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Effect of Vapor Treatment on the Caking Properties of Different Coal Types

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Abstract

Modification of the properties of caking coals through the methods of their treatment is of practical interest, especially in the context of deterioration of the raw material source for coke production and high requirements for the quality of coke. Considering the hydrophobicity of coals and their relatively high porosity, vapor treatment can be an effective method of influencing coal properties. Research on the properties of coal treated with water vapor and crude benzene vapor was conducted using different caking ability methods. Coal moistened to 10%wt. was also investigated for comparison. Four coal samples with varying degrees of coalification, ranging from medium to high rank (R_o = 0.76–1.50%) and characterized by volatile matter (V^{daf} = 20.24–37.42%), were investigated. The mechanisms of interaction between coals and water in liquid and vapor form were determined. The results demonstrate that the treatment with water vapor and crude benzene significantly affects the properties of coal A. Specifically, under the influence of water vapor, there is a decrease in the period before the formation of plasticity and an increase in the caking properties of coal A. Coal B and C have good caking ability, so the effect of treatment is less noticeable. The treatment of the coal D leads to an increase in the viscosity of the plastic mass and a decrease in the caking properties. The approaches used in the study of the impact on coal properties can be effectively implemented in production conditions.

Keywords: coking coal; vapor; moisture; crude benzene; caking ability; swelling pressure; coke; process optimization; quality control

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1. Introduction

Coal processing strategies are increasingly evaluated within the framework of sustainable development, particularly with regard to resource efficiency, environmental protection, and responsible production [1]. Despite the ongoing energy transition and the enlargement of renewable energy systems, coal continues to play a significant role both in the European Union and globally, especially in energy-intensive industries and developing

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economies [2–5]. Ensuring the availability of high-quality coal suitable for metallurgical and energy applications remains a major challenge due to the depletion of reserves and increasingly stringent technical and environmental requirements [2,6–12]. Therefore, improving the quality of available coal resources and expanding the raw material base through advanced processing technologies has become a strategic priority. Among the key parameters influencing coal utilization, moisture content is of particular importance, as it directly affects transportation, bulk density, heat consumption, and coke quality [13–18].

In metallurgical applications, where coking coal remains an essential raw material for the coking process, improving its properties is critical for maintaining coke quality. Among the various approaches to modifying coal properties, vapor treatment has attracted particular attention due to its ability to induce controlled physicochemical changes under relatively mild conditions. In contrast to conventional thermal pre-treatment or solvent-based methods, vapor exposure enables targeted interaction with the coal surface and pore structure, influencing functional groups, adsorption characteristics, and subsequent thermoplastic behavior without significant structural degradation [19–22]. Hence, steam treatment can be considered a promising and technologically feasible approach for regulating coal properties and enhancing process stability. Established technologies, such as drying, thermal pre-treatment, and coal moisture control (CMC), have demonstrated their effectiveness in improving process performance, increasing productivity, and enhancing coke quality [13,23–31]. At the same time, the influence of moisture on coal properties is complex: excessive moisture reduces caking properties and increases energy consumption, whereas controlled moisture levels can improve charge homogeneity and process stability [16,21,32–39]. The relationship between moisture, coal structure, and caking behavior is further complicated by the role of oxygen-containing functional groups, pore structure, and particle size, which govern water adsorption and reactivity [36,40,41]. Previous studies have also shown that vapor treatment can enhance caking properties under certain conditions [42–46]. However, the addition of more hydrogen-containing carriers, compared to coal, such as plant biomass in the form of wood [47,48] or cellulose [49], reduces the caking properties of coals due to the predominance of oxygen-containing groups. At the same time, the co-pyrolysis of biomass and coal contributes to the extra-carbonization of the resulting biochar [50].

Despite these advances, the mechanisms of interaction between coal and water in liquid and vapor states remain insufficiently understood. In particular, the different effects of these interactions on coals of varying degrees of coalification, their influence on structural transformations, and their role in controlling plastic layer development and caking properties have not yet been systematically investigated. The lack of mechanistic understanding limits the ability to optimize process conditions and to fully exploit vapor-based treatment technologies. Thus, the aim of this study is to investigate the effect of water vapor and crude benzene vapor treatment on the caking properties of coals with different degrees of coalification. The results are expected to contribute to the development of effective process control strategies and to provide insight into the potential application of vapor treatment as a practical tool for improving coal quality and utilization.

