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Improving stamped coal cake strength using chemical binders: Implications for resource efficiency in coke-making technology

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ABSTRACT

Stamp-charging technology has gained increasing importance in the coke-making industry, owing to its ability to utilize lower-cost coals with inferior coking properties while maintaining the required coke quality. This contributes to more efficient utilization of coal resources and improved economic performance of the coking process. However, the successful application of this technology depends on the mechanical integrity of the stamped coal cake during handling and charging into coke oven chambers. Insufficient cake strength may result in its disintegration, causing operational disturbances and fugitive emissions of raw coke oven gas to the atmosphere. This study investigates the potential of selected chemical binders to improve the mechanical strength of stamped coal cakes without adversely affecting the coking behaviour of the coal blend and the quality of the produced coke. Laboratory investigations were carried out to evaluate the influence of binder additions on the mechanical strength of stamped coal cakes, selected coking properties of the coal blend, including the Roga index (RI), free swelling index (FSI), maximum fluidity (Fmax), contraction (a), and dilatation (b), as well as the coke reactivity index (CRI) and coke strength after reaction (CSR) of the resulting coke. The maximum binder dosage was limited to 1 wt.% to identify the minimum effective dosage capable of improving stamped coal cake strength while ensuring industrial applicability, minimizing material consumption in accordance with the principles of resource efficiency, and avoiding potential adverse effects of higher binder contents on the coking process and the quality of the produced coke. The results demonstrated that chemical binders at dosages of up to 1 wt.% significantly improved the mechanical strength of stamped coal cakes without adversely affecting the coking properties of the coal blend or the key quality parameters (CRI and CSR) of the produced coke. These findings indicate that appropriately selected binders can enhance the operational reliability of stamp-charging technology while enabling more efficient utilization of lower-quality coking coals, thereby supporting resource efficiency and reducing the environmental impacts of coke production.

Keywords: stamped coke, compaction process, binder, environmental emission control, resource efficiency.

INTRODUCTION

Around 70% of global steel production is based on the integrated BF-BOF route (blast furnace-basic oxygen furnace), in which metallurgical coke serves as the primary reductant and energy source in the production of hot metal from iron ore (World Steel in Figures 2024). Despite advances in alternative technologies, the integrated BF-BOF route will remain the dominant steelmaking method over the next decade or so (Nesbitt et al., 2023). The technological development of the global coke-making industry is currently driven by Asian countries, mainly China, Japan, India, Indonesia and South Korea. It is primarily related to strong economic development (increased demand for steel) and the accompanying progress in the metallurgical industry, which results in the operation of blast furnaces with increasing volumes and increased requirements as to the quality of coke, in particular in relation to its strength parameters (Rejdak et al., 2021). The coke-making industry remains an important component of the European Union's economy, primarily due to its key role in integrated iron and steel production. Although the sector is not developing as dynamically as in Asian countries, significant investments are still being made in the European coke-making industry, focusing on the modernisation and replacement of coke oven batteries, improved energy efficiency, and emission reduction. One example is the modern coke oven battery commissioned in 2025 at the Przyjaźń Coking Plant, with an annual production capacity of approximately 610,000 tonnes of coke, making it one of the most advanced installations of its kind in Europe. In view of the global deficit of coking coals with the prime quality parameters, coking coal has been included on the EU's list of critical raw materials essential for sustainable economic development and security. Therefore, effective management of this scarce raw material is extremely important. Moreover, in recent years, low-carbon smelting technologies have boomed up in blast furnace (BF) ironmaking, such as pulverised coal injection in tuyere, BF top gas recycle, injection into hydrogen-rich gas from tuyere, etc. (Chen et al., 2025). Therefore, the role of coke as a physical support in this process is increasing, which requires extremely high strength parameters. Meeting these stringent requirements is possible using coke produced in stamped-charged coke oven batteries. The use of this technology allows for a very high charge density, which allows the use of smaller amounts of the scarce prime coking coals or even non-coking coals in the blend (Tiwari et al., 2014a). For this reason, stamp-charged coke-making technology is currently the most dynamically developing coke production technology (Rejdak et al., 2021).

A fundamental prerequisite for the effective implementation of stamp-charging coke-making technology is the production of coal cakes with sufficient density and mechanical strength to withstand handling, transportation, and charging into coke oven chambers without structural damage. Adequate mechanical integrity ensures stable operation of the coke oven battery, complete chamber filling, high process productivity, and the production of metallurgical coke meeting the required quality standards. Conversely, insufficient coal cake strength may lead to cracking or disintegration during charging, resulting in production interruptions, incomplete utilisation of chamber capacity, and deterioration of working conditions due to the need for additional manual interventions.

Beyond its operational consequences, coal cake failure also has important environmental implications. Structural damage during charging may increase fugitive emissions of untreated coke oven gas. It may contain hazardous compounds such as methane, hydrogen, carbon monoxide, volatile organic compounds and polycyclic aromatic hydrocarbons (Bigda at al., 2017a, Bigda at al., 2017b). These uncontrolled emissions contribute to atmospheric pollution, increase greenhouse gas emissions, and adversely affect occupational as well as environmental safety. The emissions occurring during stamped coal cake failure are not only a significant environmental concern but, above all, pose a serious risk to personnel directly involved in emergency response and repair operations. Furthermore, incomplete chamber filling and process interruptions reduce the efficiency of coal utilisation, increase the specific consumption of raw materials and energy per unit of coke produced, and consequently increase the environmental footprint of the coke-making process.

Although stamp-charging technology enables the use of lower-cost coking coals with inferior coking properties, thereby improving the utilisation of available coal resources and reducing dependence on premium coking coals, its broader industrial implementation requires maintaining adequate mechanical stability of the stamped coal cake. Despite continuous improvements in stamping equipment and process automation, coal cake damage during charging remains an important operational challenge in industrial practice. Consequently, there is a continuing need for the technological solutions capable of enhancing coal cake integrity without adversely affecting the coking behaviour of the coal blend or the quality of the produced coke.

One of the approaches to improve the mechanical strength of stamped coal cakes is the application of additives capable of enhancing the interparticle bonding forces within the finely crushed coking coal blend. Stronger interparticle interactions increase the structural integrity of the compacted cake, thereby reducing its susceptibility to cracking and disintegration during handling and charging into coke oven chambers. From both technological and environmental perspectives, improving coal cake stability is important because it minimises process disturbances, reduces the risk of fugitive emissions of untreated coke oven gas during charging, and contributes to more efficient utilisation of coal resources.

