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ANALYSIS OF SELECTED METHODS OF BENEFICIATING COAL SLURRIES DEPOSITED IN IMPOUNDMENTS

Jan SZPYRKA, Marcin LUTYNSKI

Silesian University of Technology, Faculty of Mining and Geology, Department of Mineral Processing and Waste Utilization, Gliwice, Poland, jan.szpyrka@polsl.pl, marcin.lutynski@polsl.pl

Abstract. The paper presents research results of the possibility to beneficiate coal slurries deposited in 21 impoundments located in the region of Silesia, Poland. Coal slurries of particle size diameter below 1 (0.5) mm were subjected to beneficiation tests with the use of the following methods: centrifugal separator, hydrocyclone, Reichert spiral separator and flotation. Applied methods showed significant differences in obtained results. The most effective method was flotation where yield was on average 64% with concentrate of high calorific value. In case of centrifugal separator and Reichert type spiral average yield was 22% and 25%, respectively. In case of hydrocyclone classifier-separator, a high yield of low quality concentrate was obtained. The study revealed that such impoundments have a high energetic potential which can be effectively used by applying a proper beneficiation technology.

keywords: coal slurry, tailings, impoundments, gravity separation

1. Introduction

The most common gravity separation methods are used successfully for particle size fractions larger than 0.1 mm. Nevertheless, below this limit with appropriate technological parameters and with the use of appropriate equipment (application of additional centrifugal force) an effective separation of finer particle sizes with high density difference is carried out. A summary of gravity separation methods taking into account particle sizes is presented in Table 1.

The latest technology of gravity separation using devices that allow to obtain high centrifugal forces significantly reduce particle size lower limit suitable for effective separation. These technologies which employ equipment of Mozley, Falcon, Knelson and Kelsey are not in use currently in Poland.

Results of coal slurries beneficiation tests from twenty one impoundments are presented in the paper. The tests were performed at the Technological Laboratory of Department of Mineral Processing and Waste Utilization within the framework of development project N R09 0006 06/2009 entitled “Identification of energetic potential of coal slurries in the national fuel balance and technological development strategy of their usage”. The project is implemented by the Institute of Mechanized

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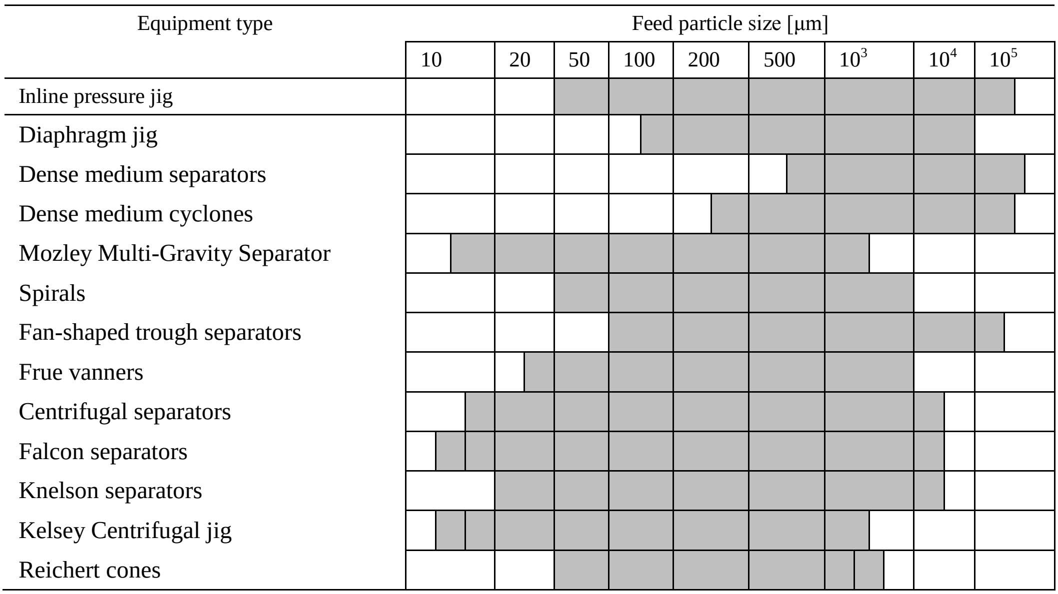
Construction & Rock Mining in Warsaw in cooperation with the Department of Mineral Processing and Waste Utilization of the Silesian University of Technology (Blaschke et al. 2011, Baic and Blaschke 2010).

