-RESEARCH PAPER-

International Journal of Mining and Geo-Engineering IJMGE

IJMGE 58-4 (2024) 359-370 DOI: 10.22059/IJMGE.2024.360260.595070

Refinement of the flotation reagent plan based on coal feed ash content

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Article History:

Received: 18 June 2023.

Revised: 01 August 2024.

Accepted: 26 September 2024.

ABSTRACT

The effect of frother dosage (67, 200, and 400 g/t), collector dosage (200, 600, and 1000 g/t), and frother type (Mixed aliphatic alcohol (MAA), Methyl Isobutyl Carbinol (MIBC), and pine oil) on the flotation performance of three coal samples with various ash contents of 45.1% (high ash content coal, HAC), 36.8% (moderate ash content coal, MAC), and 30.7% (low ash content coal, LAC) was studied. The optimal flotation conditions for each coal sample were quite different. For HAC, a clean coal with an ash content of 12.8% and a yield of 38% was produced under optimal conditions using MIBC as the frother dosage of 361 g/t, and a collector dosage of 200 g/t. In the case of MAC, a clean coal with an ash content of 10.2% and a yield of 46% was produced under optimal flotation conditions using MAA as the frother dosage of 148 g/t, and a collector dosage of 200 g/t. For LAC, a clean coal with an ash content of 9.87% and a yield of 57.4% was produced under optimal flotation conditions using pine oil as the frother dosage of 174 g/t, and a collector dosage of 1000 g/t. For LAC feed coal, in comparison with HAC feed coal, a lower frother at dosage, higher collector dosage, and pine oil frother instead of MIBC must be used. The optimal conditions for HAC flotation were validated in a coal washing plant. After conducting the necessary modifications to the flotation reagent scheme, yield, combustive material recovery (CMR) and separation efficiency (SE) of the plant increased by 5.9%, 11%, and 7.5%, respectively which results in more clean coal production of about 14160 t/y.

Keywords: *Flotation, Feed coal ash content, Flotation reagent scheme, Process optimization, Laboratory and plant validations.*

1. Introduction

Flotation is the most efficient method for fine coal washing [1-5]. This relies on the difference in particle surface hydrophobicity with coal being typically hydrophobic and most of the mineral matter hydrophilic [6-9]. Air bubbles were injected into the flotation cell and the hydrophobic coal particles were selectively attached to the air bubbles and transferred to the froth phase, while the hydrophilic minerals remained in the flotation cell [10]. Coals had different flotation characteristics depending on the coal rank, degree of coal surface oxidation, and the amount and type of mineral matter [11]. Hence, flotation reagents were mainly used in order to improve the surface hydrophobicity of low-rank and/or oxidized coal particles [12]. The effect of flotation reagents on the flotation performance has been the subject of many researches [12-15]. Xia et al. used a combination of coal tar and diesel as a collector in the flotation of a low-rank coal sample [13]. An increase of about 15-50% in the flotation yield was obtained by the mixed collector instead of diesel as collector [13]. Zhu et al. (2020) used a microemulsion collector (i.e., a combination of a surfactant and diesel) in the flotation of coal slime and a yield of 69.70% was obtained using this collector [14]. Das and Reddy used Polanga and Mahua oil as the collectors in the flotation of a non-coking coal containing 40.2% ash and a clean coal with an ash content of 22% and a yield of 60% was obtained [15]. Improving the coal flotation performance by changing the frother type has also been studied. Gupta et al. (2007) studied the effect of frother type on the flotation performance of a bituminous coal sample [16]. A better flotation selectivity was observed with MIBC frother instead of polyglycol ether frother, since MIBC produces bubbles with a more uniform and finer size than polyglycol ether frother [16]. Although there are many researches about the optimization of flotation reagents in the flotation of coal samples with a certain ash content, the effect of ash content in coal samples on the type and dosage of flotation reagents in the flotation of fine coals has not been studied. It is believed that the type and dosage of flotation reagents are closely related to the ash content of the coal. The coal washing plants are usually fed from several coal mines with various ash contents. Nonetheless, a similar reagent scheme is usually applied in the flotation circuit of coal washing plants for various coal feeds regardless of their ash content. The aim of this research is to study the effect of the type and dosage of flotation reagents on the flotation performance of coal samples with various ash contents. The coal samples were provided from the No. 1 mine, Central Mine and Madanjoo Mine in the Tabas Parvadeh coal field, central Iran with ash contents of 45.1%, 36.8%, and 30.7%, respectively. The flotation tests were conducted in the laboratory and the results were used in the optimization of the flotation reagents in the flotation circuit of the Tabas Parvadeh Coal washing plant (PTCWP), Tabas, Iran.

2. Materials and methods

2.1. Coal Washing plant

The feed coal to the PTCWP was provided from three different coal mines, including the No. 1 mine, Central Mine and Madanjoo Mine and the coals were fed to the plant separately. The annual capacity of the run of mine (ROM) coal to the plant was about 1.5 million tons, and the

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share of coal from No.1 mine, Central Mine and Madanjoo was 53.4%, 33.3%, and 13.3%, respectively. Also, Fig.1 shows the process flowsheet of the PTCWP [18]. As can be seen, the ROM coal is initially divided into three parts: coarse grain (6-50 mm), medium grain (0.5-6 mm), and fine grain (-0.5 mm). Medium grain and coarse grain fractions were transferred to the gravity separation circuits, but the fine grain fraction was transferred to the flotation circuit. About 30% of the plant feed was processed in the flotation circuit. In this circuit, there were six column flotation cells (Fig. 2.a). The diameter of the column flotation cells was 3.4 meters, their height was 8 meters, and the capacity of this circuit was 130 t/h of coal.

After screening the feed coal of the PTCWP, the fine coals (-0.5 mm) were collected in two tanks. In these tanks, to improve the hydrophobicity of coal samples, diesel was added as a collector. The amount of diesel addition was automatically adjusted and depends on the amount of coal that was pumped from these tanks to the column flotation cells. The pulp in these two tanks was sent to a distributor tank in order to be properly divided between the six column flotation cells. The pulp was transferred through a pipe from the distributor tank to the column flotation cell (Fig. 2.b) and the pulp was poured into the column flotation cell at a height of 4.5 to 5 meters from the column floor. The hydrophobic coal particles were attached to the air bubbles and raised to the surface of the flotation column, forming a froth phase and the ash materials fell to the bottom of the flotation column and formed the flotation tailings. Fig. 2.b shows the material circulation in the column flotation cell.

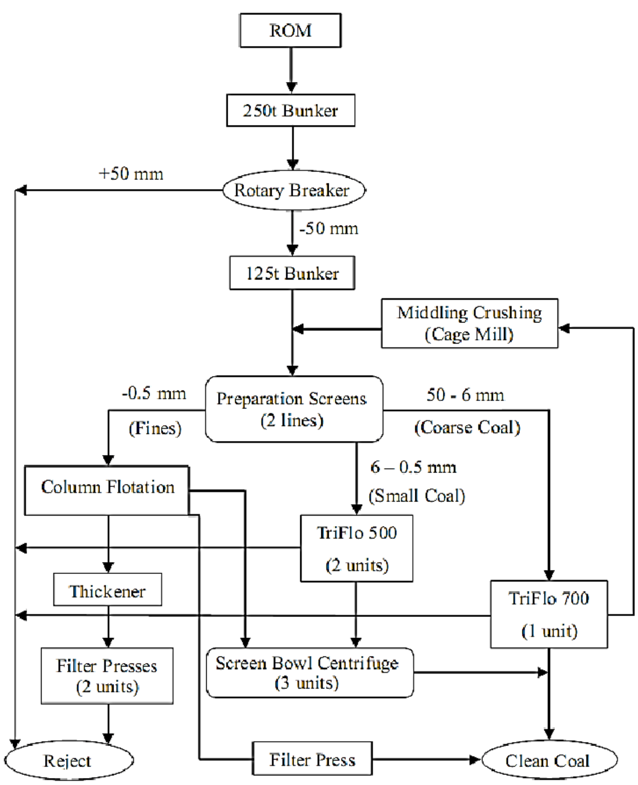


Fig.1. The process flowsheet of the Tabas Parvadeh coal washing plant (PTCWP) [18].