Although numerous studies have investigated the densification of carbonaceous materials, including coking coals, using chemical additives in briquetting processes (Borowski and Hycnar, 2013; Borowski et al., 2017; Fehse et al., 2017; Nomura, 2019), relatively little information is available regarding the use of chemical binders specifically intended to improve the mechanical strength of stamp-charged coal cakes. Previous investigations conducted by Tata Steel demonstrated that coal tar pitch (Krishnan et al., 2004) and the proprietary additive X7 (Tiwari et al., 2011; Tiwari et al., 2014b) could improve the mechanical behaviour of stamped coal cakes. However, the information on their industrial application remains limited in the published literature. Moreover, chemical additives may influence not only the mechanical properties of the coal cake but also the thermoplastic behaviour of the coal blend and, consequently, the quality of the produced coke (Tiwari et al., 2011; Tiwari et al., 2014b; Nag et al., 2015). Therefore, the selection of suitable binders requires balancing improvements in mechanical strength with the preservation of coking performance and coke quality.

In the present study, commercially available chemical additives representing different functional groups were selected to evaluate their effectiveness under conditions relevant to industrial coke-making practice. Because all of the selected substances exhibit binding properties in their primary applications, it was hypothesised that their addition to the moist coal blend would enhance interparticle bonding and thereby improve the cohesion and mechanical strength of the compacted coal charge. The additives were selected based on their commercial availability, compatibility with existing coke-making technology, effectiveness at low dosages (≤1 wt.%), and technological and environmental feasibility. Particular attention was given to the formulations that could be readily implemented under industrial conditions without requiring substantial modifications to existing production facilities.

The investigated additives comprised acrylic-polymer and styrene-acrylic-based binders, a commercially available dust suppressant based on an inorganic ionic system, and a viscous by-product generated during the coke-making process. The inclusion of the coke-making by-product was intended to evaluate its potential for internal reuse in accordance with circular economy principles, thereby promoting the valorisation of process-derived materials. The polymer-based binders and the dust suppressant were selected because they are manufactured on an industrial scale, readily available on the global market, and suitable for application at low dosages, making them promising candidates for practical implementation. In addition, the investigated polymer binders were supplied as water-based dispersions free of organic solvents, thereby reducing the potential for volatile organic compound (VOC) emissions and improving occupational and environmental safety during handling and application. The application of commercially available additives at low concentrations is consistent with the principles of resource efficiency, as it enables a significant improvement in stamped coal cake strength while minimising the consumption of auxiliary materials, limiting potential impacts on the coking behaviour of the coal blend and the quality of the produced coke, and reducing the environmental burden associated with the coke-making process.

The influence of these additives on the mechanical strength of stamped coal cakes was evaluated using the axial compression method, which is widely applied for assessing the mechanical properties of compacted particulate materials (Borowski, 2012). In parallel, their effects on the coking behaviour of the coal blend were assessed through Gieseler fluidity, Arnu-Audibert dilatometric characteristics, the Roga index (RI), and the free swelling index (FSI). The quality of the produced coke was evaluated using the coke reactivity index (CRI) and coke strength after reaction (CSR), which are internationally recognised as the principal indicators of blast furnace coke quality (Ghosh et al., 2018; North et al., 2019; Qin et al., 2025).

EXPERIMENTS

Materials

The base raw material was a coal coking blend (RCB – reference coal blend) composed of coals supplied by the largest Polish coke producer

JSW KOKS S.A. with a fixed composition: coal A – 15 wt.%, coal B – 35 wt.%, coal C – 10 wt.%, coal D – 20 wt.%, coal E – 20 wt.%. A proximate and ultimate analysis of the RCB and an analysis of the chemical composition of the ash were carried out and the results are presented in Table 1.

Moisture content of reference coal was determined according to the standards: PN-G-04611:2020-06 (total) and PN-G-04560:1998 (analytical), ash content according to PN-80/G-04512+Az1:2002, volatile matter content according to PN-G-04516:1998, sulphur content according to PN-G-04584:2001, carbon content according PN-G-04571:1998, hydrogen and nitrogen content according to PN-G-04571:1998, chlorine content according to PN-G-04534:1999. Phosphorus content was determined using the ICP-OES method according to the internal procedure Q/LCA/55/A:2021. The chemical composition of the ash was determined using the ICP-OES method in accordance with the internal procedure Q/LCA/55/A:2021. Densification and coke-making tests of coal blend were carried out with the addition of five selected chemical additives. These were commercially available additives in the form of aqueous solutions and dispersions, as well as viscous by-product of the coke-making industry, without any modifications. A brief description of the tested additives is provided in Table 2.

Methods

Stamped charge preparation

The coal blend was prepared by thoroughly mixing the coking coals with the selected chemical additive in a laboratory two-shaft Z-type mixer for 10 min to ensure uniform distribution of the additive throughout the entire mass of the blend. The additives were introduced in amounts not exceeding 1 wt.% of the dry coal blend. The dosage of each additive was calculated on a dry coal basis. Water-based additives were dosed directly into the mixer using their commercial formulations, while the total amount of process water was adjusted to obtain a final moisture content of 12 wt.%. This procedure ensured identical moisture conditions for all tested mixtures, regardless of the type of additive applied.

The additive designated as ‘T’, supplied as a highly viscous liquid, was preheated prior to mixing in order to reduce its viscosity and facilitate its uniform dispersion within the coal blend. During mixing, particular attention was paid to achieving homogeneous coating of the coal particles and preventing the formation of local agglomerates of the additive. After mixing, the prepared coal blend was transferred to airtight containers and conditioned for 24 h. This conditioning period was introduced to simulate the residence time of the coal blend in an industrial coal tower, allowing moisture redistribution and stabilisation of the interactions between coal particles and the chemical additive before the stamping process.

The coal blend used in this study had a particle size distribution in which approximately 97 wt.% of the material was smaller than 3.15 mm, corresponding to the particle size commonly used in industrial stamp-charging technology. Following conditioning, the blend was compacted using a laboratory mechanical stamping apparatus. The design and operating principles of the stamping device were described in detail elsewhere (Rejdak et al., 2022).