The purpose of the Project is quantitative and qualitative identification of coal slurries deposited in impoundments located in the area of mining activity. Coal slurry impoundments are the effect of long term activity of coal beneficiation plants. Material deposited there consists of slurries and post-flotation muds of particle size smaller than 1 (0.5) mm. Up to the thirties i.e. the time of development and introduction of froth flotation technology small size fraction gangue was difficult to remove using conventional beneficiation methods which, as a result, was significantly lowering the coke quality. Therefore, particle size smaller than 1 mm were treated as a waste. The same situation was in the case of steam coal as it was impossible to burn small particles in stoker-fired boilers.

Nevertheless, the coal slurries deposited in impoundments have an energetic potential that should be effectively utilized. Recovering the coal matter is one of such methods, effective use of the energetic potential (Lutyński and Blaschke 2009; Hycnar et al. 2005; Hycnar and Bugajczyk 2004; Karbownik and Haber 1999).

Table 1. Gravity separation chart. Adapted from (Abols and Grady, 2006)



2. Description of tests

Beneficiation tests of coal slurries were carried out in our laboratory on a semi-technical scale. Three different separation methods were tested:

— centrifugal force separation method with the use of hydrocyclone classifier-separator and centrifugal separator (Honaker et al. 1994; Driessen 1945),
— wet gravity separation method with the use of Reichert spiral separator LD4 (Atesok et al. 1993),
— physicochemical method – flotation (Tao et al. 2002).

Beneficiation tests of coal slurries were carried out with a hydrocyclone classifier-separator of ø150 mm diameter located at the Technological Laboratory of our Department. The feed of selected density was pumped to the hydrocyclone with overflow in order to maintain constant hydrostatic pressure. Before proceeding to the tests with proper samples, several tests on waste material of similar properties were carried out. The purpose of preliminary tests was to determine the range of appropriate feed density and the feed flow rate. It was found that the preferred density of the beneficiated material is 150 g/dm^3. The testing device was equipped with electromagnetic flowmeter FM 300 DN25 SPT. The testing device is designated for separation of slurries with the upper particle size limit of 1(2) mm.

Results of coal slurry beneficiation tests carried out in the hydrocyclone are presented in Table 2 and Table 3.

In gravity separation methods the quality of concentrate is lowered by the finest gangue fraction (<0.1 mm) that passes with larger and lighter coal particles to concentrates. Improvement of concentrate quality can be achieved by removing sludge from the feed or by removing the sludge from the concentrate. Sludge can be removed in the hydrocyclone. Therefore, the concentrate from the hydrocyclone was used as the feed in the beneficiation tests in the centrifugal and spiral separator.

Centrifugal separator uses a centrifugal force to separate material. It is designated to beneficiate slurries with the upper particle size limit of 1(2) mm. Vortex is created by rotating blades on a vertical shaft driven by an electric engine with transmission belt which allows changing the rotation speed. Set of blades is rotating in the cone-shaped bowl where the feed is introduced under hydrostatic pressure. Feed slurry enters centrally and is distributed outwards at the base of the cone by centrifugal force and then flows up the inclined surface of the bowl, segregating in the process, with high specific gravity particles on the outside closest to the bowl surface and low density particles on the inside which discharge over the lip at the top of the bowl.

The feed of proper density (100-150 g/dm^3) is pumped to the cone which provides a constant hydrostatic pressure. Received products are collected by gravity in two tanks.

Beneficiation tests were carried out for two feed densities of 100 and 150 g/dm^3. Due to favorable outcome only test results for the feed density of 150 g/dm^3 are presented in the paper (see Table 4).

In case of spiral separator, a Reichert LD4 type separator was used. The testing device consists of feed tank, LD4 spiral separator with two trough of six coils and a dewatering screen.

