effort to increase energy production by establishing large-capacity thermal power plants around low-quality lignite deposits that are found in other parts of the industry. However, the increase in thermal power plants leads to an increase in waste production as a by-product of energy production, creating technical, economic, and environmental problems (Kravchenko, 2018; EPA, 2020). Coal contains toxic trace elements with the potential to cause pollution, such as arsenic (As), cadmium (Cd), lead (Pb), antimony (Sb), selenium (Se), tin (Sn), and zinc (Zn) (Unver and Terzi, 2018). These elements mix with soil, surface water,

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and groundwater as waste is washed away by rainwater and carried underground (Egemen and Yurteri, 1996; Wang et al., 2022), and can reach threatening levels for living organisms by creating various environmental, land use, and health problems.

10-70% of slag obtained from burning coal is a granular material with a particle size of d_{90}≈5.0 mm and a smooth surface (Sidek et al., 2021; Yatsenko et al., 2023). However, if gas becomes trapped within the material during the melting of slags, a rougher and more porous structure is formed. Burning lignite and semi-bituminous coals produces more porous slag compared to burning bituminous coal (Wang, 2016). Fly ash and bottom ash are widely used in the cement industry. The main reasons for choosing fly ash in cement production are its fine-size structure, which reduces grinding and raw material costs, its pozzollanic properties, and its high CaO content (Pan et al., 2008; Nanda and Rout, 2021). Due to their physico-chemical properties, thermal power plant ash is also used as a raw material in the production of building materials with active components (Kosivtsov et al., 2021). Another crucial issue is the utilization of the unburned carbon (5-25%) remaining in the slag (Ryabov et al., 2019). Due to the type of materials contained in the coal fed to thermal power plants, some materials are not properly washed in coal washing facilities and efficiently burned, resulting in unburned carbon.

In the literature, wet and dry medium based-separation methods have been applied to separate unburned carbon from thermal power plant ash. In heavy-medium separation-based sink-float methods, density differences are used to separate unburned carbon from the ash content in heavy medium, which was made up from organic liquids, soluble salts, and high-density solids (Külaots et al., 2004; Kurama and Kaya, 2008). It is important to adjust proper density so that light unburned carbon particles float and the heavier ash particles settle to the bottom (Hwang et al., 2002; Vassilev et al., 2003). Furhtermore, soluble salts are preferred over organic liquids for environmental and economic reasons (Maroto et al., 1999). It is possible to recover unburned carbon with high density from slag with low density using heavy medium separation methods (Özdemir and Çelik, 2002). Light materials in slag can be recovered using jigs and spirals (Xing et al., 2019). Spirals can be used to separate heavy materials in slag and bottom ash from light components. The material fed into the spirals from above descends under the effect of centrifugal and gravitational forces. Low-density material, such as unburned carbon, moves outward, while high-density components remain inside the spiral and separated by being collected separately from the bottom of the spiral. On the other hand, jigging is used to separate unburned carbon and heavy minerals thermal power plant wastes by stratification according to density difference (Groppo et al., 2004).

Flotation is a physico-chemical method based on the separation of fine-grained hydrophobic materials from hydrophilic ones using various reagents (Şahbaz et al., 2024). Since the unburned carbon in thermal power plant wastes is in a fine particle size, flotation is the most commonly used method for a beneficial separation. Besides, parameters such as the dosage of chemicals, pH of the environment, and particle size distribution are effective in the separation process (Liu et al., 2024). Such parameters involved enhancing the hydrophobic nature of fine unburned carbon particles via collector addition and raising the chances of collision/attachment by minimizing bubble size and increasing the effective particle size (Sobhy et al., 2013; Yoon et al., 1989). In the literature, hydrocarbon oils as collectors, methyl isobutyl carbinol or pine oil as frother, sodium meta silicate as suppressant, and butanol to increase the floatability of carbonaceous particles have been studied in ash flotation (Demir et al., 2008, Yamık et al., 2008). The biggest problem in separating unburned carbon by flotation is the oxidized surfaces and porous structure of carbonaceous particles due to combustion; this results in their low hydrophobic properties, thus making the floating process more difficult. Collectors such as diesel, kerosene, and methanol are preferred in the flotation of thermal power plant wastes. The surface area of such wastes reduced to a fine size by grinding increases, while the pores formed on the surface after combustion also increase the surface area, and therefore the amount of collectors used in the flotation of such materials increases (Huang et al., 2003; Şahbaz et al., 2008). Therefore, high dosages of collector are used to float coal-based thermal power plant ashes (Uçurum et al., 2011; Yang et al., 2020). Previous studies also investigated electrostatic and leaching methods for the beneficiation of unburned carbon and rare earth metals from ash (Cangialosi et al., 2008; Izquierdo and Querol, 2011).

Since not much work has been done on the unburned carbon remaining in the slag, a significant amount of material is used in various industries without being properly utilized, resulting in the loss of unburned carbon. In this context, this study aims to investigate heavy-medium separation and flotation methods for recovering unburned carbon from the slag of Çan Thermal Power Plant.

2. Materials and Methods

2.1. Materials

The slag sample taken from Çan Thermal Power Plant in Çanakkale was subjected to characterization studies consisting of mineralogical, microscopic, and physical analyses. Subsequently, heavy-medium separation and flotation experiments were carried out as part of the physical and physico-chemical studies.

