Particle-Oil Absorption in Coal Flotation

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Abstract: This study examines the impact of systematically varying pine oil concentrations on particle-oil adsorption and the overall efficiency of froth flotation for cleaning coal samples collected from the Katras Area 4, Akashkinaree, and Moonidih coal mines. Froth flotation, utilizing diesel oil as a collector and pine oil as a frother, is a widely employed method for separating valuable coal from ash-forming mineral impurities. The primary objective of this investigation is to optimize the frother dosage to enhance the hydrophobic interactions between diesel oil and coal particles, thereby improving coal recovery, reducing ash content in the final concentrate, and maintaining an acceptable yield.

Flotation experiments were conducted using a constant diesel oil dosage of 3 ml while varying pine oil concentrations at 1.50 ml, 1.75 ml, and 2.00 ml. The performance of each frother dosage was evaluated by analyzing the ash content of the coal sample before and after flotation. The results aim to highlight the critical role of pine oil concentration in promoting effective particle-oil adsorption and improving flotation efficiency. By systematically analyzing the ash reduction achieved at different frother concentrations, the study aims to determine the role of pine oil dosage in improving particle-oil adsorption and flotation efficiency.

This investigation provides valuable insights into the relationship between frother dosage and flotation performance, contributing to the broader understanding of coal beneficiation processes. The findings can guide the optimization of frother usage in coal flotation circuits, offering practical benefits for coal preparation plants seeking to improve product quality, reduce processing costs, and enhance environmental compliance through lower ash content in the final product.

***Keywords**: Coal Flotation, Frother Concentration, Particle-Oil Absorption, Ash Content, Flotation Efficiency.*

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I. INTRODUCTION

➢ *Coal And Its Utilization:*

Coal is the most abundant fossil fuel found on the Earth, contributing approximately 55 % to global electricity generation and about 65 % in India. It is a complex, heterogeneous mixture of plant-derived materials that have undergone physical and chemical transformations over millions of years. These changes, driven by heat, pressure, and microbial activity within the Earth's crust, have resulted in coal's formation. Its primary component is carbon, with secondary elements including hydrogen, Sulphur, and others. [1][2]

The formation of coal begins with plant debris and, at its highest stage of maturity, culminates in Graphite. This transformation can either complete or halt at various stages, resulting in coals of different maturities, known as coal ranks. Coal is typically categorized into ranks such as peat, lignite, sub-bituminous, bituminous, semi-anthracite and anthracite. Peat, being the least carbon-rich and lowest in energy content, is often not classified as a true coal. As coal matures, its moisture and oxygen content decrease, while its carbon content and energy value increase. The calorific value rises from around 4,500 kcal/kg for lignite to approximately 8,500 kcal/kg for bituminous coal. [3]

In addition to its primary use in electricity generation at thermal power plants, coal is widely utilized in various other industries. This includes the production of metallurgical coke for steel manufacturing, as well as in the synthesis of polymers, fibers, dyes, and in alumina refineries. In recent years, coal has also found applications in advanced technologies such as carbon nanotubes, carbon electrodes, and carbon fibers. As a major source of carbon, most of its applications require coal in a highly purified from, making it essential to remove any unwanted impurities before use. [2][4]

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➢ *Coal Cleaning*

The mineral impurities in coal consist of materials such as shale, clay, sandstone, silica, pyrite, gypsum, sulphates and phosphates. These impurities typically fall into two categories:

- Inherent (or Fixed) impurities
- Extraneous (or Free) impurities

Inherent impurities are incorporated into the coal during its natural formation, whereas extraneous impurities are introduced later-during mining, handling, storage, or transportation. Coal cleaning refers to the process of removing or reducing these mineral impurities to enhance the efficiency and quality of coal usage. [5]

➢ *Froth Flotation*

Froth flotation is a widely established and highly effective physicochemical separation technique extensively employed in the coal processing industry for the beneficiation of coal. It serves as a crucial method for separating valuable hydrophobic coal particles from hydrophilic ash-forming mineral impurities, thereby enhancing the quality and calorific value of the final coal product [6]. This process relies on the selective adhesion of non-polar collector oils, such as diesel oil, to the surface of coal particles, rendering them hydrophobic and facilitating their attachment to air bubbles introduced into the slurry [7]. The resulting hydrophobic coal-bubble aggregates then rise to the surface, forming a stable froth layer that is skimmed off as the clean coal concentrate, leaving the hydrophilic gangue minerals behind in the pulp [7].

