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Article

The Determination of the Methane Content of Coal Seams Based on Drill Cutting and Core Samples from Coal Mine Roadway

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Abstract: The determination of methane content of coal seams is conducted in hard coal mines in order to assess the state of methane hazard but also to evaluate gas resources in the deposit. In the world's mining industry, natural gas content in coal determination is usually based on direct methods. It remains the basic method in Poland as well. An important element in the determination procedure is the gas loss that occurs while collecting a sample for testing in underground conditions. In the method developed by the authors, which is a Polish standard, based on taking a sample in the form of drill cuttings, this loss was established at a level of 12%. Among researchers dealing with the methane content of coal, there are doubts related to the procedures adopted for coal sampling and the time which passes from taking a sample to enclosing it in a sealed container. Therefore, the studies were designed to evaluate the degree of degassing of the sample taken in the form of drill cuttings according to the standard procedure and in the form of the drill core from a coal mine roadway. The results show that the determinations made for the core coincide with the determinations made for the drill cutting samples, with the loss of gas taken into account.

Keywords: methane; methane hazard; methane content of coal; direct method; gas loss

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1. Introduction

Methane content of coal seams is an important parameter for the assessment level of methane hazard in hard coal mines. The determination of this parameter in Polish mines is conducted based on the direct method, and the sample for analysis is taken in the form of drill cuttings from a borehole performed in the coal seam. The methodology of conducting the determination has been presented previously by the authors [1] and has been adopted as the national standard [2]. The research basis for the method, its scope of application and uncertainty of measurement according to the method have also been presented by the authors [1,3]. In the world mining industry, the methane content of coal seams is mostly determined using direct methods, which are more accurate than indirect methods [4–7].

An important stage in the determination of the methane content of coal is the process of taking a coal sample for testing, from the moment the sample is taken until it is closed in a sealed container. During sample collection, a partial degassing of the sample takes place, and the so-called gas loss occurs. Due to the lack of technical feasibility, this component cannot be determined by measurement; thus, it is estimated based on various procedures [8]. Some of the most popular methods used worldwide include: Bertard's Method developed in France [9], the Smith's and Williams Method [10,11], the USBM Direct Method [12], the Modified USBM Method [13–15], the GRI Method [16–18], the Australian Standard [19,20], CSIRO-CET method [21], AMST [22], and the William and Yurakov [23]. These methods are often described in the literature and constitute the reference for other researchers [24–27].

Methods also exist for measuring coalbed methane content in coal without gas loss [7]. The method described by the author monitored all methane synchronously to drilling a hole. The controlled portion of the neutral inert gas was injected into the hole during drilling, whereas a special device controlled the methane concentration at the hole's mouth.

Yang et al. [28] predicted residual gas content during coal roadway tunnelling based on drill cuttings indices and the BA-ELM (bat algorithm optimizing extreme learning machine) algorithm. The authors indicated that the developed method has higher accuracy than other methods and can effectively reveal the nonlinear relationship between drilling cuttings indices and residual gas content.

Despite the fact that the methods for coalbed methane content in coal determination are widely used in mines, researchers are concerned about the procedures adopted for taking coal samples and the time that elapses from taking the sample to closing it in a sealed container. One of the most important factors in determining the methane content of coal is the procedure to estimate the gas loss connected with taking a sample for testing. According to the current belief, the degree of sample fragmentation influences the amount of gas lost during sample collection [29–31].

Waechter et al. [32] pointed out that procedures of sampling and handling the sample have a big influence in determining the in situ sorbed gas in coals. The biggest influence is connected with regard to the estimation of gas loss. They recommend using the coring methods because they allow maximize core recovery and minimize uphole travel time. These methods also permit minimal surface core handling preparation and placement inside the canisters under given field conditions. In conclusion, they pointed out that there is not a best method for obtaining a sample from a wellbore for gas content determination. The method for collecting samples should be designed to the depth, distribution of coal deposit and restrictions of the equipment.

Due to emerging concerns, a comparative study was planned. The objective of these tests was to check the gas loss during the collection of a drill cuttings sample based on the methane content of coal in a core sample and drill cuttings sample. Comparative studies showed whether it is better to collect a core sample or drill cutting sample for determining methane content of coal in the Polish mining condition.

Within the conducted studies, a drill cutting sample and a core sample were taken from the same test borehole. This approach made it possible to compare results of methane content of coal in seam determination for both forms of sampling.

An explanation of each parameter and unit used in the article is presented in the Nomenclature section.

2. Background

Coal samples for comparative studies of methane content of coal determinations were taken from actually mined coal seams in selected hard coal mines located in the Upper Silesian Coal Basin (USCB) region. The mines in which coal samples were taken are characterized by high methane hazard. The methane content of coal seams in those mines are changed at a range of 0 to 12 m^3/t^{daf}. In Polish mines, methane content of coal is referred to the dry ash free basis.

USCB is located in the southern part of Poland. It is the biggest coal basin in Poland and one of the biggest in Europe [33]. In the south, it passes into the territory of the Czech Republic in the Ostrava–Karviná region [34]. The area of the basin is about 7490 km^2, including about 5760 km^2 in Poland [35]. The location of the USCB where the research was conducted is presented in Figure 1.