To determine the mineralogical composition of the slag sample, the X-Ray Diffraction (XRF) analytical technique was applied using the PANalytical brand Empyrean model instrument. Mineralogical analysis revealed that the dominant phases in the slag sample were quartz,

cristobalite, mullite, and hematite, while the unburned carbon content appeared as a graphite peak in the XRD graph (Figure 1).

A JEOL brand JSM-7100-F model Scanning Electron Microscope (SEM) was used to determine the microstructure and morphology of the slag sample in detail. Gold-palladium (80–20%) plating process was applied in a vacuum environment of 8.10^{-1} mbar/Pa with a current intensity of 10 mA. SEM images revealed that the slag sample generally had a spongy and irregular morphology with a rough structure containing unburned lamellar coal fragments and cenospheres in different sizes. The spongy structure of the slag was due to the gas release that occurred in its composition as a result of thermal processing during coal combustion. Additionally, the spherical morphology of cenospheres was likely attributable to the elevated temperatures to which slag particles were typically exposed; this geometry developed due to the contraction of the liquid phase during cooling (Figure 2).

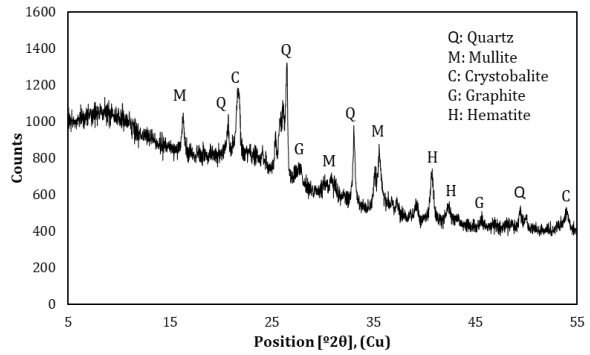


Figure 1. XRD diagram of slag sample.

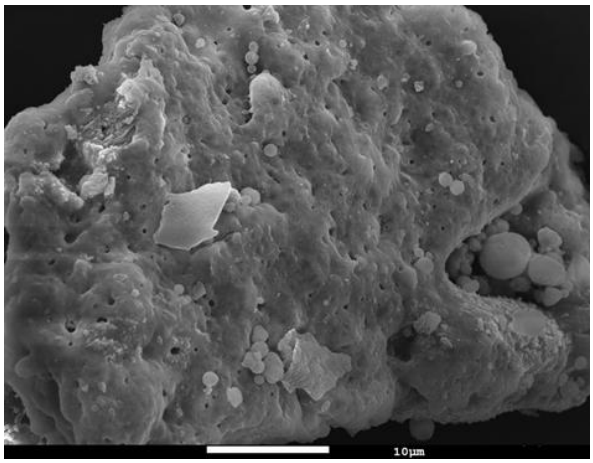


Figure 2. SEM image of slag sample.

The slag to be used in the experimental studies was first passed through a jaw crusher with an aperture of 2 mm for primary particle size reduction, and wet sieve analysis was performed to determine the size distribution of the sample. It was seen that the material was found to be -2 mm in particle size, additionally d_{80} and d_{50} values were 0.90 and 0.55 mm, respectively (Figure 3).

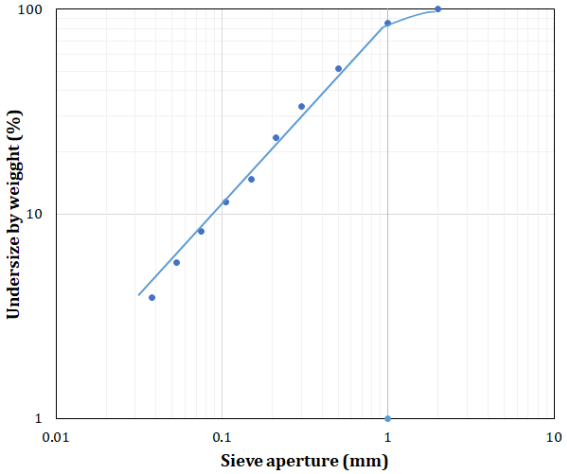


Figure 3. The particle size distribution of the sample

The ash content of the slag sample was examined as a function of size, and the results are shown in Figure 4. According to these results, the lowest and the highest ash contents of the size fractions were found to be 63.4% and 77.9% for -0.074 mm and -0.500+0.300 mm, respectively.

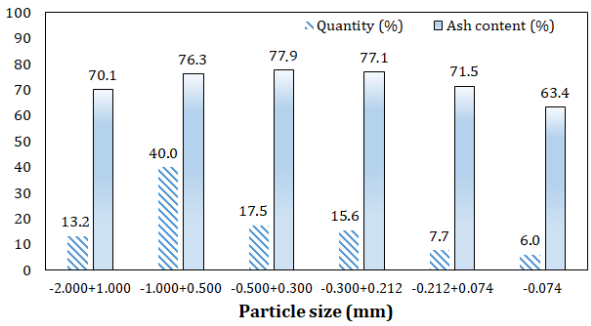


Figure 4. Ash contents of the slag according to particle size fractions by quantity.

2.2. Methods

Heavy medium separation experiments were carried out in 20-liter transparent plastic containers by the float-sink method at densities of 1.3, 1.45, 1.60, 1.75, and 1.90 g/cm^3. $ZnCl_2$ (98% pure) was used to make heavy liquid solutions. 3 kg of slag samples in -2+0.5 mm and -0.5+0.074 mm size groups were used for each float-sink experiments, separately. The experiments were conducted starting with a lower density, and the floating products were separated, and the sinking products were fed into the liquid with a higher density. Figure 5 shows the basic experimental flowsheet for heavy medium separation.