2. Materials and Methods

The present study evaluates various coking coal grades intended for use in coke production blends. The characteristics of the selected coal concentrates are presented in Table 1.

Table 1. Characteristics of coals.

Type of Coal	Proximate Analysis, %				Reflectance of Vitrinite, %
	M	A^d	V^{daf}	$S^d{}_t$	R_o
A	1.66	8.84	37.42	1.90	0.76
B	0.79	6.85	33.44	2.15	1.02
C	0.47	6.39	27.21	1.70	1.33
D	1.69	5.27	20.24	0.68	1.50

M is air-dry coal moisture; A is ash; V is volatile matter; S is sulfur; d is dry basis; daf is dry ash-free basis; t is total.

Proximate analysis of coals was carried out according to ASTM D3172-13 [51]. Vitrinite reflectance was determined according to ISO 7404-5:2009 [52]. The coal concentrates used in the study are characterized by low ash value and high sulfur content. Technical water (pH = 7.8 and hardness 6.8 mmol/dm^3) and crude benzene from coke-making plant grades BC, BC-1 [53] were used for coal treatment. Crude benzene was selected for the research since it is readily available as a byproduct of coke production, making it a practically significant reagent for potential industrial applications without additional processing. From a technical standpoint, crude benzene is characterized by a high aromatic content, making it particularly suitable for studying modifications to coal's properties.

The composition of benzene hydrocarbons is based on benzene itself and its homologs—toluene, xylenes, and trimethylbenzene. Crude benzene is a transparent, lightly moving liquid of a slightly yellow color that darkens rapidly during storage because of oxidation and polymerization of unsaturated compounds to form tar substances. The density of crude benzene is 845–920 kg/m^3, depending on its composition. The yield of crude benzene from the dry coking blend is 0.8–1.2%wt. The approximate composition of crude benzene is presented in Table 2, providing a detailed overview of its constituent hydrocarbons and trace components. This information serves as a basis for understanding the sample's chemical characteristics and evaluating its suitability for subsequent experimental applications.

Table 2. Crude benzene composition.

Component	Contents, %wt.
Benzene	55–75
Toluene	11–22
Xylenes	2.5–6
Ethyl benzene	0.2–0.4
Trimethylbenzene and ethyltoluene	1–2
Unsaturated compounds, including:	7–12
cyclopentadiene	0.6–1.0
styrene	0.5–1.0
coumarone	1.0–2.0
indene	1.5–2.5
Sulphur compounds, including:	0.6–2.8
carbon disulfide	0.3–1.4
thiophene and its alkyl homologs	0.2–1.6
Saturated hydrocarbons	0.6–1.5

The method of coal treatment used in the study involved the transmission of water vapor through a small layer of coal. The mesh size used to place the coal was 0.08 mm. The minimum particle size of coal was 0.1 mm, and the maximum was determined by the requirements for coal size by methods of studying its caking properties, as indicated in the description of the relevant methods. Water or crude benzene was placed in a flask, which was then placed on an electric furnace. A hermetically sealed funnel with a mesh was placed on top of the flask, as shown in Figure 1. Water consumption for coal treatment was 150 mL per 5 g of coal. The consumption for the treatment with crude benzene vapor was 100 mL per 5 g of coal. It was experimentally determined that the optimal amount of coal for processing was 20 g.

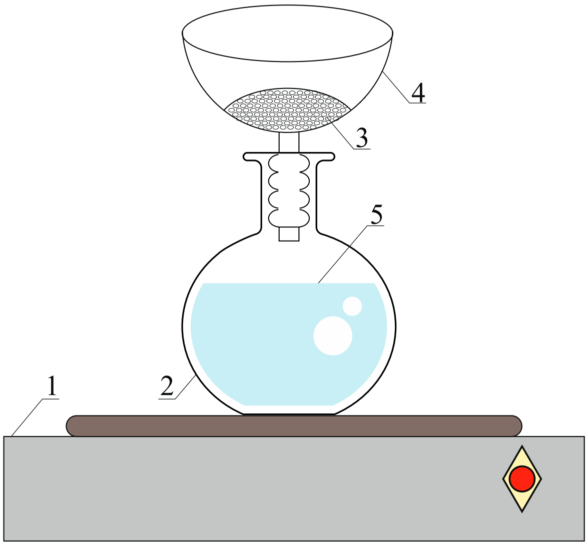

Figure 1. Laboratory setup for the treatment of coal by substance vapors: 1—electric furnace; 2—glass flask; 3—mesh; 4—place for coal; 5—liquid for treatment.

