THE EFFECT OF MOISTURE CONTENT ON THE HARDGROVE GRINDABILITY INDEX OF COAL FROM THE KOLUBARA BASIN

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In order to obtain data on the effect of moisture content on the grindability of coals, experimental research was conducted. The experiment included six samples of coal from the Kolubara basin. The samples were selected based on experimentally obtained values of their Hardgrove grindability index (HGI), in order to cover the entire range of experimental HGI values. In addition to determining the HGI, proximate, and petrographic analyses were performed on all samples.

Lignites are naturally tough, soft, and greasy when in a moist state. By reducing the moisture content, lignites become more brittle. For this reason, HGI values have different values depending on the moisture content at which they are determined.

The Hardgrove grindability index of coal (HGI) has a nonlinear dependence on the moisture content of the coal. All curves have two inflection points, one minimum and one maximum value of HGI in the tested range. The minimum values of HGI are in the range of 15 – 22 [%] of the mass fraction of total moisture in coal, while the maximum values of HGI are for a total moisture content of 5 – 13 [%].

In the case of high moisture content in coal, the obtained high values of HGI may not reflect the true grindability of the coal. These values could be misleading and not necessarily indicative of the coal's inherent characteristics. Instead, they could be a result of the imperfections in the Hardgrove method used to determine the grindability index of coal with high moisture content.

Key words: *coal, lignite, moisture, Hardgrove grindability index (HGI)*

1. Introduction

Grindability of coal is an important parameter used in design of coal comminution plants (*i. e*. mill plants). Coal grindability is determined by Hardgrove grindability index (HGI) and it is one of the characteristics of coal that directly affect capacity of pulverized coal mill [1, 2].

The high moisture content of lignite results in lower calorific value and larger sensitivity to spontaneous combustion, which increases fuel consumption and the cost in storage and transportation. Therefore, drying of lignite in pulverizes before combustion is necessary. Moisture in lignite affect pulverizes performance and combustion efficiency. Drying of lignite can change its grindability.

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Studies [3, 4] shown that pre-drying of lignite can increase the combustion efficiency of power plant boilers burning low-rank coal by 2 – 4 [%] on average. Optimizing moisture content of lignite in advance is an effective way to improve the pulverization process, to enhance thermal boiler efficiency, and hence to reduce coal consumption.

Results of experimental investigations [5] shows that the grindability of coal varies in a nonlinear way with moisture. General pattern for the HGI curves is an S-shape. Similar results are reported in [6].

The influence of moisture on the grindability of coals has been particularly examined in lower-rank coals, where it poses a specific problem [7]. Studies conducted on lignite from the Dakota state [8] have revealed that at a moisture content of 10 [%], the HGI value was 55. However, at a moisture content of 26 [%], its value drops to 43, and then it rises again to 55 at a moisture content of 38 [%].

Vuthaluru [9] investigated effects of moisture and coal blending on HGI for low-rank sub-bituminous Western Australia coals (Collie coalfield). Grindability test on coal samples of varied moisture content showed significant effect of moisture content on HGI values.

The effect of moisture on Shengli lignite breakage behavior and energy efficiency was studied experimentally using a standard Hardgrove mill fitted with a wattmeter [10]. Results showed that the energy-size reduction process for grinding lignite is markedly influenced by moisture occurrence and content. The energy efficiency was also significantly improved as the moisture content of lignite was reduced to below the air-dried level. The air-dried moisture content was the inflecting point for lignite grinding in the Hardgrove mill.

Saramak [11] showed that excess moisture could cause a decrease in grindability and produce lower throughputs of comminution circuits.

Many studies analyze the effect on coal grindability based on proximate and ultimate analysis of coal, as well as petrography. [12-16]

As the moisture content of coal is one of the major factors affecting the grindability of coal, this paper investigates the effect of moisture content on HGI values of coal from the Kolubara basin.

2. Experimental investigations

Experimental research was conducted to obtain data on the effect of moisture content on the grindability of coals. Out of a total of 65 samples of lignite from the Kolubara basin [12], the experiment included six coal samples from the Kolubara basin. The selection of samples was based on the experimentally obtained values of their grindability (HGI values), aiming to cover the entire range of experimental HGI values from the lowest to the highest. Additionally, not only proximate analysis but also organic-geochemical and petrographic analysis [17] were performed on the aforementioned samples.

