

Analysis of improving the quality of coal slurry based on the use of regression models

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Abstract. The article presents the results of research on the enrichment of fine-grained coal grades, also known as coal slurries. The research was carried out on a semi-technical scale, using the method of gravity flow enrichment on a spiral separator type Reichert LD-4. The research material used in the research were three types of coal slurries, diversified in qualitative terms that were taken from technological process of the preparation plants. The enrichment efficiency tests were carried out in relation to changes in the density of the feed directed to the separator. The best distribution results for all tested coal slurries were obtained for the feed density of $\beta = 300 \text{ g/dm}^3$, where weighted averages of ash content in the obtained concentrates reached values of several percent. A statistical analysis was also performed, to which the multiple regression model was used. Using the constructed models, it is possible to determine which technological parameters affect the process of enriching coal sludge.

1. Introduction

Coal preparation plants are intermediaries between the mining and distribution stages. The mined raw material is a mixture of grains of various sizes, which consist of both organic and mineral matter and are described by a number of quality parameters. In the case of steam coal, such parameters are ash, sulphur, moisture content and heating value. In the beneficiation process, the raw coal is separated into density fractions and after reaching the appropriate level of enrichment, the stage of creating commercial assortments takes place. Taking into account the environment protection conditions, it is increasingly important to provide products with low emissivity [1,2]. This in turn is ensured by the correct course of the technological process of the coal preparation plant, which also improves the economic effects of its production. Thus, the article focuses on the review of mathematical models used in coal preparation plants, which are used in the simulation of the technological process of the technique of enriching minerals.

2. Source and classification of hard coal tailings

Output coal mined on the surface of the mine based on the used deposit exploitation technology, is a mixture of grains of various sizes ranging from several dozen millimetres to several microns. This mixture consists of coal grains, gangue, coal and dirt bands and carbonaceous shale. Thus, the generation of tailings is inseparably connected with the activity of hard coal mining. It is assumed that the extraction of one ton of coal is accompanied by the formation of about 400 kg of tailings [4], and



according to other estimates, the amount of waste generated can range from 200 to 400 kg [5,6]. The ratio of the amount of tailings to coal production in individual mines varies, which results from the different geological structure and technical conditions of coal mining and processing.

At the present time, the utility value represented by the mined rock excavated from the bottom does not meet any form of interest on the part of potential buyers, due to the relatively high content of gangue in relation to the useful (coal) grains. Excessive amount of gangue that goes into the mined rock may result from ripping the roof and the floor when mining the deposit. The waste rock from the useful grains is separated using the enrichment processes.

Useful grains are separated from waste rock using the enrichment processes. These processes can be carried out in an aqueous and air medium, however, considering the very low accuracy of aerodynamic enrichment (high values of imperfection index), in domestic technological gravitational enrichment the main medium in which the separation process takes place is the aqueous medium [3]. The smallest grains in the <1mm class, commonly referred to as slurries, arise as a result of coal enrichment processes. Coal slurries by definition fall within lower quality parameters, i.e. low calorific value and high ash content. Considering the fact that the slurry products have a certain energy potential, it seems reasonable to undertake all actions aimed at its complete recovery [11,12]. The process of improving the quality of coal slurry can be carried out through the use of selected methods of gravity enrichment, i.e. enrichment on shaking tables, spiral separators, enrichments using centrifugal force or flotation enrichment [7,8,9,10]. Taking into account the economic conditions of the enrichment process for coal sludges, the cheapest of the abovementioned separation methods is enrichment on spiral coils.

3. Methodology and Data

The research on the possibility of improving the quality parameters of coal slurries was carried out on a spiral separator Reichert LD4. Three types of slurries diversified in terms of quality were analysed. The slurries analysed were named respectively Slurry 1, Slurry 2, Slurry 3. Prior to being directed to the concentrator unit, the slurries were subjected to a quantitative and qualitative analysis, the obtained results are presented in table 1.

Table 1. Quantitative and qualitative analysis of raw slurries.