Table 1. Properties of the reference coal blend (RCB)

Parameter	Value [%]
Moisture (analytical), W_t^a	0.9 ± 0.1
Ash (analytical), A^a	8.9 ± 0.2
Volatile matter (analytical), V^a	24.59 ± 0.17
Total sulphur (analytical), S_t^a	0.61 ± 0.04
Sulfur in coal ash (analytical), S_A^a	0.62 ± 0.06
Combustible sulphur (analytical), S_C^a	0.09 ± 0.05
Total carbon (analytical), C_t^a	80.0 ± 0.6
Total hydrogen (analytical), H_t^a	4.38 ± 0.27
Nitrogen (analytical), N^a	1.41 ± 0.15
Oxygen (analytical - calculated), O_d^a	9.39
Chloride (analytical), Cl^a	0.149 ± 0.030
Phosphorus (analytical), P^a	0.055 ± 0.002
Chemical composition of ash	
Silicon dioxide, SiO_2	43.49 ± 3.04
Aluminum oxide, Al_2O_3	27.10 ± 2.67
Iron oxide, Fe_2O_3	6.91 ± 0.62
Calcium oxide, CaO	3.07 ± 0.17
Magnesium oxide, MgO	1.98 ± 0.17
Sodium oxide, Na_2O	1.54 ± 0.17
Potassium oxide, K_2O	2.70 ± 0.33
Titanium oxide, TiO_2	1.20 ± 0.06
Manganese oxide, Mn_3O_4	0.07 ± 0.01
Phosphorus oxide, P_2O_5	1.43 ± 0.14
Sulphur oxide, SO_3	2.30 ± 0.13
Barium oxide, BaO	0.28 ± 0.02
Strontium oxide, SrO	0.16 ± 0.02

Table 2. Chemical additives used for research

Additive sign.	Type
'T'	By-product of the coke-making industry, viscous liquid.
'A'	Commercially available binder for the paint production based on an acrylic polymer, an aqueous emulsion.
'SA'	Commercially available binder based on styrene-acrylic copolymer, aqueous dispersion.
'SAG'	Commercially available binder based on a mixture of styrene-acrylic copolymer and ethylene glycol, aqueous dispersion.
'DS'	Commercial solution of dust suppressant based on a mixture of in-organic base in ionic equilibrium with acids.

Evaluation of the density of the stamped charge

The density of the stamped coal charge was determined as the quotient of the mass of the charge and its volume. The mass of the stamped charge was approximately 600 g on a dry basis. The density of the coal charge was calculated as an average value for twelve prepared samples of stamped coal cake (six samples for compressive strength and six samples for shear strength test).

Evaluation of the mechanical strength of the stamped charge

The tests for assessing the mechanical strength of the stamped coal charges were carried out with use of universal strength testing machine presented in Figure 1. This stand enables strength tests to be performed at a maximum force of 5 kN. Research included tests of the compressive and shear strength of stamped charges.

Compressive strength test procedure

The stamped coal charge was placed between the pressure plates of the test device presented in Figures 1a and 1b and then subjected to compression at a speed of 2 mm/min, recording the pressure force on-line (Figure 1c). A sample during the measurement of the shear strength presents Figure 1d. The force increased until the stamped cake was destroyed and then decreased. The quotient of the maximum value of the measured force to the surface of the sample subjected to the load corresponds to the mechanical compressive strength, expressed in kPa. The compressive strength of stamped cake was determined for 6 individual charges with each chemical additive, and the given strength value was the average of 6 tests. The accuracy of the mean value of the measured quantity for a given measurement series was determined based on the extended uncertainty (U) of the arithmetic mean.

$$U(\bar{x}) = k \cdot u(\bar{x}) = k \cdot \frac{s}{\sqrt{n}} \tag{1}$$

where: $U(\bar{x})$ – expanded uncertainty, k – expansion factor (k = 2; significance level α = 0.05), $u(\bar{x})$ – standard uncertainty of the mean value, s – standard deviation of a single measurement from a sample, n – number of measurements (6 tests).

Shear strength test procedure

The stamped coal cake was placed in a special form presented in Figure 1a. Half of the stamped charge was immobilised between the mould pressing elements, the other half was subjected to pressure at a speed of 2 mm/min. The pressure force gradually increased until the sample broke into two equal parts. The value of mechanical shear strength for a given sample was calculated as the quotient of the maximum recorded force and the area on which the shear stress acted. The shear strength was determined for 6 individual stamped charge samples with chemical additives, and the given strength value was the average of 6 tests. The accuracy of the mean value of the measured quantity for a given measurement series was determined based on the expanded uncertainty of the arithmetic mean as in the case of compressive strength.

Testing the coke-making properties of coal blend with chemical additives

Coal blends with five chemical additives were subjected to evaluation of their coke-making properties. The determination of coal blend plastic properties was carried out by the Gieseler method based on PN-G-04565:1994 which is consistent with ISO 10329:2009. Arnu-Audibert test which allow determining of dilatometric properties of coal blend was carried out based on the ISO 349:1975 standard. The Roga index (RI) determination was based on the PN-G-04508:2020-05 standard. The determination of the free swelling index (FSI) was performed according to ISO 501: 2012.

