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RELATIONSHIPS AMONG COKING COALS AND RELATED COKES CHARACTERISTICS: A STATISTICAL EVALUATION

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ABSTRACT

From 61 coking coals, 36 coal blends were prepared. Using a pilot coke oven, cokes were prepared from both 61 coking coals (Type I cokes) and 36 coal blends (Type II cokes). Coals were characterized by 14 coal characteristics and cokes by Coke Reactivity Index CRI and Coke Strength after Reaction with CO₂ CSR. For the study of mutual statistic relationships among experimentally determined characteristics of coals and cokes, the Factor (FA) and Regression Analyses (RA) were used. FA distributed characteristics of coals and Type I cokes into 4 factors while characteristics of coal blends and Type II cokes were distributed into 7 factors. In case of pure coals and Type I cokes, strong relationships with high correlation coefficients ($R > |0.60|$) were more abundant than in case of coal blends and Type II cokes. FA was used for the selection of coal characteristics that influence the coke quality the most significantly. These characteristics were then recalculated by RA for the predictions of CRI/CSR of Type I cokes. Predictions of CRI/CSR of Type II cokes were calculated from coal blends by the same procedure. The comparison of the predicted and experimentally determined CRI and CSR indexes showed much more reliable prediction of CRI/CSR indexes calculated from coals than calculated from coal blends. This study also explains the dominant reasons of this observation.

1. INTRODUCTION

The selection of coking coals plays a key role in the production of high-quality metallurgical cokes. Coals must be of suitable chemical, physical and technological properties that determine the quality of produced coke (Leonard et al., 1996; Van Krevelen, 1993). The quality of coke mostly depends on the properties of the coking coals and only partially on coking conditions (Prasad et al., 1996). Therefore, the relationships among coal and related coke characteristics were studied by numerous authors (Barriocanal et al., 2003; Díaz-Faes et al., 2007; Díez et al., 2002; Krzesińska et al., 2002; Kumar et al., 2008; Pusz et al., 2003; Sakurovs, 1997; Sakurovs et al., 2007; Todoschuk et al., 2004; Zhang et al., 2004).

The produced coke should exhibit namely high mechanical strength characterized by CSR and low reactivity characterized by CRI index (Koszorek et al., 2009; Šakurovs et al., 2007). A high negative correlation between CRI and CSR was verified by numerous authors (e.g. Koszorek et al., 2009; Menéndez et al., 1999). Many of these correlations were also displayed visually (North et al., 2018). Therefore, for the prediction of the coke quality, some authors propose to calculate only CSR (North et al., 2017; Suresh et al., 2012; Tiwari et al., 2013).

One of the simplest models for the coke quality prediction was based on the mean vitrinite reflectance and the inertinite content in the parent coals (Miura, 1978). For the preparation of the coke with sufficiently high CSR index, some studies recommend using blends of coals with high mean R_o values (Chaudhuri et al., 1990; Pusz et al., 2009). Currently, particular attention is paid to coal macerals and optical properties in relation to CRI and CSR indexes (Gupta et al., 2012; Pusz et al., 2009, 2003). For example, the prediction model for the calculation of CRI/CSR based on the reflectance parameters (R_{max} , R_{min} and bireflectance R_{bi}) showed that higher inertinite content in parent coals (≥ 30 vol.%) could produce lower-quality cokes with increased CRI and decreased CSR indexes (Pusz and Buszko, 2012). In addition, the full maceral reflectance parameter (FMR) based on automated microscopy of individual coal grains was modified and a new Combined Coal Index (CCI) has been proposed, which improved the accuracy of coke CSR prediction (Gupta et al., 2012).

Recently, the prediction model based on the additivity law and the optical texture of cokes carbonized from individual coals was developed. Moreover, some corrections of the relative proportions of the individual coals present in coal blends were

used. A clear cause-and-effect relationship between optical texture and CRI/CSR of the cokes was found, which could be used as a relevant tool for understanding the coal blending and corresponding coke quality (Flores et al., 2017).

Vitrinite reflectance can also be used for the prediction of the quality of cokes derived from coal blends. A novel method of classifying vitrinite reflectance distributions using self-organizing maps was already presented to capture the multimodal nature of coal blends. Despite some limitations, this model seems to be a promising approach for capturing the underlying vitrinite distribution behavior, and for inferring the implications of blending decisions on coke quality (North et al., 2017).

The relationships among CRI/CSR indexes, chemical composition and physical parameters of cokes were also studied using Czech metallurgical cokes; nevertheless, only five of the calculated relationships were statistically significant. Anyway, the highest correlation coefficients were obtained for the relationship between the pycnometer density of cokes and CSR index ($R = 0.925$) or CRI index ($R = -0.828$), which could be used for the prediction of commercial coke quality (Lech et al., 2017).

Promising results of the CRI/CSR prediction of cokes have been shown using models based on multiple coal characteristics. Zhang et al. (2004) presented the model based on V^d , A^d , S_t , the caking index G and Gieseler fluidity IgF parameters, the mineral catalysis index (MCI), including coal rank and plastic properties of coal. Among these models belong also a procedure using Composite Coking Potential (CCP) coefficient with 12 selected parameters of parent coals suggested by Tiwari et al. (2003) and adaptive neurofuzzy inference system (ANFIS) using the functional relationships among numerous coal blend properties and corresponding CSR indexes reported by Suresh et al. (2012). More information and some other models used for the prediction of the coke quality are described in review papers (de Cordova et al., 2016; North et al., 2018).

The aim of this paper is to search for such characteristics of parent coals that can significantly influence the prediction of CRI and CSR indexes, which could be used for the improvement of the commercial cokes quality.

2. MATERIALS, METHODS, COAL AND COKE CHARACTERISTICS

For the purpose of this study, the set of 61 coal samples including 7 coal types from the Upper Silesian Coal Basin (Czech Republic and Poland) and 1 from the Appalachian Coal Basin (USA) were used. The samples were selected according to the coalification degree (coal rank) - 5 samples exhibited low volatile matter content ($V^{daf} \leq 22.0\%$), 41 samples were medium volatile matter coals ($22.0\% < V^{daf} < 31.0\%$) and 15 samples exhibited high volatile matter content ($V^{daf} > 31.0\%$) (ASTM D388-05, 2005). In addition to these samples, other

36 coal blends were prepared by blending the aforementioned coals with the required quality. From these coals (61) and coal blends (36), the cokes were produced in a pilot coke oven under the standard coking conditions. The cokes originating from pure coals were referred to as Type I cokes (61 samples) and the cokes prepared from the coal blends were referred to as Type II cokes (36 samples).