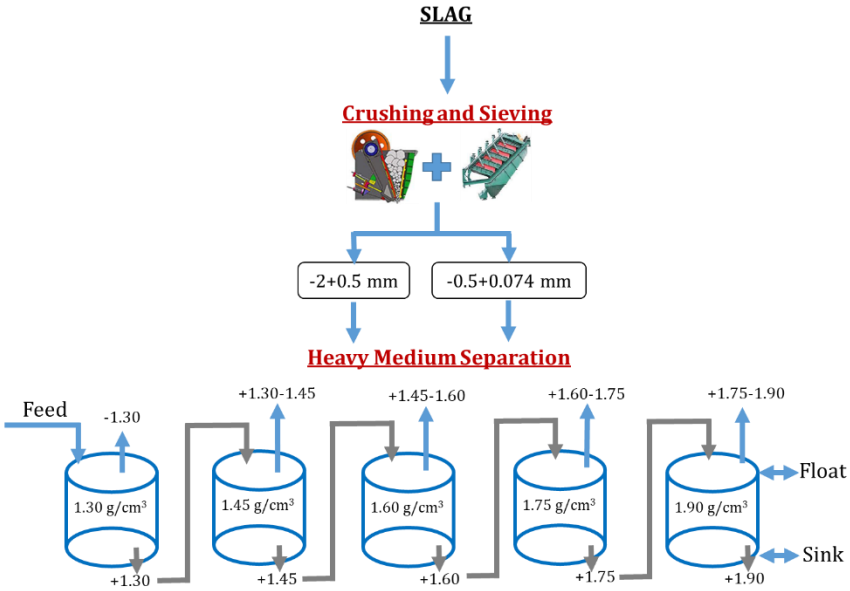


Figure 5. Heavy medium separation experimental flowsheet.

To separate fine-sized unburned carbon as a physico-chemical mineral separation method, flotation experiments were applied to ground slag that had been sieved to -74 µm particle size. In the flotation experiments, Na_2SiO_3 as a silicate depressant; kerosene, diesel, and montanol as collectors; and iso-octanol as a frother were used (Chen et al., 2019). 5 min. of conditioning time and 3 min of flotation time was applied, and the impeller speed was 1300 rpm at different pH values using a 0.1 M HCl solution. The experimental procedure of the flotation experiments is shown in Figure 6. The samples obtained from experimental studies were dried in an oven at 105°C. After the drying process, the samples were heated at 850°C for 2 hours to evaluate the unburned carbon in the samples, and the ash content was determined and calculated according to equation 1.

$$\text{Ash content, \%} : \frac{\text{The weight of residual ash after heat treatment}}{\text{The weight of feed slag}} \text{ x } 100 \quad (1)$$

The concentrates obtained from the experimental studies were compared in terms of combustible recovery as given in equation 2.

$$\text{Combustible recovery, \%} = 100 \text{ x } \frac{C \text{ x } (100-c)}{F \text{ x } (100-f)} \quad (2)$$

F= weight of feed material (g), C= weight of concentrate (g), f= ash content of feed material (%), c= ash content of concentrate (%).

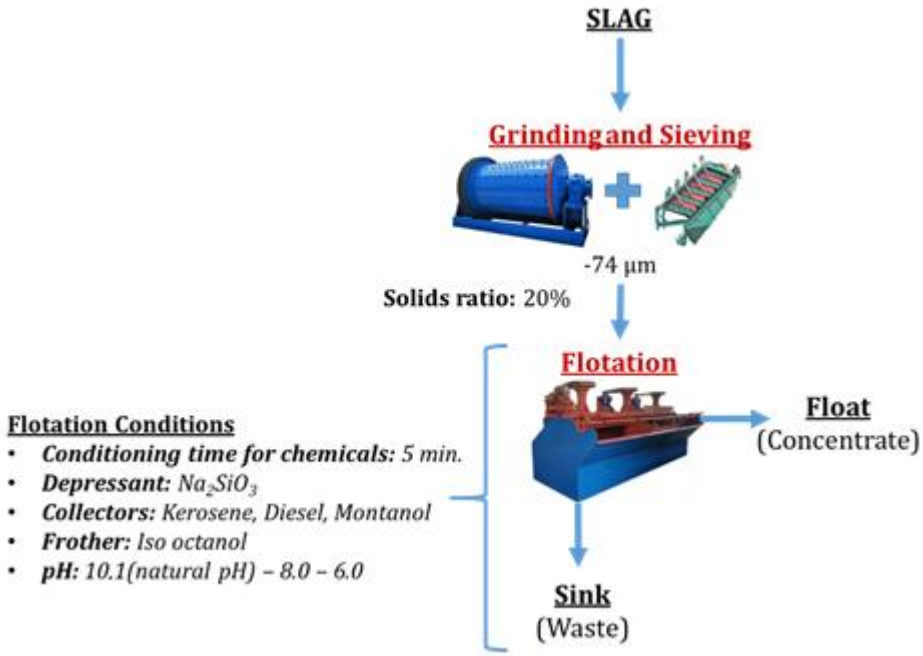


Figure 6. Flowsheet for flotation experiments.