Within the entire area of USCB 500, coal seams were recognized (average thickness of about 1.20 m), out of which only 200 are of commercial use significance [36]. The USCB stratigraphic division is widely presented in the publications [33,37].

The USCB is a deep molasse basin of polygenetic origin. The geological setting of the USCB is widely described in publications [38–40].

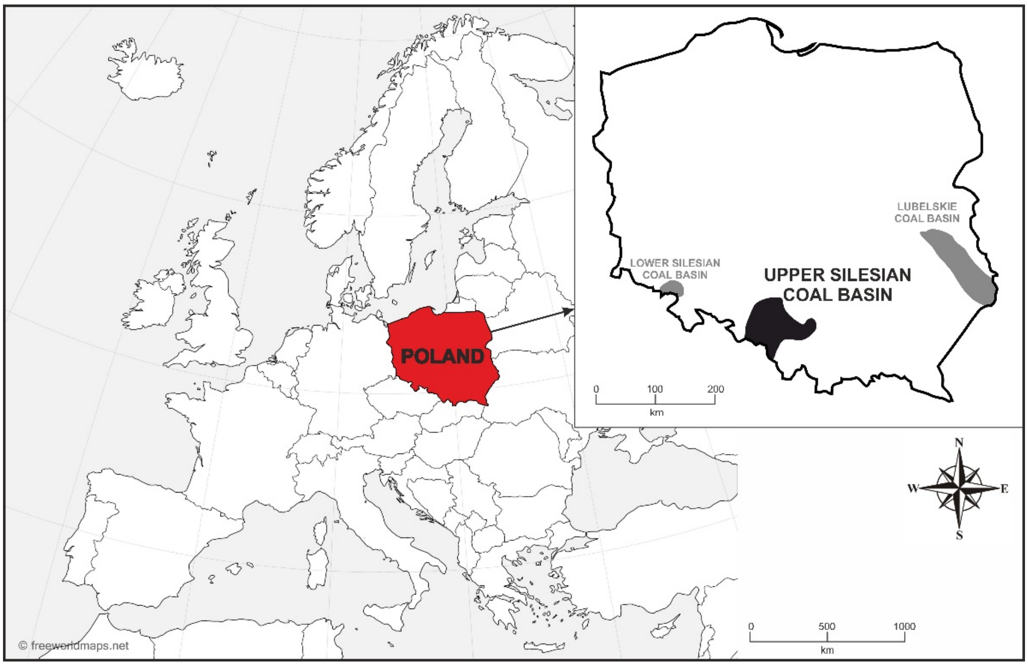

Figure 1. Location of USCB in Poland.

The boundary of the USCB is determined by the range of the Upper Carboniferous coal-bearing formations and partly by the fault lines. In the west, it is limited by folded Low Carboniferous (Kulm) formations. The north-eastern boundary is hidden under Permian and Triassic formations. Below the coal-bearing formations, there are folded Lower Palaeozoic formations, on which inconsistent Devonian (coal limestone) and Lower Carboniferous formations lie. The southern boundary runs under the overthrust of the Carpathian flysch. It is an erosion border. Precambrian metamorphic formations occur here with Cambrian and Devonian formations above. The Carboniferous roof is located here at the depth of less than 2000–3000 m, reaching even 5000 m [35]. The bedrock of the Upper Silesian Coal Basin is made of Precambrian, Cambrian, Devonian and partly of younger Carboniferous rocks [41].

The gas content in the multiple seams of the USCB varies considerably, both vertically and horizontally. Methane bearing coal seams occur between 500 and 1200 m below the ground. The methane content of the coal ranges from 0.01 to 18.00 m^3/t^{daf} [42]. Most gas-rich coal seams are located at a depth 1200 m below the ground surface at the south part of the USCB [39,43]. In addition, the variability of the methane content is observed at the same depth, even within one mine. Given the wide range of methane content in the coal seams, it is necessary to precisely determine the content at the seam site where mining will be planned.

The samples being analysed in the article came from different coal seams (group 300 and group 400) located at different depths. The position of coal seams group 300 and 400 in the stratigraphic division are presented in the publications [33,37].

The coal seams of group 300 are located in layers classified as Westphal A and B. The coal seams of group 300 are built mainly of mudstone and siltstone; however, in the upper part of the lithological profile, the share of sandstone increases. These layers reach their maximum thickness in the western part of the USCB, whereas in the eastern direction, they become gradually thinner until they disappear completely. Among the coal seams of this group, numbered 301–328, there are 28 industrial coal seams, in which total thickness is estimated at 38 m. The main coal seam for the Orzesze layer is coal seam 318, which is up to 2.5 m thick [44]. The coal seams in the form of bundles remain a characteristic element of such ones.

The Group 400 coal seams, however, comprise the Namur C and partly the Wesphal A [36] layers. These layers are represented by clay stones, overlain by sandstones, most frequently fine-grained, as well as siltstones and coal, occurring in coal seams from 0.6 to 4.3 m in thickness.

3. Materials and Methods

3.1. Collection of Coal Samples for Testing

The samples were taken from coal layers in the advancing face of the heading. Each sampling was carried out on a freshly exposed coal seam. The samples were taken as both drill cuttings and core samples. Drill cuttings and core samples were taken from the same borehole.