The determination of the HGI values of the coal samples was conducted in accordance with the ISO 5074 standard.

The proximate analysis of the coal samples was conducted in accordance with international standards, specifically:

- ISO 5071-1 – Brown coals and lignites – Determination of the volatile matter in the analysis sample;
- ISO 1171 – Solid mineral fuels – Determination of ash content;

- ISO 5068-1 – Brown coals and lignites – Determination of moisture content – Part 1: Indirect gravimetric method for total moisture;
- ISO 5068-2 – Brown coals and lignites – Determination of moisture content – Part 2: Indirect gravimetric method for moisture in the analysis sample.

The analysis of coal lithotypes was performed according to the standards set by the International Committee for Coal and Organic Petrology (ICCP). The description of lithotypes was carried out based on the classification developed by Jacob [18] and modified by Ercegovac [19]. Maceral analysis was performed on a Leitz DMPL microscope under monochromatic and ultraviolet reflected light, with a 40× objective lens and a 10× eyepiece, on 500 points (ISO 7404-3) in oil immersion. The maceral description followed the terminology developed by the ICCP for huminite, liptinite, and inertinite nomenclature. The determination of total organic carbon content was performed after the removal of carbonates with diluted hydrochloric acid (in a ratio of 1:3 [v/v]) using a Vario EL III CHNS/O analyzer. The isolation of soluble organic matter (maltenes) into saturated hydrocarbons, aromatic hydrocarbons, and NSO fractions was carried out on a Kohnen-Willsch MPLC (medium pressure liquid chromatography) chromatograph following a standard procedure. The saturated and aromatic hydrocarbon fractions were analyzed using gas chromatography-mass spectrometry (GC-MS) technique and SIM (Single Ion Monitoring) method. [17]

At the beginning of the testing, the determination of total moisture content and the mass of the absolutely dry sample was performed to monitor the change in total mass over days. The sample mass measurements were carried out daily, and the mass fraction of total moisture in the sample was calculated.

The initial determination of HGI values was conducted when the sample reached a total moisture content of approximately 30 [%], and then at every 5 [%] decrease in moisture content, namely 25 [%], 20 [%], 15 [%], 10 [%], and 5 [%]. The samples were air-dried, taking into account atmospheric conditions, which resulted in some samples requiring a longer time to reach the desired mass fractions of moisture. Upon reaching the desired moisture content, an appropriate mass of coal was taken from the total sample using a splitter to obtain a representative sample for determining the HGI value of the considered sample.

To demonstrate the trend of decreasing grindability for sample no. 5 after the maximum, the sample was dried in a dryer at 40 [°C] to reduce the moisture mass fraction below 5.25 [%]. The drying was performed in a dryer because, due to atmospheric conditions and low moisture content, it was not possible to further extract moisture from the sample through natural means. After drying at 40 [°C], the determination of total moisture content in the sample was carried out following the ISO 5068-1 standard.

3. Results and discussion

In Table 1, the results of the proximate analysis of the selected coal samples are presented.

Table 1 Proximate analysis of coal samples

No.	HGI, [–]	V_a, [%]	$W_{h,a}$, [%]	A_a, [%]	WG, [%]	W_h, [%]	W, [%]	V, [%]	A, [%]
1	30.7	39.54	12.51	19.20	41.93	7.27	49.20	22.96	11.15

2	35.8	39.30	12.10	20.42	44.78	6.68	51.46	21.70	11.28
3	42.0	38.62	11.24	22.96	43.48	6.35	49.83	21.83	12.98
4	44.9	37.11	8.79	33.26	45.20	4.82	50.02	20.34	18.23
5	48.5	33.61	9.14	36.48	42.54	5.25	47.79	19.31	20.96
6	56.9	31.93	7.99	42.49	41.37	4.68	46.05	18.72	24.91

What should be noted is the different impact of air-dry moisture and residual moisture content on grindability. Residual moisture has a clear negative effect on grindability, while the effect of air-dry moisture causes varying impacts [12]. Air-dry moisture leads to the sticking and agglomeration of coal mass.

In Table 2, the results of lithotype composition of the coal samples are presented, while Table 3 shows the results of maceral composition.