	Slurry 1		Slurry 2		Slurry 3	
Size grade [mm]	Yield Y (%)	Ash content A ^a (%)	Yield Y (%)	Ash Content A ^a (%)	Yield Y (%)	Ash content A ^a (%)
>0.75	41,32	21,17	55,89	44,06	52,21	23,01
0.7-0.5	32,11	32,50	7,84	44,98	7,77	16,14
0.5-0.315	31,88	21,65	7,42	41,51	5,82	19,35
0.315-0.2	33,32	13,27	19,61	40,83	14,02	20,14
0.2-0.1	30,17	17,41	3,73	39,81	6,47	23,59
< 0.1	27,73	14,01	5,51	48,00	13,71	32,94

source: own elaboration

Analysing the data contained in table 1, it can be noticed that Slurry 2 in relation to the other two materials is characterized by the worst qualitative parameters (the highest ash content) in all analysed

size grades. Ash content of individual size grades of Slurry 1 and Slurry 3 occurs in similar values, except for size grades 0.2-0.1mm and <0.1mm Slurry 1, where the ash content reaches a few percent.

Knowing the ash content in individual size grades in the tested raw slurries, they were directed to enriching on a spiral coil concentrator type Reichert LD4. The beneficiation of slurries was performed depending on the changing density of the feed successively $\beta=350 \text{ g/dm}^3$ and $\beta= 300 \text{ g/dm}^3$. Such selection of density of the feed was influenced by the conducted trial series aimed at the optimal selection of technological parameters of the separation. The feed for Reichert LD4 spiral was directed without pre-desliming (removing of clay) to check the effect of the increased amount of clays on the separation process. The feed for the concentrator was fed from a sender tank equipped with a mechanical stirrer and an aerator. As a result of enriching the feed, three separation products were obtained, i.e. concentrate, semi-finished product and tallings, from which samples were taken for technical analysis. Quantitative and qualitative analysis of enriched slurries Slurry 1, Slurry 2, Slurry 3 for density $\beta=350 \text{ g/dm}^3$ and $\beta= 300 \text{ g/dm}^3$ are presented in figures 1-6.

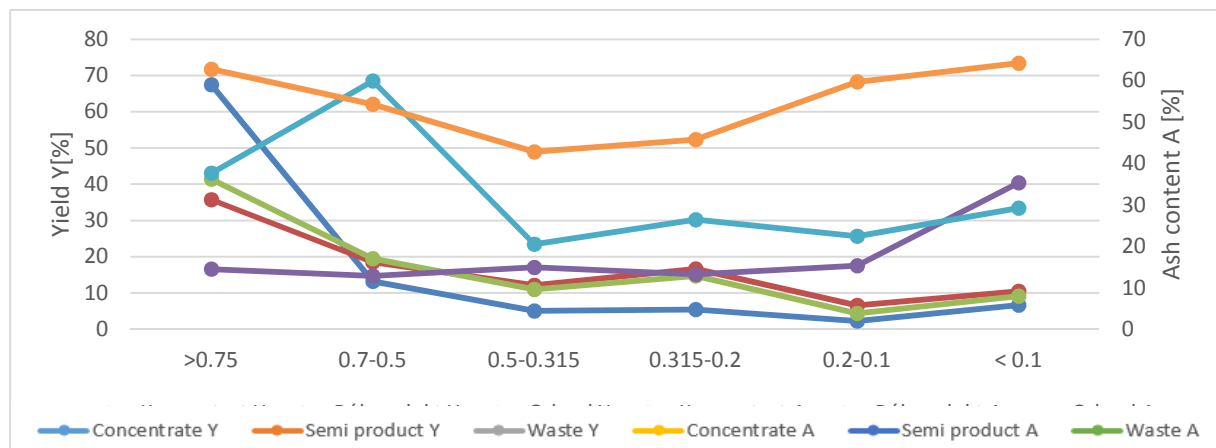


Figure 1. Quantitative and qualitative analyses of products for enrichment Slurry 1 density feed $\beta=350 \text{ g/dm}^3$.