2.2. Materials

The coal samples were provided from the No.1 mine (high ash content coal, HAC), the Central Mine (moderate ash content coal, MAC), and the Madanjoo Mine (low ash content coal, LAC) which are located in Tabas Parvadeh coal field, Tabas, central Iran. In the Tabas Parvadeh coal field, the coals are coking or metallurgical grade. Coal samples were taken from the feeding conveyor belt of the TPCWP using an automatic sampler. The coal samples were then divided into two size fractions by screening (of mesh no. 35), and the fraction passing through the sieve was used in the flotation experiments.

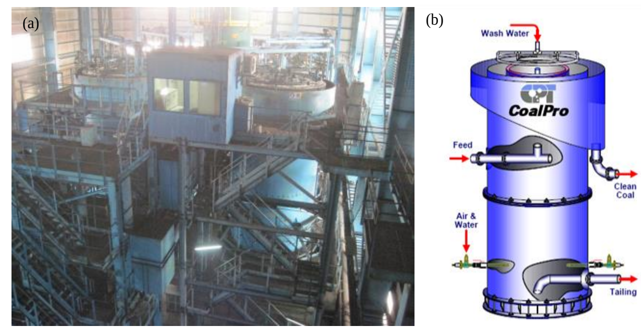


Fig. 2. (a) The column flotation cells in the PTCWP, and (b) A schematic representation of the column flotation cell.

2.3. Methods

The flotation experiments were carried out in a 3-L Denver laboratory flotation cell. The pulp temperature, conditioning time, and rotation speed were kept constant in all of the flotation experiments at 30°C, 5 minutes, and 1000 rpm, respectively. The pH of the flotation pulp was in the range of 8-8.5 (i.e., neutral pH) in all of the flotation experiments.

The effect of two quantitative variables (frother dosage and collector dosage) and two categorical variables (frother type and ash content of coal samples) at three levels was studied on the flotation performance. Table 1 shows the parameters and their levels. The selection of process parameters and their levels was made based on the usual flotation reagents in the flotation of coal, previous experiences in the TPCWP, the availability of the flotation reagents, and the economics of the process. The design of experiments was performed by Design Expert 7 (DX7) software. The DX7 software serves as a specialized tool and simplifies the planning, execution, and analysis of experiments based on the principles of the design of experiments. The software follows a systematic approach and allows users to change input factors, evaluate their impact on output, and optimize processes or systems. The DX7 software effectively examines multiple variables, identifies key influencing factors, and facilitates the creation of robust experimental designs. The technique of 3^4 full factorial experimental design was selected. In statistics, a full factorial experiment is an experiment whose design consists of two or more factors, each of which has discrete possible values or levels, and in which experimental units take all possible combinations of these levels among all of these factors. A full factorial design can also be called a fully crossed design. Such an experiment allows the researcher to study the effect of each factor on the response variable as well as the effect of the interaction between the factors on the response variable.

After each flotation test, the ash content of the floating and sinking phases was determined and the yield (i.e., weight recovery) and combustible material recovery (CMR) of clean coal were determined according to the following equations:

$$Yield\ \% = 100 * (f - t)/(c - t) \quad (1)$$

$$CMR\ \% = Yield\ \% * (100 - c)/(100 - f) \quad (2)$$

In which, c is the ash content of floating phase, t is the ash content of sinking phase, and f is ash the content of feed.

The ash content of coal samples was determined based on the ASTM standard [19]. Hence, the coal sample was ground to -250 µm. A certain weight of the ground coal sample was heated at a temperature of 500-750°C for one hour. Afterwards, the weight of the remaining material was determined and the ash content of the coal samples was determined according to Eq. 3 [19]:

Ash content (weight %) = (weight of remaining material after heating/ initial weight of coal sample) *100 (3)

3. Results and discussion

3.1. Characterization of the coal samples

The results of the proximate analysis of the coal sample of the No.1 mine have been presented in Table 2. It is noticeable that the ash and fixed carbon content of the sample were 45.1%, and 39.2%, respectively. The sieve analysis of the coal sample of the No.1 mine was performed and all of the size fractions were subjected to the ash content determination test. The results are presented in Fig. 3.a. As demonstrated, the size fraction less than 45 µm had the maximum ash content (54.5%) among the other size fractions, since the clay-sized minerals accumulate more in fine size fractions. The size fractions of +212-300 µm and +300-500 µm also had high ash content (52% and 43.4%, respectively). This is due to the locking of mineral matter with the coal in the coarse particle size fractions.

Table 2 also shows the proximate analysis of the coal sample of the Central Mine. As can be seen, the ash content of this coal sample was 36.8% which is lower than the ash content of the coal sample of the No. 1 mine. The weight percent and ash content of various size fractions of the coal sample of the Central Mine is shown in Fig. 3.b. As shown, the largest and smallest size fractions (i.e., +300-500 µm and -45 µm, respectively) have more ash content and weight percent than the other size fractions.

Table 2 shows that the ash content of the Madanjoo coal sample was 30.7%. The sieve analysis of the coal sample was performed. The ash content and weight percent of all the size fractions were determined and the results can be seen in Fig. 3.c. It is evident that the size fraction less than 45 µm had the highest ash content among the other size fractions.

As can be seen in Table 2, the ash content of the coal samples of the No.1 mine, Central Mine and Madanjoo Mine was 45.1%, 36.8% and 30.7%, respectively. Therefore, the coal sample of the No.1 mine had the highest ash content. The ash content of the Central Mine coal sample was between the No. 1 mine and the Madanjoo Mine coal samples, and the Madanjoo coal sample had the lowest ash content compared to the other coal samples. Hence, the coal samples of the No.1 mine, Central Mine and Madanjoo Mine were considered as high ash content coal (HAC), moderate ash content coal (MAC), and low ash content coal (LAC), respectively and they were used in the experiments.

Table 1: Experimental factors and levels in Full Factorial design.

Factor	Level 1	Level 2	Level 3
Ash content of coal samples (A)	High Ash Coal (HAC) from No.1 mine	Moderate Ash Coal (MAC) from Central Mine	Low Ash Coal (LAC) from Madanjoo Mine
Frother type (B)	Mixed aliphatic alcohol (MAA)	Methyl isobutyl carbinol (MIBC)	Pine oil
Frother dosage (g/t) (C)	67	200	400
Collector dosage (g/t) (D)	200	600	1000

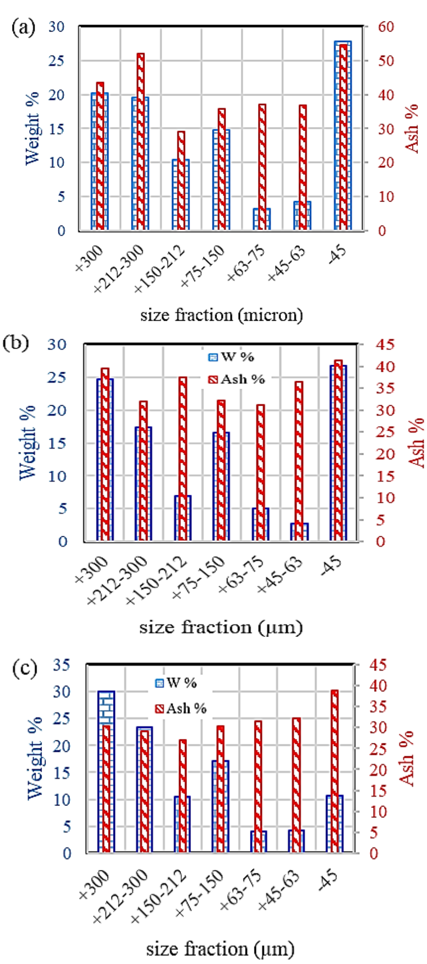


Fig.3. The weight percent and ash content of various size fractions of the coal samples of (a) No.1 mine, (b) Central Mine, and (c) Madanjoo Mine.