Table 2 Lithotype composition (wt [%]) of studied samples

No.	Matrix coal	Xylite-rich coal							Dop-plerite coal	Charcoal	Mineral-rich coal	Mineral matter
		Pale yellow type	Dark yellow type	Brown type	Black type	Yel-low^a	Brown and black^b	Total				
1	17.20	0.00	45.75	33.70	0.93	45.75	34.63	80.38	0.16	0.08	1.40	0.78
2	45.55	0.02	20.78	29.47	2.22	20.80	31.69	52.49	0.05	0.02	0.60	1.29
3	57.85	0.00	11.68	28.55	1.00	11.68	29.55	41.23	0.04	0.02	0.59	0.27
4	56.20	0.00	16.26	24.47	0.98	16.26	25.45	41.71	0.65	0.03	0.85	0.56
5	58.47	0.03	15.89	14.72	1.15	15.92	15.87	31.79	0.06	0.03	3.54	6.11
6	47.23	0.001	6.48	31.68	0.03	6.48	31.71	38.19	0.03	0.07	8.32	6.19

a) Xylite yellow = pale yellow type + dark yellow type
b) Xylite brown and black = brown type + black type

Prevailing lithotype in all studied samples is matrix coal, except sample 1 for which the xylite-rich coal is the dominant type (Table 2). Brown xylite type is the dominant xylite-rich type in almost all samples. Only in the sample 1 dark yellow type prevails.

Huminite is the prevailing maceral group in all samples (Table 3). Most abundant macerals are textinite, ulminite and densinite with a variable amount of attrinite and corpohuminite. Content of gelinite is low. Liptinite ranges from 4.2 to 8.3 vol. [%]. Percentages of inertinite range from 3.0 to 4.2 vol. [%]. The content of mineral matter varies between 6.3 and 30.6 vol. [%].

Organic geochemical properties and molecular composition of the organic matter in detail are given in [12, 17].

Table 3 Maceral composition (vol [%]) of studied samples

Maceral	Sample					
	1	2	3	4	5	6
Te	53.6	44.7	45.4	29.1	37.6	13.3
Ul	5.6	14.0	11.7	11.9	15.3	9.0
At	1.8	5.9	0.9	8.0	4.7	10.1
De	12.5	13.8	20.9	25.5	16.6	21.4
Ge	0.6	0.2	1.7	0.6	0.5	0.9
Ch	4.5	3.2	5.1	3.9	3.7	2.5
HUM	78.6	81.8	85.7	79.0	78.4	57.2

Sp	2.1	0.7	0.9	1.1	1.2	3.0
Cu	0.3	0.5	0.0	0.3	0.3	0.2
Re	1.2	1.0	0.3	2.2	1.1	1.1
Su	3.2	1.0	2.2	1.1	1.1	2.3
Ld	1.5	1.0	0.9	0.6	1.3	1.4
LIP	8.3	4.2	4.3	5.3	5.0	8.0
Fu	0.3	1.5	0.0	0.3	0.3	0.0
Sf	0.0	0.0	0.6	0.8	0.3	0.5
Ma	0.3	0.0	0.0	0.3	0.0	0.5
Fn	2.7	0.5	0.9	0.8	1.2	1.4
Id	0.6	1.4	2.2	0.8	1.3	1.8
INER	3.9	3.4	3.7	3.0	3.1	4.2
MM	9.2	10.6	6.3	12.7	14.5	30.6
Te – textinite; Ul – ulminite; At – attrinite; De – densinite; Ge – gelinite; Ch – corpohuminite; HUM – total huminite; Sp – sporinite; Cu – cutinite; Re – resinite; Su – suberinite; Ld – liptodetrinite; LIP – total liptinite; Fu – fusinite; Sf – semifusinite; Ma – macrinite; Fn – funginite; Id – inertodetrinite; INER – total inertinite; MM – total mineral						

The dependency of moisture changes in the samples over time is presented in Figure 1.