Approximately 500 kg batches of coals (prepared for the carbonization) were grinded in a pilot coal crusher into fractions lower than 3 mm (90 %) and homogenized for 15 minutes. Tested coal batches were inserted into the pilot coke oven with a movable wall and the stamp charging was used. The density of charge (with 10 % humidity) was about 1020 kg/m^3 . The coal batches were heated from each side by six electric heating elements to the temperature of $1040 \text{ }^\circ\text{C}$ for 22 hours so that the temperature of $1000 \text{ }^\circ\text{C}$ in the middle of the charge was achieved. Cokes prepared in the pilot coke oven were then displaced into the quenching car and quenched by water for ca. 10 minutes. The cooled and dry cokes were then subjected to stabilization. The pilot coke oven is used for the verification of the quality and checking the safety of coking process (Corporate Coke Lab Center of ArcelorMittal, Czech Republic).

For the coal and/or coal blend samples, the following characteristics were determined in accordance with ASTM/ISO standards: ash content A^d (ISO 1171, 2010), volatile matter V^d (ISO 562, 2010), contraction a and dilation b (ISO 349, 1975), Swelling Index SI (ISO 501, 2012), Gieseler maximum fluidity F_{max} (ASTM D2639/D2639M-16, 2016), Alkali Index $Alk. I.$ (Eq. 1), Alkalis (Eq. 2), and Catalytic Index $Cat. I.$ (Eq. 3) (ASTM D4326-13, 2013)

$$Alk.I. = 10^{-2} \cdot A^d \cdot Cat.I. \quad (1)$$

$$Alkalis = Na_2O + K_2O \quad (2)$$

$$Cat.I. = \frac{(Fe_2O_3 + CaO + MgO + Na_2O + K_2O)}{(SiO_2 + Al_2O_3)} \quad (3)$$

A petrographic analysis of coal (reflectance of vitrinite R_r , vitrinite $Vitr$, inertinite $Inert$, liptinite $Lipt$) was determined according to ISO 7404 (ISO 7404-5, 2009; ISO 7404-3, 2009) and performed using microscopic assembly of Nikon Labophot 2 with a DS-CCD Nikon DS-5M camera equipped with immersion lens with a magnification of 40x and a Märzhäuser motorized scanning stage. Cokes were characterized by Coke Reactivity Index CRI and Coke Strength after Reaction with CO_2 CSR (ISO 18894, 2006). Once received the coals, coking in the pilot coke oven and laboratory analyses were performed without delay. Mutual relationship between CRI and CSR values for Type I and II cokes is depicted (Fig. 1) and it indicates a strong negative correlation, which is consistent with $R^2 = 0.977$ (Menéndez et al., 1999) and $R^2 = 0.953$ (Flores et al., 2017).

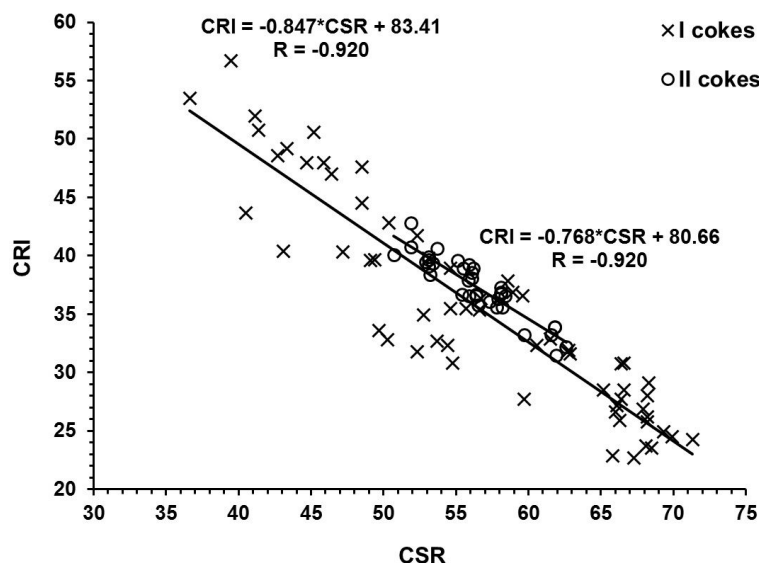


Fig. 1 Experimentally determined Coke Reactivity Index (CRI) vs. Coke Strength after Reaction with CO₂ (CSR) of Type I cokes and Type II cokes.

3. STATISTICAL EVALUATION OF COALS AND COKES PROPERTIES

3.1. BASIC STATISTICS

Experimentally determined characteristics of pure coals and corresponding Type I cokes (61 samples) as well as coal blends and related Type II cokes (36 samples) were evaluated using QC.Expert 2.7 (TriloByte Statistical Software, Ltd., Pardubice, Czech Republic). For pure coals and Type I cokes, the statistical results are shown in Table 1(a) and the same for coal blends and Type II cokes is summarized in Table 1(b).

Normality is evaluated based on a combination of skewness and kurtosis. The normal (i.e. the Gaussian) distribution exhibits skewness close to 0 and kurtosis of ca. 3. If the differences of skewness and kurtosis values from 0 and 3 are statistically significant, the distribution cannot be regarded as symmetrical. In cases where normality is rejected, the torque characteristics (i.e. the mean, standard deviation STD and variance) are replaced by robust characteristics (i.e. by the median, median standard deviation and median variance). The number of outliers for the studied characteristics (i.e. values considered as suspicious of remoteness) are listed in Table 1.

Comparing the mean values of coal and coal blend characteristics, the lower values of b (26 %), F_{max} (56 %) and Vitr (14 %) and somewhat greater values of Inert (14 %) and Cat. I. (18 %) were obtained for coal blends. In case of other characteristics, the differences were lower than 10 %.

The standard deviations (STD) of coal blend characteristics are much lower than those of coal characteristics. Moreover, STD of Type II cokes are lower than those of Type I cokes (Table 1). Lower STD values for coal blend and Type II cokes characteristics relate to the blending principle.