Table 2. The chemical analysis of the coal samples.

Feed coal sample	Proximate analysis				Sulfur (%)
	Ash (%)	Moisture (%)	Volatile matter (%)	Fixed Carbon (%)	
No.1 Mine	45.1	0.9	14.8	39.2	1.04
Central Mine	36.8	0.7	15.9	46.6	1.49
Madanjoo Mine	30.7	0.6	20.2	48.5	1.63

3.2. The effect of process parameters of flotation on the ash content of clean coal

Table 3 shows the analysis of variance (ANOVA) table for the selected factorial model in the case of clean coal ash content response. The model F-value of 26.08 indicates that the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. The model terms are significant when the P-value of the model terms is less than 0.0500. Hence, the model terms, including A, B, C, D, AC, and BC are significant.

Table 4 shows fit statistics for the clean coal ash content. The R^2 value was 0.9456 which is near unity. It confirms the goodness of fit of the model. It is noticeable that the difference between the Predicted R^2 and Adjusted R^2 was less than 0.2 which indicates that they were in reasonable agreement. Adequate precision measures the signal-to-noise ratio. A ratio greater than 4 was desirable. As can be seen in Table 4, the signal-to-noise ratio was 19.617 which indicates an adequate signal. This model can be used to navigate the design space.

Fig.4 shows the residual plots for the clean coal ash content modelling. As can be seen, all of the residual plots confirm the model validity.

After confirmation of the model validity by the ANOVA table and the residual plots, the effect of model parameters on the ash content of clean coal will be discussed in the following sections.

3.2.1. High ash content coal (the coal sample of the No.1 mine)

The effect of frother type on the product ash content of the No.1 mine

Table 3. The ANOVA table for the selected factorial model for the clean coal ash content.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	320.48	32	10.01	26.08	< 0.0001	significant
A-Kind of Feed	203.05	2	101.52	264.39	< 0.0001	
B-Frother Type	32.58	2	16.29	42.42	< 0.0001	
C-Frother dosage	55.46	2	27.73	72.22	< 0.0001	
D-Collector dosage	9.17	2	4.59	11.94	< 0.0001	
AB	2.77	4	0.6925	1.80	0.1436	
AC	7.52	4	1.88	4.90	0.0022	
AD	0.4886	4	0.1222	0.3181	0.8645	
BC	5.12	4	1.28	3.34	0.0173	
BD	1.81	4	0.4531	1.18	0.3316	
CD	2.50	4	0.6244	1.63	0.1830	
Residual	18.43	48	0.3840			
Cor Total	338.91	80				

Table 4. Fit statistics for the clean coal ash content.

Std. Dev.	0.6197	R^2	0.9456
Mean	11.12	Adjusted R^2	0.9094
C.V. %	5.57	Predicted R^2	0.8451
		Adeq Precision	19.6174

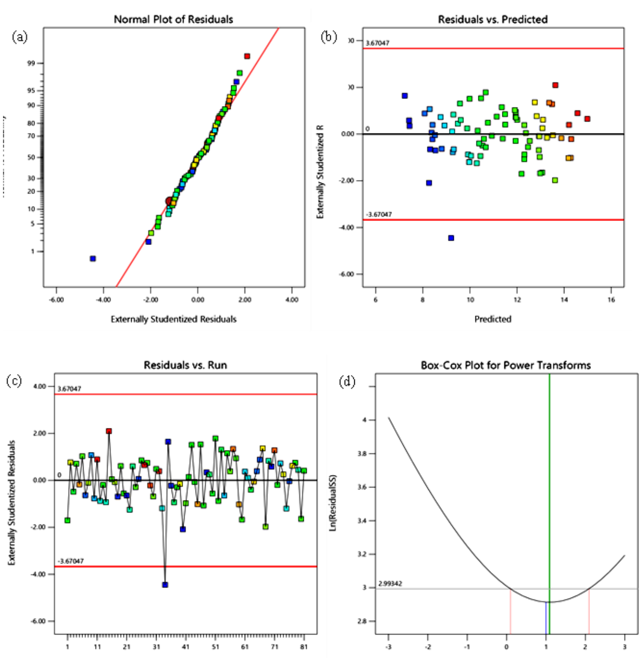


Fig. 4. (a) Normal plot of residuals, (b) plot of residuals vs. predicted, (c) plot of residuals vs. run number, and (d) Box-Cox plot for the clean coal ash content modelling.

coal sample is shown in Fig. 5.a. As can be seen, clean coal ash content using both the MAA and MIBC frothers was 13.19%. Hence, these two frothers had nearly the same performance in the reduction of ash content of the clean coal. The clean coal ash content increased to 14.39% using the pine oil frother. Hence, the ash content of clean coal using the MIBC type frother decreased rather than the pine oil type frother. The MIBC type frother had lower foam stability than the pine oil type frother. Furthermore, the MIBC produced finer and more closely-sized bubbles compared to the pine oil frother. Hence, the MIBC frother was able to produce lower ash content coal compared to the pine oil type frother and in other word, the MIBC was a more selective frother compared to the pine oil frother [16].

Fig. 5.b shows the effect of frother dosage on the clean coal ash content of the No.1 mine coal sample. As can be seen, the product ash content increased from 12.31% to 12.76% by increasing the frother dosage from 67 g/t to 200 g/t. Further increasing the frother dosage to 600 g/t increased the product ash content to 13.10%. This is due to the reduction of the surface tension of aqueous solutions by increasing the frother dosage. Furthermore, the foam stability increases by increasing the frother dosage. This may result in clean coal with higher ash content [16]. Fig. 5.c shows the effect of collector dosage on the clean coal ash content. As can be seen, the clean coal ash content increased from 11.14% to 12.31% by increasing the flotation dosage from 200 g/t to 600 g/t. Any further increase of the flotation dosage from 600 g/t to 1000 g/t had no significant effect on the clean coal ash content.

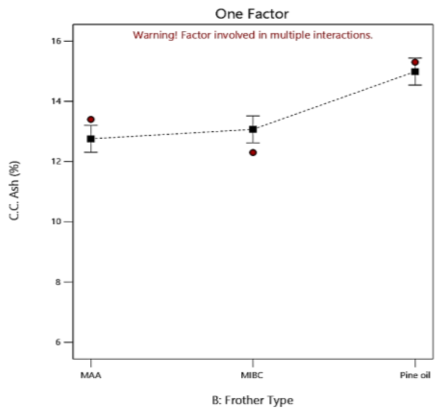
Coal inherently has a hydrophobic surface, but the oxidation of its surface or its locking with ash leads to a decrease in its surface hydrophobicity. The addition of the collector increases the surface hydrophobicity of coal particles, which leads to an increase in the recovery of coal particles, but due to the fact that it can transfer some of the coal particles locked with the ash to the concentrate, it increases the ash content of the clean coal.