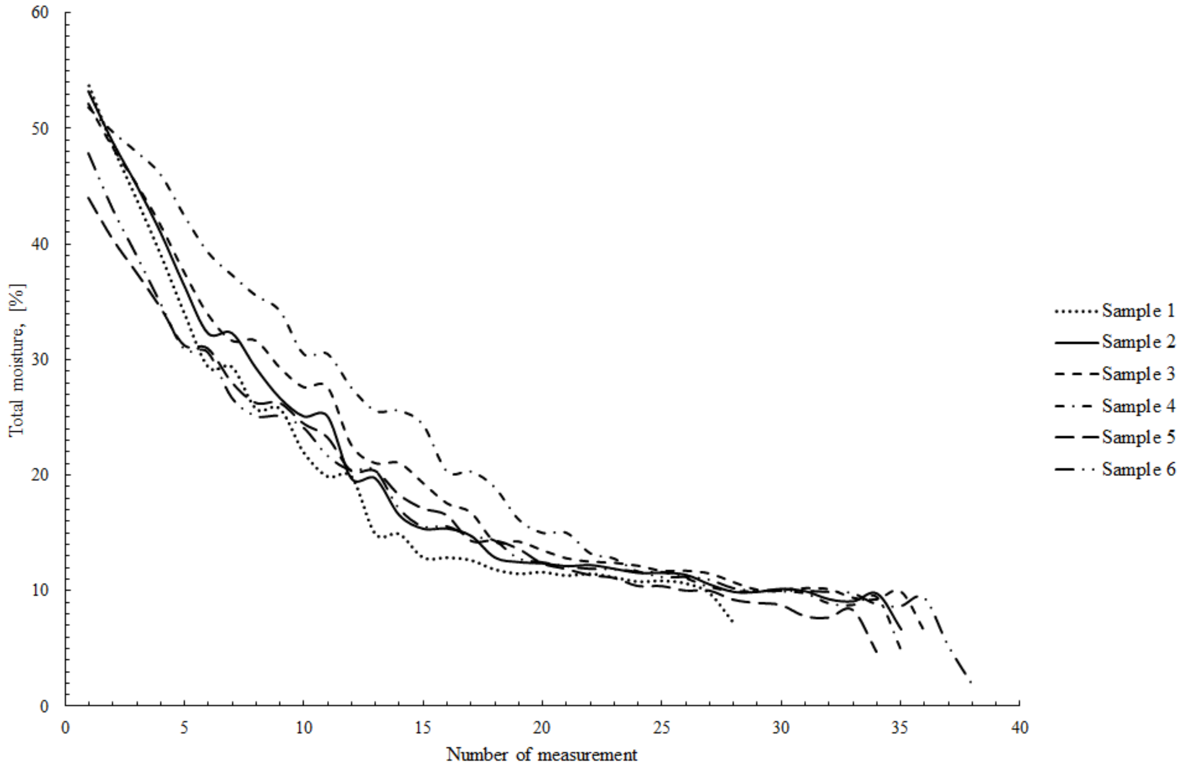

Figure 1 The dependence of the change in the mass fraction of total moisture in the samples

The experimentally obtained results of HGI values for different mass fractions of total moisture in coal samples are presented in Table 4 and shown in Figures 2 – 7.

Table 4 Experimentally obtained results of HGI values for different mass fractions of total moisture

Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6	
W. [%]	HGI	W. [%]	HGI	W. [%]	HGI	W. [%]	HGI	W. [%]	HGI	W. [%]	HGI
30.27	52.3	32.60	63.6	31.88	57.8	31.17	66.1	30.76	70.4	29.88	60.1
26.79	47.5	25.51	56.0	27.37	52.0	25.81	60.7	26.33	54.6	24.71	44.5
20.92	45.2	19.29	51.9	20.72	44.6	20.79	57.3	20.39	52.7	19.81	40.1
16.07	43.5	16.06	52.3	14.01	41.3	15.05	61.0	14.24	53.7	15.32	41.1
10.42	45.6	9.93	51.1	9.61	44.3	9.91	57.6	10.12	58.3	9.42	44.8
7.26	30.7	6.68	35.8	6.41	42.0	4.82	44.9	4.68	56.9	5.25	48.5
										1.90	44.5