Moreover, along with CRI and CSR indexes, the other two coke characteristics were determined - ash content A^d (coke) ranging from 6.10 to 13.60 and volatile combustibles V^d (coke) from 0.60 to 3.70 %. These complementary characteristics were not included in the statistical evaluation.

3.2. FACTOR ANALYSIS

3.2.1. COALS (FOR TYPE I COKES)

The factor analysis (FA) is a multidimensional statistical method based on the analysis of the mutual relationships of the variables and an assumption that these relationships are the results of a small number of underlying immeasurable factors. Thus, the purpose of FA is to reduce the number of variables and reveal the structure of relationships among them. One of the basic objectives of the factor analysis is to assess the relationship structure of the monitored variables and to determine whether they can be aggregated into groups in which the studied variables correlate together and have as little correlation as possible with other variables in other groups (factors) (Jöreskog et al., 1976; Klika et al., 2014).

FA was used for the evaluation of the experimentally determined characteristics of coals and related Type I cokes. The data used for this calculation contained 14 coal and 2 coke characteristics for 61 coals and related Type I cokes. The factor loadings calculated from 16 variables in the set of 61 coal and 61 coke (Type I) samples are presented in Table 2. The highest factor loading for each characteristic is then assigned to one of the factors F1- F4 (Table 3).

In each of the 4 factors the variables are divided into 2 groups. For example, the factor 1 (F1) is represented by 5 characteristics (A^d, SI, Vitr, Alkalis, CSR) in the first positive group (the positive factor loading) and by 5 characteristics (Lipt, Inert, Cat. I.,

Table 1 Basic statistics of coal and coke characteristics, (a) for pure coals and Type I cokes, (b) for coal blends and Type II cokes.

(a)	Coals											I cokes				
	A ^d (%)	V ^d (%)	a (%)	b (%)	SI (-)	F _{max.} (ddpm)	R _r (%)	Vitr (%)	Lipt (%)	Inert (%)	Cat. I. (-)	Alk. I. (-)	Alkalis (%)	S ^d (%)	CRI (%)	CSR (%)
Mean	7.27	24.8	23.8	49.0	7.30	540	1.10	56.6	6.78	36.6	0.28	2.14	0.21	0.54	35.5	56.6
Minimum	4.70	16.4	15.0	6.00	5.00	3.00	0.84	37.5	0.5	15.3	0.15	1.08	0.074	0.35	22.7	36.6
Maximum	11.3	31.3	33.0	181	8.50	9023	1.54	80.3	11.8	51.4	0.94	5.4	0.39	0.74	56.7	71.3
STD	1.38	3.65	3.80	3.32	0.75	61.0	0.006	12.6	3.1	10.4	0.02	0.12	0.081	0.1	8.91	9.68
Variance	1.89	13.3	14.5	11.0	0.56	3717	3.75	158	9.64	109	<0.001	0.014	0.007	0.01	79.4	93.8
Skewness	0.32	-0.064	0.27	1.28	-0.83	5.56	1.08	-0.057	-0.29	-0.069	1.53	1.21	0.11	-0.14	0.55	-0.23
Kurtosis	3.05	3.06	2.98	6.67	3.38	36.1	5.02	1.76	1.93	1.71	5.13	4.94	2.07	2.07	2.31	1.81
Normality	Acc.	Acc.	Acc.	Rej.	Acc.	Rej.	Rej.	Acc.	Acc.	Acc.	Rej.	Rej.	Acc.	Acc.	Acc.	Acc.
Outliers	0	4	0	1	0	2	5	0	0	0	2	1	0	0	0	0

Note: ^d – dry basis; Rej. – rejected; Acc. – accepted; STD – standard deviation.

(b)	Coal blends											II cokes				
	A ^d (%)	V ^d (%)	a (%)	b (%)	SI (-)	F _{max.} (ddpm)	R _r (%)	Vitr (%)	Lipt (%)	Inert (%)	Cat. I. (-)	Alk. I. (-)	Alkalis (%)	S ^d (%)	CRI (%)	CSR (%)
Mean	7.00	26.0	24.6	38.7	7.10	346	1.02	49.7	7.40	42.6	0.34	2.36	0.19	0.52	37.3	56.4
Minimum	6.27	24.1	20.0	24.0	6.00	3.00	1.01	46.7	5.50	29.9	0.25	1.96	0.17	0.45	31.5	50.7
Maximum	7.87	27.3	29.0	69.0	7.50	201	1.07	63.8	9.30	46.8	0.52	3.80	0.23	0.58	42.8	62.2
STD	0.36	0.68	2.18	9.26	0.39	37.5	0.004	0.41	0.88	0.38	0.007	0.056	0.017	0.034	2.58	3.09
Variance	0.13	0.46	4.76	85.8	0.15	1406	<0.001	0.17	0.77	0.15	<0.001	0.003	<0.001	0.001	6.67	9.57
Skewness	0.64	-0.62	0.011	0.87	-0.71	1.19	1.14	2.96	-0.47	-2.93	1.22	1.73	0.44	-0.22	-0.35	0.29
Kurtosis	3.63	3.32	2.68	4.39	3.02	4.00	3.63	11.76	2.54	12.18	4.52	5.99	2.32	2.61	2.71	2.44
Normality	Acc.	Acc.	Acc.	Acc.	Acc.	Rej.	Rej.	Rej.	Acc.	Rej.	Rej.	Rej.	Acc.	Acc.	Acc.	Acc.
Outliers	0	0	0	0	0	0	0	2	0	2	3	2	0	0	0	0

Note: ^d – dry basis; Rej. – rejected; Acc. – accepted; STD – standard deviation.

Table 2 The factor loadings for coals and their cokes (Type I) after Varimax rotation.