3. Results and Discussion

3.1. Heavy Medium Separation Experiments

Zinc chloride ($ZnCl_2$) was used to adjust the density in the heavy medium separation experiments performed with samples divided into -2+0.5 mm and -0.5+0.0.074 mm size fractions. The results of the heavy medium separation experiment and the floating curves are shown in Figure 7.

It was seen that material quantity and ash content increased for both -2+0.5 mm and -0.5+0.074 mm size fractions with increasing density. This tendency to increase showed a different trend at -1.45+1.30 g/cm^3, which was explained by the inorganic particles, which had a spherical shape after the burning process (Li et al., 2024). These spherical-shaped materials resulted in the concentration of inorganic materials at lower densities (Ma et al., 2023). In heavy medium experiments, only 56.1% and 41.0% of ash content floated products were obtained at 1.3 g/cm^3 for -2+1 mm and -0.5+0.074 mm of size fractions, respectively. At densities higher than 1.9 g/cm^3, the ash content exceeded 76%. This feature arises from the mineralogical properties of the sample. The fact that some particles in the sample had a hollow spherical structure reduced their true specific gravity. Additionally, the presence of micron-sized inorganic substances increased the ash content of unburned carbon particles.

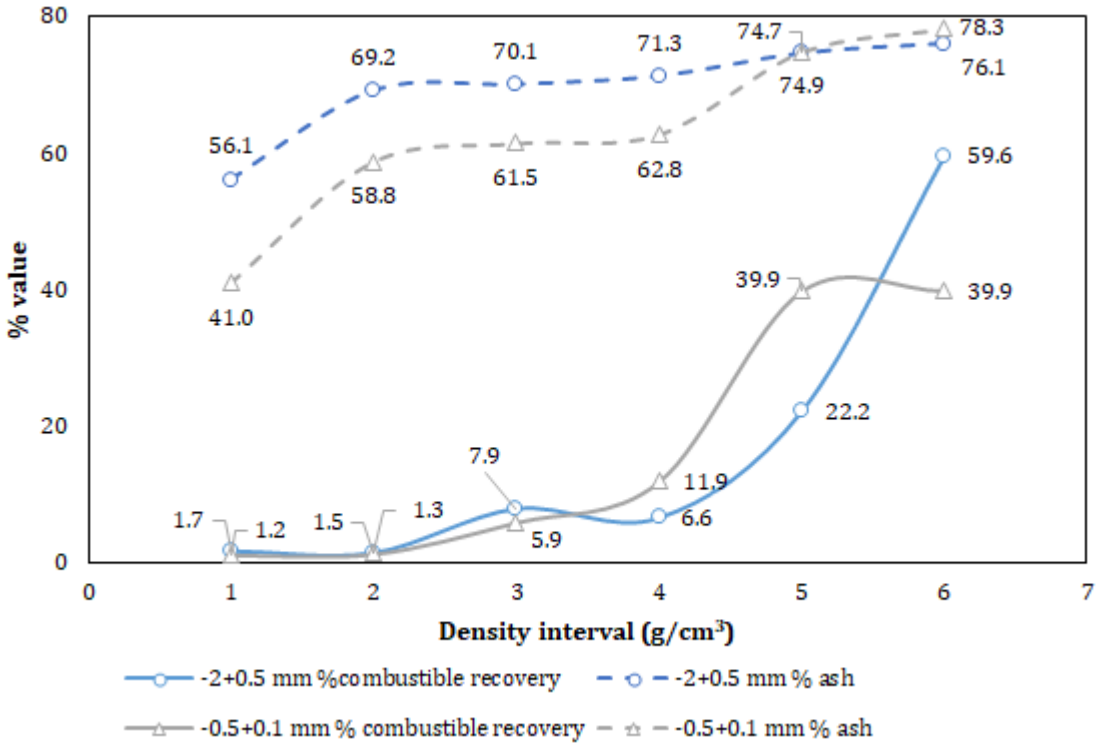


Figure 7. Results for heavy medium separation -2+0.5 mm and -0.5+0.1 mm size fractions according to density.

3.2. Flotation Tests

In the flotation tests applied to the slag sample, the experiments were conducted by varying the collector type and pH. Triplicate experiments were realized for flotation experiments and standard deviations were given for ash contents and combustible recovery. It was aimed to obtain a concentrate with the lowest ash content using a Denver-type flotation cell with a 1 L capacity, and the conditions are presented in Table 1.

The flotation experiments were initiated to investigate the effect of collector dosage at natural pH (10.1). The collector dosages were explained as 1st, 2^{nd,} and 3rd in Figure 8 and already given in Table 2. The ash content and combustible recovery results of flotation concentrates, according to different collector types and dosages, are shown in Figure 7.

Table 1. Flotation conditions

Collectors	Kerosene, Diesel, Montanol
pH	10.1 – 8.0 – 6.0
Particle size	-74 µm
Solids ratio	20%
Depressant	1000 g/t of Na_2SiO_3
Frother	600 g/t of Iso-octanol
Conditioning time	5 min. for each flotation reactive
Impeller speed	1300 rpm
Flotation time	3 min.