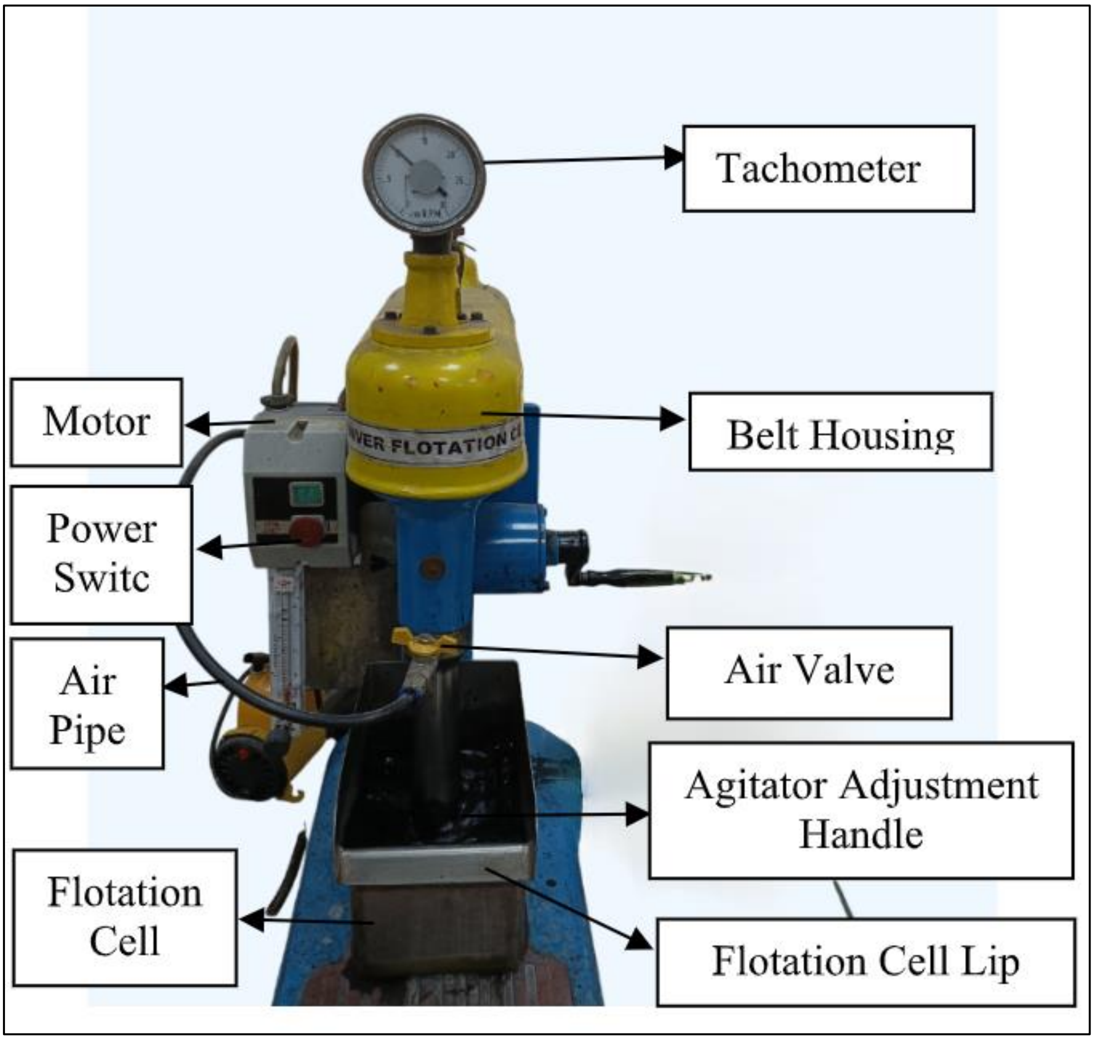

Fig. 1 Denver Flotation Cell

The formation and stability of this froth layer are critically dependent on the presence and concentration of frothers, which are surface-active agents that reduce the surface tension of water, thereby facilitating the generation of a stable dispersion of air bubbles with an appropriate size distribution for efficient particle attachment [8]. Pine oil is a commonly utilized frother in coal flotation due to its ability to produce a moderately stable froth with desirable bubble characteristics [9]. The frother dosage is a crucial operational parameter that profoundly impacts overall flotation performance. Insufficient frother concentration can lead to the formation of unstable and short-lived froth, resulting in inadequate coal recovery. Too much frother, on the other hand, creates a froth that's too stable, which can trap unwanted hydrophilic gangue particles in the concentrate, leading to higher ash content [10].

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This study aims to investigate the impact of systematically varying pine oil concentrations on the fundamental aspect of particle-oil adsorption and the subsequent overall efficiency of froth flotation in cleaning coal sample obtained from the Katras Area 4, Akashkinaree, and Moonidih coal mines in India. By maintaining a constant dosage of diesel oil as a collector and carefully varying the pine oil concentration, this research seeks to elucidate the critical role of frother dosage in promoting effective hydrophobic interaction between diesel oil and coal particles. The performance of each frother concentration will be quantitatively evaluated by analyzing the reduction in ash content achieved in the final coal concentrate after the flotation process. The primary goal is to identify the ideal pine oil concentration that achieves peak coal recovery alongside the lowest possible ash content in the refined coal. The findings of this investigation are expected to provide valuable insights into the complex relationship between frother dosage and flotation performance in the context of these specific Indian coal sample, thereby offering practical guidance for the optimization of frother usage in industrial coal flotation circuits to improve product quality, reduce processing costs, and enhance environmental compliance through the production of lower-ash coal.