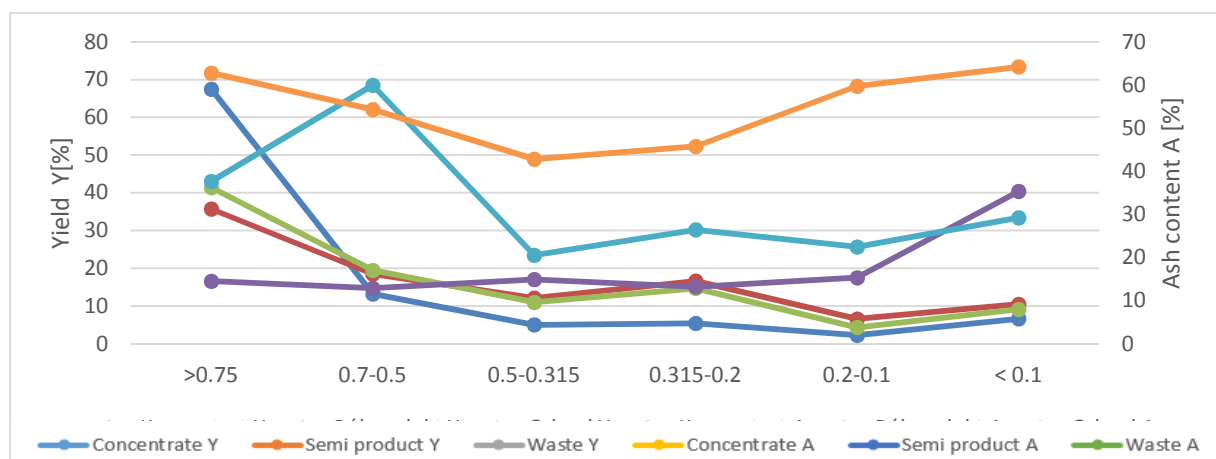


Figure 2. Quantitative and qualitative analyses of products for enrichment Slurry 1 density feed $\beta=300 \text{ g/dm}^3$.

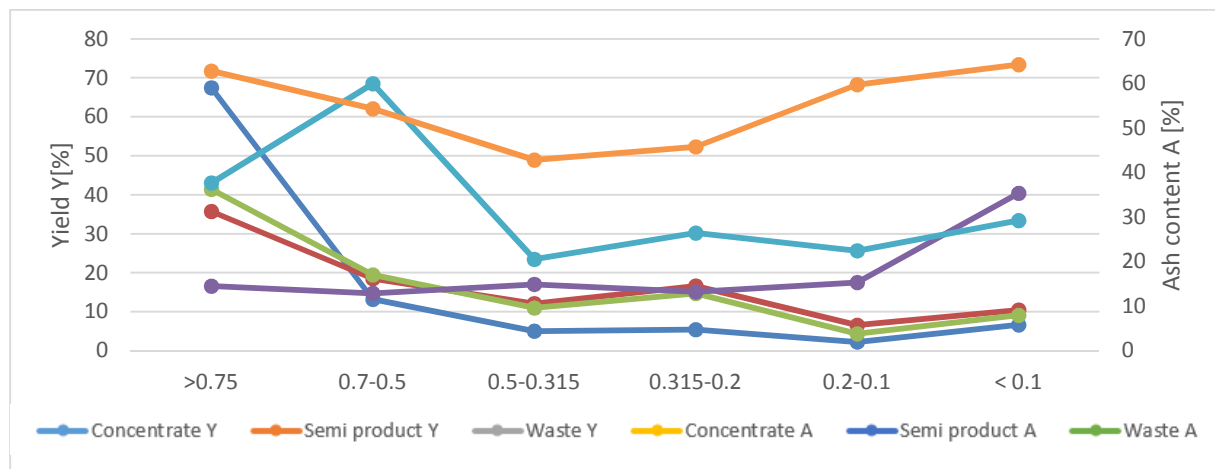


Figure 3. Quantitative and qualitative analyses of products for enrichment Slurry 2 density feed $\beta=350 \text{ g/dm}^3$.