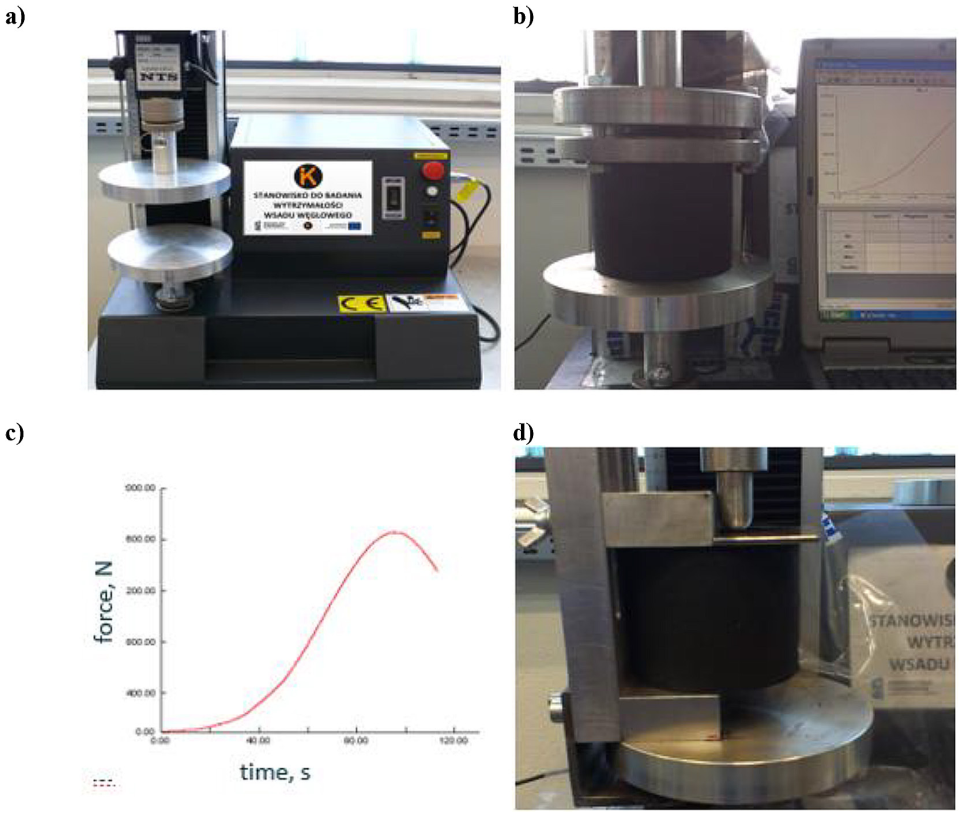

Figure 1. Stand for testing the mechanical strength of the stamped coal charge (a); a sample during the compressive strength measurement (b); an example of a screenshot during the compressive strength test (c); a sample during the measurement of the shear strength (d)

Coking process simulation and coke properties evaluation

Coke production tests of stamped charges were carried out in the Karbotest installation, which simulates the conditions of the coking process in a coking chamber. The coking process continued until the temperature of 950 °C was reached in the charge axis. Karbotest installation and coking test procedure was described in more detail in papers (Rejdak et al., 2020; Ściążko et al., 2020). CRI and CSR parameters of obtained cokes were determined according to ISO: 18894:2006.

RESULTS AND DISCUSSION

The study focused on evaluating the mechanical strength and density of stamped coal cakes containing chemical additives. In addition, the coke-making properties of the coal blends and key quality parameters of cokes produced with use of these additives were determined. The crucial factors determining the proper coke production process in stamp-charged coke oven batteries are the appropriate density and strength of the stamped coal cake. The density is responsible for the higher strength of the coke, the higher throughput of the oven and has an impact on coke quality. Compressive and shear strength enable safe loading of the coal cake into the furnace. Safe loading of coal cake is a necessity not only from a productivity perspective but also to control the heat input to the furnaces, thereby ensuring the safety of the furnaces and the quality of the coke.

The mechanical strength of the coal cake is the resultant of a number of technological factors, such as basic coal parameters (volatile matter content, moisture content, mineral matter content and particle size distribution), homogenisation of the coal blend, as well as proper stamping operation, guaranteeing uniform density in the entire volume of the coal charge (Rejdak 2018; Rejdak et al., 2020). A particularly important condition for the effectiveness of the compaction operation is also ensuring the appropriate moisture content in the blend, which at the same time has a negative impact on the economic and ecological balance of the coking process (the higher energy consumption and higher amount of waste water).

The influence of five additives of various origins with concentrations in the range of 0–1 wt.% on the mechanical properties of the stamped cake i.e. compressive and shear strength, and density have been investigated. The additives tested were a by-product of the coke-making industry marked as ‘T’, acrylic polymer ‘A’, commercially available binders based on styrene-acrylic copolymer: ‘SA’ and ‘SAG’, and dust suppressant ‘DS’ (Table 2).

The basic coke-making properties of the reference coal blends with 1 wt.% of additives were determined, namely: Roga index (RI), FSI, fluidity index (F_{max}) and the contraction and dilatation using the Arnu-Audibert method. Technological parameters of cokes with 1 wt.% of additives were assessed, i.e.: Coke reactivity index (CRI) and coke strength after reaction (CSR).

Compressive and shear strength, density of the stamped coal cake

The introduction of the chemical additive into the coal coking blend was aimed at enhancing the mechanical integrity (stability) of the stamped coal charge, with particular emphasis on improving its compressive strength. Among the mechanical strength indicators, uniaxial compressive strength was selected as the primary metric for assessing charge integrity due to its widespread use and reliability. Shear strength was employed as a supplementary parameter to provide additional insight into the cohesion and stability of the stamped cake. The results of average value compressive strength, shear strength and density of stamped coal cakes with all tested chemical additives are presented in Table 3.

The tests of the mechanical strength and the density of stamped cakes were carried out for different concentrations of the ‘T’ additive (by-product of the coke-making industry), namely: 0.1, 0.3, 0.5, and 1.0 wt.%. The dependence of the compressive and the shear strength on the concentration of the ‘T’ additive in the stamped charge is shown in Figures 2a and 2b.

This additive had a positive effect on the compressive strength, with the maximum increase observed at a content of 1%, amounting to 18.6%. At 0.5 wt.%, a slight deviation was observed, which is most likely attributable to a measurement error and does not significantly affect the overall interpretation of the results. At the same time, for this additive in amount in the range of 0.1–0.5 wt.%, an increase in shear strength of 14.4–15.3% was recorded compared to the coal charge with no additive. At an additive level of 1 wt.%, the positive effect of T was no longer observed.

The dependence of the strength of the stamped cakes on the concentration of ‘A’ additive is presented in Figures 3a and 3b.

Additive ‘A’ is a binder for paint production based on an aqueous emulsion of an acrylic polymer. This additive significantly improved the mechanical strength of stamped coal cake - both compressive and shear. The compressive strength increased by 1.0–16.4% in the tested range (0.025–1.0 wt.%). The highest value of comprehensive strength was recorded for the additive concentration of 0.3 wt.% – increase by 16.4% compared to the stamped coal cakes produced with use of pure reference coal blend. The shear strength increased by 32.2% for 0.3 wt.% additive addition. The minimum content of ‘A’ additive improving the strength of the stamped coal cake was 0.025 wt.%.

The effect of the ‘SA’ additive (binder, aqueous dispersion of styrene-acrylic copolymer) on the strength and density of the stamped cakes was tested for concentrations of 0.025, 0.05, 0.1, 0.3, 0.5, and 1.0 wt.%. The results are presented in Figures 4a and 4b.

The ‘SA’ additive showed high effectiveness even at low contents in terms of testing the compressive strength of the stamped coal charge. A significant increase in compressive strength was observed by 7.8% for 0.05 wt.% of the substance, up to a maximum of 16.7% for 0.3 wt.% of the additive content. However, its effect of ‘SA’ addition on the shear strength was smaller. The maximum increase was achieved for 0.05 wt.% additive concentration, which was 11.0%.