In an excavation of a coal seam, the first sampling was performed in the form of drill cuttings. The drill cuttings sample came from the depth of 3.5–4.0 m. Drilling was carried out with a drill bit with a crown of 76 mm in diameter. Drill cuttings were sieved through screens. A portion of about 100 cm^3 of cuttings of grain class above 1.0 mm was placed in an air sealed container. Activities from the moment of starting the drilling at the depth of 3.5–4.0 m until closing the sample in an air sealed container were performed within 120 s. The adopted method of sampling complies with the requirements of Polish Standard [2].

Having taken a drill cuttings sample of coal from the hole, a core sample of 59 mm in diameter was taken. The sampling consisted of deepening the hole with a core barrel attached to the drill bit. The core sample was approximately 4 cm long. The core sample, immediately after drilling an appropriate section, was placed and closed in a separate air sealed container.

A schematic showing the coal sampling locations for testing is shown in Figure 2.

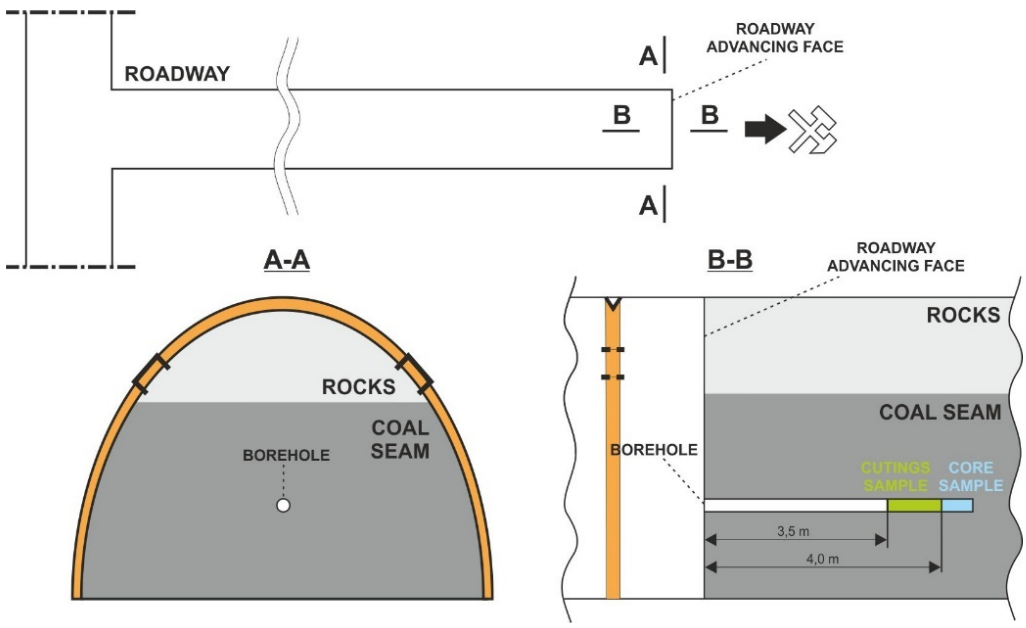

Figure 2. Coal sampling locations for testing.

As a result of the conducted tests, a total of 99 pairs of samples was taken. Coal samples collected in the mine and closed in air sealed containers were later tested in a laboratory.

Figure 3 presents a histogram showing the distribution of the number of samples taken in each depth interval. The highest number of samples came from the depth range of −600 to −650 m above sea level as well as −550 to −600 m above sea level. The average ground elevation in the mine areas where the samples were collected is 280 m above sea level.

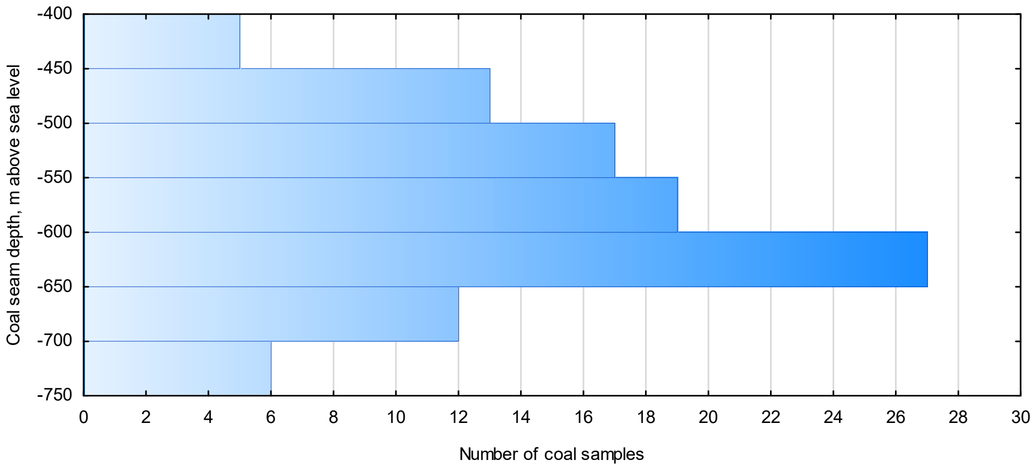

Figure 3. Histogram showing the number of samples taken for the tests in individual intervals of coal seam depth.