II. MATERIALS AND METHODS

A. *Materials*

Three distinct coal samples were procured from the following coal mines located in India: Katras Area 4, Akashkinaree, Moonidih, Diesel oil served as the collector in the froth flotation process, while Pine oil was utilized as the frother. The as-received coal samples, with a nominal size of approximately 12 inches in radius (this seems unusually large for a starting particle size; assuming it refers to the initial lumps before crushing), were subjected to a two-stage size reduction process. Initially, the coal was crushed using a cone crusher to reduce the particle size to approximately ½ inch. Subsequently, a roller crusher was employed to further reduce particle size to -72 mesh (210µm). A -72 mesh (210µm) sieve was used for the purpose of screening the crushed coal to ensure a consistent particle size distribution for the flotation experiments. For accurate weighing of coal sample, an analytical balance with high precision was employed. A hot air oven was used to determine the moisture content, while a muffle furnace was utilized for assessing both ash content and volatile matter. Froth flotation experiments were conducted using a Denver flotation cell.

B. *Methods*

➢ *Experimental Procedure*

The experimental procedure involved two primary stages: proximate analysis of the raw coal samples and froth flotation experiments with varying frother dosages.

- *Proximate Analysis*

Before the flotation experiments, a proximate analysis was performed on each of the three coal samples (Katras Area 4, Akashkinaree, and Moonidih) to establish their initial characteristics. For each sample, 1 gram of coal was accurately weighed using the analytical balance. The following parameters were determined according to standard coal analysis procedures:

- ✓ Moisture Content (%): Moisture content was assessed by heating the coal sample in a hot air oven at 100-105°C for one hour, or until a constant weight was achieved. The percentage weight loss was recorded as the moisture content.
- ✓ Ash content (%): Determined by completely combusting the moisture-free coal sample in the muffle furnace at 800-805°C temperature for one hour in the presence of air until only ash remained. The residual ash's weight was calculated as a percentage of the coal's initial dry weight.
- ✓ Volatile Matter (V.M.) (%): Determined by heating the moisture-free coal sample in a muffle furnace at a 900°C specific high temperature for a seven minutes fixed duration in the absence of air. The volatile matter was determined by calculating the percentage weight loss after moisture was removed.
- ✓ Fixed Carbon (%): Calculated by difference, using the formula:

$$\text{Fixed Carbon (\%)} = [100 - (\text{Moisture \%} + \text{V.M. \%} + \text{Ash \%})]$$

This initial proximate analysis provided a baseline for evaluating the effectiveness of the froth flotation process in reducing the ash content.

- *Froth Flotation Experiments*

Froth flotation experiments were conducted for each of the three samples with a constant collector dosage and systematically varied frother dosages. For each experiment, the following procedure was followed:

- ✓ Pulp Preparation: 300 grams of the -72 mesh (210µm) size coal sample was mixed with 2700 ml of water in the Denver flotation cell (Fig. 1), resulting in a 10% (w/v) pulp density. The mixture was agitated for 5 minutes to ensure proper wetting and mixing of the coal particles with media.
- ✓ Collector Addition: A constant dosage of 3ml of diesel oil (collector) was added to the pulp, and the mixture was conditioned for another 5 minutes under agitation to promote the adsorption of the collector into the hydrophobic coal particles.
- ✓ Frother Addition: Pine oil (frother) was added to the pulp at three different concentrations: 1.50 ml, 1.75 ml and 2.00 ml. respectively. After adding the frother, the pulp was agitated for 5 minutes to condition it, allowing the frother to generate a stable froth.
- ✓ Froth Collection: Air pressure was applied to the flotation cell to facilitate the generation and collection of froth. The froth, carrying the hydrophobic coal particles, was collected in a separate container at 10 second interval for a total duration of 50 seconds for each experiment. This resulted in five froth fractions for each flotation test.
- ✓ Concentrate Processing: The collected froth fractions (containing the coal concentrate) were combined and then dried in the hot air oven until a constant weight was achieved.

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- ✓ Ash Content Determination of Concentrate: The dried coal concentrate was then subjected to ash content analysis using the muffle furnace, following the same procedure as described in the proximate analysis.
- ✓ Data Analysis: The ash content of the fine coal concentrate obtained at each pine oil dosage (1.50 ml, 1.75 ml, and 2.00 ml) for each of the three-coal sample was analyzed and compared to the initial ash content of the respective raw coal samples. This enabled the assessment of how different pine oil concentrations affected ash reduction and the overall effectiveness of the froth flotation process. Additionally, the clean coal concentrate's yield was determined by comparing the concentrate's weight to the initial coal sample's weight.

This systematic variation of pine oil concentration while keeping the diesel oil dosage constant allowed for the determination of the optimal frother dosage for maximizing coal recovery, maximizing ash content in the concentrate, and achieving an acceptable yield for each of the coal samples from the Katras Area 4, Akashkinaree, Moonidih coal mines.

III. RESULTS AND DISCUSSIONS

This study investigated the impact of varying pine oil concentrations on the froth flotation efficiency of coal samples from the Katras Area 4, Akashkinaree, Moonidih coal mines. The objective was to optimize frother dosage for enhanced coal recovery and ash reduction. Flotation experiments were carried out using a fixed amount of diesel oil (3 ml) and different concentration of pine oil (1.50 ml, 1.75 ml and 2.00 ml). The ash content of the coal sample before and after flotation was analyzed to evaluate the effectiveness of each frother dosage.

A. Characterization of Raw Coal Samples

The proximate analysis of the coal samples revealed significant differences in their initial composition (Table 1).

Table 1: Proximate Analysis of Raw Coal Samples

Coal Sample	Moisture (%)	Ash (%)	Volatile Matter (%)	Fixed Carbon (%)
Katras Area 4	1.63	37.17	19.46	41.74
Akashkinaree	1.49	27.47	25.38	45.66
Moonidih	1.73	24.86	23.23	50.18

As shown in Table 1, the initial ash content varied considerably, with Katras Area 4 exhibiting the highest ash content (37.17%) and Moonidih the lowest (24.86%). These differences in initial ash content are important to consider when evaluating the effectiveness of the flotation process.