3.2.2. Moderate ash content coal (the coal sample of the Central Mine)

The effect of frother type on the clean coal ash content of the Central Mine coal sample is shown in Fig. 6.a. As can be seen, the minimum ash content of the flotation concentrate is obtained by the MAA frother. Furthermore, the clean coal ash content increased by pine oil type frother rather than the MAA and MIBC type frothers. A similar case was observed for the coal sample of the No.1 mine. Fig. 6.b also shows the effect of frother dosage on the clean coal ash content of the Central Mine coal sample. As demonstrated, increasing the frother dosage from 67 g/t to 200 g/t had a negligible effect on the clean coal ash content, but increasing the frother dosage from 200 g/t to 400 g/t increased the clean coal ash content from 9.97% to 11.80%. Moreover, Fig. 6.c shows the effect of collector dosage on the product ash content in the case of the Central Mine coal sample. As can be observed, increasing the collector dosage from 200 g/t to 600 g/t increased the clean coal ash content from 8.41% to 9.88% and any further increase in the collector dosage from 200 g/t had no significant effect on the clean coal ash content.

3.2.3. Low ash content coal (the coal sample of the Madanjoo Mine)

The effect of frother type on the clean coal ash content of the



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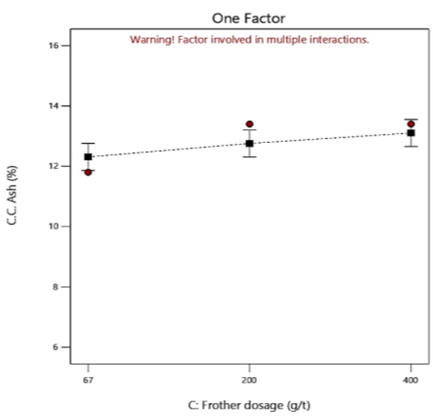

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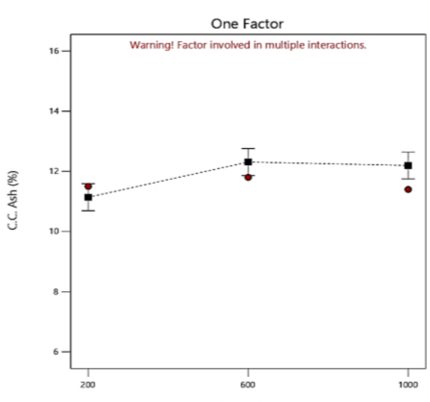
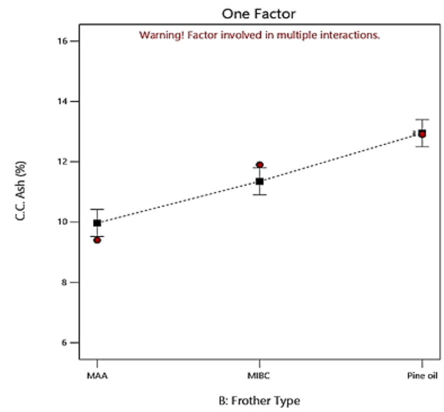


(c)

Fig.5. The effect of (a) frother type (frother dosage 200 g/t, collector dosage 600 g/t), (b) frother dosage (MAA as frother type, collector dosage 600 g/t), and (c) collector dosage (MAA as frother type, frother dosage 67 g/t) on the clean coal ash content of the No.1 mine coal sample



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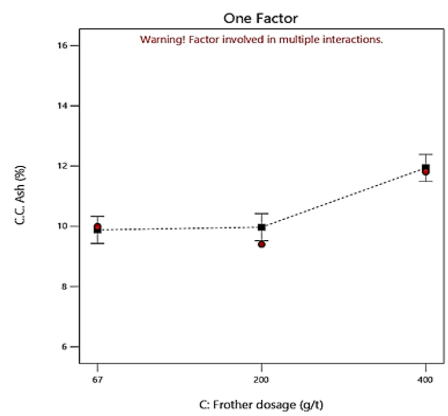

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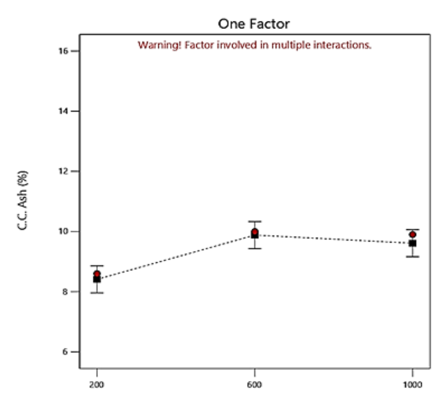

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Fig.6. The effect of (a) frother type (frother dosage 200 g/t, collector dosage 600 g/t), (b) frother dosage (MAA as frother type, collector dosage 600 g/t) and (c) collector dosage (MAA as frother type, frother dosage 67 g/t) on the clean coal ash content of the Central Mine coal sample.

Madanjoo coal sample is shown in Fig. 7.a. it is apparent that the clean coal ash content increased using pine oil type frother instead of the MAA and MIBC type frothers. The MAA is more efficient in the production of a flotation concentrate with lower ash content than the MIBC.

Fig. 7.b shows the effect of frother dosage on the clean coal ash content of the Madanjoo coal sample. It is clear that increasing the frother dosage from 67 g/t to 200 g/t had no significant effect on the product ash content, but increasing the frother dosage to 400 g/t, increased the ash content of the flotation concentrate.

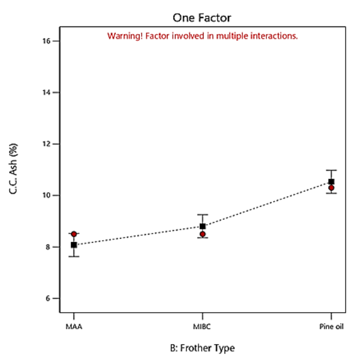
Fig. 7.c shows the effect of collector dosage on the clean coal ash content of the Madanjoo coal sample. As demonstrated, the ash content of the flotation concentrate increased from 7.23% to 8.31% by increasing the collector dosage from 200 g/t to 600 g/t. Increasing the collector dosage to more than 600 g/t had no significant effect on the ash content of the clean coal.

3.3. The effect of process parameters on the clean coal yield

Table 5 shows the ANOVA results for the selected factorial model in the case of clean coal yield response. The model is significant, since the

Table 5. The ANOVA table for the selected factorial model for the yield of clean coal.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	8526.57	32	266.46	23.19	< 0.0001	significant
A-Kind of Feed	2254.95	2	1127.47	98.14	< 0.0001	
B-Frother Type	1636.14	2	818.07	71.21	< 0.0001	
C-Frother dosage	2468.86	2	1234.43	107.45	< 0.0001	
D-Collector dosage	739.18	2	369.59	32.17	< 0.0001	
AB	710.94	4	177.73	15.47	< 0.0001	
AC	41.26	4	10.32	0.8979	0.4726	
AD	238.81	4	59.70	5.20	0.0015	
BC	186.16	4	46.54	4.05	0.0066	
BD	105.21	4	26.30	2.29	0.0733	
CD	145.06	4	36.27	3.16	0.0221	
Residual	551.44	48	11.49			
Cor Total	9078.00	80				



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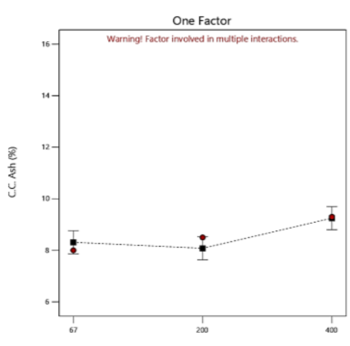

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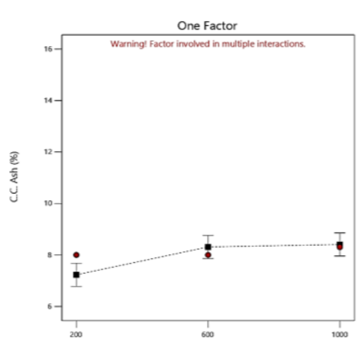

(c)

Fig.7. The effect of (a) frother type (frother dosage 200 g/t, collector dosage 600 g/t), (b) frother dosage (MAA as frother type, collector dosage 600 g/t), and (c) collector dosage (MAA as frother type, frother dosage 67 g/t) on the clean coal ash content of the Madanjoo coal sample.

model F-value is 23.19. There is only a 0.01% chance that an F-value this large could occur due to noise. The model terms including A, B, C, D, AB, AD, BC, CD are significant, since their P-value is less than 0.0500.