Characteristic	Factor 1	Factor 2	Factor 3	Factor 4
A ^d	0.686	0.170	-0.158	-0.410
V ^d	-0.030	0.930	0.161	0.084
a	0.034	0.853	0.011	-0.014
b	0.154	-0.169	0.899	-0.223
SI	0.647	-0.301	0.151	-0.244
F _{max.}	0.111	0.221	0.845	-0.043
R _r	-0.075	-0.933	0.030	-0.148
Vitr	0.919	-0.045	0.239	-0.112
Lipt	-0.744	0.519	-0.158	0.247
Inert	-0.874	-0.156	-0.325	0.122
Cat. I.	-0.871	0.130	-0.068	0.430
Alk. I.	-0.869	0.260	-0.226	0.224
Alkalis	0.815	0.248	-0.134	-0.314
S ^d	0.436	0.265	0.353	-0.537
CRI	-0.717	0.188	-0.107	0.615
CSR	0.600	-0.595	0.125	-0.445

Table 3 The results of the factor analysis of coal and related Type I coke characteristics.

Factor	Group (+)	Group (-)	R > 0.6
F1	A ^d , SI; Vitr; Alkalis; CSR	Lipt; Inert; Cat. I.; Alk. I.; CRI	24
F2	V ^d , a	R _r	3
F3	b; F _{max.}	-	1
F4	-	S ^d	-
R among F1 – F4 factors			4
Total number			32

Note: R – correlation coefficients

Table 4 The highest correlation coefficients (R) between characteristics contained in factor F1.

Characteristics	R	Characteristics	R	Characteristics	R
Vitr – Inert	-0.935	Alk. I. – CRI	0.752	Vitr – Alkalis	0.672
Cat. I. – Alk. I.	0.918	Vitr – CRI	-0.748	Lipt – Inert	0.668
Lipt – CSR	-0.904	Alkalis – CRI	-0.712	Vitr – CSR	0.659
A ^d – Alkalis	0.891	Cat. I. – CSR	-0.710	SI – CRI	-0.658
CRI – CSR	-0.875	Inert – CRI	0.696	SI – Lipt	-0.646
Cat. I. – CRI	0.848	Alk. I. – CSR	-0.694	SI – CSR	0.640
Lipt – CRI	0.802	Inert – Alkalis	-0.691	SI – Vitr	0.639
Vitr – Lipt	-0.779	A ^d – CRI	-0.676	A ^d – Cat. I.	-0.631

Alk. I., CRI) in the second negative group (the negative factor loading). The correlation coefficients among characteristics in the first (+) group of F1 are within the range from 0.371 to 0.917 and those of the second (-) group from 0.390 to 0.847. The correlation coefficients among any variable (characteristic) of the first and the second group vary from -0.328 to -0.935. The factor 1 contains 24 total correlation coefficients ranging from |0.631| to |0.935| (Table 4).

Next factors F2, F3 and F4 can be explained analogously, but they contain much lower number of characteristics and correlation coefficients inside each factor. The total number of the strongest correlation coefficients $n(R) = 32$, where 3 of them belong to F2 and 1 to F3 factors. Remaining 4 strongest correlation

coefficients belong to characteristics included between 2 different factors (Table 3). Assignment of coal characteristics by factor analysis is illustrated in Figure 2.

In the first factor F1, the sum of all 3 coal macerals equals to 100 % (Fig. 3A); therefore, the information on the content of one of these macerals is redundant. Furthermore, alkali index (Fig. 3B) includes catalytic index (Eq. 1) and also the correlation coefficients between Vitr – Inert and Cat. I. – Alk. I. are high; for this reason, one of these characteristics can be eliminated from regression equations as well. Therefore, for further consideration (regression analysis) the number of coal characteristics in F1 factor can be reduced to 6.

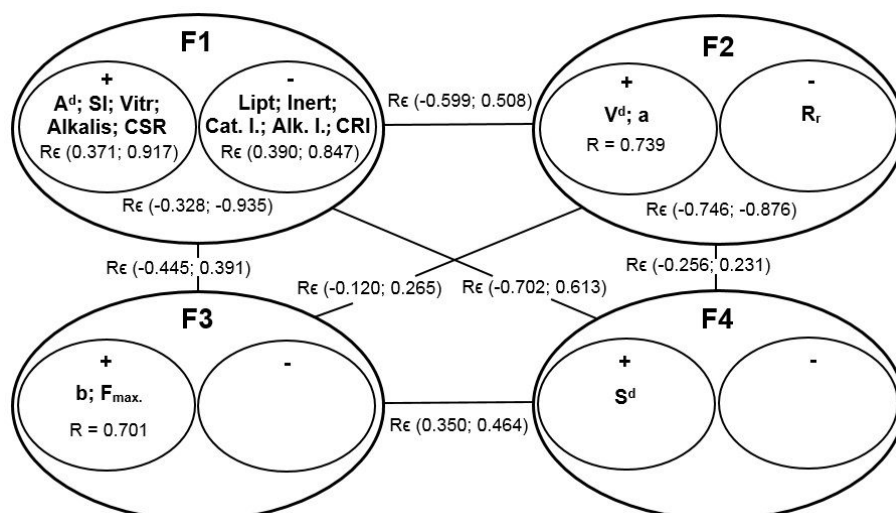


Fig. 2 Scheme of calculated factors F1, F2, F3 and F4 with their mutual correlation coefficients among coal and Type I coke characteristics.

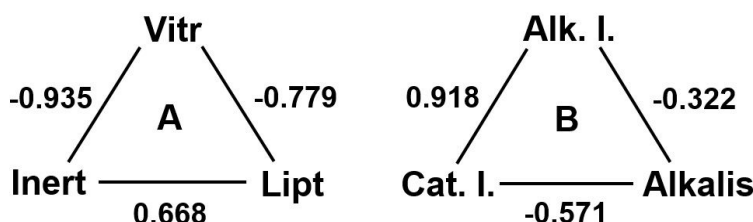


Fig. 3 Correlation coefficients among coal macerals (A) and characteristics containing alkali elements (B).

3.2.2. COAL BLENDS (FOR TYPE II COKES)

FA was also used for the evaluation of 14 experimentally determined characteristics of 36 coal blends and related CRI and CSR indexes of 36 cokes (Type II). From these data the factor loadings were calculated and the highest factor loading for each characteristic assigned to one of the factors F1- F7 (Table 5).