B. Effect of Pine Oil Concentration on Ash Deduction

The result of the flotation experiments, presented in Table 2, 3 and 4, demonstrate a clear relationship between pine oil concentration and ash reduction.

Table 2: Ash % of Katras Area 4 coal flotation products at different quantity of pine oil concentration.

Time (s)	1.50 ml Pine Oil	1.75 ml Pine Oil	2.00 ml Pine Oil
10	25.6005	25.3917	25.1864
20	27.0375	26.6178	26.1656
30	27.4018	26.9395	26.7130
40	27.5605	27.3270	26.7203
50	27.9213	27.6235	26.7628
Tailing	30.9395	29.9038	28.3755

Table 3: Ash content (%) of Akashkinaree coal flotation products at different pine oil concentrations

Time (s)	1.50 ml Pine Oil	1.75 ml Pine Oil	2.00 Pine Oil
10	19.8631	19.4637	18.7344
20	20.0694	19.6504	19.7578
30	20.2203	19.9026	19.4621
40	20.4960	19.9441	19.5170
50	20.6858	20.1350	19.8461
Tailing	25.0373	24.2587	23.1205

Table 4: Ash Content (%) of Moonidih coal mines flotation products at different pine oil concentrations

Time (s)	1.50 ml Pine Oil	1.75 ml Pine Oil	2.00 ml Pine Oil
10	16.9786	15.8197	14.1794
20	17.3042	16.1102	14.8207
30	17.4274	16.1874	15.1355
40	17.5481	16.5155	15.2083
50	19.2039	17.1906	15.5373

Tailing	21.8358	20.8345	20.1312

C. Graphical Representation

- *Explanation of the Graph (Ash% vs. Time)*

The graph represents the variation in ash content (%) of coal slurry samples with respect to time (seconds) for three distinct coal sources: Katras Area 4, Akashkinaree, and Moonidih.

For all three coal samples, ash percentage decreases initially with time during the experiment, likely due to the separation or removal of high-ash impurities in the early phase. After reaching a minimum, ash content begins to rise again, indicating the collection of heavier or more mineral-rich particles as time progresses beyond optimal separation.