Changes in the compressive and shear strength of the stamped charge depending on the concentration of the ‘SAG’ additive (binder, aqueous dispersion of styrene-acrylic co-polymer with ethylene glycol) are shown in Figures 5a and 5b.

‘SAG’ additive showed effectiveness at low concentrations in the range of 0.025–0.1 wt.%. However, at a higher concentration (0.3 wt.%), it had a neutral effect on the mechanical properties of the stamped cake and even tended to deteriorate the strength parameters. The compressive strength increased by 6.4–9.4% (in the range of 0.025–0.1 wt.% of the addition), while the shear strength increased by 8.4% (for 0.025 wt.% of the addition) and also by 19.5% (for 0.1 wt.% addition). Figure 6 presents the dependence of the compressive

Table 3. Summary of the density, compressive and shear strength results of stamped coal charges for selected additives depending on their quantity

Additive content [wt.%]	Density [kg/m³]	Compressive strength [kPa]	Change in compressive strength [%]	Shear strength [kPa]	Change in shear strength [%]
		RCB			
0	1000 ± 1	154.0 ± 5.4	-	11.8 ± 1.2	-
		RCB + 'T'			
0.100	999 ± 1	156.0 ± 4.2	1.3	13.6 ± 0.9	15.3
0.300	1006 ± 1	167.7 ± 3.6	8.9	13.5 ± 0.7	14.4
0.500	994 ± 2	160.2 ± 5.4	4.0	13.5 ± 0.5	14.4
1.000	1008 ± 1	182.6 ± 7.4	18.6	11.4 ± 0.4	-3.4
		RCB + 'A'			
0.025	995 ± 1	155.5 ± 4.9	1.0	13.8 ± 0.7	16.9
0.050	999 ± 1	166.0 ± 5.2	7.8	13.8 ± 1.1	16.9
0.100	997 ± 2	173.7 ± 5.4	12.8	12.8 ± 0.8	8.5
0.300	996 ± 3	179.3 ± 4.0	16.4	15.6 ± 0.6	32.2
0.500	1000 ± 1	174.6 ± 2.0	13.4	14.8 ± 0.5	25.4
1.000	995 ± 2	172.1 ± 5.8	11.8	15.2 ± 0.6	28.8
		RCB + 'SA'			
0.025	1003 ± 1	153.8 ± 5.1	-0.1	12.3 ± 0.6	4.2
0.050	1001 ± 1	166.0 ± 6.3	7.8	13.1 ± 0.7	11.0
0.100	1004 ± 4	175.2 ± 5.3	13.8	12.6 ± 1.2	6.8
0.300	1000 ± 4	179.7 ± 2.2	16.7	11.1 ± 0.5	-5.9
0.500	1004 ± 4	169.5 ± 4.0	10.1	12.4 ± 1.0	5.1
1.000	1000 ± 3	169.1 ± 2.0	9.8	10.8 ± 0.7	-8.5
		RCB + 'SAG'			
0.025	1002 ± 1	166.4 ± 5.1	8.1	12.8 ± 0.8	8.5
0.050	998 ± 4	163.9 ± 7.6	6.4	11.5 ± 0.9	-2.5
0.100	999 ± 1	168.5 ± 5.4	9.4	14.1 ± 1.5	19.5
0.300	995 ± 4	154.9 ± 4.2	0.6	10.9 ± 0.8	-7.6
		RCB + 'DS'			
0.025	997 ± 2	155.4 ± 4.2	0.9	13.8 ± 0.4	16.9
0.050	1002 ± 1	157.7 ± 7.4	2.4	11.8 ± 1.4	0.0
0.100	1001 ± 1	161.7 ± 3.2	5.0	13.3 ± 0.8	12.7
0.300	1006 ± 1	158.1 ± 3.2	2.7	13.0 ± 1.0	10.2
0.500	1001 ± 1	149.0 ± 3.4	-3.2	11.9 ± 1.2	0.8
1.000	1008 ± 2	161.9 ± 6.4	5.1	10.3 ± 1.2	-12.7

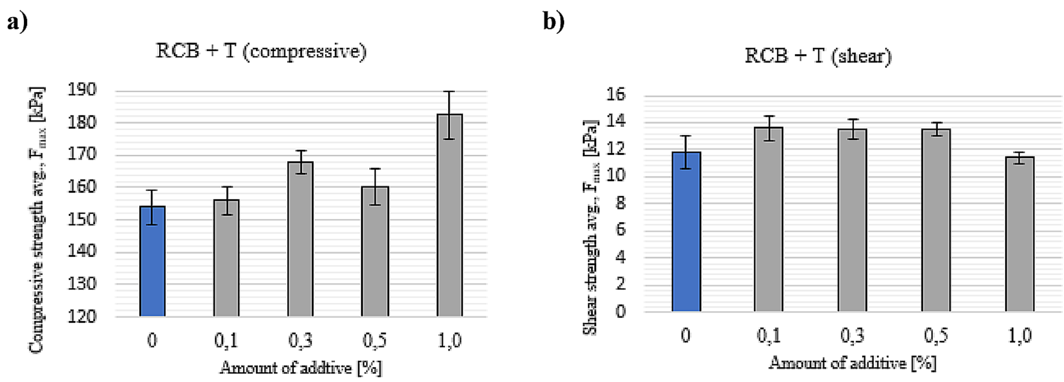

Figure 2. Compressive (a) and shear strength (b) of the stamped coal cake depending on the amount of 'T' additive

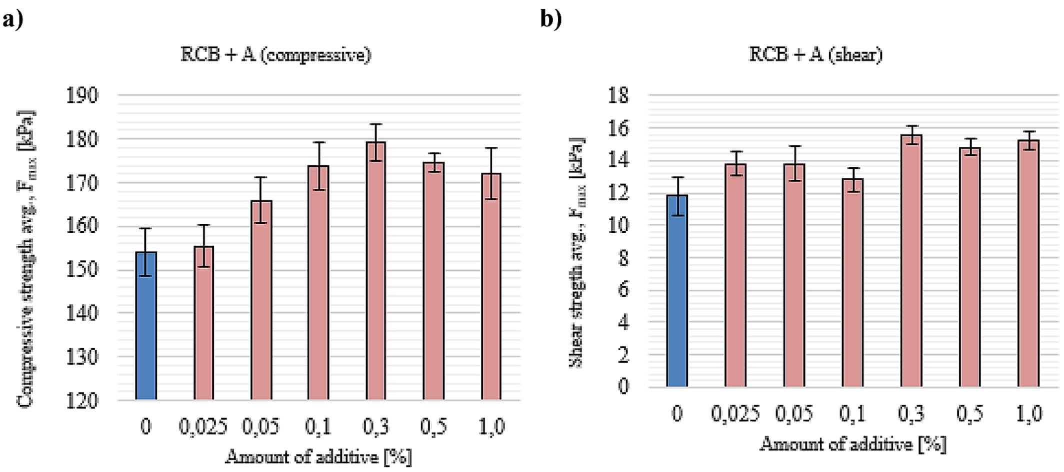

Figure 3. Compressive (a) and shear strength (b) of the stamped coal cake depending on the amount of 'A' additive