The experiment procedure consisted of heating the substance to the boiling point and treating the coal with steam. The experiments showed that effective treatment of coal with water vapor required 5 min, whereas treatment with benzene vapor required 3 min. Crude benzene vapor began to be released at a temperature of about 65 °C, which is associated with the presence of light fractions in crude benzene.

Considering that the investigation focused on the properties of coal brought to an air-dry state (Table 1), it was important from a practical standpoint to compare the results with the properties of coal in its original state. Therefore, the caking properties were also determined for samples artificially moistened to 10%wt. This is the average moisture content of coal used for processing.

The following methods were used to investigate the effect of processing on coal caking properties: plastometric analysis, determination of caking ability using the Roga method, dilatometric studies, and determination of swelling pressure dynamics.

The plastometric properties of coals were determined in accordance with ISO/DTS 4699 [54]. The method consists of slow heating of coal weighing 100 ± 1 g and with a particle size of less than 1.6 mm at a rate of 3 °C/min in the range from 250 °C to 730 °C, with determination of the dynamics of the plastic layer thickness (y, mm) and shrinkage (x, mm). Under the conditions of the experiment, the coal is subjected to pressure and heated on one side (from the bottom). As a result, at different heights from the heating surface, the coal undergoes different stages of thermal destruction. During heating in a metal cup, the following layers are present sequentially and simultaneously (from top to bottom): the initial coal, dried coal, a plastic layer, a semi-coke layer, and coke. The study is performed in parallel in two test cups.

The caking ability was assessed using the Roga test according to the standard [55]. The method consists of heating a mixture of coal and lean additive (1 g of the investigated coal and 5 g of anthracite) at 850 °C under constant pressure and determining the mechanical strength of the residue obtained. The crucible with the well-mixed blend, after pressing under a load, is covered with a lid and placed on a stand in a muffle furnace for 30 min.

After holding in the furnace, the crucible is removed, the residue is cooled, and then sieved through a sieve with 1 mm-diameter holes. Particles larger than 1 mm are placed in a drum, which rotates for 5 min at a frequency of 50 ± 2 rpm. After rotating in the drum, the residue is sieved again. This is repeated a total of 3 times, after which the caking ability of the coal, expressed by the Roga Index (RI), is calculated by the formula

$$\mathrm{RI} = \left(\frac{a+d}{2} + b + c\right) \cdot \frac{100}{3 \cdot Q} \tag{1}$$

where RI—index of caking ability, units;

Q—total mass of the residue obtained, g;

a—residue on the sieve after heating, g;

b, c, d—residue on the sieve after 1, 2, 3 runs in the drum, g.

The dilatometric indicators of coal were determined according to the method described in [56]. The method consists of heating 2 ± 0.01 g of coal compressed in a metal tube (pressure is 218 MPa) and determining the heating period before the start of swelling (*Pb*, s), the swelling period (*Ps*, s), and the value of swelling (swelling index *Is*, mm) under conditions of free swelling of coal in the tube. Dilatometric indicators are determined for each sample in two parallel samples.

The swelling pressure was determined on a modernized apparatus in accordance with the methodology described in detail in [49,56]. This method is based on rapid heating at a constant oven temperature (500 °C) of a coal sample compressed at 218 MPa, with a mass of 2 ± 0.01 g, and determining the dynamics of swelling pressure when an initial external pressure of 2 MPa is applied.

Applying external pressure to coal allows for obtaining additional characteristics of coal plasticity at the stage of its softening and plastic state, as well as during the period of penetration into the plastic mass. During the study, a curve is obtained, as shown in Figure 2.