In contrast to total numbers of factors $n(F) = 4$ calculated for previous 61 coals and related cokes (Type I) (section 3.2.1), for 36 coal blends and Type II cokes data, $n(F) = 7$ factors were calculated. The characteristics of coal blends and Type II cokes are distributed within 7 factors indicating that there are poor correlations among them (Table 6). The total number of the correlation coefficients $n(R)$ being higher than $|0.60|$ is much lower (4) than that obtained for pure coals and Type I cokes data (32). They are Vitr – Inert (-0.970), Cat. I. – Alk. I. (0.957), CRI – CSR (-0.918) and V^d – S^d (0.628). Moreover, the correlation coefficients of coal blend characteristics with CRI and/or with CSR indexes are even lower than $R = 0.360$. This is in striking contrast to 14 high correlation coefficients with $R > |0.60|$ between CRI (8) and/or CSR (6) with coal characteristics presented before in section 3.2.1 (Table 4). Also, the total number of factors $n(F)$ and the total number of the correlation coefficients $n(R) > |0.60|$ for coals and

cokes (Type I) and for coal blends and cokes (Type II) are quite different (Fig. 4).

In this study, correlation coefficients between studied characteristics calculated for the coal blends exhibited significantly lower values than those calculated for pure coking coals. It can be attributed to the fact that coal blends were prepared by blending of the coking coal samples thereby averaging their characteristics; i.e., variances of their characteristics are typically much lower than those of pure coking coals (Table 1). Moreover, coal blending probably resulted in low correlation coefficients calculated for the relationships of CRI and CSR (Type II) with the characteristics of coal blends.

3.3. REGRESSION ANALYSIS

3.3.1. TYPE I COKES (FROM COALS)

For the prediction of CRI and CSR, the following regression equations (4 and 5) based on coal characteristics have been proposed. They are:

$$CRI_j = \sum_{i=1}^n k_i^* \cdot P_{i,j} + const \quad (4)$$

$$CSR_j = \sum_{i=1}^n k_i^{**} \cdot P_{i,j} + const \quad (5)$$

where $P_{i,j}$ is the i -th characteristic of the j -th coal sample; k_i^* and/or k_i^{**} are the i -th coefficients related to $P_{i,j}$; $const$ is constant; CRI_j and/or CSR_j are indexes

Table 5 The factor loadings for coal blends and their cokes (Type II) after Varimax rotation.

Characteristic	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
A ^d	0.020	-0.777	-0.026	0.061	0.151	0.012	0.115
V ^d	-0.095	0.075	0.061	-0.093	-0.917	0.209	0.032
a	0.233	-0.178	-0.091	0.026	0.080	0.796	-0.116
b	-0.194	0.718	0.094	-0.056	0.014	0.487	0.228
SI	0.049	0.239	-0.074	-0.114	0.002	0.109	0.762
F _{max.}	-0.189	0.467	0.043	-0.051	-0.273	0.704	0.144
R _r	-0.039	0.058	-0.194	0.090	0.441	0.202	-0.632
Vitr	0.088	-0.009	0.976	0.107	-0.109	-0.018	-0.091
Lipt	-0.251	-0.175	-0.386	-0.297	0.421	-0.056	0.549
Inert	-0.027	0.061	-0.985	-0.035	0.001	0.036	-0.056
Cat. I.	-0.150	0.223	-0.071	-0.952	-0.005	0.010	0.103
Alk. I.	-0.137	0.003	-0.083	-0.964	0.038	0.004	0.137
Alkalis	-0.111	-0.852	0.169	0.115	0.036	0.134	-0.211
S ^d	0.248	0.144	0.016	0.145	-0.823	-0.142	0.058
CRI	-0.952	0.018	-0.033	-0.119	0.141	-0.026	-0.063
CSR	0.949	-0.020	0.098	0.159	0.006	0.058	-0.045

Table 6 The results of the factor analysis of coal blends and related Type II coke characteristics.

Factor	Group (+)	Group (-)	R > 0.6
F1	CSR	CRI	1
F2	b	A ^d , Alkalis	
F3	Vitr	Inert	1
F4	-	Cat. I.; Alk. I.	1
F5	-	V ^d , S ^d	1
F6	a; F _{max.}	-	-
F7	SI; Lipt	R _r	-
R among F1 – F7 factors			-
Total number			4

Note: R – correlation coefficients

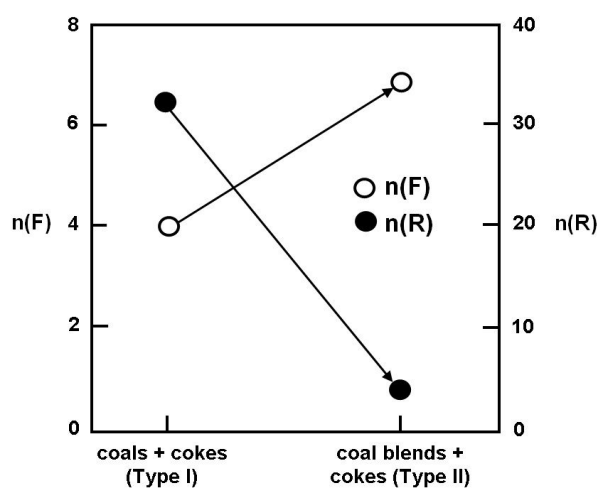


Fig. 4 Trends of the total number of factors $n(F)$ and total number of the correlation coefficients $n(R) > |0.60|$ between coals and cokes (Type I) and coal blends and cokes (Type II).

of the j -th coke sample and n is the number of coal characteristics.

The results of the FA allow distinguish importance of the individual coal characteristics for the calculation of CRI and CSR prediction. For example, the S^d characteristic included in the factor F4 (Fig. 2) exhibited rather poor correlations with other characteristics; therefore, it was omitted from further regression calculation.