3.2. Methodology for the Determination Methane Content of Coal

The coal samples collected at the excavations were sent to a laboratory for determination of the methane content. Immediately after the samples were handed over, they underwent the process of grinding. Steel containers were placed in the shaker and the coal was crushed by steel balls placed in containers with samples. After the grinding was completed, the coal samples were degassed using a rock sample degassing apparatus. After degassing the coal, the gas pressure in the measuring container was read as well as the air temperature in the laboratory, in order to relate the results to the STP conditions. A gas sample was also taken from the measurement container in order to determine the percentage concentration of methane s_{CH_4} concentration in the extracted gas. This procedure allowed the desorbing gas and the residual gas in the coal sample to be determined as a single component.

The final stage of laboratory testing was to measure the mass of coal taken for testing and to determine the selected physical parameters of coal. For each sample, the mass of coal m_w was determined as well as the content of the total moisture W_c and ash content A_a. The density of coal d_{rd} was also determined. In Polish conditions, these parameters are determined according to industry standards. In the research, the result of methane content of coal was referred to as the dry ash free basis, as such a conversion method is practically applied in Polish hard coal mining.

For the coal sample taken in the form of drills, the gas loss was calculated according to the standard procedure [2]. According to this procedure the gas loss is 12%. The estimation of gas loss in methodology for determining methane content of coal seams has been presented previously by the authors [1].

In the case of the core sample, no gas loss was added, because after drilling a hole with a core barrel, the sample was immediately closed in a container.

The algorithm for the calculation of methane content of coal for drill cutting and core samples is presented in Figure 4. The presented algorithm step by step explains including particular parameters in the procedure of determining the methene content of coal. For calculation of the methane content of the coal sample, the procedure was the same as the drill cutting samples. Only for the drill cutting samples was the 12% gas loss taken into account.

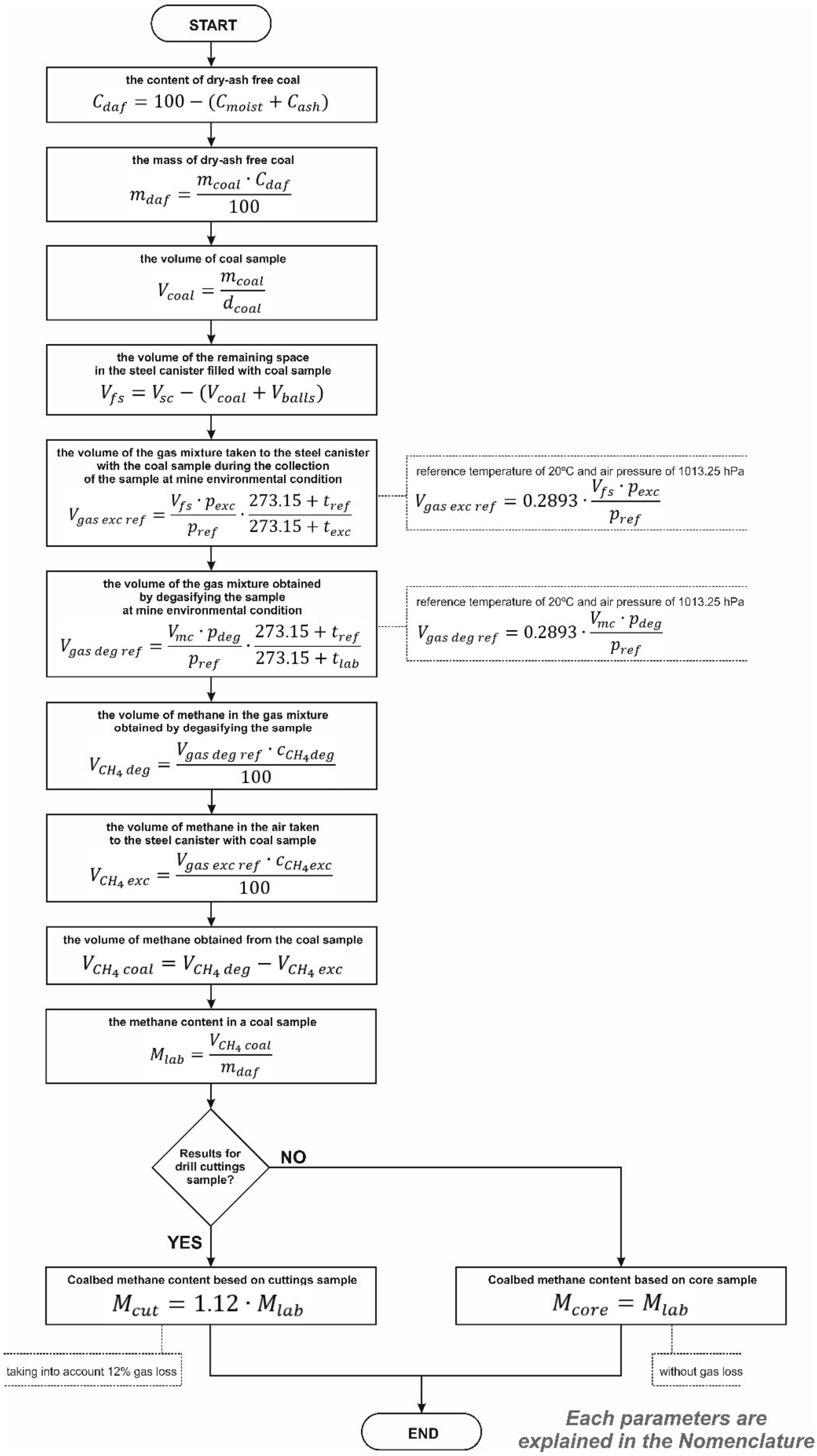

Figure 4. Algorithm for calculating methane content of coal for the drill cutting and core samples.