- *Katras Area 4 Sample:*

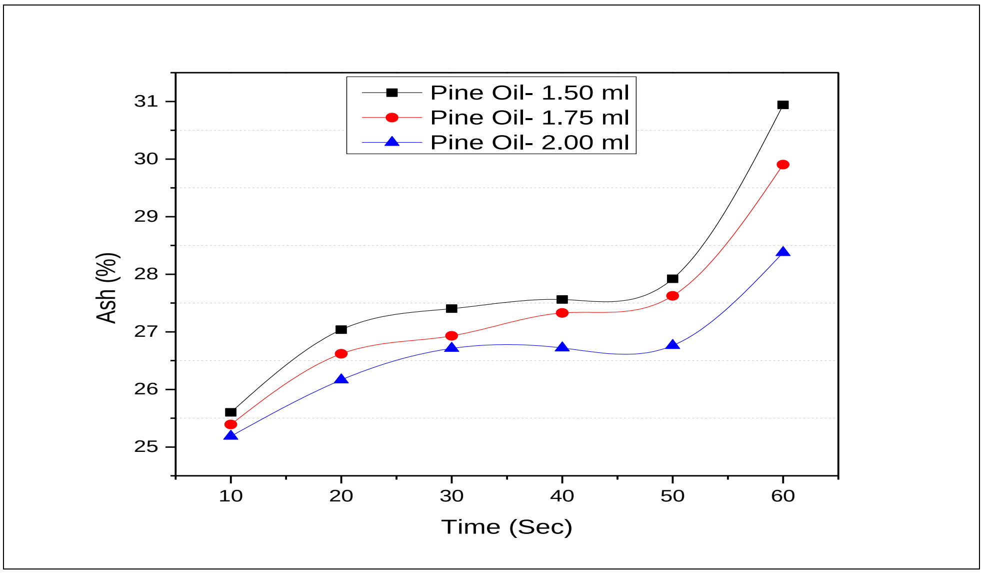

Fig 2: Ash % with Respect to time for Katras Area 4

Exhibits the steepest initial drop in ash content, indicating in Fig 2 that ash rejection is most efficient in early seconds (10–30s). The ash content rises again after about 40 seconds, suggesting that the clean coal fraction is confined to a narrow time window and later fractions are less pure.

- *Akashkinaree Sample:*

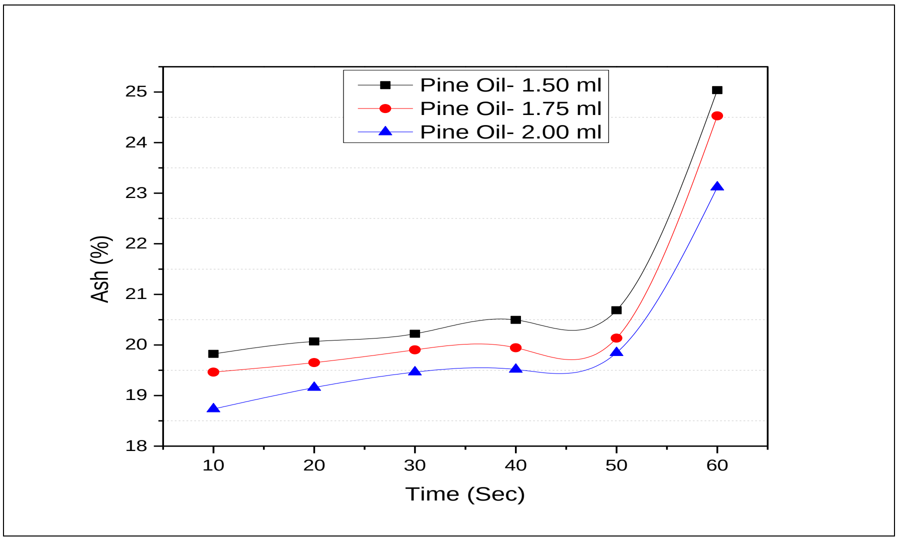

Fig 3: Ash % with Respect to Time for Akashkinaree

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Displays in Fig 3 a relatively smoother curve, with a moderate decline in ash content, reaching the lowest around 40 seconds. Beyond this point, a slight increase is seen, possibly due to re-entrainment or loss of separation sharpness.