For the evaluation of the k_i^* and/or k_i^{**} coefficients and constants $const$ in Eqs. 4 and 5, the P_{ij} experimental characteristics of coals and experimentally determined CRI/CSR_j values of Type I cokes were used. These coefficients as well as constants ($const$) were calculated using regression analysis and they are given for different variants in Table 7. For the variant 1, the k_i^* and/or k_i^{**} coefficients were calculated for 13 coal characteristics (F1, F2 and F3 factors) and for variant 2, they were calculated for 8 coal characteristics (factor F1). In the variant 3, the coal characteristics in F1 were reduced by Vitr and Alk. I. and in variant 4 only the Lipt and Inert were used. However, the reduction of characteristics in variants 3 and 4 in Eqs. 4 and 5 is

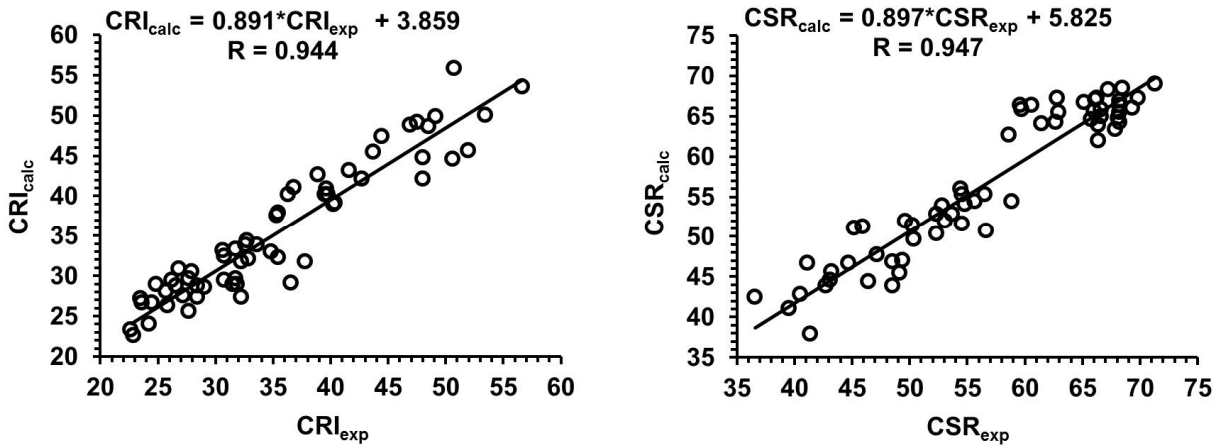


Fig. 5 Plots between predicted (calc) and experimentally (exp) determined Type I coke indexes. Left – CRI; right – CSR.

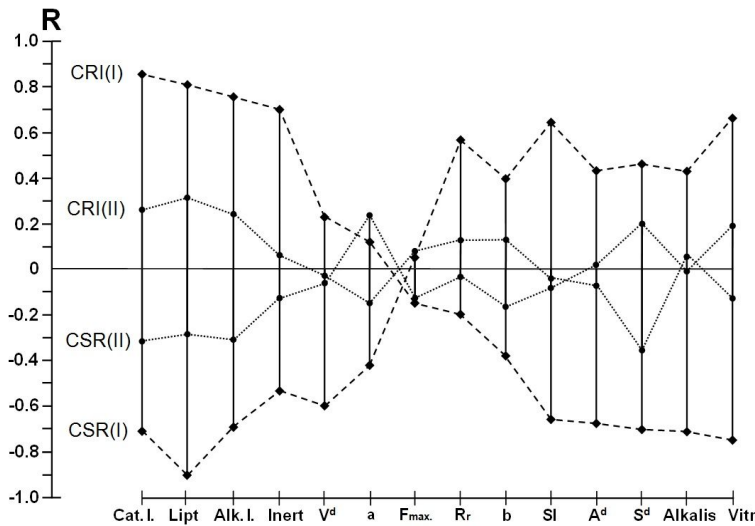


Fig. 6 Zig-zag plots of the correlation coefficients (R) and pure coal (I) and/or coal blend (II) characteristics. CRI(I) and CSR(I) zig-zag plots predicted from pure coal (I) characteristics (sec. 3.3.1.); CRI(II) and CSR(II) zig-zag plots predicted from coal blend (II) characteristics (sec. 3.3.2.).

supported by adding new constants (Table 7). Moreover, k_i^* and k_i^{**} coefficients and constants *const* were also calculated from regression equations (Eqs. 4 and 5) for each of 14 single P_{ij} coal characteristics (A^d , V^d , a, b, SI, $F_{max.}$, R_r , Vittr, Lipt, Inert, Cat. I., Alk. I., Alkalis, S^d) and experimentally determined CRI_j/CSR_j values of I cokes. These data are not presented here.

Conversely, for all calculated k_i^* and k_i^{**} coefficients, *const* and the relevant P_{ij} coal characteristics, the CRI and CSR indexes were predicted (Eqs. 4 and 5). These predicted data were compared with experimentally determined CRI/CSR and correlation coefficients R were calculated. The correlations are very high for variants 1-4 (Table 7) but they drop when the coal characteristics from F2 or F3 factors for CRI/CSR prediction are used (not shown). The best regression functions between predicted CRI_{calc} and experimentally determined

CRI_{exp} ($R = 0.944$) as well as predicted CSR_{calc} and experimentally determined CSR_{exp} ($R = 0.947$) are plotted in Figure 5.

CRI and CSR of Type I cokes were separately predicted using pure coal characteristics. After that, they were compared with relevant experimentally determined CRI and CSR indexes, their correlation coefficients R calculated and plotted versus these coal characteristics (Fig. 6). These curves confirm a negative correlation between both Type I coke indexes. The differences in R between both zig-zag curves are more significant for Cat. I., Alk. I., Lipt and Inert as well as for Vittr, SI, Alkalis and A^d characteristics of F1 factor, while the differences in R between CRI(I) and CSR(I) zig-zag curves for V^d , a, $F_{max.}$, b, R_r characteristics of F2 and F3 factors are less significant (Fig. 6). These results also show the dominant role of coal characteristics included within factor F1.

Table 7 Calculated k_i^* , k_i^{**} coefficients, constants *const* and correlation coefficients R for the prediction of CRI and CSR of Type I cokes.