Table 6 shows the fit statistics for the yield of clean coal. The goodness of fit of the model was confirmed, since the R^2 value is 0.9393 which is near unity. The Predicted R^2 of 0.8270 was in reasonable agreement with the Adjusted R^2 of 0.8988, sine the difference was less than 0.2. Adequate precision measured the signal-to-noise ratio. A ratio greater than 4 is desirable. In this research, it was 21.045 which confirmed an adequate signal. This model can be used to navigate the design space.

Fig. 8 shows the residual plots for the clean coal yield modelling. As can be seen, all of the residual plots confirmed the model validity.

After confirmation of the model validity by the ANOVA table and the residual plots, the effect of model parameters on the clean coal yield is discussed below.

Table 6. Fit statistics for the yield of clean coal.

Standard Deviation	3.39	R^2	0.9393
Mean	41.07	Adjusted R^2	0.8988
C.V. %	8.25	Predicted R^2	0.8270
		Adeq Precision	21.0451

3.3.1. High ash content coal (the coal sample of the No.1 mine)

Fig. 9.a shows the effect of frother type on the yield of the clean coal for the No.1 mine coal sample. As can be observed, the clean coal yield by the MAA and MIBC as frother was lower than that of pine oil for the coal sample of the No.1 mine. It is due to this fact that pine oil is more surface active than MIBC and it has more foam stability than MIBC [16]. Furthermore, MIBC produces finer and more closely-sized bubbles [16].

Fig. 9.b shows the effect of frother dosage on the clean coal yield of the coal sample of the No.1 mine. As it is evident, the clean coal yield increased from 28.35% to 33.35% and then to 40.34% by increasing the frother dosage from 67 g/t to 200 g/t, and then to 400 g/t. It is due to this fact that the foam stability increased by rising the frother dosage [16].

Fig. 9.c shows the effect of collector dosage on the clean coal yield for the coal sample of the No.1 mine. As can be seen, the clean coal yield increased from 19.24% to 28.35% and then to 31.07% by increasing the collector dosage from 200 g/t to 600 g/t, and then to 1000 g/t. The addition of the collector increased the surface hydrophobicity of the coal particles with a partially oxidized surface and it created this chance for them to enter the flotation concentrate. Hence, it resulted in the increase of the flotation yield.

3.3.2. Moderate ash content coal (the coal sample of the Central Mine)

The effect of frother type on the clean coal yield of the Central Mine coal sample is shown in Fig. 10.a. It is clear that the pine oil frother had

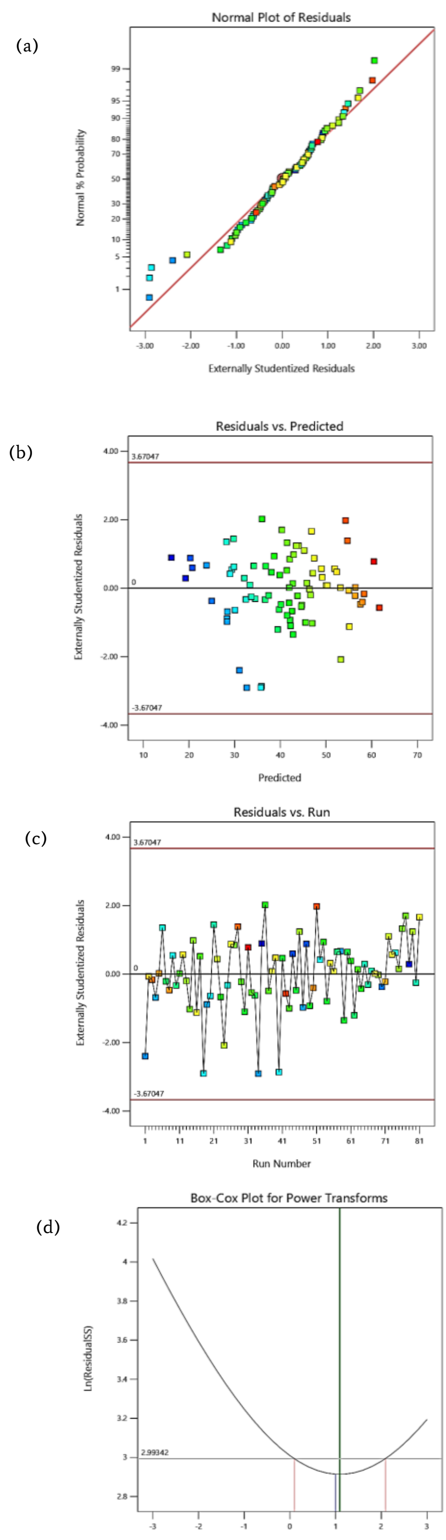

Fig. 8. (a) Normal plot of residuals, (b) plot of residuals vs. predicted, (c) plot of residuals vs. run number, and (d) Box-Cox plot for the clean coal yield modelling.

the higher clean coal yield in comparison with the other frothers. The effect of frother dosage on the clean coal yield of the Central Mine coal sample is shown in Fig. 10.b. It is evident that the clean coal yield increased from 42.12% to 45.80% and then to 50% by increasing the frother dosage from 67 g/t to 200 and then to 400 g/t.

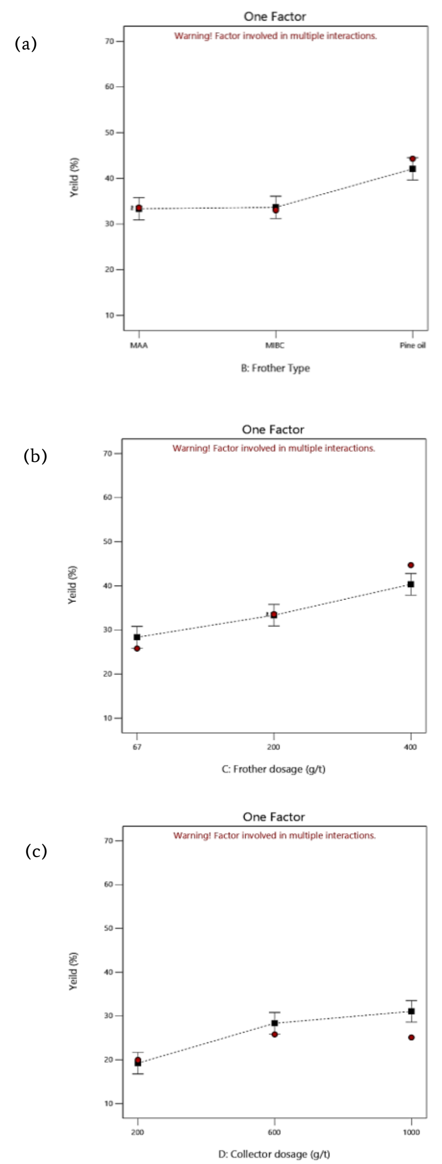

Fig.9. The effect of (a) frother type (frother dosage 200 g/t, collector dosage 600 g/t), (b) frother dosage (MAA as frother type, collector dosage 600 g/t), and (c) collector dosage (MAA as frother type, frother dosage 67 g/t) on the clean coal yield of No.1 mine coal sample.