Table 2. Quality parameters of coal slurry products classification in hydrocyclone classifier-separator of diameter 150 mm. Slurry density 150 g/dm^3

Impoundment	underflow		overflow		feed
	Yield g_k [%]	Ash content A^a [%]	Yield g_o [%]	Ash content A^a [%]	Ash content A^a [%]
1	47.5	31.64	52.50	35.93	33.89
2	55.58	26.12	44.42	47.53	35.63
3	49.52	39.64	50.48	45.94	42.82
4	50.03	57.45	49.97	68.84	63.14
5	59.66	71.63	40.34	74.01	72.59
6	51.05	42.51	48.95	55.30	48.77
7	77.35	43.87	22.65	53.63	46.08
8	63.4	56.87	36.6	62.17	58.81
9	57.89	25.13	42.11	44.34	33.22
10	44.23	46.22	55.77	61.82	54.92
11	52.08	43.91	47.92	47.96	45.85
12	50.58	32.2	49.42	24.00	28.15
13	59.24	24.21	40.76	34.78	28.52
14	57.43	22.36	42.57	34.88	27.69
15	45.61	30.96	54.39	42.80	37.4
16	47.57	34.88	52.43	38.28	36.66
17	50.5	34.21	49.5	38.07	36.12
18	50.74	35.67	49.26	37.29	36.47
19	43.79	48.63	56.21	62.90	56.65
20	47.50	44.06	52.5	51.77	48.11
Av.	53.10	39.60	46.94	48.11	43.57

The feed was supplied by gravity from a tank with a high-speed stirrer and further agitated with air from a compressor. Rotation of stirrer and air-lift prevent from sedimentation of feed in the tank and provide constant feed density.

Initial tests were carried out in order to determine the preferred range of feed density, feed flow rate and to adjust settings of feed driving blades and product collectors.

Tests were carried out on samples from seventeen and nineteen impoundments with two feed densities (300 g/dm^3 and 400 g/ dm^3). Favorable results were observed for feed density of 400 g/ dm^3. Results are presented in Table 5.

Laboratory flotation tests of coal slurries were carried out in laboratory froth flotation cells with volume of 1 dm^3. The density of the coal slurry was 100 g/dm^3.

It should be mentioned that the experience of the Department employees shows that in case of flotation process, results obtained in the laboratory differ significantly from the results obtained in industrial flotation cells.

Two flotation agents which are in common use in coal beneficiation plants, were used for the tests. Initial tests were performed in order to determine the optimum amount of flotation agent. Further tests were carried out for flotation agent concentration of 0.4, 0.5 and 0.6 kg per Mg of dry material. Best results were obtained for the concentration of flotation agent of 0.6 kg per Mg of dry material.

Table 3. Quality parameters of concentrate (underflow from hydrocyclone classifier-separator) obtained for classification of 0.1 mm sorted particle size

Impoundment	Concentrate (underflow)				
	Yield	Ash content	Hydroscopic moisture	Sulfur content	Calorific value
	γ_k %	A^a [%]	W^{ex} [%]	S_c^a [%]	Q^a [%]
1	47.50	31.64	6.65	1.34	18121
2	55.58	26.12	6.43	0.76	20362
3	49.52	39.64	5.30	1.02	17281
4	50.03	57.45	4.41	0.58	9295
5	59.66	71.63	4.59	0.66	8576
6	51.05	42.51	5.32	0.96	15990
7	77.35	43.87	1.33	3.42	16277
8	63.40	56.87	1.22	2.04	12027
9	57.89	25.13	2.89	0.70	24234
10	44.23	46.22	4.09	1.09	13444
11	52.08	43.91	1.50	1.05	17972
12	50.58	32.2	2.19	0.35	24363
13	59.24	24.21	1.99	0.61	24,557
14	57.43	22.36	2.02	0.83	25501
15	45.61	30.96	1.88	0.86	21415
16	47.57	34.88	2.21	0.85	21085
17	50.50	34.21	1.69	1.12	21161
18	50.74	35.67	2.22	1.06	21844
19	43.79	48.63	3.30	0.82	12008
20	47.50	44.06	2.12	0.74	18022
Av.	53.10	39.60	3.16	1.04	16950

Tests were conducted on samples from all impoundments. A positive flotation test result was assumed when 80% of the samples had a positive flotation effect. In case of samples from one impoundment a positive test was considered when 66% of the samples had a yield greater than 30% and the ash content in concentrate was lower than 25%. These criteria were fulfilled for the samples from 12 impoundments. Results of tests for the flotation agent 2 which was considered as preferable are presented in Table 6.

3. Results of investigation

Results of tests carried out were summarized in Tables 2 to 8. In Tables 7 and 8 a comparison of selected results from different separation methods is shown. Presented results are both for concentrate and tailings. It seems that obtained results indicate the efficiency of selected method (Fig. 1). In Figures 2 and 3 washability curves for the two most favorable results of hydrocyclone separation are presented.