4. Results and Discussion

The results of the determinations of the methane content of coal are presented in Table 1. In 46 cases, the methane content of coal obtained was based on the drill cuttings sample and was higher than that obtained based on the core sample. In one case, the values were equal, while in the remaining 52 cases, the higher methane content of coal was obtained based on the core sample.

Table 1. Results of methane content of coal determinations based on drill cuttings and core samples.

Number of Coal Samples Pair	Coal Seam	Depth, m above Sea Level	Methane Content of Coal (Core Sample) M_{core}, m^3/t^{daf}	Methane Content of Coal (Drill Cuttings Sample) M_{cut}, m^3/t^{daf}
1	417	−473	0.184	0.328
2	417	−448	0.344	0.561
3	417	−473	0.369	0.261
4	417	−481	0.405	0.349
5	417	−438	0.442	0.499
6	417	−425	0.524	0.395
7	417	−492	0.533	0.363
8	417	−461	0.572	0.463
9	329	−618	0.615	0.703
10	417	−513	0.726	0.505
11	418	−550	0.857	1.468
12	418	−516	1.031	0.982
13	417	−539	1.056	1.349
14	409	−708	1.167	1.114
15	417	−474	1.208	0.561
16	406	−611	1.232	2.315
17	406	−603	1.327	1.875
18	329	−492	1.404	1.837
19	418	−500	1.512	0.846
20	417	−673	1.635	1.541
21	409	−717	1.639	1.228
22	409	−602	1.740	2.055
23	404	−483	1.742	1.758
24	409	−701	1.747	3.572
25	329	−488	1.784	2.005
26	410	−628	1.823	1.396
27	330	−589	1.946	2.027
28	409	−690	2.147	1.932
29	404	−467	2.228	2.193
30	416	−614	2.238	2.824
31	417	−542	2.242	1.957
32	329	−415	2.274	2.498
33	410	−675	2.346	3.799
34	410	−602	2.476	2.333
35	417	−542	2.528	3.134
36	410	−578	2.635	2.981
37	410	−533	2.708	1.686
38	417	−699	2.804	2.977
39	418	−588	3.035	2.810
40	410	−522	3.111	2.471
41	409	−723	3.173	2.293
42	404	−533	3.225	3.334
43	404	−487	3.289	4.008
44	409	−630	3.374	3.627
45	410	−529	3.401	3.387
46	415	−637	3.427	5.674
47	417	−673	3.509	3.302
48	417	−653	3.510	2.456
49	416	−599	3.521	4.799
50	409	−632	3.544	3.567
51	417	−667	3.545	4.678
52	410	−673	3.589	4.235
53	417	−672	3.601	2.570
54	417	−675	3.622	3.809
55	410	−619	3.834	2.817
56	418	−552	4.116	3.439
57	409	−621	4.212	3.950
58	410	−617	4.283	2.897
59	417	−682	4.300	2.832
60	404	−490	4.431	4.668

Table 1. *Cont.*

Number of Coal Samples Pair	Coal Seam	Depth, m above Sea Level	Methane Content of Coal (Core Sample) M_{core}, m^3/t^{daf}	Methane Content of Coal (Drill Cuttings Sample) M_{cut}, m^3/t^{daf}
61	404	−514	4.480	4.564
62	404	−508	4.525	4.188
63	404	−491	4.529	5.531
64	417	−684	4.595	4.138
65	410	−626	4.614	6.311
66	406	−616	4.717	8.402
67	413	−532	4.788	3.355
68	410	−605	4.825	4.388
69	413	−537	4.953	4.320
70	416	−614	4.972	4.492
71	348	−593	5.233	8.505
72	406	−588	5.242	5.018
73	413	−487	5.248	4.059
74	348	−643	5.271	8.144
75	410	−544	5.654	7.903
76	404	−489	5.679	4.928
77	410	−588	5.724	4.878
78	409	−720	5.882	5.882
79	404	−516	5.905	4.704
80	405	−596	6.074	5.159
81	417	−720	6.173	4.139
82	416	−598	6.187	5.118
83	416	−600	6.202	5.727
84	410	−581	6.280	7.165
85	348	−649	6.418	9.124
86	410	−635	6.459	7.090
87	348	−592	6.477	6.574
88	406	−617	6.561	5.755
89	406	−617	6.763	5.969
90	406	−611	6.816	6.874
91	348	−586	7.271	8.375
92	348	−590	7.271	8.375
93	348	−589	7.533	8.317
94	406	−616	7.550	6.984
95	406	−589	7.860	7.059
96	406	−617	7.866	6.604
97	410	−583	9.209	9.450
98	406	−623	9.289	8.439
99	348	−598	10.460	7.325

Differences in results between core and drill cuttings samples may result from various factors. Despite the application of a uniform procedure, the determinations were performed by different teams, which could generate errors during sample collection. A further part of the article shows a more detailed analysis of the obtained results.

The range of selected physical parameters for coal samples is presented in Table 2.

Table 2. Variation of selected physical parameters for coal samples.