The effect of collector dosage on the clean coal yield of the Central Mine coal sample is shown in Fig. 10.c. It can be seen that increasing the dosage of the collector from 200 g/t to 600 g/t increased the clean coal yield from 32.13% to 42.12%, and increasing the the dosage of collector from 600 g/t to 1000 g/t had no significant effect on the clean coal yield.

Fig.10. The effect of (a) frother type (frother dosage 200 g/t, collector dosage 600 g/t), (b) frother dosage (MAA as frother type, collector dosage 600 g/t), and (c) collector dosage (MAA as frother type, frother dosage 67 g/t) on the clean coal yield of the Central Mine coal sample

3.3.3. Low ash content coal (the coal sample of the Madanjoo Mine)

The effect of frother type on the clean coal yield for the Madanjoo coal sample is shown in Fig. 11.a. The clean coal yield was greater when using pine oil frother type than the MAA and MIBC frothers, so that the clean coal yield using MAA, MIBC, and pine oil as the frother was 34.51%, 37.46%, and 58.33%, respectively. The effect of frother dosage on the clean coal yield of the Madanjoo coal sample is shown in Fig. 11.b.

The clean coal yield increased from 29.78% to 34.51% and then to 39.43% by increasing the frother dosage from 67 g/t to 200 g/t and then to 400 g/t. The effect of collector dosage on the clean coal yield for the Madanjoo coal sample is shown in Fig. 11.c. The clean coal yield increased from 16.17% to 29.78% and then to 35.99% by increasing the dosage of collector from 200 g/t to 600 g/t and then to 1000 g/t.

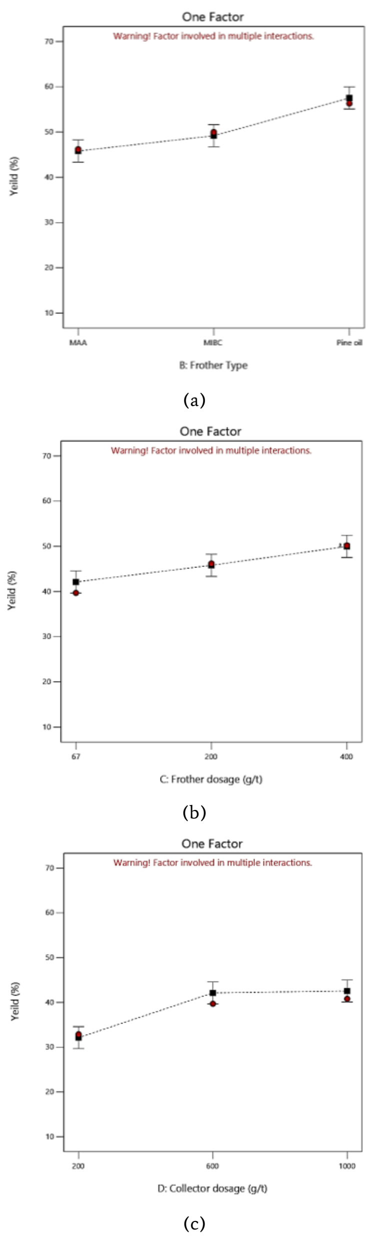

Fig.10. The effect of (a) frother type (frother dosage 200 g/t, collector dosage 600 g/t), (b) frother dosage (MAA as frother type, collector dosage 600 g/t), and (c) collector dosage (MAA as frother type, frother dosage 67 g/t) on the clean coal yield of the Central Mine coal sample.

3.4. Prediction and optimization

The optimization of the flotation performance of the three coal samples was performed by the DX7 software through optimization mode in order to maximize the clean coal yield and minimize the ash content of the clean coal. Fig. 12.a shows the optimization results for the coal sample of the No.1 mine. As can be seen, a clean coal with a yield of 37.95% and ash content of 12.76% can be produced at the MIBC frother dosage of 361 g/t and a dosage of collector of 200 g/t. Fig. 12.b shows the optimization results for the coal sample of the Central Mine. A clean coal with a yield of 45.98% and ash content of 10.24% can be produced in the flotation conditions of MAA as the frother with the dosage of frother 148 g/t and the collector dosage of 1000 g/t. The results of the flotation process optimization of the Madanjoo coal sample is shown in Fig. 12.c. A clean coal with a yield of 57.38% and ash content of 9.87% can be produced at flotation conditions of pine oil as the frother with the dosage of frother 174 g/t, and dosage of collector of 1000 g/t.

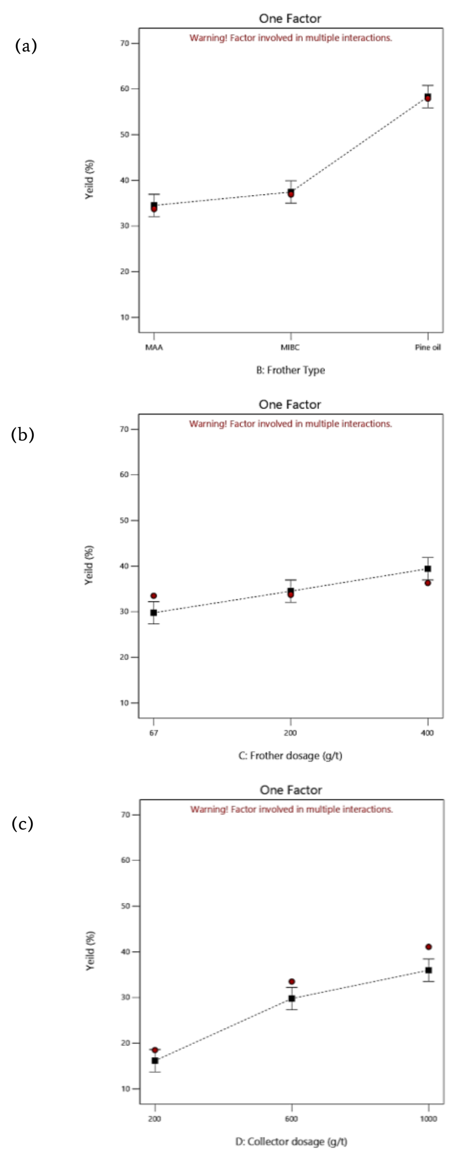

Fig.11. The effect of (a) frother type (frother dosage 200 g/t, collector dosage 600 g/t), (b) frother dosage (MAA as frother type, collector dosage 600 g/t), and (c) collector dosage (MAA as frother type, frother dosage 67 g/t) on the clean coal yield of the Madanjoo Mine coal sample.

the flotation optimization results of the three coal samples with various ash contents confirmed that from a feed coal with a lower ash content, a clean coal with lower ash content and higher yield was obtained. In the case of low ash content feed coal in comparison with high ash content feed coal, a lower frother dosage, higher collector dosage, and pine oil instead of the MIBC, as frother were required for the production of the desired clean coal.

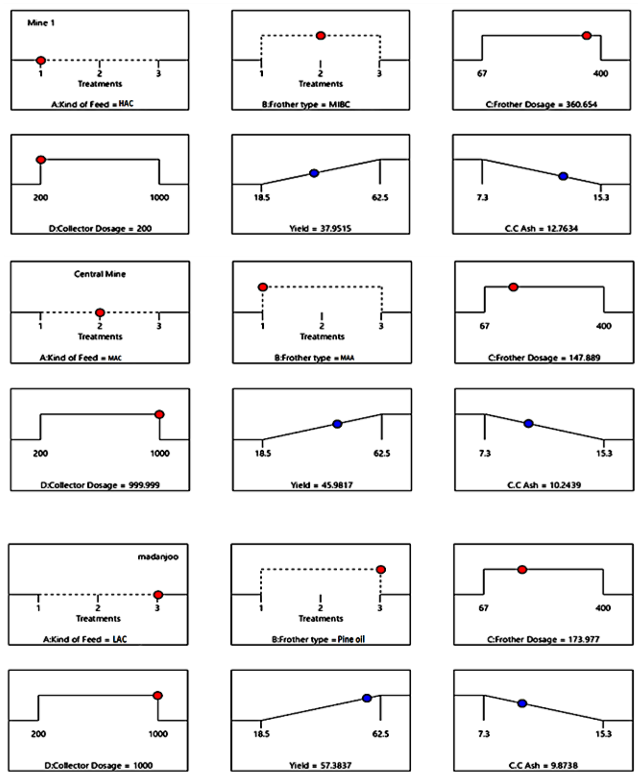

Fig. 12. The optimization results for the flotation performance of the coal sample of (a) No.1 mine, and (b) Central Mine, and c. Madanjoo Mine.