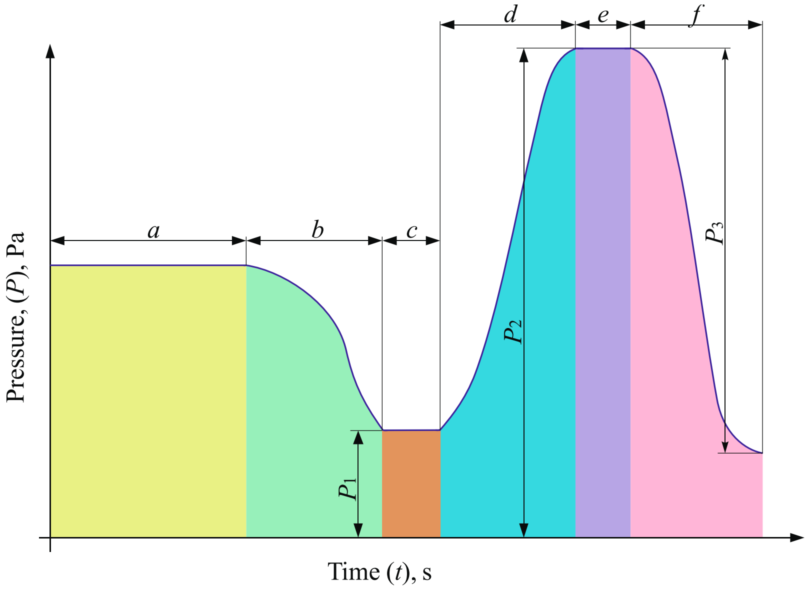

Figure 2. General view of the swelling pressure dynamic curve: *a*—the period of thermal stability of coal before softening, s; *b*—the period of coal softening, s; P_1—the softening pressure or primary shrinkage of coal, Pa; *c*—the equilibrium period of external pressure and coal charge pressure, s; *d*—the duration of the swelling pressure, s; P_2—the maximum of swelling pressure, Pa; *e*—the period of equilibrium of the external pressure and the pressure of the coal plastic mass, s; *f*—the period of penetration of the thermocouple cover into the plastic mass, s; P_3—the pressure of plastic mass penetration, Pa.

Additionally, for a more detailed differentiation of coal caking properties, a complex indicator, $P_2 \cdot d/100$, can be used, which characterizes the swelling pressure potential of coal, Pa·s. The indicators of coal swelling pressure dynamics are determined for each sample in two tests.

3. Results and Discussion

3.1. Plastometric Indicators

The results of determining the plastometric indicators of the initial coal and coal treated with steam and crude benzene, as well as moistening to 10% by mass, are presented in Table 3.

Table 3. Plastometric indicators of initial and treated coal.

Coal	**Plastometric Indicators**							
	Initial Coal		**Steam Treatment**		**Crude Benzene Vapor Treatment**		**Moistened Coal (10%wt.)**	
	y, mm	**x, mm**	**y, mm**	**x, mm**	**y, mm**	**x, mm**	**y, mm**	**x, mm**
A	12	34	13	31	11	35	10	30
B	24	20	26	22	22	21	22	23
C	18	17	18	19	16	20	16	22
D	14	9	14	13	12	10	10	11

The results show a tendency that steam treatment does not reduce the plastic properties of coal. The increase in value y (mm) for coal A and B was within the experimental error (1–2 mm). At the same time, crude benzene vapor treatment showed a clear tendency to reduce the maximum thickness of the plastic layer. The greatest loss in this indicator was observed for coal D. A more pronounced deterioration in the plastic properties of coal was observed when it was moistened to 10%wt. As for plastometric shrinkage (x, mm), it did not change significantly and was within the experimental error relative to the reference.

3.2. Roga Index

The results of determining the caking ability of samples using the Roga method are presented in Table 4, and Figure 3 shows the caking ability results for initial coal, water-treated coal, and water-moistened coal at 10%wt.

Table 4. Roga index of initial and treated coal.

Coal	**Roga Index (RI), Units**			
	Initial Coal	**Steam Treatment**	**Crude Benzene Vapor Treatment**	**Moistened Coal (10%wt.)**
A	27	36	22	16
B	67	67	68	56
C	69	65	68	53
D	59	56	51	42

The highest caking ability is characteristic of the well-caking coal concentrates, B and C. The effect of water vapor and gaseous crude benzene on these coals is minimal due to the high initial caking ability. However, when moistened to 10%wt., the caking ability deteriorates significantly (Figure 3).