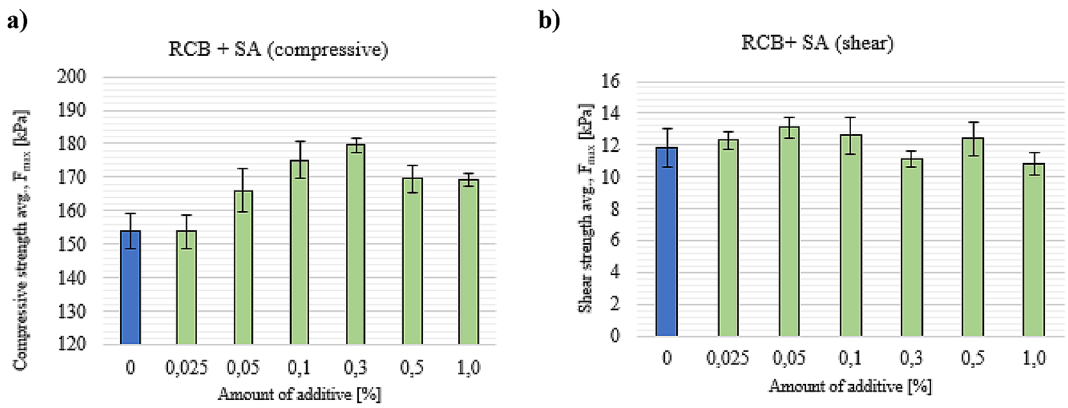

Figure 4. Compressive (a) and shear strength (b) of the stamped coal cake depending on the amount of 'SA' additive

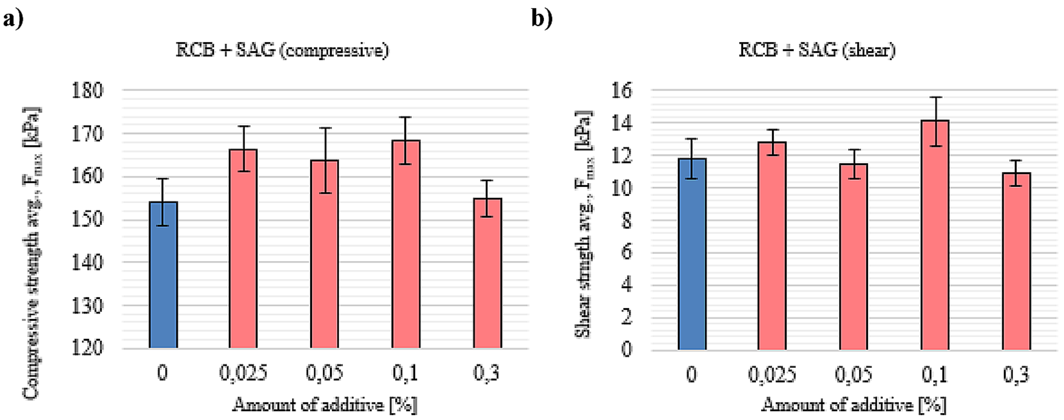

Figure 5. Compressive (a) and shear strength (b) of the stamped coal cake depending on the amount of 'SAG' additive

(Figure 6a) and shear strength (Figure 6b) of the stamped charge on the concentration of the 'DS' additive (dust suppressant solution).

This additive did not significantly change the compressive strength. The compressive strength values obtained for individual amounts of additive did not differ significantly from the reference value and were within the measurement uncertainty range. Although a certain increase in compressive strength was observed (particularly at an additive level of 0.1%), the obtained values fall within the range of the expanded measurement uncertainty.

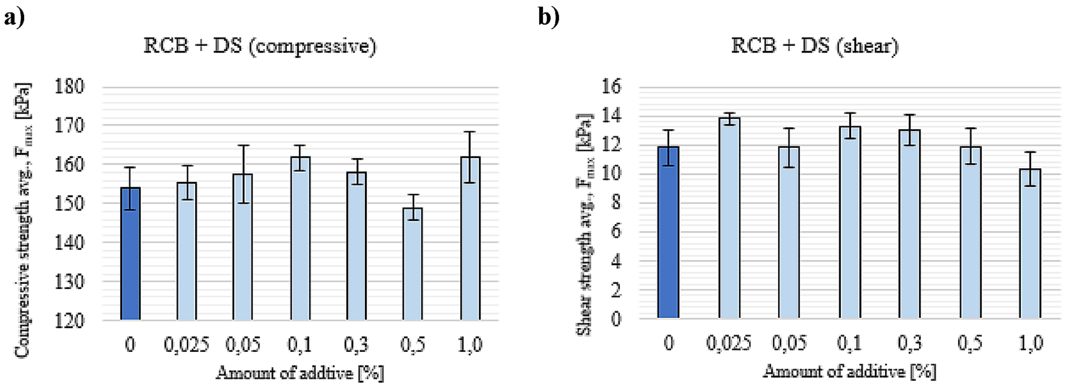

Figure 6. Compressive (a) and shear strength (b) of the stamped coal cake depending on the amount of 'DS' additive

A similar situation was noted for shear strength: at lower concentrations up to 0.1%, a slight increase was observed (with the exception of the deviation at 0.05%), but the changes are relatively small and should be interpreted with caution.

It was observed that the additives introduced into the coal blend for the coking process, while enhancing the cohesion of the coal charge, did not result in significant change in the density of the stamped charges. The changes in density observed as a result of the introduction of chemical additives are relatively small (0.1–0.8%) and fall within the range of the measurement uncertainty (Table 3).