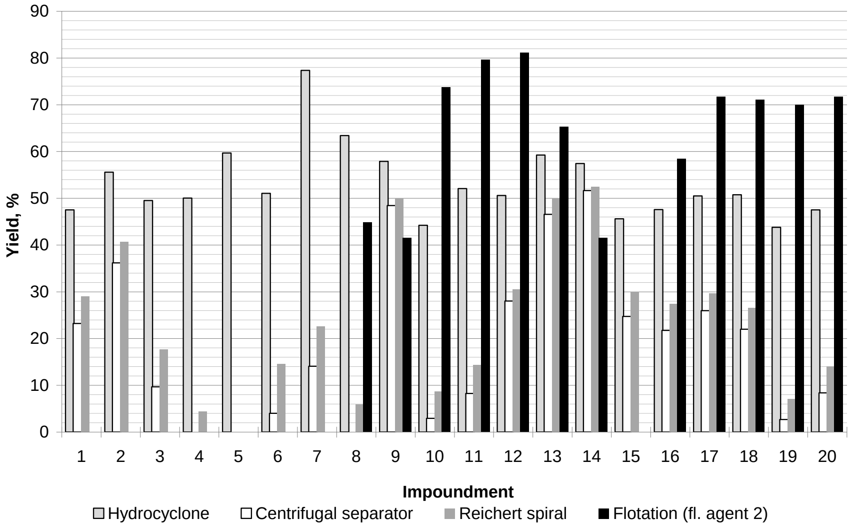


Fig. 1. Comparison of concentrate yields obtained with each separation method

Table 4. Concentrate parameters after sludge removal in centrifugal separator for feed density of 150 g/dm^3

Impoundment	Concentrate				Tailings				Concentrate yield with regard to the feed
	Yield	Ash content	Calorific value	Hydroscopic moisture	Yield	Ash content	Calorific value	Hydroscopic moisture	
	γ_o [%]	A^a [%]	Q^a [kJ/kg]	W^{ex} [%]	γ_o [%]	A^a [%]	Q^a [kJ/kg]	W^{ex} [%]	γ_{kc} [%]
1	48.88	21.14	18916	5.32	51.12	41.68	14199	4.09	23.22
2	65.08	20.68	20654	5.46	34.92	36.26	16158	6.12	36.17
3	19.54	20.31	22042	4.11	80.46	44.33	14065	3.99	9.68
4	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-
6	7.84	22.06	21043	5.71	92.16	44.25	14409	4.51	4.00
7	18.20	21.59	25840	1.26	81.8	48.83	14015	1.19	14.08
8	-	-	-	-	-	-	-	-	-
9	83.67	20.47	24104	2.51	16.33	49.01	13403	1.84	48.44
10	6.59	21.68	18965	4.72	93.41	47.95	12260	4.25	2.91
11	15.84	19.93	25046	1.73	84.16	48.42	14723	1.78	8.25
12	55.41	20.47	24095	1.93	44.59	46.78	15914	2.51	28.03
13	78.61	21.14	24164	2.06	21.39	35.49	19068	2.25	46.57
14	89.92	21.56	24315	2.31	10.08	29.50	20484	1.12	51.64
15	54.23	20.46	24430	2.23	45.77	43.40	16531	2.60	24.73
16	45.68	21.51	24043	1.96	54.32	46.12	15398	2.22	21.73
17	51.41	21.86	23802	2.39	48.59	47.28	15173	2.49	25.96
18	43.33	21.15	24281	2.06	56.67	46.77	15604	2.38	21.99
19	6.12	22.35	18519	6.13	93.88	50.34	12165	4.38	2.68
20	17.62	21.82	24124	2.83	82.38	48.82	15294	2.64	8.37
Av.	41.64	21.19	22846	3.22	58.35	44.42	15227	2.96	22.26

Table 5. Parameters of separation of concentrate after sludge removal beneficiated in six coils LD4 of Reichert spiral separator for the feed density of 400 g/dm^3