3.5. Validation results

3.5.1. Laboratory Validation

3.5.1.1. No.1 mine coal sample

In order to validate the optimization results for the coal sample of the No.1 mine, a laboratory flotation test was conducted so that the flotation conditions were set at optimal the conditions (i.e., MIBC, frother dosage of 361 g/t, and collector dosage of 200 g/t). This validation test was repeated in triplicate and the results are presented in Table 7. As demonstrated, the clean coal yield in the validation tests was 40.2, 39.8, and 39.1% with an average value of 39.7%. Furthermore, the clean coal ash content in the validation tests was 12.6%, 12.4%, and 12.3% with an average value of 12.43%. Furthermore, the prediction of the DX7 software for the clean coal yield and ash content at optimal conditions was 37.95% and 12.78%, respectively. Moreover, the average clean coal yield and ash content values in the validation tests with the values predicted by the DX7 software had a difference of 4.41% and 2.82%, respectively. It confirmed the optimization results obtained by DX7 software.

3.5.1.2. Central Mine coal sample

The optimization results predicted by the software for the Central Mine coal sample were validated by conducting a laboratory flotation test at optimal conditions (i.e., MAA, as frother, frother dosage 148 g/t, collector dosage 1000 g/t). This validation test was repeated in triplicate and the results are presented in Table 8. The clean coal yield in the validation tests was 46.3, 45.7, and 46.5% with an average value of 46.17%. Furthermore, the product ash content in the validation tests was 10.4%, 10.2%, and 10.6% with an average value of 10.4%. The prediction of the DX7 software for the clean coal yield and ash content at optimal conditions was 45.98% and 10.24%, respectively. The average clean coal yield and ash content values in the validation tests with the values predicted by the DX7 software had a difference of 0.41% and 1.54%, respectively. It confirmed the optimization results obtained by DX7 software.

3.5.1.3. Madanjoo Mine coal sample

The optimization results predicted by the software for the coal sample of the Madanjoo Mine were validated by conducting a laboratory flotation test at optimal conditions (i.e., pine oil, as frother, the dosage of frother 174 g/t, collector dosage 1000 g/t). This validation test was repeated in triplicate and the results are presented in Table 9. As can be seen, the clean coal yield in the validation tests was 60.2, 59.5, and 59.8% with an average value of 59.83%. Furthermore, the product ash content in the validation tests was 10.5%, 10.1%, and 10.7% with an average value of 10.4%. The prediction of the DX7 software for the clean coal yield and ash content at optimal conditions was 57.38% and 9.87%, respectively. The average clean coal yield and ash content values in the validation tests with the values predicated by the DX7 software had a difference of 4.09% and 5.10%, respectively. It confirmed the optimization results predicted by the DX7 software.

3.5.2. Plant validation test

The reagent scheme in the TPCWP was set based on the optimal conditions predicted by the DX7 software (i.e., MIBC, as frother, the dosage of frother 361 g/t, and collector dosage 200 g/t) for the No.1 mine feed coal, since the plant was fed from the No.1 coal mine during this research. In order to determine the flotation process performance, sampling was performed from the feed, concentrate, and the tailings of the flotation cells.

Table 7. The laboratory validation tests for the flotation optimization of the coal sample of the No.1 mine.

Validation	W %	Ash %	Distribution of ash	Cumulative wt%	Ash cumulative distribution	Cumulative ash %
Validation-1	18.5	10.8	199.4	18.5	199.4	10.8
	21.7	14.2	308.4	40.2	507.8	12.6
	59.8	68.1	4073.6	100.0	4581.4	45.8
	100	45.8				
Validation-2	13.4	10.5	141.1	13.4	141.1	10.5
	26.3	13.3	350.1	39.8	491.2	12.4
	60.2	67.4	4059.9	100.0	4551.1	45.5
	100	45.5				
Validation-3	15.8	9.7	153.1	15.8	153.1	9.7
	23.3	14.1	329.1	39.1	482.2	12.3
	60.9	67.5	4109.3	100.0	4591.5	45.9
	100	45.9				

Table 8. The laboratory validation tests for the flotation optimization of the coal sample of the Central Mine.

Validation	W %	Ash %	Distribution of ash	Cumulative wt%	Ash cumulative distribution	Cumulative ash %
Validation-1	32.8	9.5	311.6	32.8	311.6	9.5
	13.5	12.5	168.6	46.3	480.2	10.4
	53.7	57.7	3099.4	100.0	3579.6	35.8
	100	35.8				
Validation-2	32.7	10	327.5	32.7	327.5	10
	13.0	10.8	140.2	45.7	467.7	10.2
	54.3	56.6	3071.9	100.0	3539.5	35.4
	100	35.4				
Validation-3	33.9	10	338.6	33.9	338.6	10
	12.7	12.3	156.0	46.5	494.6	10.6
	53.5	57.3	3063.2	100.0	3557.8	35.6
	100	35.6				

Table 9. The laboratory validation tests for the flotation optimization of the coal sample of the Madanjoo Mine.

Validation	W %	Ash %	Distribution of ash	Cumulative wt%	Ash cumulative distribution	Cumulative ash %
Validation-1	36.1	8.3	299.8	36.1	299.8	8.3
	24.1	13.7	330.6	60.2	630.4	10.5
	39.8	57.7	2293.7	100.0	2924.0	29.2
	100	29.2				
Validation-2	34.1	7.9	269.7	34.1	269.7	7.9
	25.4	13	330.2	59.5	599.9	10.1
	40.5	58	2346.7	100.0	2946.6	29.5
	100	29.5				
Validation-3	36.9	8.9	328.7	36.9	328.7	8.9
	22.9	13.5	309.0	59.8	637.7	10.7
	40.2	57.4	2306.3	100.0	2944.0	29.4
	100	29.4				

Table 10. The plant validation tests for the flotation optimization of the coal sample of the No.1 mine.