Parameter	Minimum	Maximum	Average	Standard Deviation
Methane content of coal seams determined for core samples M_{core}, m^3/t^{daf}	0.18	10.46	3.81	2.33
Methane content of coal seams determined for drill cutting samples M_{cut}, m^3/t^{daf}	0.26	9.45	3.85	2.43
Protodyakonov coefficient of coal strength,	0.30	0.96	0.46	0.18
Moisture content, %	1.25	9.82	3.33	1.60
Ash content, %	1.50	28.23	9.09	6.65

Figure 5 presents a box plot showing the variation of the methane content of coal is particular seams. The number of coal samples pairs are presented for each coal seams. In the plot, the middle point indicates the average value of the determined methane content of coal. The box represents the 95% confidence interval, while the whiskers represent the minimum and maximum values. A higher number of coal seams occurs deeper. The average methane content of coal for deeper coal seams reached higher values. This statement corresponds with other researches for USCB [33,37].

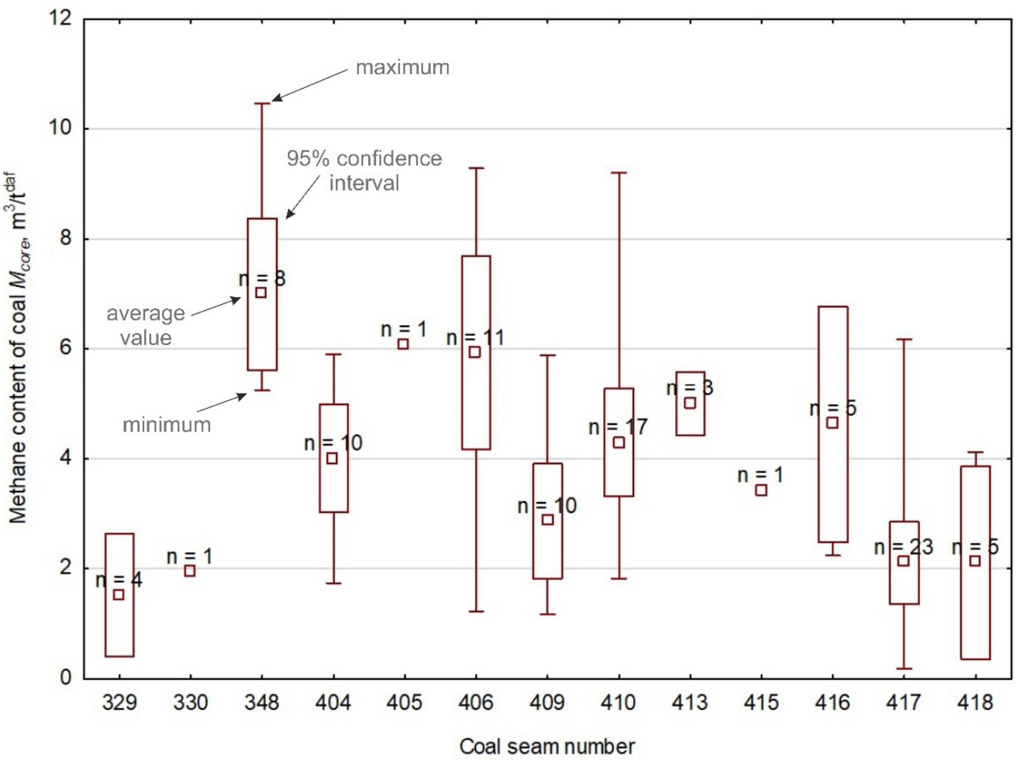

Figure 5. Variation of methane content of coal in particular seams (n is the number of coal samples pairs in a coal seam).

Conversely, Figure 6 presents a histogram showing the distribution of the methane content of coal determined for the coal samples. The coal seams with methane content of coal ranging from 2 to 5 m^3/t^{daf} yielded the largest number of determinations.

The plot in Figure 7 shows the variation in the methane content of the coal for the drill cutting samples corresponding to the core samples. Despite some differences in the methane content of the coal for particular pairs of samples, the linear approximation for all samples shows that the results reached, according to the core samples and drill cutting samples, are practically the same.

Figure 8 presents a graph comparing the methane content of coal obtained from a core sample in comparison, with the methane content of coal obtained from a drill cuttings sample taking into account 12% gas loss. On the basis of the presented graph and the marked approximation line with the directional coefficient of 0.992, which is close to 1, it can be stated that the results obtained with the methodology according to the standard [2] based on the drill cuttings sample are practically the same as those obtained for the determination performed on the core sample (without gas loss). The coefficient of determining R^2 for the linear dependence of the methane content of coal for the core sample and drill cuttings is equal to 0.946. It can be concluded that almost 95% determinations of methane content of coal for the core sample and drill cuttings sample, including 12% gas loss, obtains the same value.