Variants	Coke indexes	1 A ^d	2 V ^d	3 a	4 b	5 SI	6 F _{max.}	7 R _r	8 Vitr	9 Lipt	10 Inert	11 Cat. I.	12 Alk. I.	13 Alkalis	const	R
1	CRI	-0.533	-0.119	0.138	-0.016	-0.792	<0.001	7.311	0.146	1.603	0.257	20.19	0.331	6.384		0.944
	CSR	0.398	-0.945	-0.201	0.010	0.957	<0.001	-30.59	1.318	-0.937	1.391	-6.014	-2.973	-12.11		0.947
2	CRI	-0.592				-0.957			0.254	1.302	0.392	19.29	0.753	3.533		0.937
	CSR	0.403				1.089			0.656	-1.487	0.804	-13.62	-1.778	-8.846		0.930
3	CRI	-0.408				-0.953				1.067	0.139	23.44		3.941	24.13	0.937
	CSR	-0.031				1.080				-2.191	0.144	-23.45		-9.812	68.69	0.929
4	CRI									1.735	0.303				12.60	0.867
	CSR									-2.802	0.033				74.41	0.877

Note: columns 1-13 – k_i^* and k_i^{**} coefficients for 1-13 coal characteristics; *const* – calculated constant; R – correlation coefficient between predicted and experimental CRI and/or CSR.

Table 8 Calculated k_i^* , k_i^{**} coefficients, constants *const* and correlation coefficients R for the prediction of CRI and CSR of Type II cokes.

Variants	Coke indexes	1 A ^d	2 V ^d	3 a	4 b	5 SI	6 F _{max.}	7 R _r	8 Vitr	9 Lipt	10 Inert	11 Cat. I.	12 Alk. I.	13 Alkalis	14 S ^d	const	R
1	CRI	5.666	1.988	-0.373	0.039	0.303	-0.002	60.25	-1.000	-0.210	-1.036	142.7	-19.74	19.42	-36.92		0.616
	CSR	-20.95	-2.633	0.543	-0.104	-1.086	0.006	-47.31	3.114	2.888	2.982	-440.2	60.69	-16.97	40.13		0.642
2	CRI	-1.318	1.173	-0.355	0.026	-0.115	0.003	30.83		0.665	0.018		0.416	26.43	-33.51		0.591
	CSR	0.602	-0.082	0.487	-0.066	0.223	-0.002	45.20		0.174	-0.190		-1.494	-38.70	29.55		0.458
3	CRI	-1.233	1.779	-0.365	0.025	0.187	<0.001	58.15		0.919	-0.050		0.214	24.93	-34.69	-45.06	0.605
	CSR	0.333	-1.989	0.519	-0.061	-0.729	0.001	-40.85		-0.625	-0.089		-0.860	-33.99	33.28	142.0	0.568

Note: columns 1-14 – k_i^* and k_i^{**} coefficients for 1-14 coal characteristics; *const* – calculated constant; R – correlation coefficient between predicted and experimental CRI and/or CSR.

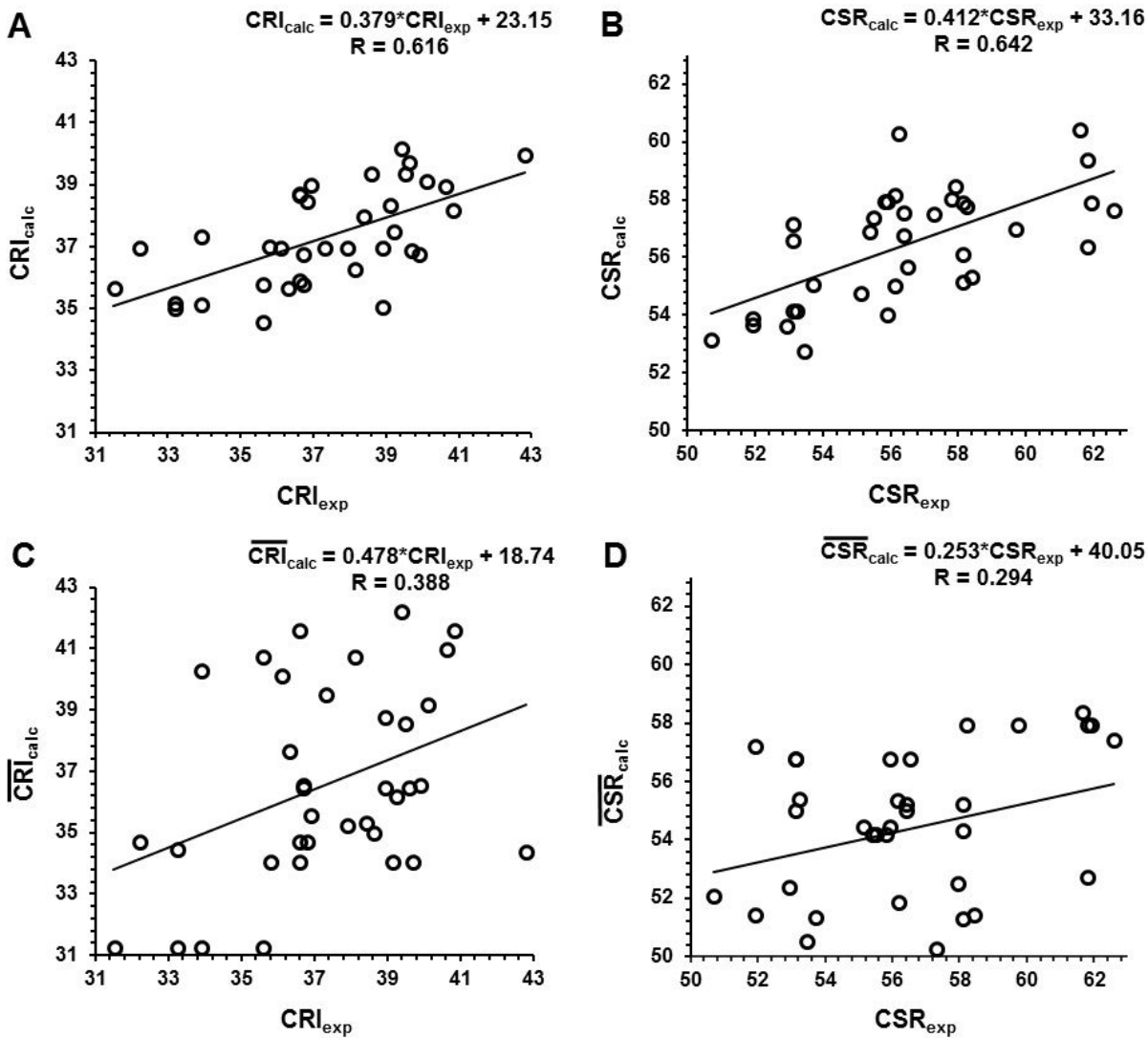


Fig. 7 Plots between calculated (calc) and experimentally (exp) determined Type II coke indexes. A – CRI, B – CSR, (both predicted in sec. 3.3.2.); C – \overline{CRI} , D – \overline{CSR} , (both calculated as weighted means in sec. 3.4.).