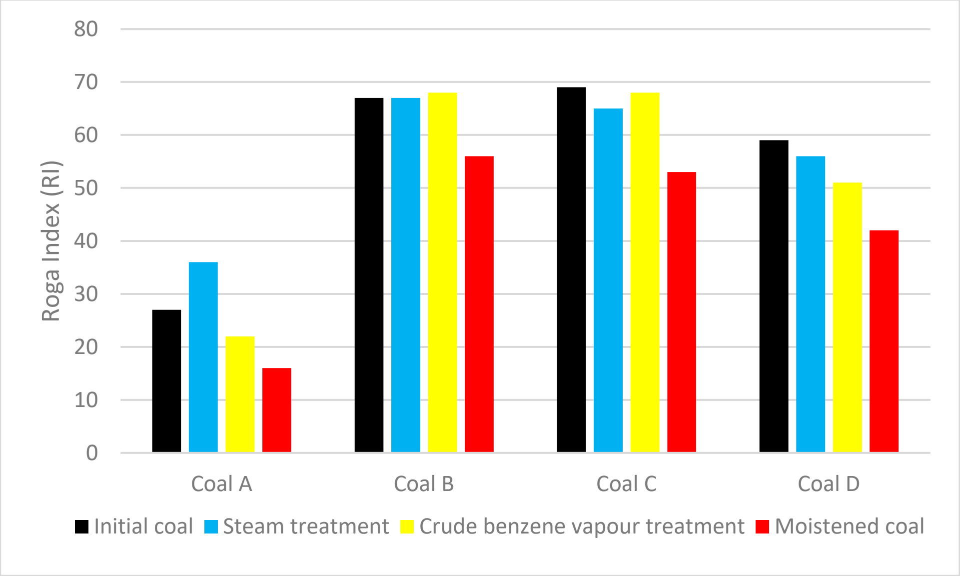

Figure 3. Results of the caking ability for initial and treated coal by Roga index.

The caking ability of coal A improves when treated with water vapor. This can be explained by the relatively high reactivity of coal to surface activation, which has a favorable effect on the subsequent processes of diffusion, adsorption, and thermal destruction kinetics. To confirm this, the time required to heat the coal before thermal destruction begins should decrease.

Moisture content of up to 10%wt. significantly reduces the caking properties of all coal grades, since moisture acts as ballast and has no significant effect on the physicochemical transformations of coal during destruction, except for additional heat and time required to dry the coal.

Generally, when coal is treated with water vapor, there is a tendency for the caking ability of the treated coal to decrease in the metamorphism range. As the aromaticity and energy of chemical bond-breaking increase with the degree of coal metamorphism (from A to D), the effect of steam treatment decreases. Coal destruction occurs sequentially with the breaking of oxygen-containing compounds: N-O (bond energy 221.1 kJ/mol), C-O (358.3 kJ/mol), then C-C bonds (346.1 kJ/mol), followed by the carbon-hydrogen (carbon-hydrogen) bond C-H (413.6 kJ/mol), oxygen-hydrogen O-H (463.4 kJ/mol), and then the more aromatic double bonds of carbon C=C (610.9 kJ/mol).

Coal A has a lower degree of metamorphism among the samples studied, and the presence of water has a more visible effect on chemical destruction processes. Coal B and C have a higher number of aromatic bonds and are also characterized by high caking properties among other types of coal. Coal D has the highest degree of aromaticity among the studied coals and has the strongest chemical bonds, which determines the longest interaction period during processing.

Functional groups containing oxygen are a key factor influencing water vapor adsorption [57]. This study shows that steam treatment promotes the removal of oxygen-containing groups, especially OH-groups, from coal molecules. It reduces the number of self-associated OH-hydrogen bonds in the coal macromolecular network, thereby facilitating the destruction of coal macromolecules and allowing treated coal to form a much larger number of hydrocarbons.

It should be emphasized that moistened coal is more susceptible to oxidation, as moisture catalyzes the formation of oxygen-containing functional groups and promotes radical reactions [58,59]. Coal at low (room) temperatures generates free radicals and increases the concentration of paramagnetic centers in the presence of oxygen, an indicator of chemical interaction with oxygen [60]. As the temperature rises, the amount and rate of oxygen absorption increase. Additionally, the presence of water accelerates the chemical reaction between coal and oxygen, primarily leading to the formation of carboxyl groups.

3.3. Dilatometric Indicators

The results of determining the dilatometric indicators of the initial and treated coal are presented in Table 5.

Table 5. The dilatometric indicators of the initial and treated coal.

Coal	The Period Before the Start of Swelling (*Pb*, s)				Swelling Index (*Is*, mm)				The Swelling Period (*Ps*, s)			
	Initial Coal	Steam Treatment	Crude Benzene Vapor Treatment	Moistened Coal (10%wt.)	Initial Coal	Steam Treatment	Crude Benzene Vapor Treatment	Moistened Coal (10%wt.)	Initial Coal	Steam Treatment	Crude Benzene Vapor Treatment	Moistened Coal (10%wt.)
A	298	275	340	350	19	23	22	16	140	205	152	120
B	340	310	330	360	140	155	133	130	350	365	360	340
C	343	325	320	362	117	130	116	112	359	338	370	340
D	460	410	351	475	54	55	50	50	268	310	378	250

When treated with steam, the heating time to the beginning of swelling (*Pb*, s) decreases for all coals. That is, coal after treatment becomes more reactive, as expected. A reduction in *Pb* usually leads to an increase in *Is*. The largest increase in the swelling index is observed in coal B and C, which is explained by their high initial caking properties. The period during which coal remains in a plastic state (except for coal C) also increases according to the *Ps* parameter. The greatest effect on *Ps* is observed for coal A and D.