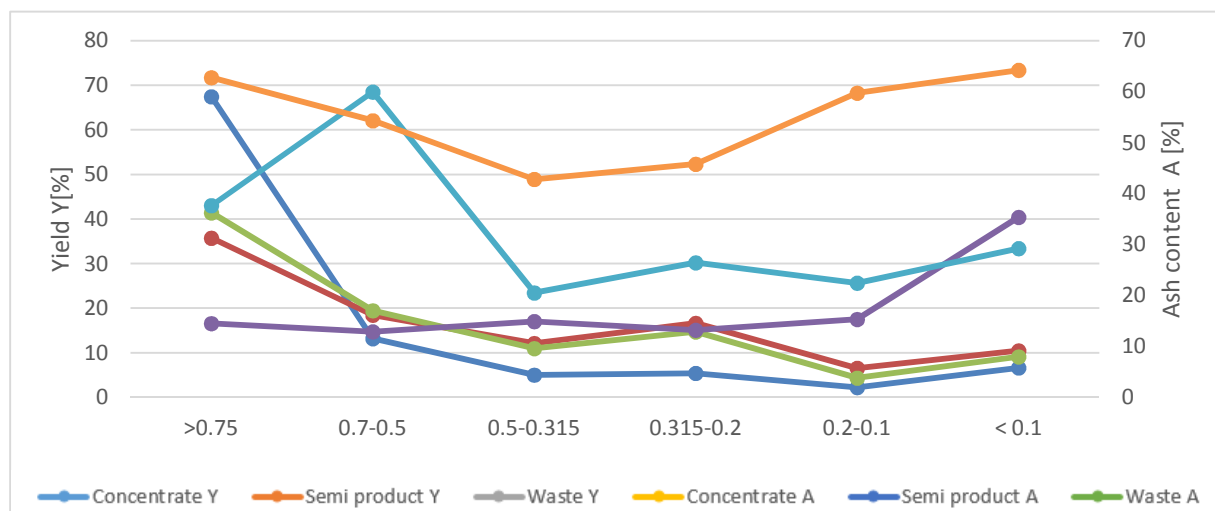


Figure 4. Quantitative and qualitative analyses of products for enrichment Slurry 2 density feed $\beta=300 \text{ g/dm}^3$.

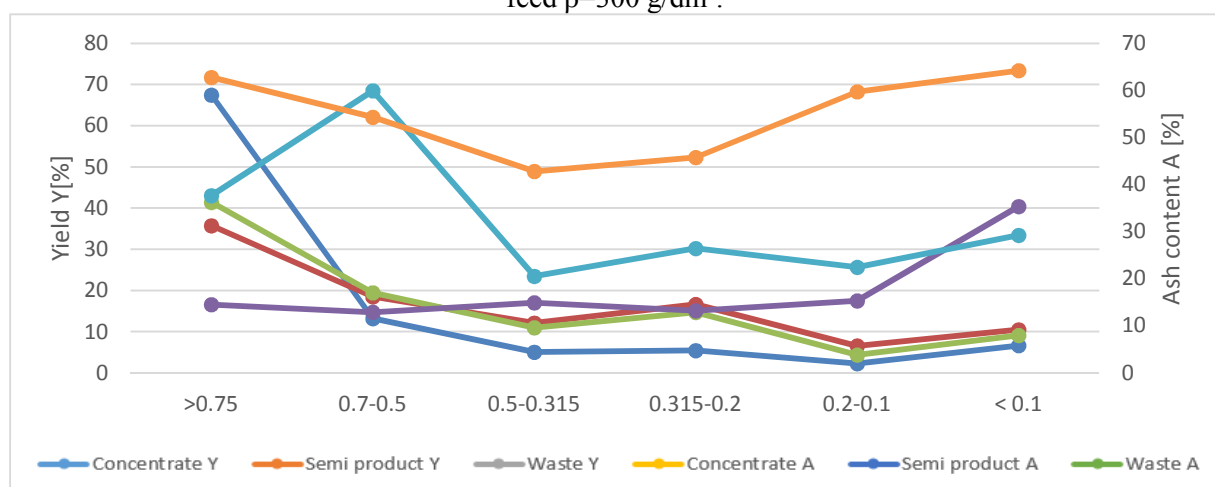


Figure 5. Quantitative and qualitative analyses of products for enrichment Slurry 3 density feed $\beta=350 \text{ g/dm}^3$.