The influence of the additives on the cohesion of the compacted coal charge most likely results from their direct modification of the interaction forces between wetted coal particles. The cohesion of a compacted coal charge is governed by several factors, including particle-size distribution and the degree of comminution, which determine the available interparticle contact area; bulk density, which controls particle packing and therefore the number of interparticle contacts as well as the cumulative magnitude of the interaction forces; particle shape, which affects mechanical interlocking; and the surface properties of the particles, including the forces associated with interparticle moisture, such as capillary forces and liquid bridges. The addition of chemical agents modifies both the interparticle interactions and the properties of the liquid phase present in the mixture, which, in the reference blend, consists of water. In particular, the additives may alter the surface tension and contact angle, thereby affecting both the strength of existing water bridges and the formation of new polymer-solution liquid bridges (Simons at al., 2024). The additives may also change the viscosity of the liquid phase between the coal particles, which in turn affects the work of adhesion and determines the degree of cohesion of the coal agglomerate (Ennis at al., 1990).

Owing to their different physicochemical properties, the individual additives affect these parameters in different ways, and their overall influence therefore represents the combined result of several competing mechanisms. The differences observed between the compressive- and shear-strength measurements may likewise arise from the different failure mechanisms involved in the two tests. During uniaxial compression of granular materials, considerably more complex interactions occur between the particles, including the simultaneous development of compressive, tensile and shear stresses, accompanied by mechanical interlocking that is strongly influenced by particle shape (Kun at al., 2013). In a shear test, by contrast, particle sliding along a defined failure plane plays a more prominent role, and the introduced additives may facilitate this process by reducing interparticle friction. Consequently, the result of the uniaxial compression test reflects the combined effects of compression, shear, tensile stresses, friction, particle interlocking and the failure of interparticle bridges, rather than merely the intrinsic resistance of the material to compression. As indicated above, compressive strength therefore constitutes the principal parameter used to assess the mechanical integrity of the produced compacted coal charges. Moreover, the shear strength test demonstrated higher sensitivity and susceptibility to inconsistencies, likely due to the increased vulnerability of the compacted structure to damage or disruption during testing. This increased sensitivity is presumed to contribute to the greater measurement error and result scatter observed in the shear strength data.

The decrease in strength observed at higher additive dosages may result from excessive surface coverage of the particles, which can enhance lubrication and plasticization of the contact zones, thereby reducing the internal friction of the material.

As mentioned earlier, although the problem of the destruction of the stamped charge during the charging of coke oven chambers is a real issue, there is not much information in the literature on this subject. This topic, however, has been addressed in only a few articles. In one of them, researchers from India investigated the effect of coal tar pitch on the strength of the stamped charge and the quality of the coke produced (Krishnan et al., 2004). When 0.5 wt.% coal tar pitch was added to a coal blend with 7 wt.% moisture content, a significant increase in coal cake strength (both compressive and shear) – approximately 10% – was observed, relative to a reference blend with 9 wt.% moisture and no binder. However, at concentrations above ~2 wt.%, a decline in mechanical strength was observed. The incorporation of coal tar pitch also contributed to a reduction in energy consumption during the stamping and coking process stages, while simultaneously improving the rheological characteristics of the coal blend. This facilitated the use of lower-grade coals in coke production. Researchers at Tata Steel (India) have developed also a novel binder, designated 'X7', which has been shown to significantly enhance the structural integrity of stamped coal cakes and increase throughput in coking ovens (Tiwari et al., 2011; Tiwari et al., 2014b). The application of 'X7' not only improved the quality parameters of the produced coke but also contributed to a reduction in specific energy consumption associated with stamp-charged coke production. Laboratory-scale experiments demonstrated that the addition of 'X7' to coal blends, at concentrations ranging from 0.10 to 0.50 wt.%, led to an increase in coal cake mechanical strength by approximately 3.0–5.0%.

However, in authors' case, experimental investigations showed that the incorporation of chemical additives into the coal blend had no statistically significant effect on the density of the resulting stamped coal charges.

In summary, it should be concluded that introduction of a binder additive to the coal coking blend modified the surface properties of coal particles and strengthened intermolecular interactions. This modification may have some influence on coal particle rearrangement during the stamping process, thereby improving the mechanical integrity of the stamped charge. In this context, beyond the known interdependencies between bulk density, cohesion, blend characteristics, and stamping parameters, an additional influential factor is introduced – namely, the type and concentration of the additive employed.

Coke-making properties of the reference coal blends with chemical additives

The additive may influence not only the densification behaviour and mechanical performance of the stamped coal charge, but also the coke-making properties of the coking blend and the quality of the final coke produced. Therefore, the primary technological challenge lies in optimising the mechanical strength of the stamped coal charge without compromising and ideally enhancing of coke-making properties and quality characteristics of the produced metallurgical coke.

The investigations into the coke-making properties of blends enriched with chemical additives were undertaken to assess their impact on the quality of the produced coke. The primary objective was to verify whether the presence of such substances induces any adverse effects. As is known from the available literature data, addition of various additives of different origin to coal blends used for coke production may have varying effects on the coking properties of the blend and, consequently, on the quality of the coke produced (Kieush et al., 2022; Koveria et al., 2020; Koskela et al., 2019; Nomura et al., 2003; Diez et al., 2005; Yustanti et al., 2021).

Even if their application were to enhance the mechanical strength of the stamped coal charge but simultaneously deteriorated the quality parameters of the resulting coke, the use of these additives would have to be considered unjustified. Coke-making properties characterise the behaviour of the coal charge blend during the pyrolysis process, in particular when coal passes through the plastic state. Based on their changes, it is possible to determine the potential impact of the introduced chemical additive on the quality of the main final product of the coking process – coke.

The subject of the research was the assessment of the following parameters: the RI, the FSI, the F_{max} and contraction (a) and dilatation (b) index using the Arnu-Audibert method. One of the key parameters in metallurgical coke production is the "caking-ability" of the coal blend, often characterised by its sintering capacity, which reflects the ability of coal to form coherent coke structures during carbonisation. This property is quantitatively assessed using the RI. Higher RI values indicate a greater tendency to form larger and mechanically stronger coke sinters in the devolatilisation zone of the coke oven. The FSI is a measure of the ability of coal to swell and cake when heated. It is a test that indicates the caking capacity of coal, which is important for determining its suitability for coke-making processes. More information on the importance of these parameters for the coking process can be found in the publication (Rejdak et al., 2022).

In both the investigations of the effect of additives on coking properties and the coking tests, a 1% addition of the substances was applied. It was assumed that if an additive at this concentration does not exert an adverse effect on the considered properties, then lower dosages are likewise unlikely to cause significant alterations. The results of coke-making properties of reference coal blend with chemical additives are presented in Figures 7–11, the addition of 1% of the substance did not exert a significant effect on the coking properties of the reference coal blend.