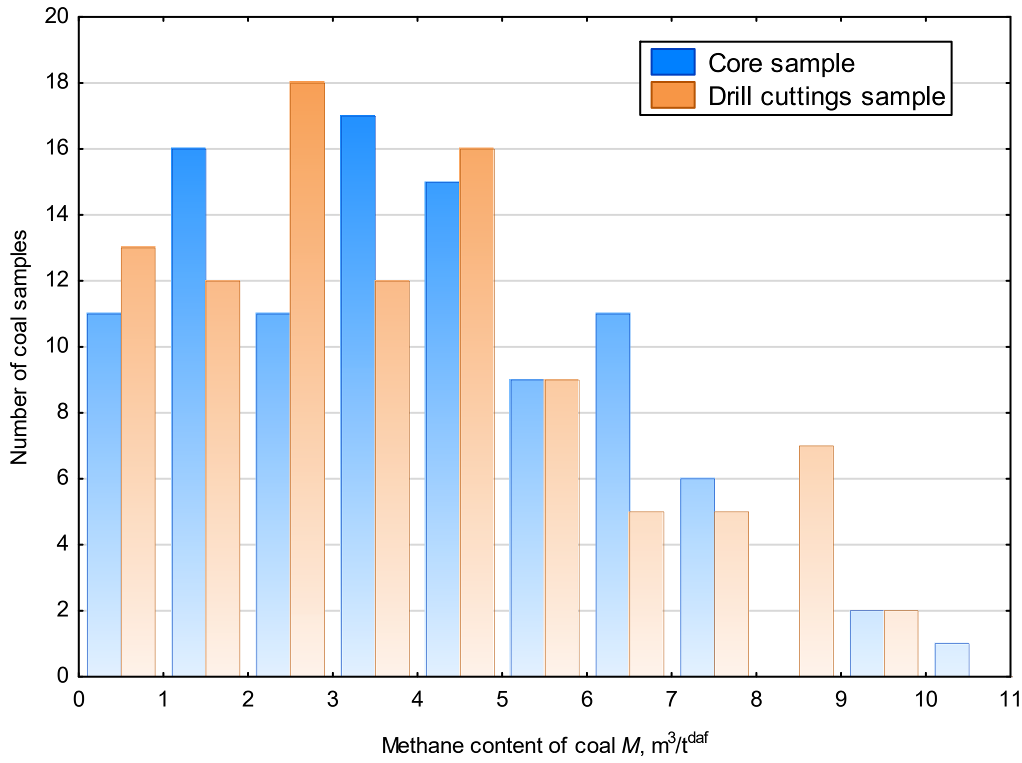

Figure 6. Distribution of the determined methane content of coal.

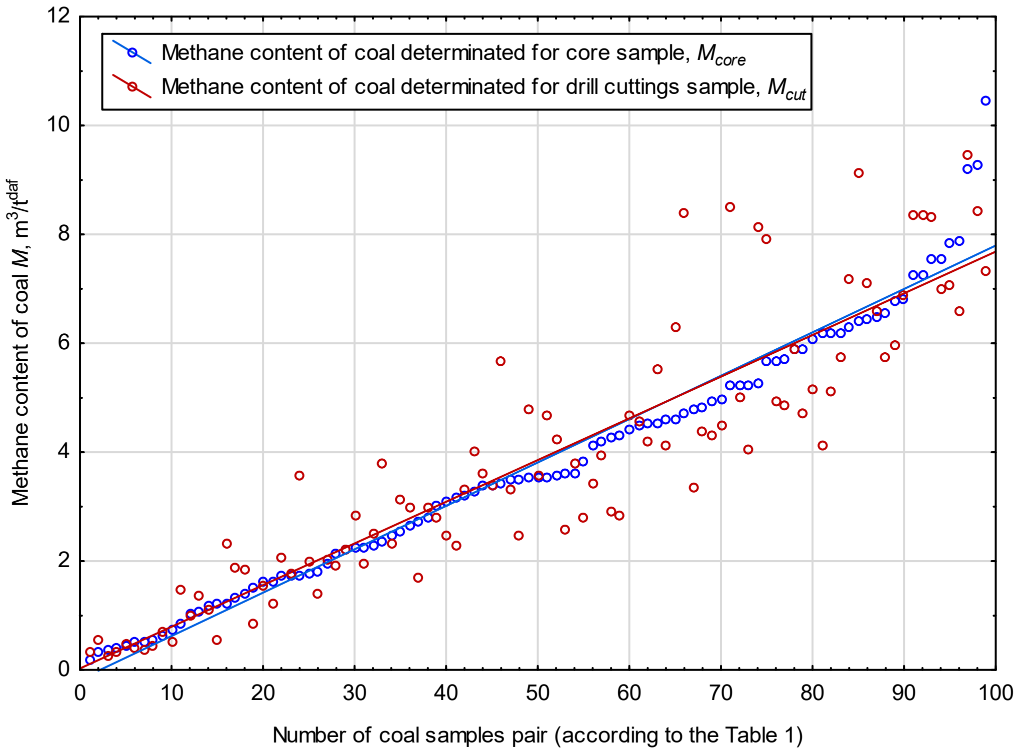

Figure 7. Variation in methane content of coal for drill cuttings samples corresponding to the core samples.