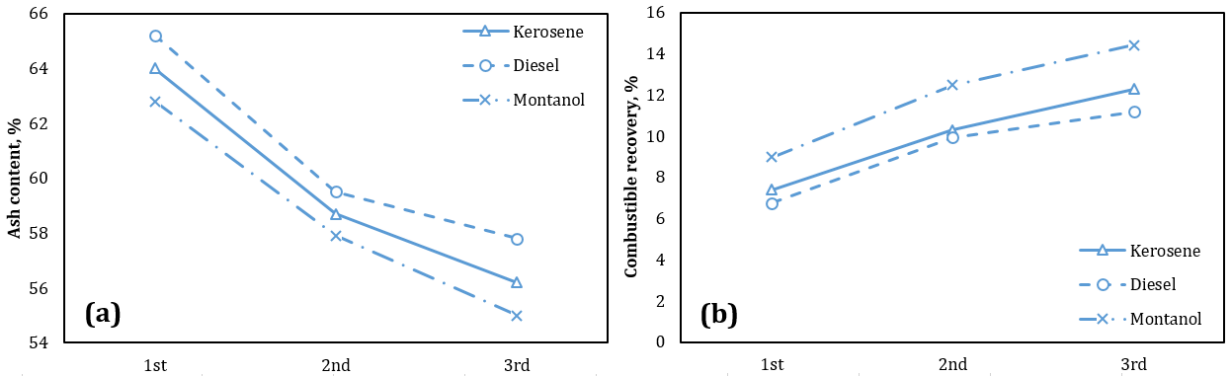


Figure 8. (a) Ash content and (b) Combustible recovery results according to different collector types and dosage

Table 2. Flotation experiments and collector dosages

Experiment / Collector	1st	2nd	3rd
Kerosene	2000	4000	6000
Diesel	1000	2000	3000
Montanol	200	400	600

Flotation tests were carried out at natural pH (10.1) by increasing the collector dosage and obtaining a concentrate. As a result of the flotation tests conducted based on the collector amount, it was determined that as the dosage increased for each collector type, the ash content decreased and the combustible recovery increased. In flotation experiments where kerosene was increased from 2000 g/t to 6000 g/t, diesel from 1000 g/t to 3000 g/t, and methanol from 200 g/t to 600 g/t, the ash contents of the concentrates decreased from 64±2.3% to 56.2±2.0%, from 65.2±2.5% to 57.8±2.1%, and from 62.8±2.2% to 55.0±2.0%, while combustible recovery increased from 7.4±0.2% to 12.3±0.3%; from 6.7±0.2% to 11.2±0.3%; and from 9.0±0.2% to 14.4±0.4%, respectively (Figure 8).

To investigate the effects of different pH environments on flotation, the experiments were conducted by reducing the natural pH (10.1) to pH 8 and pH 6 and keeping the collector dosages constant at 6000 g/t for kerosene, 3000 g/t for diesel, and 600 g/t for methanol. The concentrates were obtained from the flotation experiments realized at different pH levels, and changes in ash content and combustible recovery were examined in relation to pH. The pH-dependent flotation experiments revealed that ash content and combustible recovery increased as pH decreased. As the pH value decreased from 10.1 to 6, the ash content/combustible recovery values of the concentrates for kerosene, diesel, and montanol were 56.2±2.1/12.3±0.3% to 63.4±2.3/15.9±0.4%, from 57.8±2.2/11.2±0.3% to 62.1/15.3±0.4%, and from 55.0±2.1/14.4±0.4% to 61.9±2.3/17.9±0.5%, respectively (Figure 9).

SEM/EDX analyses were performed to examine the content and structure of the concentrates obtained from heavy medium separation (Float for particle size: -0.5+0.074 mm; Density: -1.3 g/cm^3) and flotation (pH: 10.1; Montanol: 600 g/t) experiments. Figure 10a shows the cenospheres bound to the structure of the sample floating as a result of heavy medium separation, and it was understood that the particle release size of cenospheres was below 5 µm. Cenospheres, filled with air, reduced the specific gravity and therefore caused them to float together with unburned carbon, which had a relatively lower specific gravity. Therefore, the recovery of unburned carbon in the sample was limited, and the ash content increased (Bennehalli, 2025). Similarly, the bound cenospheres in the flotation concentrate came with the froth due to the lighter structure, limiting the selective recovery of unburned carbon depending on surface properties, and therefore, high ash contents were obtained (Figure 10b).

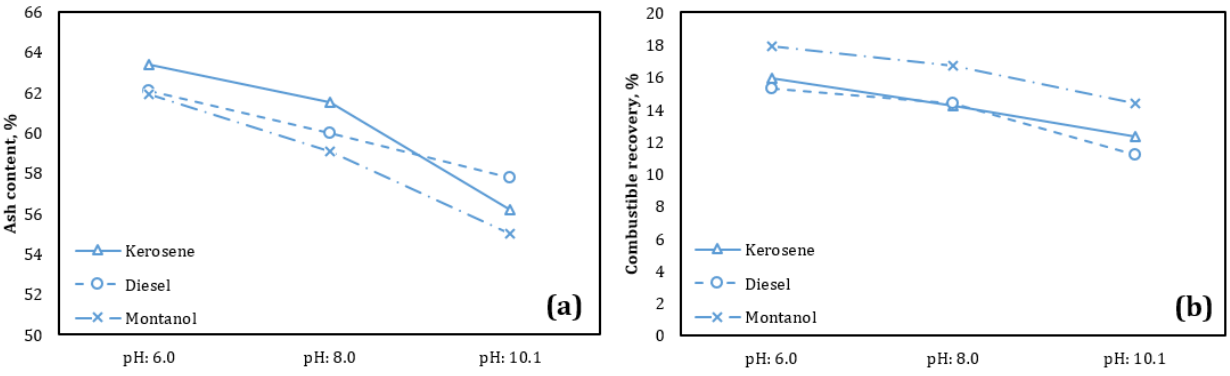


Figure 9. (a) Ash content and (b) Combustible recovery results according to pH.