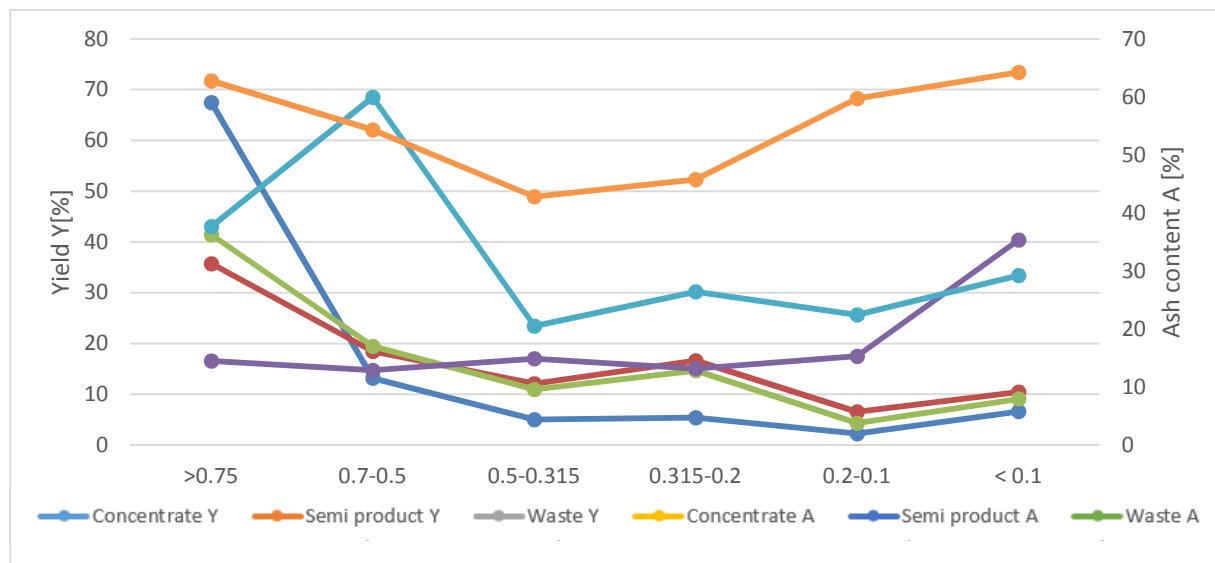


Figure 6. Quantitative and qualitative analyses of products for enrichment Slurry 3 density feed $\beta=300 \text{ g/dm}^3$.

The analysis of the enrichment process of the three studied slurries at given densities of the feed shows that the best results were obtained for the Slurry 1 concentrate and the density of the feed $\beta=300 \text{ g/dm}^3$. Similar results were obtained for the Slurry 3 concentrate and the density of the feed $\beta=300 \text{ g/dm}^3$. The concentrates of Slurry 1 and Slurry 3 for density $\beta=350 \text{ g/dm}^3$ are characterized by a higher content of ash in individual size grade. This phenomenon is most probably affected by too much solid phase in the feed and is connected with the unfavourable course of the grain separation process that occurs as a result of the impact of the restrained settling velocity. Ash content in semi-finished products of Slurry 1 and (Slurry 3) suggests that it is necessary to subject these products to secondary enrichment due to some content of useful grains in them. In the case of Slurry 2, a very small improvement in the value in use was found for both feed densities. Apparently, in the case of this material, the enrichment processes previously carried out on it were so accurate that only grains of gangue remained in the size grades of this slurry.

4. Research method - statistical analysis

In order to verify the assumed H_0 hypothesis that the enrichment process does not change the quality parameters of the analysed slurries, in the face of the alternative H_1 hypothesis that there is a change in the quality parameters of the analysed slurries, a multiple regression model was built. The general purpose of multiple regression is to quantify the relationship between many independent variables (explanatory) and dependent variable (criterial). The changeable variable is the yield and ash content of raw slurries, while the explanatory variables are the content of yield and ash after the enrichment process. In multiple regression, the rest of the model is assumed to be normally distributed, and again, despite that most tests (in particular, test F) are quite resistant to deviations from this assumption, it is always a good habit before drawing final conclusions to check how the distributions of major variables that are subject of the study look.

5. Results of research - statistical analysis of the correctness of the slurries enrichment process on spiral separator.

The first stage of statistical analysis is to determine basic descriptive statistics. This stage was made using the box plots chart (shown in figure 7) to show how the measures of the central position and the measure of variability of non-enriched products change (Zmn 1 and Zmn 2) against the products obtained after the enrichment process (Zmn 3 to Zmn 14). The following variable designations have been adopted:

- Zmn 1 – amount of yield in raw slurries
- Zmn 2 – ash content in the raw slurries
- Zmn 3 – amount of yield in product “concentrate” for the density of the feed $\beta=350 \text{ g/dm}^3$
- Zmn 4 – ash content in the product “concentrate” for the density of the feed $\beta=350 \text{ g/dm}^3$
- Zmn 5 – amount of yield in product “concentrate” for the density of the feed $\beta=300 \text{ g/dm}^3$
- Zmn 6 – ash content in the product “concentrate” for the density of the feed $\beta=300 \text{ g/dm}^3$
- Zmn 7 - amount of yield in product “semi-finished product” for the density of the feed $\beta=350 \text{ g/dm}^3$
- Zmn 8 – ash content in the product “semi-finished product” for the density of the feed $\beta=350 \text{ g/dm}^3$
- Zmn 9 - amount of yield in product “semi-finished product” for the density of the feed $\beta=300 \text{ g/dm}^3$
- Zmn 10 - ash content in the product “semi-finished product” for the density of the feed $\beta=300 \text{ g/dm}^3$
- Zmn 11– amount of yield in product “tailings” for the density of the feed $\beta=350 \text{ g/dm}^3$
- Zmn 12– ash content in the product “tailings” for the density of the feed $\beta=350 \text{ g/dm}^3$
- Zmn 13– amount of yield in product “tailings” for the density of the feed $\beta=300 \text{ g/dm}^3$
- Zmn 14 – ash content in the product “tailings” for the density of the feed $\beta=300 \text{ g/dm}^3$