Treatment of coal concentrates with crude benzene vapors shows a clear tendency toward deterioration of dilatometric indicators. Thus, *Pb* for coal A increases, while *Is* increases within the range of error, as does *Ps*. Coals B, C, and D are characterized by a decrease in *Is* and an increase in *Ps*, which can be explained by an increase in the viscosity of the plastic mass and, as a result, an increase in its gas permeability.

When treated with crude benzene vapors, the caking properties tend to reduce, but B and C coals are on par with the reference, which is explained by their high caking characteristics. It should be highlighted that when treating coal with crude benzene vapors, significant moistening of the coal on the surface of the mesh was observed. The moisture content of the treated coal was determined to be 9.5%. In fact, the mechanism of vapor treatment can be represented as a diffusion–adsorption process. The diffusion stage consists of delivering steam to the reaction surface of the coal, followed by physical adsorption. In this case, there is no heating of the coal to initiate the interaction. The diffusion process can be intensified by increasing the steam flow rate and reducing the particle size of the coal.

The dilatometric indicators of coal moistened to 10% confirmed the deterioration in coal caking properties observed by the Roga method. Figure 4 shows a diagram of the change in the swelling index for initial coal, coal treated with water vapor, crude benzene, and coal moistened to 10%wt.

3.4. Swelling Pressure Parameters

The indicators of swelling pressure dynamics (Table 6) sufficiently characterize the effect of treatment on changes in coal properties, as they illustrate changes in the pre-plastic state, plastic state, and solidification in a more differentiated form than the dilatometric method.

Table 6. Effect of treatment on coal swelling pressure indicators.

Sample	P_1, kPa	P_2, kPa	P_3, kPa	*a*, s	*b*, s	*c*, s	*d*, s	*e*, s	*f*, s	$P_2 \cdot d/100$, kPa·s
Initial coal A	1160	2052	2052	222	105	6	54	11	98	1108.1
Steam treatment	1134	2094	2094	209	98	6	58	10	99	1214.5
Crude benzene vapor treatment	1169	2061	2061	234	100	7	55	10	95	1133.6
Moistened coal (10%wt.)	1184	2038	2038	245	110	8	52	9	92	1059.8
Initial coal B	1575	3012	3012	282	87	8	85	15	221	2560.2
Steam treatment	1568	3025	3025	275	85	9	88	13	225	2662.0
Crude benzene vapor treatment	1584	2994	2994	280	83	8	82	11	191	2455.1
Moistened coal (10%wt.)	1580	2970	2970	292	88	8	78	10	187	2316.6
Initial coal C	1787	2310	2310	332	105	9	73	11	206	1686.3
Steam treatment	1770	2342	2342	316	100	8	75	10	212	1756.5
Crude benzene vapor treatment	1774	2320	2320	322	101	7	77	9	208	1786.4
Moistened coal (10%wt.)	1812	2282	2282	345	110	8	70	10	195	1597.4
Initial coal D	1991	3590	1479	321	173	18	205	70	286	7359.5
Steam treatment	2026	3525	1490	305	150	17	194	65	294	6838.5
Crude benzene vapor treatment	2015	3542	1488	310	155	15	198	66	268	7013.2
Moistened coal (10%wt.)	2053	3584	1465	336	174	15	204	72	280	7526.4