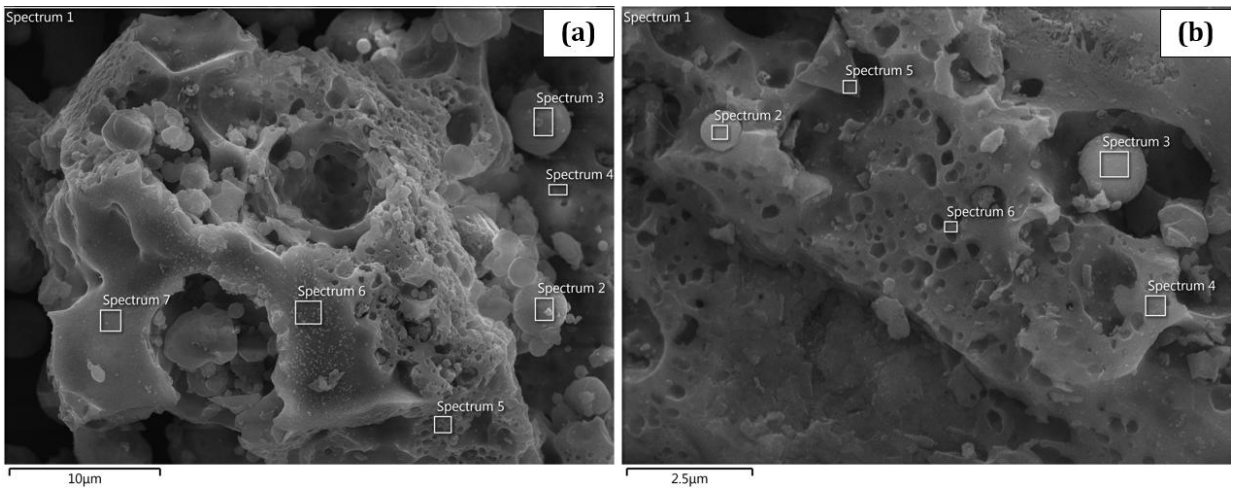


Figure 10. SEM/EDX analysis of (a) Heavy medium separation and (b) Flotation concentrate.

4. Conclusion

In this study, it was investigated to obtain unburned carbon from the slags of the Çan Thermal Power Plant using heavy-medium separation and flotation methods. And, the results obtained from the experimental studies are given below: Chemical, structural, and physical analyses were performed to determine the properties of the slag. As a result of the size analysis, d_{80} = 0.90 mm and d_{50} size was found to be 0.55 mm. The ash content of the slag was determined according to the particle size, and it was found to be 74.7%.

Mineralogical analysis of the slag revealed quartz and cristobalite, originated form silicates, mullite originating from clay minerals, hematite as an iron mineral, and graphite as unburned carbon was detected.

In the enrichment experiments carried out by heavy medium separation, the lowest ash product was obtained in the -0.5+0.074 mm size group, and the floating product with a density of 1.3, with an ash content of 41.0%.

A concentrate with 55.0% ash content and 14.4% combustible recovery was obtained in the flotation experiments using 600 g/t montanol at natural pH (10.1). The mineralogical structure took the greatest share in the non-enrichment of unburned carbon from slag. Just as there were micron-sized ash-forming elements in the unburned carbon, the excessive amounts of cenospheres in the slag played a negative role, especially in enrichment by flotation.

Since the presence of unburned carbon and mineral substances in the slag limited the possibilities of enrichment by physical methods, a combination of mineral processing and enrichment methods must be attempted to obtain high-purity unburned carbon at submicron sizes. In this case, applying physical enrichment methods following selective dissolution will play a significant role in increasing the degree of purity.

Author Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	E.D.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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This section is not mandatory, but in this section, you can acknowledge any support given which is not covered by the author's contribution sections. This may include administrative and technical support or donations in kind (e.g., materials used for experiments).

References

Behera, S., Mishra, D., Singh, P., Mishra, K., Mandal, S. K., Ghosh, C., Kumar, R., & Mandal, P. K. (2021). Utilization of mill tailings, fly ash and slag as mine paste backfill material: Review and future perspective. *Construction and Building Materials*, *309*, Article 125120. https://doi.org/10.1016/j.conbuildmat.2021.125120

Bennehalli, B., Poyil, S. S., Lokesh, B., Nagaraja, S., Basavaraju, S., Rispandi, & Ammarullah, M. I. (2025). A review on the formation, recovery, and properties of coal fly ash (CFA)-derived microspheres for sustainable technologies and biomedical applications. *Next Materials*, *9*, Article 101172. https://doi.org/10.1016/j.nxmate.2025.101172

Cangialosi, F., Notarnicola, M., Liberti, L., & Stencel, J. M. (2008). The effects of particle concentration and charge exchange on fly ash beneficiation with pneumatic triboelectrostatic separation. *Separation and Purification Technology*, *62*(1), 240–248. https://doi.org/10.1016/j.seppur.2008.01.031

Chen, X., Gu, H. G., Liu, D., & Zhu, R. (2019). The flotation separation of barite-calcite using sodium silicate as depressant in the presence of sodium dodecyl sulfate. *Physicochemical Problems of Mineral Processing*, *55*(2), 346–355. https://doi.org/10.5277/ppmp18136