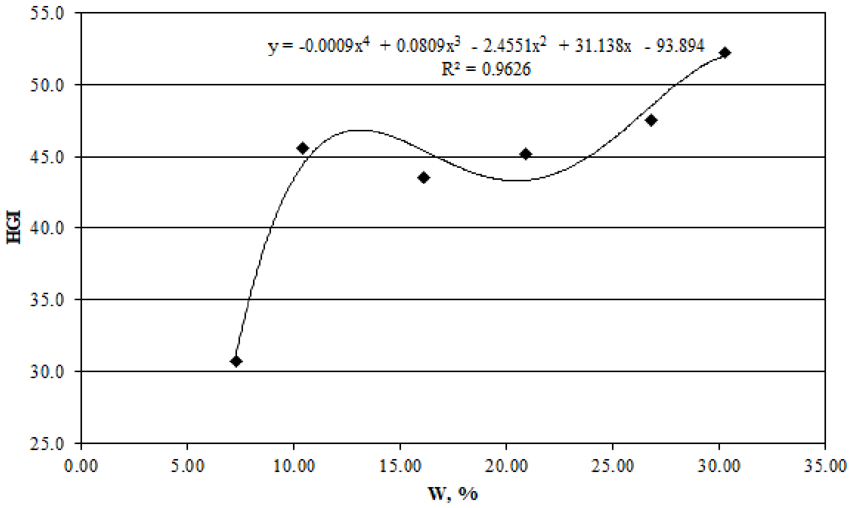

Figure 2 Effect of total moisture content on HGI values for sample 1

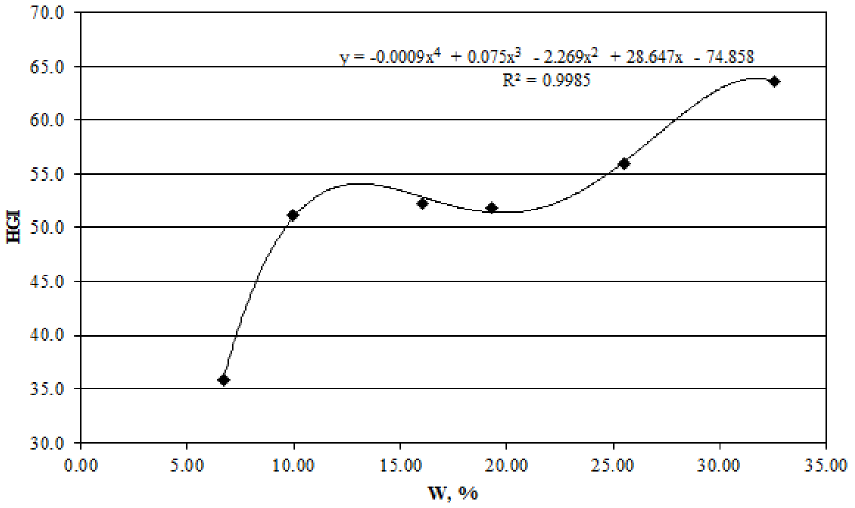

Figure 3 Effect of total moisture content on HGI values for sample 2

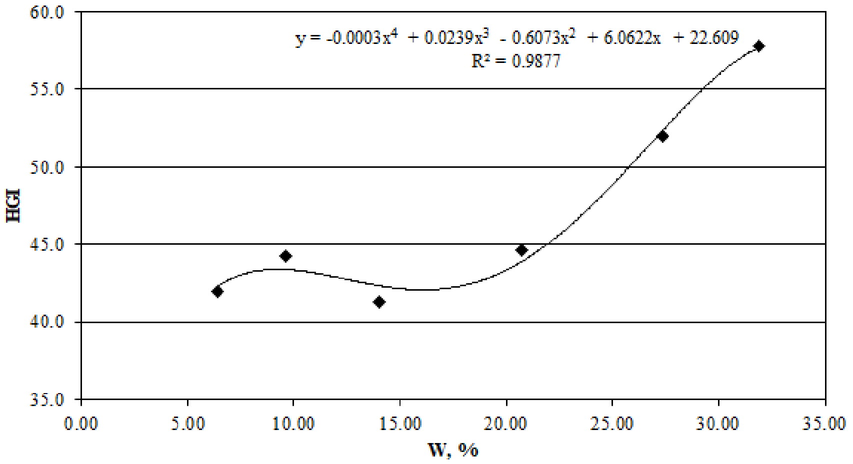

Figure 4 Effect of total moisture content on HGI values for sample 3

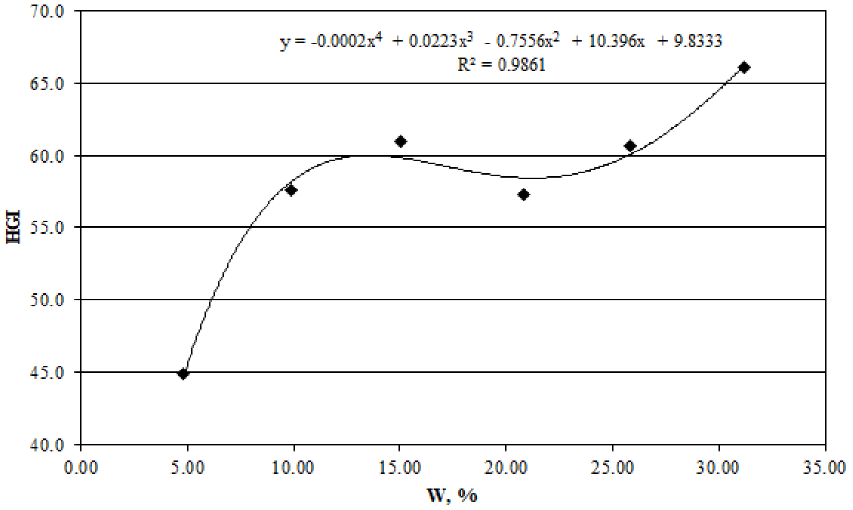

Figure 5 Effect of total moisture content on HGI values for sample 4

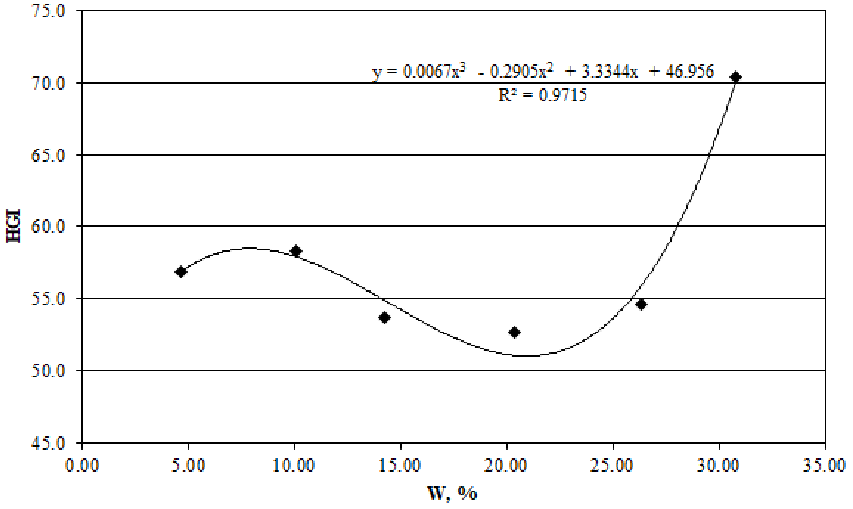

Figure 6 Effect of total moisture content on HGI values for sample 5