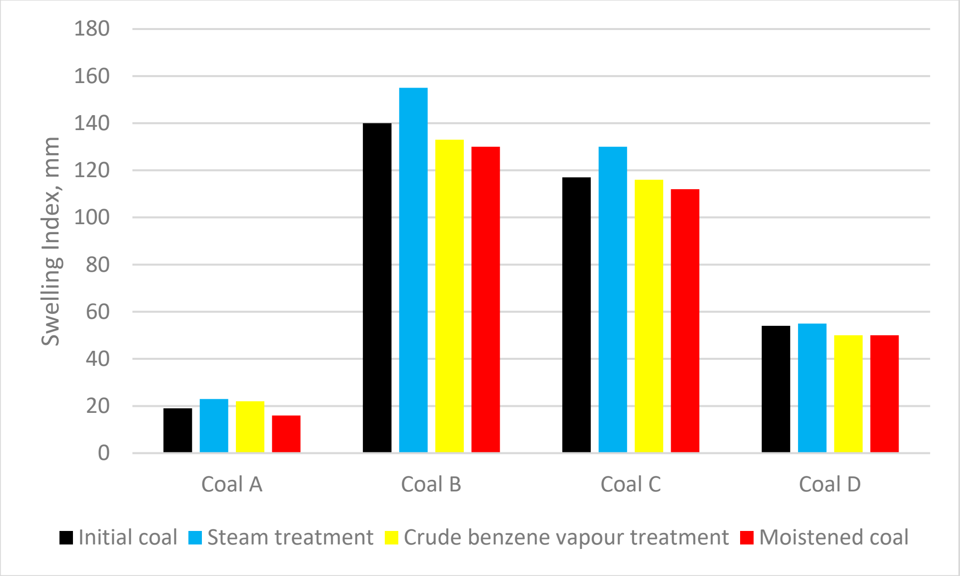

Figure 4. The effect of coal treatment on the swelling index.

After steam treatment, the heating time required to soften coal (*a*, s) is reduced for all coal types. An important result is the reduction in the time required to soften coal to a plastic state (*b*, s) and the reduction in the initial shrinkage of coal (P_1, Pa). That is, the time required for plastic mass accumulation is reduced. As a result, the intensity of thermal destruction increases with the formation of a larger amount of plastic mass and a decrease in its viscosity, as evidenced by an increase in swelling pressure (P_2, Pa). The maximum swelling pressure tends to increase, except for coal D. However, for this type of coal, a decrease in the maximum swelling pressure is a positive result from the point of view of furnace exploitation. It is associated with a decrease in the coal mass pressure as a result of a decrease in the viscosity of the plastic mass formed. The duration of the swelling pressure (*d*, s) changes proportionally to the change in the maximum swelling pressure. Also, with the increase in P_2, there is an increase in the force required to penetrate the plastic mass (P_3, Pa) and the time required for penetration (*f*, s).

During exposure to crude benzene vapors, period *a* also tends to decrease, except for coal A. At the same time, period *b* decreases for all types of coal, and P_1 tends to increase within the experimental error range. The maximum swelling pressure P_2 also changes within the range of error and increases slightly for coals A and C. The duration of the swelling pressure *d* changes in proportion to the change in P_2. The decrease in the period *f* for coal, except for C, indicates a decrease in the amount of plastic mass formed, which is subject to the pressure of the cover penetration into plastic mass.

A comparison of the effects of treatment with water vapor and crude benzene shows an identical effect on the dynamics of swelling pressure, but there is a greater improvement in the caking properties of coal A when treated with water vapor than with crude benzene. Also, for coal D, the complex indicator characterizing the expansion potential of coal ($P_2 \cdot d/100$, Pa·s) decreases more noticeably (see Figure 5), which is beneficial for the operation of coke ovens.