Demir, U., Yamik, A., Kelebek, S., Oteyaka, B., Ucar, A., & Sahbaz, O. (2008). Characterization and column flotation of bottom ashes from Tuncbilek power plant. *Fuel*, *87*(6), 666–672. https://doi.org/10.1016/j.fuel.2007.05.040

Deniz, C., Boke, Y., Aydin, O., & Benim, A. (2021). Computational analysis of pulverized coal co-firing with biomass in 150 MWE unit of Tuncbilek thermal power plant. *Journal of Thermal Science and Technology*, *41*(1), 37–50

Egemen, E., & Yurteri, C. (1996). Regulatory leaching tests for fly ash: A case study. *Waste Management & Research*, *14*(1), 43–50. https://doi.org/10.1177/0734242x9601400105

EPA. (2020). Environmental Protection Agency. *Steam electric power generating effluent guidelines*. https://www.epa.gov/eg/steam-electric-power-generating-effluent-guidelines

Groppo, J., Robl, T., & Hower, J. C. (2004). The beneficiation of coal combustion ash. *Geological Society, London, Special Publications*, *236*(1), 247–262. https://doi.org/10.1144/gsl.sp.2004.236.01.15

Guttikunda, S. K., & Jawahar, P. (2014). Atmospheric emissions and pollution from the coal-fired thermal power plants in India. *Atmospheric Environment*, *92*, 449–460. https://doi.org/10.1016/j.atmosenv.2014.04.057

Huang, Y., Takaoka, M., & Takeda, N. (2003). Removal of unburned carbon from municipal solid waste fly ash by column flotation. *Waste Management*, *23*(4), 307–313. https://doi.org/10.1016/s0956-053x(02)00069-7

Hwang, J. Y., Sun, X., & Li, Z. (2002). Unburned carbon from fly ash for mercury adsorption: I. Separation and characteristics on unburned carbon. *Journal of Minerals & Materials Characterization & Engineering*, *1*, 39–60

Izquierdo, M., & Querol, X. (2011). Leaching behaviour of elements from coal combustion fly ash: An overview. *International Journal of Coal Geology*, *94*, 54–66. https://doi.org/10.1016/j.coal.2011.10.006

Kosivtsov, Y. Y., Chalov, K., Sulman, M. G., Lugovoy, Y., Novichenkova, T., Petropavlovskaya, V., Gadzhiev, S., & Popel, O. (2021). Use of ash and slag waste from thermal power plants as an active component of building materials. *Chemical Engineering Transactions*, *88*, 331–336. https://doi.org/10.3303/cet2188056

Kravchenko, J., & Lyerly, H. K. (2018). The impact of coal-powered electrical plants and coal ash impoundments on the health of residential communities. *North Carolina Medical Journal*, *79*(5), 289–300. https://doi.org/10.18043/ncm.79.5.289

Külaots, I., Hurt, R. H., & Suuberg, E. M. (2004). Size distribution of unburned carbon in coal fly ash and its implications. *Fuel*, *83*(2), 223–230. https://doi.org/10.1016/s0016-2361(03)00255-2

Kumar, A., Paul, B., & Singh, S. (2010). A study on backfill properties and use of fly ash for highway embankments. *International Journal of Engineering, Science and Technology*, *2*(7).

Kurama, H., & Kaya, M. (2008). Usage of coal combustion bottom ash in concrete mixture. *Construction and Building Materials*, *22*(9), 1922–1928. https://doi.org/10.1016/j.conbuildmat.2007.07.008

Li, L., Liu, J., Li, X., Peng, Z., Han, C., Lian, W., Xue, B., Gao, C., Zhang, Q., & Huang, W. (2024). Physicochemical characteristics of residual carbon and inorganic minerals in coal gasification fine slag. *Molecules*, *29*(16), Article 3956. https://doi.org/10.3390/molecules29163956

Liu, K., Jiang, J., Takasu, K., Zhang, Y., Zu, K., Gao, W., Yu, R., & Yao, W. (2024). Carbon removal flotation performance and economic analysis of different coal fly ash using waste fried oil as a collector. *Separation and Purification Technology*, 354, 129131. https://doi.org/10.1016/j.seppur.2024.129131

Ma, G., Huang, H., Liu, J., Dong, L., Bilal, M., Shao, H., & Tao, D. (2023). Effects of carrier particles on flotation removal of unburned carbon particles from fly ash. *Powder Technology*, *434*, Article 119247. https://doi.org/10.1016/j.powtec.2023.119247

Maroto-Valer, M. M., Taulbee, D. N., & Hower, J. C. (1999). Novel separation of the differing forms of unburned carbon present in fly ash using density gradient centrifugation. *Energy & Fuels*, *13*(4), 947–953. https://doi.org/10.1021/ef990029s

Mohsen, M. O., Aburumman, M. O., Diseet, M. M. A. A., Taha, R., Abdel-Jaber, M., Senouci, A., & Taqa, A. A. (2023). Fly ash and natural pozzolana impacts on sustainable concrete permeability and mechanical properties. *Buildings*, *13*(8), Article 1927. https://doi.org/10.3390/buildings13081927

Nanda, B., & Rout, S. (2021). Properties of concrete containing fly ash and bottom ash mixture as fine aggregate. *International Journal of Sustainable Engineering*, *14*(4), 809–819. https://doi.org/10.1080/19397038.2021.1920641

Oktay, Z. (2009). Investigation of coal-fired power plants in Turkey and a case study: Can plant. *Applied Thermal Engineering*, *29*(2–3), 550–557. https://doi.org/10.1016/j.applthermaleng.2008.03.025