➢ *Moonidih Sample:*

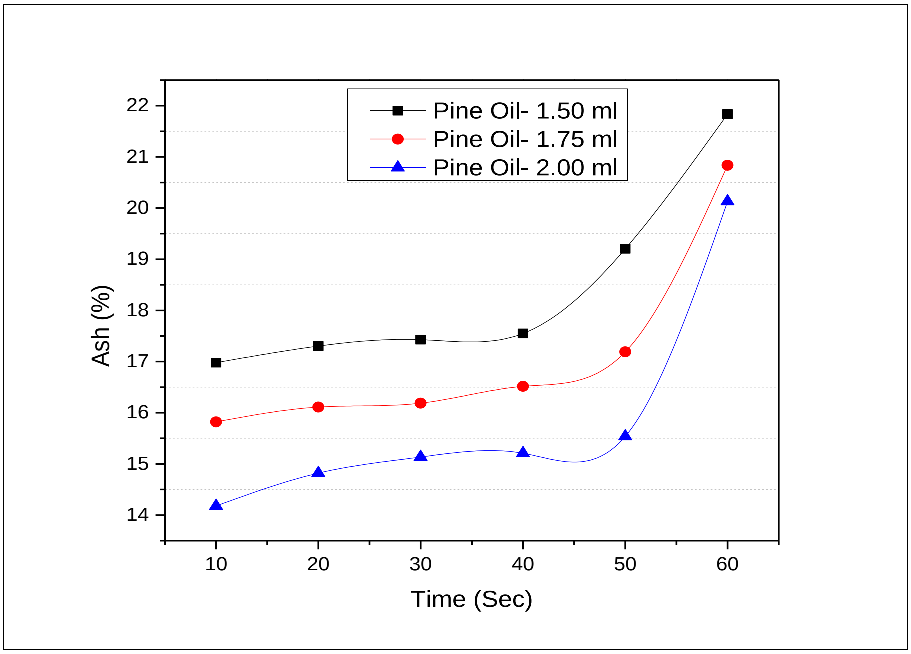

Fig 4: Ash % with respect to time for Moonidih

Shows in Fig 4, ash% reduces significantly up to around 30–40 seconds, suggesting effective removal of ash-forming minerals in early flotation or classification. After 40 seconds, ash percentage starts increasing, indicating that finer high-ash particles or middlings are being recovered in later fractions.

➢ *Technical Interpretation:*

This time-dependent trend is typical in froth flotation or hydrocyclone separation, where lighter, cleaner coal particles are recovered first, and denser, ash-rich particles settle or exit later.

The point of minimum ash percentage indicates the optimum collection time window for clean coal.

The variation across samples demonstrates that feed characteristics and washability differ among the mines, affecting separation performance.

D. Yield Analysis After Flotation

Table 5: Yield and Average Ash Content of Coal Concentrates

Coal Sample	**Yield (%)**	**Average Ash Content (%)**
Katras Area 4	75.66	27.1404
Akashkinaree	66.00	20.2589
Moonidih	66.66	17.6924

The yield and average ash content of the concentrate for each coal sample are presented in Table 5.

IV. DISCUSSION

The data clearly indicates that increasing the pine oil concentration generally resulted in a reduction of ash content in the coal concentrate. As observed in Tables 2,3, and 4, and further visualized in the graphs, the lowest ash content was consistently achieved with a pine oil dosage of 2.00 ml across all three coal samples. Increasing the pine oil dosage to 2.00 ml resulted is the most effective ash reduction for the coal samples from Katras Area 4, Akashkinaree, and Moonidih. This suggests that a higher frother concentration enhances the formation of stable froth, facilitating the selective flotation of hydrophobic coal particles and the rejection of hydrophilic ash-forming minerals.

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The initial ash content of the raw coal significantly influenced the final ash content of the concentrate. For instance, Katras Area 4, with the highest initial ash content, retained a higher ash content in the concentrate compared to Moonidih, which had the lowest initial ash content.

It is noteworthy that the ash content tended to increase after 50 seconds of flotation. This observation implies that prolonged flotation beyond this point might lead to the entrainment of gangue particles into the froth, thereby increasing ash content of the concentrate. This could be due to the instability of the froth or the carryover of finer particles with increased agitation time. Therefore, optimizing the flotation time is crucial to achieve the desired ash reduction while maximizing coal recovery.

The yield analysis (Table 5) reveals a trade-off between ash reduction of coal recovery. While Moonidih exhibited the lowest average ash content, it also showed a lower yield compared to Katras Area 4. This highlights the importance of balancing product quality (low ash content) with economic considerations (high yield) in industrial applications.

IV. CONCLUSION

This study demonstrates the significant impact of pine oil concentration on the froth flotation efficiency of coal.

- The ash % vs. time graph reveals valuable insights for optimizing the separation time window in pilot-scale testing.
- Based on the curves, Moonidih and Katras Area 4 samples show sharper separation, whereas Akashkinaree may require modified conditions (e.g., pressure or reagent adjustment) for better ash rejection.
- These findings are critical for defining process control strategies and time-based sampling in flotation setups.

Optimizing flotation time is essential for effective coal beneficiation, requiring a careful balance between lowering ash content and maintaining high yield. The finding of this study provides valuable insights for optimizing frother usage in coal flotation circuits, which can lead to improved product quality, reduced processing cost, and enhanced environmental compliance.

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