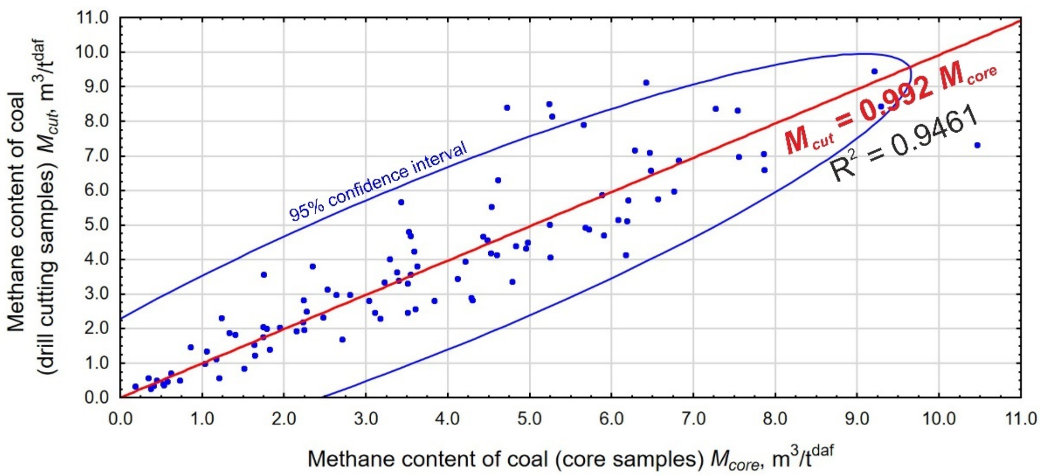

Figure 8. Comparison of methane content of coal based on drill cutting samples and the methane content of coal for the core samples.

The conducted research allows to draw a conclusion that, for the purpose of methane content of coal determination, it is correct to take samples in the form of core samples as well as drill cuttings samples with appropriate consideration of gas loss related to taking a sample for analysis. The results obtained for both forms of samplings were the same. Due to technical reasons, drill cuttings sampling is easier to perform under mining excavation conditions. Therefore, for the purpose of methane content of coal determination, it is recommended to take drill cutting samples taking into account with gas losses during their collection.

5. Conclusions

The comparison of the determination of the methane content of coal based on drill cuttings and core samples, carried out in the course of the research, confirms the necessity of taking into account the gas loss during the coal sample collection for research. In the method developed by the authors, such a loss should be assumed at the level of 12%.

Within the planned research, the results of 99 pairs of methane content of coal determinations were compared, in which a sample was taken both in the form of a core and in the form of drill cuttings. In the case of the drill cuttings samples, the gas loss related to their collection for tests was added, which resulted from previously conducted studies and was accepted in the developed method remaining a Polish standard.

Comparative studies have demonstrated the validity of the adopted gas loss value. The results of the tests obtained indicate that almost 95% determination of methane content of coal based on a core sample and drill cuttings sample with the consideration of gas loss shows the same value.

In the case of coal mine workings, making a borehole and taking a drill cuttings sample is technically more accessible and faster to perform than taking a drilling core. Drilling boreholes for collecting drill cuttings samples can be performed using standard drilling rigs located in each roadway face in a hard coal mine. Collection core samples require additional drilling equipment in the roadway faces, significantly increasing test costs. Therefore, in light of the comparison carried out, it can be concluded that drill cuttings sampling taking into account gas loss is a correct practice for determining the methane content in hard coal mines, and it adequately captures the degassing of the coal sample at the time of sampling.

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Nomenclature

C_{ash}	the ash content in coal, %
$c_{CH_4 deg}$	the methane concentration in the gas mixture obtained by degasifying the sample, cm^3
$c_{CH_4 exc}$	the methane concentration in the mine excavation, %
C_{daf}	the content of dry-ash-free coal in the sample, %
C_{moist}	the total moisture content in coal, %
d_{coal}	coal density, g/cm^3
M	the methane content of coal, m^3/t^{daf}
m_{coal}	the mass of the coal sample, g
M_{core}	the methane content of coal determined for core sample, m^3/t^{daf}
M_{cut}	the methane content of coal determined for drill cuttings sample, m^3/t^{daf}
m_{daf}	the mass of dry-ash-free coal, g
M_{lab}	the methane content of the coal determined in the laboratory, m^3/t^{daf}
p_{deg}	the pressure of the gas mixture obtained by degasifying the sample in the measuring tank, hPa
p_{exc}	the atmospheric pressure in the mine excavation, hPa
p_{ref}	the reference pressure (p_{ref} = 1013.25 hPa), hPa
p_{sat}	the saturation pressure during sorption measurements, MPa
t_{exc}	the air temperature in the mine excavation, °C
t_{lab}	the temperature of the air in the laboratory, °C
t_{ref}	the reference temperature (t_{ref} = 20 °C), °C
V_{balls}	the volume of the balls in the steel canister, cm^3
$V_{CH_4\ coal}$	the volume of the methane obtained from the coal sample, cm^3
$V_{CH_4\ deg}$	the volume of the methane in the gas mixture obtained by degasifying the sample, cm^3
$V_{CH_4\ exc}$	the volume of methane in the air taken to steel canister in the mine, cm^3
V_{coal}	the volume of the coal sample, cm^3
V_{fs}	the volume of the remaining space in the steel canister with the coal sample, cm^3
$V_{gas\ exc\ ref}$	the volume of the gas mixture taken to the steel canister with the coal sample during the collection of the sample with reference to the on-site conditions, cm^3
$V_{gas\ deg\ ref}$	the volume of the gas mixture obtained by degasifying the sample with reference to the on-site conditions, cm^3
V_{mc}	the volume of the measuring canister, cm^3
V_{sc}	the volume of the steel canister, cm^3

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