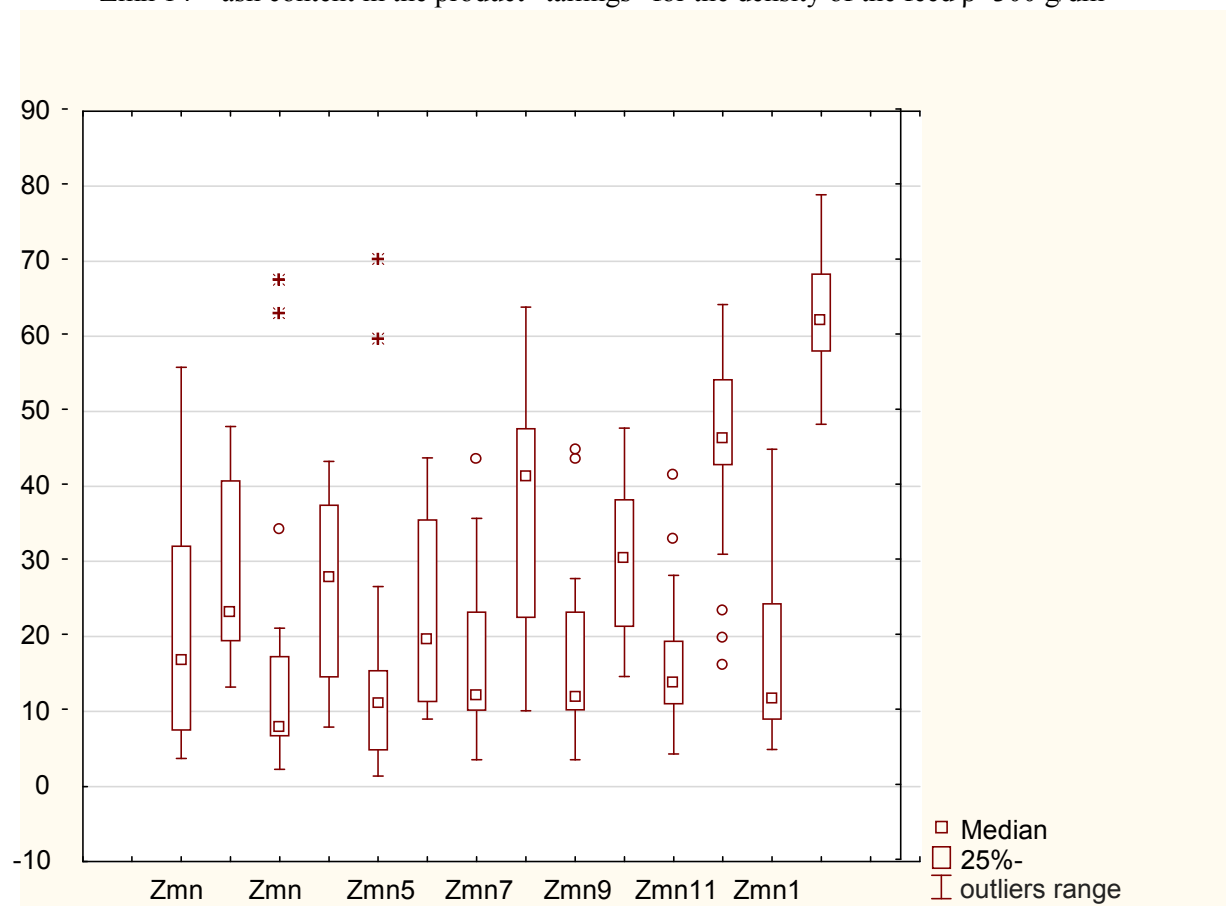


Figure 7. Box plots chart for the analysed variables.

Visual analysis shows that the variables differ significantly from each other. It means that in the enrichment process a product with different parameters can be obtained.

In order to verify the reliability of the adopted research methodology, the normality of the analysed variables was examined, as shown in figure 8.