Impoundment	Concentrate				Tailings				Yield	Concentrate yield with regard to the feed
	Yield	Ash content	Calorific value	Hydroscopic moisture	Yield	Ash content	Calorific value	Hydroscopic moisture	Ash content	
	γ_o [%]	A^a [%]	Q^a [kJ/kg]	W^{ex} [%]	γ_o [%]	A^a [%]	Q^a [kJ/kg]	W^{ex} [%]	A^a [%]	γ_{kc} [%]
1	61.15	21.10	18825	5.64	38.85	48.23	12680	3.19	31.64	29.05
2	73.12	22.14	20271	5.51	26.88	36.95	15950	6.18	26.12	40.64
3	35.62	21.86	21523	4.40	64.38	49.48	12480	3.79	39.64	17.64
4	8.69	22.07	21042	4.83	91.31	60.82	7114	3.10	57.45	4.35
6	28.43	22.81	20760	5.72	71.57	50.34	12581	4.16	42.51	14.51
7	29.14	21.20	25843	1.22	70.86	53.19	12113	1.19	43.87	22.54
8	9.21	23.81	24258	1.13	90.79	60.22	9479	1.59	62.17	5.84
9	86.12	20.47	24335	2.36	13.88	54.04	11518	2.65	25.13	49.85
10	19.63	21.45	19136	4.71	80.37	52.27	11272	4.17	46.22	8.68
11	27.47	22.31	24241	1.70	72.53	52.09	13545	1.80	43.91	14.31
12	60.25	20.33	24459	1.90	39.75	50.19	14831	2.63	32.20	30.47
13	84.38	22.52	23763	2.08	15.62	33.34	19879	2.21	24.21	49.99
14	91.33	21.84	24333	2.19	8.67	27.84	21879	2.19	22.36	52.45
15	65.61	23.26	23352	2.10	34.39	45.65	15528	2.97	30.96	29.92
16	57.63	22.27	23666	2.15	42.37	52.03	13192	2.03	34.88	27.41
17	58.73	21.46	24035	2.31	41.27	52.35	13581	2.62	34.21	29.66
18	52.35	21.39	24195	2.25	47.65	51.36	14012	2.23	35.67	26.56
19	16.11	20.82	18756	5.83	83.89	53.97	11486	4.23	48.63	7.05
20	29.42	21.35	24256	2.67	70.58	53.53	14008	2.67	44.06	13.97
Av.	47.07	21.81	22687	3.19	52.93	49.36	13533	2.93	35.66	24.99

Table 6. Coal slurry flotation results, flotation agent # 2

Impoundment	Feed ash content A^a, %	Product	Yield %	Ash content in products A^a %	Calorific value of concentrate, Q^a kJ/kg
8	50.8	C T	44.8 55.1	22.7 73.3	24 687
9	60.9	C T	41.5 58.5	31.2 82.9	20 670
10	27.2	C T	73.7 26.3	14.5 65.8	27 620
11	28.6	C T	79.6 20.4	15.9 80.3	27 120
12	28.6	C T	81.1 18.9	16.4 81.1	26 880
13	48.0	C T	65.3 34.7	29.4 82.9	21 525
14	60.9	C T	41.5 58.5	31.2 82.9	24 520
16	44.3	C T	58.4 41.6	23.6 76.8	24 670
17	36.7	C T	71.7 28.3	19.2 79.8	25 875
18	36.2	C T	71.1 28.9	19.5 76.7	25 810
19	37.3	C T	70.0 30.0	19.3 77.4	25 845
20	36.5	C T	71.7 28.3	21.3 76.3	25 465

C – concentrate, T – tailings

Table 7. Comparison of selected coal slurry concentrate parameters beneficiated by different methods