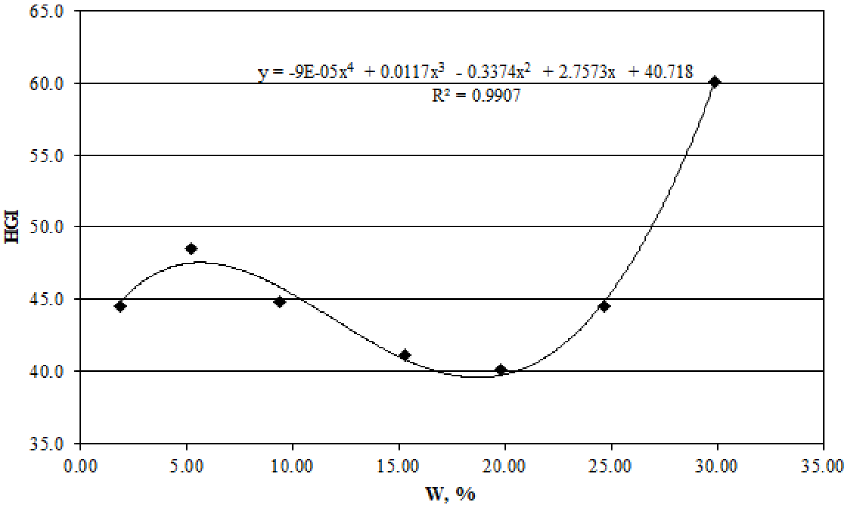

Figure 7 Effect of total moisture content on HGI values for sample 6

As seen in Figures 2 to 7, the Hardgrove grindability index (HGI) exhibits a non-linear dependence on the mass fraction of total moisture in coal. All curves have two inflection points, one minimum and one maximum HGI value within the tested range. The minimum HGI values correspond to a mass fraction of total moisture in the range of 15 – 22 [%], while the maximum HGI values are observed at moisture fractions of 5 – 13 [%].