Özdemir, O., & Çelik, M. S. (2002). Characterization and recovery of lignitic fly ash byproducts from the Tuncbilek power station. *Canadian Metallurgical Quarterly*, *41*(2), 143–150. https://doi.org/10.1179/cmq.2002.41.2.143

Pan, J. R., Huang, C., Kuo, J., & Lin, S. (2008). Recycling MSWI bottom and fly ash as raw materials for Portland cement. *Waste Management*, *28*(7), 1113–1118. https://doi.org/10.1016/j.wasman.2007.04.009

Ryabov, Y. V., Delitsyn, L. M., Ezhova, N. N., & Sudareva, S. V. (2019). Methods for beneficiation of ash and slag waste from coal-fired thermal power plants and ways for their commercial use (a review). *Thermal Engineering*, *66*(3), 149–168. https://doi.org/10.1134/s0040601519030054

Şahbaz, O., Öteyaka, B., Kelebek, Ş., Uçar, A., & Demir, U. (2008). Separation of unburned carbonaceous matter in bottom ash using Jameson cell. *Separation and Purification Technology*, *62*(1), 103–109.

https://doi.org/10.1016/j.seppur.2008.01.005

Şahbaz, O., Uçar, A., Emer, Ç., & Karagüzel, C. (2024). Advanced techniques on fine and coarse particle flotation. In *Advances in material research and technology* (pp. 55–76). Springer. https://doi.org/10.1007/978-3-031-49175-7_3

Sidek, N., Ma, H., Rahman, A. S. A., & Ruzilan, P. E. (2021). Physical properties and shear strength of boiler slag. *Acta Mechanica Malaysia*, *4*(1), 01–04. https://doi.org/10.26480/amm.01.2021.01.04

Sobhy, A., & Tao, D. (2013). High-efficiency nanobubble coal flotation. *International Journal of Coal Preparation and Utilization*, *33*(5), 242–256. https://doi.org/10.1080/19392699.2013.810623

IEA (2025). International Energy Agency. *New IEA market report sees increasing competition from other power sources, though developments in China's electricity sector will remain key for coal's prospects*. Global coal demand has reached a plateau and may well decline slightly by 2030. https://www.iea.org/news/global-coal-demand-has-reached-a-plateau-and-may-well-decline-slightly-by-2030

Uçurum, M., Toraman, Ö. Y., Depci, T., & Yoğurtçuoğlu, E. (2011). A study on characterization and use of flotation to separate unburned carbon in bottom ash from Çayirhan power plant. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *33*(6), 562–574. https://doi.org/10.1080/15567030903117638

Unver, I. K., & Terzi, M. (2018). Distribution of trace elements in coal and coal fly ash and their recovery with mineral processing practices: A review. *Journal of Mining and Environment*, *9*(3), 641–655

Vassilev, S. V., Menendez, R., Alvarez, D., Diaz-Somoano, M., & Martinez-Tarazona, M. (2003). Phase-mineral and chemical composition of coal fly ashes as a basis for their multicomponent utilization: 1. Characterization of feed coals and fly ashes. *Fuel*, *82*(14), 1793–1811. https://doi.org/10.1016/s0016-2361(03)00123-6

Wang, G. C. (2016). Nonmetallurgical slags. In *The utilization of slag in civil infrastructure construction* (pp. 63–85). Woodhead Publishing

Wang, L., Tao, Y., Su, B., Wang, L., & Liu, P. (2022). Environmental and health risks posed by heavy metal contamination of groundwater in the Sunan coal mine, China. *Toxics*, *10*(7), Article 390. https://doi.org/10.3390/toxics10070390

Williams, O., Newbolt, G., Eastwick, C., Kingman, S., Giddings, D., Lormor, S., & Lester, E. (2016). Influence of mill type on densified biomass comminution. *Applied Energy*, *182*, 219–231. https://doi.org/10.1016/j.apenergy.2016.08.111

Xing, Y., Guo, F., Xu, M., Gui, X., Li, H., Li, G., Xia, Y., & Han, H. (2019). Separation of unburned carbon from coal fly ash: A review. *Powder Technology*, *353*, 372–384. https://doi.org/10.1016/j.powtec.2019.05.037

Yamık, A., & Dogruoz, A. (2008). Recovery of unburned carbon by conventional flotation of bottom ashes from Tuncbilek thermal power plant. *Journal of the Southern African Institute of Mining and Metallurgy*, *108*(3), 171–177

Yang, L., Li, D., Zhang, L., Yan, X., Ran, J., Wang, Y., & Zhang, H. (2020). On the utilization of waste fried oil as flotation collector to remove carbon from coal fly ash. *Waste Management*, *113*, 62–69. https://doi.org/10.1016/j.wasman.2020.05.045

Yatsenko, E. A., Goltsman, B. M., Izvarin, A. I., Kurdashov, V. M., Smoliy, V. A., Ryabova, A. V., & Klimova, L. V. (2023). Recycling ash and slag waste from thermal power plants to produce foamed geopolymers. *Energies*, *16*(22), Article 7535. https://doi.org/10.3390/en16227535

Yoon, R. H., & Luttrell, G. H. (1989). The effect of bubble size on fine particle flotation. *Mineral Processing and Extractive Metallurgy Review*, *5*(1-4), 101–122. https://doi.org/10.1080/08827508908952646