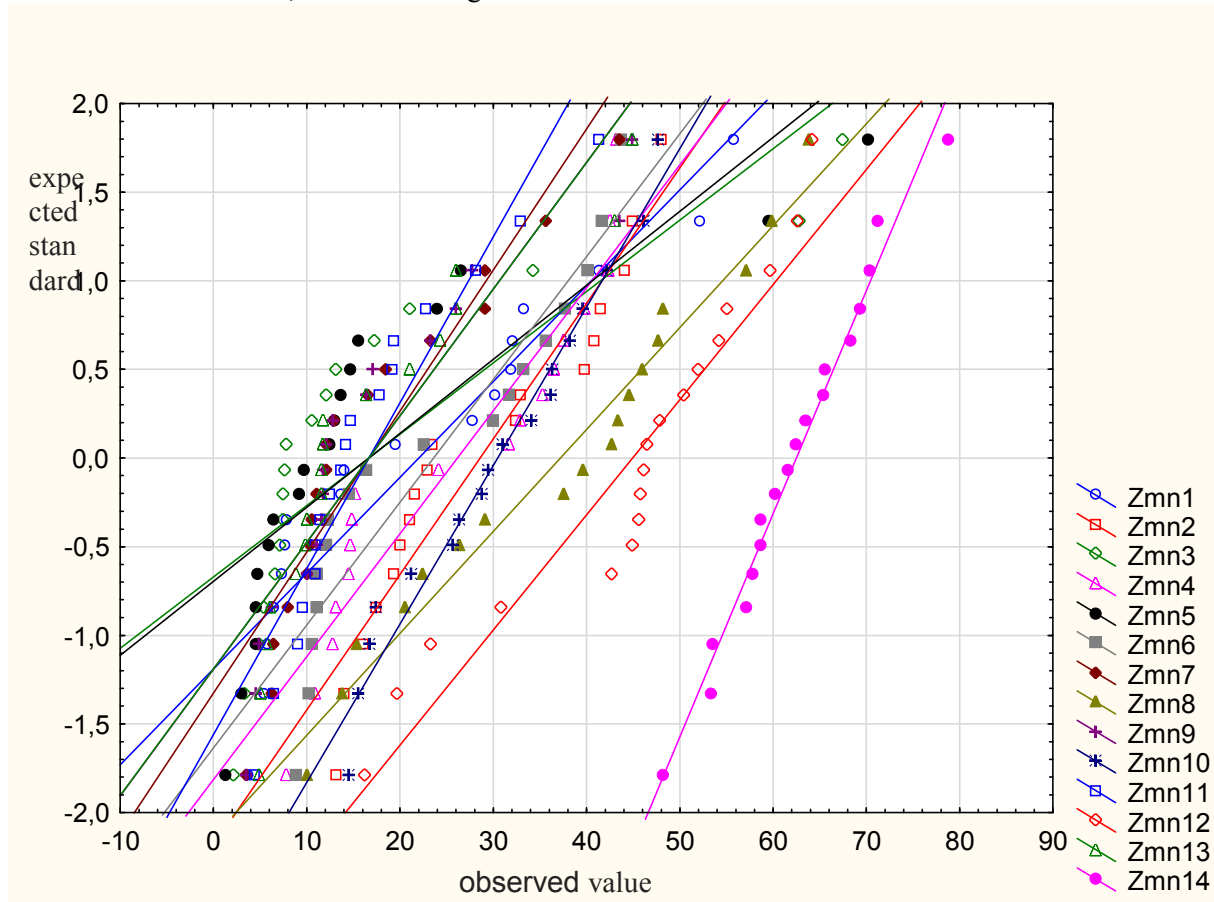


Figure 8. Normality diagram of the analysed variables.

From the analysis, it can be seen that a multiple regression model can be built for each product. The following assumptions have been adopted in the research methodology:

- multiple regression models were created separately for the yield and ash content of raw slurries,
- the explanatory variables were respectively: concentrate, semi-finished product and tallings for the density of the feed $\beta=350 \text{ g/dm}^3$ and $\beta=300 \text{ g/dm}^3$,
- in the multiple regression model, both yield and ash content were introduced,

With red, parameters which are statistically significant according to the assumed H_0 hypothesis were marked, which means that raw slurry has similar quality parameters as the product after the enrichment process. The results of calculations are included in table 2-7.

Table 2. A multiple regression model for the yield of raw slurries and concentrate.

Effect	One-dimensional significance tests for Zmn1 Parameterization with sigma-restrictions Decomposition of effective hypotheses; Standard evaluation error: 12.8340				
	SS	Degrees of freedom	MS	F	p
Constant term	905,107	1	905,1071	5,495101	0,035611
Zmn1	205,527	1	205,5269	1,247798	0,284194
Zmn2	544,294	1	544,2939	3,304526	0,092199
Zmn3	81,400	1	81,4000	0,494197	0,494459
Zmn4	795,421	1	795,4207	4,829171	0,046708

Table 3. A multiple regression model for the ash content of raw slurries and concentrate.