Imp.	Hydrocyclone			Centrifugal separator, 150 g/dm^3			Reichert spiral, 400g/dm^3			Flotation, flotation agent # 2		
	Yield γ_k %	Ash content A^a [%]	Calorific value Q^a [%]	Yield γ_k %	Ash content A^a [%]	Calorific value Q^a [kJ/kg]	Yield γ_k %	Ash content A^a [%]	Calorific value Q^a [kJ/kg]	Yield γ_k %	Ash content A^a [%]	Calorific value Q^a [kJ/kg]
1	47.50	31.64	18121	23.22	21.14	18916	29.05	21.10	18825	-	-	-
2	55.58	26.12	20362	36.17	20.68	20654	40.64	22.14	20271	-	-	-
3	49.52	39.64	17281	9.68	20.31	22042	17.64	21.86	21523	-	-	-
4	50.03	57.45	9295	-	-	-	4.35	22.07	21042	-	-	-
5	59.66	71.63	8576	-	-	-	-	-	-	-	-	-
6	51.05	42.51	15990	4.00	22.06	21043	14.51	22.81	20760	-	-	-
7	77.35	43.87	16277	14.08	21.59	25840	22.54	21.20	25843	-	-	-
8	63.40	56.87	12027	-	-	-	5.84	23.81	24258	44.8	22.7	24 687
9	57.89	25.13	24234	48.44	20.47	24104	49.85	20.47	24335	41.5	31.2	20 670
10	44.23	46.22	13444	2.91	21.68	18965	8.68	21.45	19136	73.7	14.5	27 620
11	52.08	43.91	17972	8.25	19.93	25046	14.31	22.31	24241	79.6	15.9	27 120
12	50.58	32.2	24363	28.03	20.47	24095	30.47	20.33	24459	81.1	16.4	26 880
13	59.24	24.21	24.557	46.57	21.14	24164	49.99	22.52	23763	65.3	29.4	21 525
14	57.43	22.36	25501	51.64	21.56	24315	52.45	21.84	24333	41.5	31.2	24 520
15	45.61	30.96	21415	24.73	20.46	24430	29.92	23.26	23352	-	-	-
16	47.57	34.88	21085	21.73	21.51	24043	27.41	22.27	23666	58.4	23.6	24 670
17	50.50	34.21	21161	25.96	21.86	23802	29.66	21.46	24035	71.7	19.2	25 875
18	50.74	35.67	21844	21.99	21.15	24281	26.56	21.39	24195	71.1	19.5	25 810
19	43.79	48.63	12008	2.68	22.35	18519	7.05	20.82	18756	70.0	19.3	25 845
20	47.50	44.06	18022	8.37	21.82	24124	13.97	21.35	24256	71.7	21.3	25 465
Av.	53.10	39.61	16950	22.26	21.19	22846	24.99	21.81	22687	64.2	22.02	25057

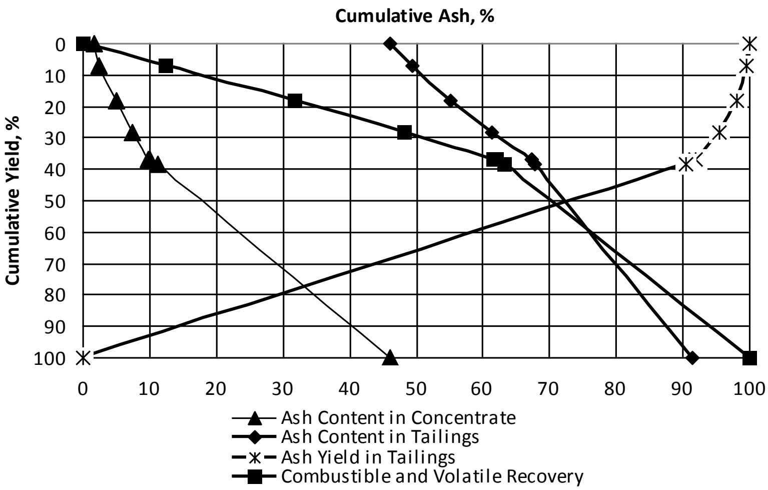


Fig. 2. Washability (Henry) curves of coal slurry from impoundment 9

Table 8. Comparison of selected coal slurry tailings parameters from different separation methods