The obtained high HGI values for samples with high moisture content should be interpreted with caution. Based on the obtained curves (figures 2 – 7), one might mistakenly conclude that it is easier to grind coal with high moisture content compared to coal with a residual moisture content. However, this contradicts practical experience, which dictates that quality coal grinding cannot be achieved without drying it in mills. Additionally, it can be inferred that the Hardgrove method for determining HGI values in high moisture content coal is not applicable and does not provide realistic practical results.

One possible explanation for the obtained high HGI values at high moisture fractions in coal lies in the following: during the determination of HGI values for samples with high moisture content, coal adhesion was observed both on the balls and on the working bowl of the apparatus. This coal adhesion hampers the coal flow that has not entered the grinding process in the Hardgrove mill. In other words, an undetermined amount of coal is repeatedly ground (as not the entire sample enters the grinding process), resulting in a fraction that passes through the 75 [μm] sieve, leading to unrealistically high HGI values. Therefore, the high HGI values in samples with high moisture content are a consequence of method imperfections (mill design) rather than coal characteristics.

The increase in HGI values after the minimum is explained by the weakening of the coal structure due to a decrease in moisture content, leading to the appearance of cracks in the coal structure during drying. The subsequent decrease in HGI values as the moisture content approaches zero is explained by the characteristics of dry coal ash. Similar results regarding the influence of moisture on HGI values have been reported in the literature [5, 6].

Through experimental investigations of the M-12 beater wheel mill in thermal power plant Nikola Tesla B, it was determined that the average moisture content in the pulverized coal was 13.15 [%]. Therefore, it can be considered that the mill operates with approximately optimal moisture content in terms of HGI values. It should be noted that the guaranteed moisture content value in the pulverized coal for the M-12 mill was 10 [%]. [2, 12]

4. Conclusions

The study provides an analysis of the influence of total moisture content in coal on certain values. The experiment included six samples of coal from the Kolubara basin. In addition, petrographic and organic geochemical analyses were previously conducted on all six studied samples.

The moisture content in coal has a significant influence on the Hardgrove grindability index (HGI). It is important to note that the relationship between moisture content and HGI is not linear. Experimentally obtained curves have two inflection points, one minimum and one maximum HGI value within the tested range.

In the case of high moisture content in coal, the obtained high values of Hardgrove grindability index (HGI) should be taken with caution to avoid drawing the incorrect conclusion that coal with high moisture content is easier to grind. This statement is in line with practical experience, which suggests that effective coal grinding cannot be achieved without drying it beforehand.

On the other hand, lower moisture content generally leads to higher HGI values. When coal has a lower moisture content, it becomes drier and more brittle. This increased brittleness facilitates the grinding process, as the coal particles are more easily broken and pulverized.

The effect of moisture on grindability varies depending on other factors such as coal rank, mineral matter content, and particle size distribution. Therefore, for the future work, it is necessary to consider these factors along with moisture content when assessing the grindability of coal using the HGI test.

Overall, controlling the moisture content of coal is essential in optimizing its grindability and subsequent utilization in various industrial processes, such as coal pulverization for power generation in thermal power plants or coal preparation for industrial applications.

Nomenclature

A – ash content in coal (mass fraction), [%]
A_a – ash content in analysis sample of coal (mass fraction), [%]
HGI – Hardgrove grindability index, [–]
V – volatile matter in coal (mass fraction), [%]
V_a – volatile matter in analysis sample of coal (mass fraction), [%]
W – total moisture in coal (mass fraction), [%]
WG – air-dry moisture (mass fraction), [%]
W_h – residual moisture content, [%]
$W_{h,a}$ – moisture content in analysis sample of coal (mass fraction), [%]

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