Effect	One-dimensional significance tests for Zmn2 Parameterization with sigma-restrictions Decomposition of effective hypotheses; Standard evaluation error: 7,4612				
	SS	Degrees of freedom	MS	F	p
constant term	307,8048	1	307,8048	5,529201	0,035133
Zmn1	0,0059	1	0,0059	0,000107	0,991922
Zmn2	15,8331	1	15,8331	0,284416	0,602820
Zmn3	0,3245	1	0,3245	0,005829	0,940303
Zmn4	171,8997	1	171,8997	3,087892	0,102386
Error	723,6962	13	55,6689		

Table 4. A multiple regression model for yield of raw slurries and semi-finished products.

Effect	One-dimensional significance tests for Zmn1 Parameterization with sigma-restrictions Decomposition of effective hypotheses; Standard evaluation error: 13,0103				
	SS	Degrees of freedom	MS	F	p
Constant term	481,420	1	481,4204	2,844133	0,115543
Zmn1	0,426	1	0,4257	0,002515	0,960767
Zmn2	187,762	1	187,7621	1,109260	0,311426
Zmn3	860,191	1	860,1908	5,081832	0,042073
Zmn4	683,329	1	683,3286	4,036966	0,065745
Error	2200,482	13	169,2679		

Table 5. A multiple regression model for the ash content of raw slurries and semi-finished products.

Effect	One-dimensional significance tests for Zmn2 Parameterization with sigma-restrictions Decomposition of effective hypotheses; Standard evaluation error: 7,6280				
	SS	Degrees of freedom	MS	F	p
Constant term	8,2323	1	8,2323	0,14148	0,712878
Zmn3	22,8318	1	22,8318	0,39239	0,541888
Zmn4	234,0743	1	234,0743	4,02286	0,066160
Zmn5	50,0208	1	50,0208	0,85967	0,370726
Zmn6	780,5730	1	780,5730	13,41514	0,002867
Error	756,4179	13	58,1860		

Table 6. A multiple regression model for yield of raw slurries and tallings.

Effect	One-dimensional significance tests for Zmn1 Parameterization with sigma-restrictions				
	Decomposition of effective hypotheses; Standard evaluation error:14,8908				
	SS	Degrees of freedom	MS	F	p
Constant term	14,828	1	14,8283	0,066874	0,799993
Zmn7	32,698	1	32,6977	0,147463	0,707179
Zmn8	159,725	1	159,7255	0,720344	0,411387
Zmn9	617,620	1	617,6195	2,785395	0,119018
Zmn10	14,239	1	14,2387	0,064215	0,803917
Error	2882,555	13	221,7350		

Table 7. A multiple regression model for the ash content of raw slurries and tallings.

Effect	One-dimensional significance tests for Zmn2 Parameterization with sigma-restrictions				
	Decomposition of effective hypotheses; Standard evaluation error:10,9619				
	SS	Degrees of freedom	MS	F	p
Constant term	1273,725	1	1273,725	10,59995	0,006259
Zmn11	117,461	1	117,461	0,97751	0,340859
Zmn12	84,926	1	84,926	0,70675	0,415719
Zmn13	186,112	1	186,112	1,54882	0,235279
Zmn14	795,289	1	795,289	6,61840	0,023178
Error	1562,123	13	120,163		

The statistical analysis carried out shows that the enrichment process has improved the quality parameters of coal products. Therefore, the accepted methodology in the article is justified. It is also possible to detect a human error during the beneficiation process, which significantly affected the deterioration of this process. This is evident by the statistical significance of the multiple regression model coefficient. A well-conducted enrichment process is characterized by a lack of correlation between the quality parameters of raw slurries and the products obtained, as confirmed in scientific articles [9,10,11].

6. Summary

The process of slurries beneficiation in a spiral concentrator has shown that it is possible to improve the utility value of products (slurries) often considered as unprofitable waste. This possibility depends on the initial state of the feed, i.e. the ash content and the amount of clays in the material as well as the correctly selected technological parameters. The subject of statistical analyses were data defining the quality of feed, concentrates, semi-finished products and tallings. They were analysed in terms of ash content and yield. The statistical analysis carried out confirmed the relationship between the technological parameters of the enrichment process and the obtained products. The selected, optimal parameters of the technological process will allow to obtain concentrates from slurries in an economically feasible way. The proposed method can also capture errors that arise in this process, which in turn will have a positive effect on reducing the costs of the beneficiation process.

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