3.3.2. TYPE II COKES (FROM COAL BLENDS)

Similarly as in section 3.3.1., the k_i^* and/or k_i^{**} coefficients and constants *const* of linear regression (Eqs. 4 and 5) were evaluated using P_{ij} experimental characteristics of coal blends and experimentally determined CRI_j/CSR_j of Type II cokes. For variant 1, 4 coal blend characteristics (factors F1-F7) were used. Then, for variant 2, 12 coal blend characteristics (reduced from factors F1-F7 by Vitr and Cat. I.) and for variant 3, the above 12 coal blend characteristics were used and added by constant *const* (Table 8).

Analogously to section 3.1.1., CRI and CSR indexes were predicted (Eqs. 4 and 5) and compared with experimentally determined CRI/CSR. In contrast to coals (sec. 3.3.1.), the calculated correlation coefficients R are lower.

In variants 1-3, the correlation coefficients R range from 0.591 to 0.616 for CRI and from 0.458 to 0.642 for CSR, respectively (Table 8). As expected, the correlation coefficients also drop with the decreasing number of coal blend characteristics (not

shown). The best regression functions between predicted CRI_{calc} and experimentally determined CRI_{exp} (Fig. 7A) as well as between predicted CSR_{calc} and experimentally determined CSR_{exp} (Fig. 7B) show lower correlation coefficients than those for Type I cokes (Table 7).

The correlation coefficients R plotted in the zig-zag curves (Fig. 6) CRI(II) and CSR(II) are also much lower comparing with CRI(I) and CSR(I).

3.4. WEIGHTED MEANS

Except CRI and CSR prediction of Type II cokes based on regression Eqs. 4 and 5, the next prediction was calculated as weighted means of \overline{CRI} and \overline{CSR} by Eq. 6.

$$\overline{P}_{i,j} = \frac{\sum P_{i,j,m} \cdot w_m}{100} \quad (6)$$

where $\overline{P}_{i,j}$ is the weighted mean of the *i*-th Type II coke characteristic (\overline{CRI}_j and \overline{CSR}_j) of the *j*-th Type

II coke sample; $P_{i,j,m}$ – is the i -th coke index (CRI_j or CSR_j) of the m -th sample of Type I coke used for the calculation of $\overline{P_{i,j}}$ characteristic of the j -th sample of Type II cokes; w_m – percentages of the m -th sample of Type I cokes used for the calculation of the $\overline{P_{i,j}}$.

While the prediction of CRI and CSR indexes for Type I cokes is very good (Fig. 5), the prediction of Type II cokes carbonized from coal blends is poorer (Figs. 7A and 7B). This is due to lower correlation coefficients and also due to the slopes of both regression curves that are far from 1.00. The results of $\overline{CRI/CSR}$ prediction of Type II cokes calculated as weighted means were also compared with experimentally determined CRI/CSR indexes but this comparison shows the poorest results (Figs. 7C and 7D).

4. CONCLUSION

A combination of the factor (FA) and regression analyses (RA) was used to predict CRI and CSR indexes of Type I cokes (prepared from pure coal samples) and Type II cokes (prepared from coal blends) in a pilot coke oven. Coals and coal blends were characterized by 14 coal characteristics (A^d , V^d , contraction a and dilation b , SI, F_{max} , R_r , Vitr, Lipt, Inert, Cat. I., Alk. I., Alkalis, S^d) and cokes were characterized by CRI and CSR indexes.

FA distributed 16 characteristics of coals and Type I cokes into 4 factors containing 32 correlation coefficients with $R > |0.60|$ while in coal blends and Type II cokes data, 7 factors and 4 correlation coefficients with $R > |0.60|$ were calculated. The CRI and CSR of I and II cokes were predicted by RA based on the selected coal and/or coal blend characteristics in respect to the results of FA.

For the prediction of CRI and CSR of I cokes, the best regression equations were based on the coal characteristics presented in factor F1 (A^d , SI, Cat. I., Alk. I., Alkalis, Vitr, Inert, Lipt), that contained the highest number of coal characteristics with the highest correlation coefficients (e.g. R varied from 0.930 to 0.947, variants 1 and 2). The good prediction (high R between predicted and experimentally calculated CRI/CSR) was even obtained using regression based only on one coal characteristic. For example, the highest correlation coefficients R for CRI and/or CSR were obtained for the relationship with: Lipt (0.802/-0.904), Alk. I. (0.751/-0.694) and Vitr (-0.748/0.659), respectively.

In contrast, the prediction of CRI and CSR of Type II cokes is poor due to very low correlation coefficients R between predicted and experimentally calculated CRI/CSR values. The best regression equations were based on the 14 coal characteristics presented in all 7 factors (variant 1, Table 8). The highest 4 correlation coefficients R for this prediction varied from 0.628 to 0.970. In addition to them, among all coal blend and Type II coke characteristics, other the highest correlation coefficients between CRI/CSR and any of the coal blend characteristic

were: CRI – Lipt (0.309), CRI – S^d (-0.356), CSR – Cat. I. (-0.315) and CSR – Alk. I. (-0.309). Very good CRI/CSR predictions cannot be obtained due to low correlation coefficients.

A combination of the factor (FA) and regression analyses (RA) can be a good tool for CRI/CSR predictions calculated from coal blend characteristics. Anyway, our results showed that the more coal and/or coal blend characteristics are used, the better CRI/CSR predictions for Type I and/or II cokes are found.

However, in case of coal blends and Type II cokes, using numerous characteristics was not fully successful for a very good prediction of CRI/CSR indexes ($R = 0.616$ for CRI, $R = 0.642$ for CSR). In any case, this prediction was still better than that one based on assumption of their CRI/CSR values calculated as weighted means ($R = 0.388$ for CRI, $R = 0.294$ for CSR). This paper showed that prediction of CRI/CSR of cokes (Type II) carbonized from coal blends mixed from coals of the Upper Silesian Coal Basin cannot be successfully calculated neither from various regression equations nor by weighted means of cokes (Type I).

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