Validation	Size µm	Feed		Concentrate		Tail		Yield %	CMR %	SE %
		W %	Ash %	W %	Ash %	W %	Ash %			
1	+500	14.7	58.7	3.7	4.5	17.5	62.5	6.6	15.1	14.6
	+300-500	22.0	45.2	25.8	5.3	18.9	69.1	37.5	64.7	60.3
	+150-300	16.5	52.3	11.7	7.5	14.3	66.9	24.6	47.7	44.1
	-150	46.8	46.2	58.8	16.4	49.3	71.3	45.7	71.0	54.8
	total	100	48.8	100	12.1	100	68.7	35.1	60.3	51.7
2	+500	13.0	54.4	5.7	4.5	22.0	64.1	16.3	34.1	32.7
	+300-500	20.4	39.8	11.2	6.1	17.8	63.3	41.1	64.1	57.8
	+150-300	16.3	57.8	15.9	7.6	13.7	71.8	21.8	47.7	44.9
	-150	50.3	44.4	67.1	16.8	46.5	69.2	47.3	70.8	52.9
	total	100	46.9	100	13.4	100	67.4	37.9	61.8	51.0
3	+500	17.8	58.2	5.0	4.7	19.6	59.9	3.1	7.0	6.8
	+300-500	20.0	48.2	19.1	6.2	17.3	73	37.1	67.2	62.5
	+150-300	16.2	49.7	21.4	8.7	14.3	64.2	26.1	47.4	42.8
	-150	46.0	45.6	54.5	17.2	48.8	70.3	46.5	70.8	53.3
	total	100	49.0	100	12.7	100	67.9	34.1	58.5	49.6

Sampling was performed every 20 minutes during three hours and the samples were mixed and sent to the laboratory for the required analysis. In the laboratory, the samples were divided into four size fractions (+500 μm, +300-500 μm, +150-300 μm, -150 μm) through sieve analysis and the weight percent and ash content of each size fraction were determined. Sampling from the flotation circuit of the TPCWP was performed in triplicate and the results are also presented in Table 10. As can be seen, the clean coal ash content in three validation tests was 12.1%, 13.4%, and 12.7% with an average of 12.73%. The average clean coal ash content had a 0.24% difference from the value predicted by the DX7 software. The clean coal yield is 35.1%, 37.9%, and 34.1% with an average value of 35.7%. The average clean coal yield had a 6.3% difference from the value predicted by the DX7 software. Hence, the results of the laboratory optimization test are validated in the plant scale with high accuracy.

4. Conclusion

1) The results of the laboratory experimental design tests showed that at the confidence level of 95%, coal sample type, frother dosage, frother type, and collector dosage were the most effective parameters, affecting the clean coal ash content, respectively.

2) The results of the laboratory experimental design tests showed that at the confidence level of 95%, frother dosage, coal sample type, frother type, and collector dosage were the most effective parameters, affecting the clean coal yield, respectively.

3) The optimal flotation conditions for each coal sample with different ash content were quite different. For the coal sample of the No.1 mine with feed ash content of 45.1%, a clean coal with ash content of 12.8% and yield of 38% was produced at optimal conditions of MIBC, as the frother, with the dosage of frother 361 g/t, and the collector dosage of 200 g/t. In the case of the Central Mine coal sample with feed ash content of 36.8%, a clean coal with ash content of 10.2% and yield of 46% was produced at optimal flotation conditions of MAA, as the frother, with the dosage of frother 148 g/t, and the dosage of collector 200 g/t. For the Madanjoo coal sample with feed ash content of 30.7%, a clean coal with ash content of 10% and yield of 57.4% was produced at the optimal flotation conditions of pine oil, as the frother, with the dosage of frother 174 g/t, and the collector dosage of 1000 g/t.

4) The accuracy of the predicted optimum flotation conditions was validated by running laboratory flotation tests. The laboratory validation tests showed that a clean coal with ash content and yield of 12.4% and 39.7% from the No.1 mine coal sample, 10.4% and 46.2% from the Central Mine coal sample, and 59.8% and 10.4% from the Madanjoo coal sample can be produced which confirmed the high accuracy of the optimization results obtained by the DX7 software.

5) From a feed coal with lower ash content in comparison to a high ash content feed coal, a clean coal with lower ash content and higher yield was produced at lower frother dosage, higher collector dosage, and using pine oil frother instead of the MIBC frother.

6) The accuracy of the predicted optimal flotation conditions for the No.1 coal sample was further validated in the flotation circuit of the Parvadeh coal washing plant. A clean coal with ash content of 12.73% and yield of 35.7% was produced in the flotation circuit of the Parvadeh coal washing plant which showed a negligible deviation from the results which predictd by the DX7 software.

Acknowledgement

The authors are thankful to the Director of Tabas Parvadeh Coal Company (TPCCO) for giving permission to perform this research project in the Tabas Parvadeh coal washing plant and to publish this paper.

Refrences

[1] Yang, Z., Xia, Y., Wei, C., Cao, Y., Sun, W., Liu, P., Cheng, H., Xing, Y. & Gui, X. (2019). New flotation flowsheet for recovering combustible matter from fine waste coking coal. Journal of Cleaner Production, 225, 209-219.

[2] Mao, Y., Xia, W., Peng, Y. & Xie, G. (2019). Ultrasonic-assisted flotation of fine coal: A review. Fuel Processing Technology, 195, 106150.

[3] Gui, X., Cao, Y., Xing, Y., Yang, Z., Wang, D. & Li, C. (2017). A two-stage process for fine coal flotation intensification. Powder Technology, 313, 361-368.

[4] Xia, W., Zhou, C. & Peng, Y. (2017). Enhancing flotation cleaning of intruded coal dry-ground with heavy oil. Journal of Cleaner Production, 161, 591-597.

[5] Naik, P. K., Reddy, P. S. R. & Misra, V. N. (2005). Interpretation of interaction effects and optimization of reagent dosages for fine coal flotation. International Journal of Mineral Processing, 75(1-2), 83-90.

[6] Li, D., Zhang, C., Li, X., Yang, L., Yan, X., Wang, L., Liu, Q. & Zhang, H. (2020). Experimental study on the preconditioning of fine coal particles surface modification using a new type flow mixer. Fuel, 268, 117361.

[7] Ding, L. P. (2010). Effect of collector interfacial tension on coal flotation of different particle sizes. Industrial & engineering chemistry research, 49(8), 3769-3775.

[8] Wang, G., Bai, X., Wu, C., Li, W., Liu, K. & Kiani, A. (2018). Recent advances in the beneficiation of ultrafine coal particles. Fuel Processing Technology, 178, 104-125.

[9] Wang, Y., Xing, Y., Gui, X., Cao, Y. & Xu, X. (2018). The characterization of flotation selectivity of different size coal fractions. International Journal of Coal Preparation and Utilization, 38(7), 337-354.

[10] Prakash, R., Majumder, S. K. & Singh, A. (2018). Flotation technique: Its mechanisms and design parameters. Chemical Engineering and Processing-Process Intensification, 127, 249-270.

[11] Chang, Z., Chen, X. & Peng, Y. (2017). Understanding and improving the flotation of coals with different degrees of surface oxidation. Powder Technology, 321, 190-196.

[12] Wen, B., Xia, W. & Sokolovic, J. M. (2017). Recent advances in effective collectors for enhancing the flotation of low rank/oxidized coals. Powder Technology, 319, 1-11.

[13] Xia, W., Wu, F., Jaiswal, S., Li, Y., Peng, Y. & Xie, G. (2021) Chemical and physical modification of low rank coal floatability by a compound collector. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 610, 125943.

[14] Zhu, X., He, M., Zhang, W., Wei, H., Lyu, X., Wang, Q., You, X. & Li, L. (2020). Formulation design of microemulsion collector based on gemini surfactant in coal flotation. Journal of Cleaner Production, 257, 120496.

[15] Das, B. & Reddy, P. S. R. (2010). The utilization of non-coking coal by flotation using non-conventional reagents. Energy Sources Part A, 32(19), 1784-1793.

[16] Gupta, A. K., Banerjee, P. K., Mishra, A. & Satish, P. (2007). Effect of alcohol and polyglycol ether frothers on foam stability, bubble size and coal flotation. International Journal of Mineral Processing, 82(3), 126-137.

[17] Zhang, Z., Yang, J., Wang, Y., Dou, D. & Xia, W. (2014). Ash content prediction of coarse coal by image analysis and GA-SVM. Powder Technology, 268, 429-435.

[18] Dehghan, R. & Aghaei, M. (2014). Evaluation of the performance of Tri Flo separators in Tabas (Parvadeh) coal washing plant. Research Journal of Applied Sciences, Engineering and Technology, 7(3), 510-514.

[19] ASTM D3174 (2013). “Standard test method for ash in the analysis sample of coal and coke from coal”. Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.