Imp.	Hydrocyclone		Centrifugal separator, 150 g/dm^3		Reichert spiral 400g/ dm^3		Flotation, flotation agent # 2	
	Yield γ_k %	Ash content A^a [%]	Yield γ_k %	Ash content A^a [%]	Yield γ_k %	Ash content A^a [%]	Yield γ_k %	Ash content A^a [%]
1	52.50	35.93	51.12	41.68	70.95	48.23	-	-
2	44.42	47.53	34.92	36.26	59.36	36.95	-	-
3	50.48	45.94	80.46	44.33	82.36	49.48	-	-
4	49.97	68.84	-	-	95.65	60.82	-	-
5	74.01	74.01	-	-	85.49	50.34	-	-
6	55.30	55.30	92.16	44.25	77.46	53.19	-	-
7	53.63	53.63	81.8	48.83	94.16	60.22	-	-
8	62.17	62.17	-	-	50.15	54.04	55.1	73.3
9	44.34	44.34	16.33	49.01	91.32	52.27	58.5	82.9
10	61.82	61.82	93.41	47.95	85.69	52.09	26.3	65.8
11	47.96	47.96	84.16	48.42	69.53	50.19	20.4	80.3
12	24.00	24.00	44.59	46.78	50.01	33.34	18.9	81.1
13	34.78	34.78	21.39	35.49	47.55	27.84	34.7	82.9
14	34.88	34.88	10.08	29.50	70.08	45.65	58.5	82.9
15	42.80	42.80	45.77	43.40	72.59	52.03	-	-
16	38.28	38.28	54.32	46.12	70.31	52.35	41.6	76.8
17	38.07	38.07	48.59	47.28	73.44	51.36	28.3	79.8
18	37.29	37.29	56.67	46.77	92.95	53.97	28.9	76.7
19	62.90	62.90	93.88	50.34	86.03	53.53	30.0	77.4
20	51.77	51.77	82.38	48.82	75.01	49.36	28.3	76.3
Av.	46.90	48.11	58.35	41.68	75.01	48.23	35.8	78.02

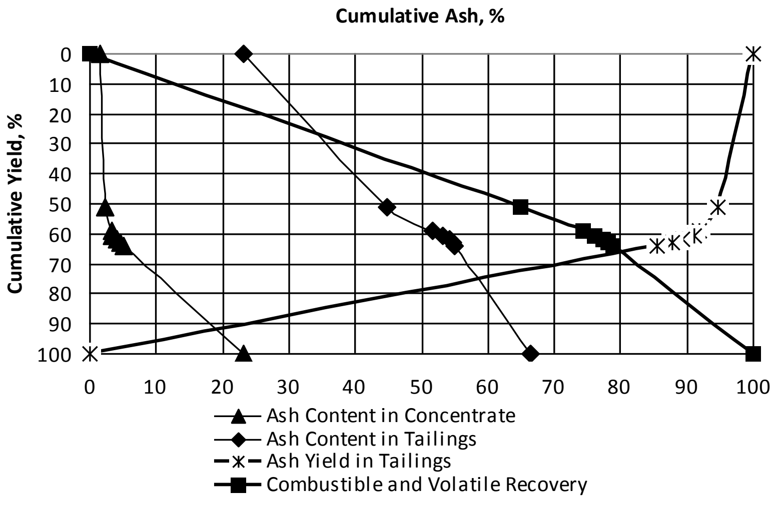


Fig. 3. Washability (Henry) curves of coal slurry from impoundment 13

4. Conclusions

Four separation methods presented in the paper show significant differences in results. The most effective method is the froth flotation where yield was on average 64%, calorific value of the concentrate was approximately 25 MJ/kg and the ash content approximately 22%. Moreover, tailings showed high ash content. Performed tests reported that due to flotation agent used this method cannot be applied to all tested coal slurries. Thus, if this method is to be applied for fine particle size coal tailings, other more efficient flotation agents must be applied (Laskowski 2004).

Much less favorable results were obtained with the centrifugal separator and Reichert type LD4 spiral separator. In material used in these types of separators particle size below 0.1 mm was initially separated in the hydrocyclone. The average yield for the Reichert spiral was 25% and for the centrifugal separator 22%. The calorific value of the concentrate was 22.687 MJ/kg and 22.846 MJ/kg, respectively, and ash content 25% and 22%, respectively. Low ash content was observed in tailings which was approximately 48% and 58% for the Reichert spiral and centrifugal separator respectively.

In case of hydrocyclone separation of particle below 0.1 mm in size, a significant yield (53%) was obtained, while the quality was low. The concentrate had a high ash content (39.6%) and low calorific value (16.95 MJ/kg) whereas tailings had low ash content (48.11%). Thus, the separation was inefficient due to the fact that the concentrate had approximately 38% particles smaller than 0.1 mm fraction and according to the study of Szpyrka and Lutyński (2012) these particle have a high ash content.

In conclusion, it should be noted that there is a possibility to upgrade fine coal particles. This process is of great importance because of considerable amount of coal deposited in impoundments. An alternative for fine coal beneficiation is a direct combustion in fluidized bed furnaces. Such furnaces are designed and manufactured taking into account individual characteristics of the fuel, i.e. particle size and quality parameters. Some of the materials tested fulfill these criteria (Blaschke 2005, Grudziński 2005).

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