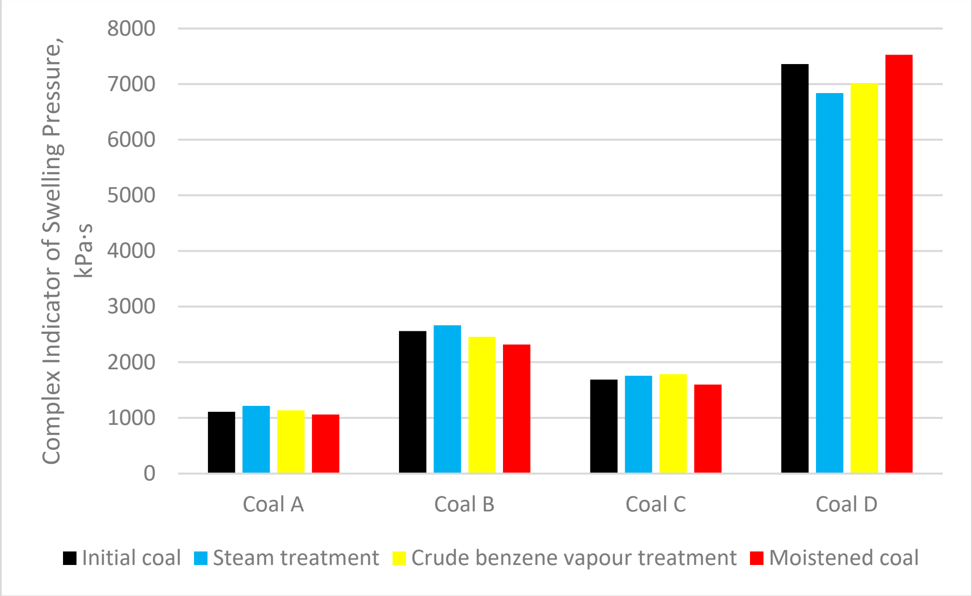

Figure 5. The effect of coal treatment on the complex indicator of swelling pressure.

Moisturizing coal to 10%wt. significantly affects the caking properties and maximum swelling pressure. Thus, period *a* increases significantly, as well as period *b* and P_1. The maximum swelling pressure decreases, as does the pressure time influence (*d*, s). At the same time, the pressure P_3 and period *f* decrease. The complex indicator $P_2 \cdot d/100$ declines for coals A, B, and C and increases for D, indicating a noticeable deterioration in the caking properties of all types of coal compared to the reference and to those treated with steam or crude benzene vapors.

3.5. Mechanistic Insights into Coal–Vapor Interactions and Their Effect on Caking Properties

The coals studied demonstrate different behaviors during steam treatment depending on their degree of carbonization and caking properties. Coal A, characterized by the lowest rank and a higher content of reactive functional groups, is more sensitive to physicochemical transformations. The presence of moisture promotes structural relaxation and the partial breakdown of weaker aliphatic and oxygen-containing bonds in the macromolecular structure.

In contrast, coals B and C, which possess a more developed aromatic structure and exhibit pronounced caking properties, show greater resistance to structural degradation. Their behavior suggests that the interaction of water with the coal is largely limited to surface modification. Coal D, which possesses the highest degree of aromaticity and the most condensed structure, demonstrates the greatest stability and, consequently, requires a longer interaction time for noticeable modification during processing.

From a mechanistic perspective, oxygen-containing functional groups play a key role in interactions with water vapor by acting as adsorption centers. Furthermore, moisture significantly influences oxidation processes. Moist coal is more sensitive to low-temperature oxidation, as water promotes the formation of oxygen-containing functional groups and facilitates radical reactions [59,60]. Even at temperatures close to room temperature, interaction with oxygen leads to the formation of free radicals and an increase in the concentration of paramagnetic centers, indicating the onset of chemical interaction. When coal is treated with crude benzene vapor, a more pronounced diffusion–adsorption process is observed. This leads to significant coal wetting and the formation of oxygen-containing functional groups, which negatively affect the coal's caking properties.

4. Conclusions

From the perspective of process optimization and quality control, the management of operational parameters, such as vapor treatment conditions and moisture content, is critical for achieving stable, predictable caking behavior and improving overall coal utilization efficiency. The comprehensive study of the effect of steam and crude benzene treatment, as well as moistened coal, on the caking properties of various types of coking coal allows provide the following scientific and practical conclusions:

(1) Processing with steam and crude benzene can be used as a controlled technological tool to specifically influence the characteristics of coal during pyrolysis, enabling targeted regulation of the caking process and quality within a process management framework.

(2) The diffusion–adsorption mechanism occurs during coal treatment with vapors. Low-rank coal exhibits higher reactivity and a greater propensity for physicochemical modification under steam treatment, which can be utilized for controlled adjustment of caking behavior and optimization of process conditions.

(3) The most noticeable effect of treatment with water vapor and crude benzene is observed for the lowest and highest coalified samples among those studied, which are characterized by low caking properties. Water vapor treatment of coal A reduces the time to transition to a plastic state and increases caking properties. For coal D, steam treatment increases the viscosity of the plastic mass and decreases its caking characteristics. Medium-ranked coal B and C, with initially high caking ability, reduce the effect of treatment.

(4) Artificially moistening coal to 10%wt. leads to a noticeable deterioration in the caking properties of coal compared to steam treatment, indicating a different mechanism of interaction between coal and water in the liquid and vapor states. This highlights the importance of selecting appropriate process conditions to ensure quality consistency.

(5) The proposed approach demonstrates promising potential for industrial application, as steam treatment under controlled and relatively mild conditions allows for the targeted modification of coal properties without significant structural degradation. This contributes to improved caking properties, enhanced process predictability, and more efficient use of raw materials within existing processing systems.

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