The observed variations in the Roga index and the free swelling index fall within the limits of the expanded uncertainty of these determinations. Some variations were observed in the maximum fluidity value determined by the Gieseler method (F_{max}). For additives ‘A’ and ‘SA’, a slight decrease in F_{max} was recorded, which is unlikely to be of technological significance. In contrast, additives ‘T’, ‘SAG’, and ‘DS’ exhibited a beneficial effect on the plastic properties of the reference coal blend, which can be considered a favourable outcome. The Fmax index increased by 38%, 31% and 16%, respectively, compared to the coal without the additives. The presence of thermoplastic components contributed to the enhanced softening and flow characteristics of the blend. This enhanced flow behaviour improves the uniformity and homogeneity of the plastic phase, which is critical for optimal coke formation. Improved plasticity and fluidity during the coking process contribute positively to the sintering and consolidation of coal particles, enabling the formation of a more coherent and mechanically robust coke structure. Consequently, the elevated Fmax values resulting from the addition

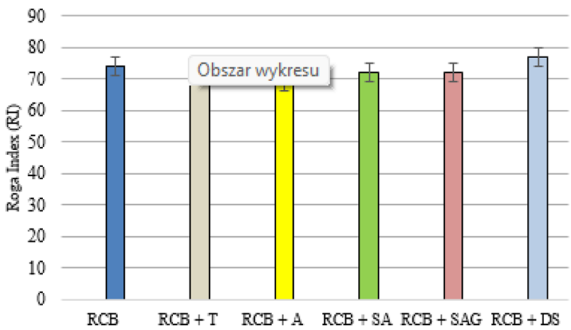

Figure 7. Influence of the chemical additive on the RI value

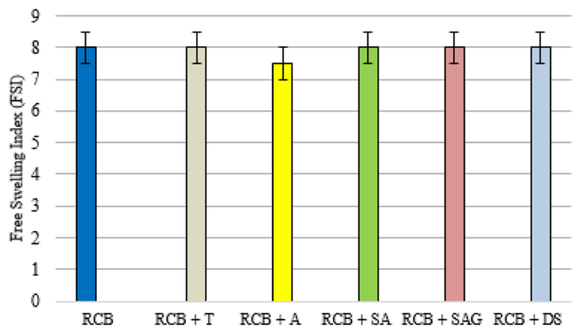

Figure 8. Influence of the chemical additive on the free swelling index (FSI) value

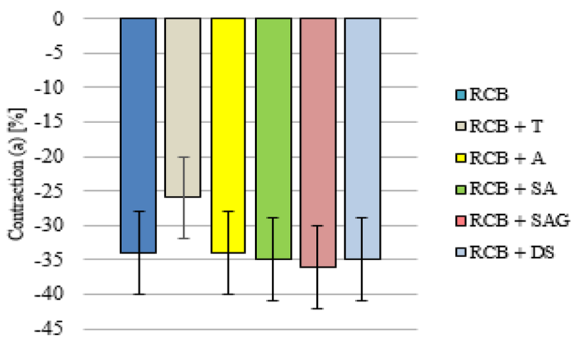

Figure 9. Influence of the chemical additive on the contraction parameter (a)

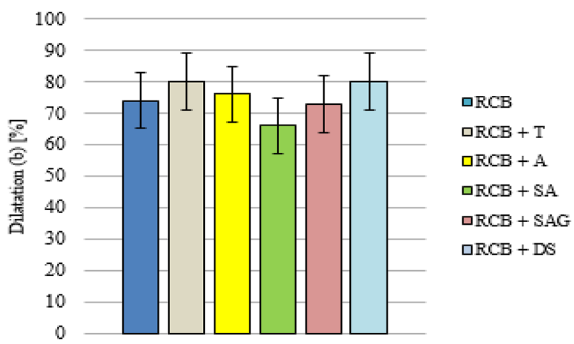

Figure 10. Influence of the chemical additive on the dilatation parameter (b)

of these binders may lead to improved quality parameters of the final metallurgical coke, such as increased mechanical strength and stability, which are essential for blast furnace performance.

The CRI and CSR parameters of the coke obtained from the reference coal blends with chemical additives. The results of the assessed properties of cokes with 1 wt.% addition of the chemical additives, i.e. CRI and CSR are presented in Figures 12 and 13.

Given that chemical additives may influence not only the mechanical strength of stamped coal cakes but also the coking behaviour of the coal blend and the quality of the resulting coke, their effect on the key technological properties of coke was also evaluated. The assessment focused on the CRI and CSR, which are internationally recognised indicators of blast furnace coke quality. CRI characterises the reactivity of coke toward carbon dioxide at elevated temperatures, whereas CSR reflects its mechanical strength after gasification and, consequently, its ability to withstand the severe thermo-mechanical conditions prevailing in the blast furnace.

The coking tests were performed using an additive concentration of 1 wt.%, which was selected as a common reference level for all investigated substances. This concentration represented the maximum dosage applied in the study and therefore constituted a conservative ("worst-case") scenario for assessing any potential influence of the additives on the carbonisation process and the quality of the resulting coke. In contrast, the mechanical strength of the stamped coal cakes was evaluated over a broader range of additive dosages to identify the minimum effective concentration for each additive. Consequently, demonstrating the absence of adverse effects at 1 wt.% provides confidence that the lower concentrations required to improve coal cake strength are likewise unlikely to impair the technological properties of the produced coke.

The results demonstrated that the investigated additives did not produce statistically significant changes in either CRI or CSR. The CRI values of all the tested cokes fell within a relatively narrow range of 31.7–32.3, while the CSR values ranged from 53.6 to 55.6. The measured values remained within the range of expanded measurement uncertainty relative to the reference blend (Table 8; RCB), indicating that the additives did not adversely affect the reactivity, post-reaction mechanical strength, or overall high-temperature performance of the coke. This finding is particularly important from the perspective of blast furnace operation, as maintaining stable CRI and CSR values is essential for ensuring adequate burden permeability, preserving the mechanical stability of the coke column, and maintaining efficient reducing conditions throughout the furnace.

Overall, the results indicate that appropriately selected chemical binders can significantly improve the cohesion and mechanical strength of stamped coal cakes without compromising the technological quality of the resulting coke. This confirms that the strengthening effect is achieved without substantially altering the carbonisation process or the microstructure responsible for the metallurgical performance of the coke.

Nevertheless, laboratory investigations represent only the first stage in evaluating the industrial applicability of the proposed approach. Before implementation in commercial coke plants, long-term industrial-scale trials are required to

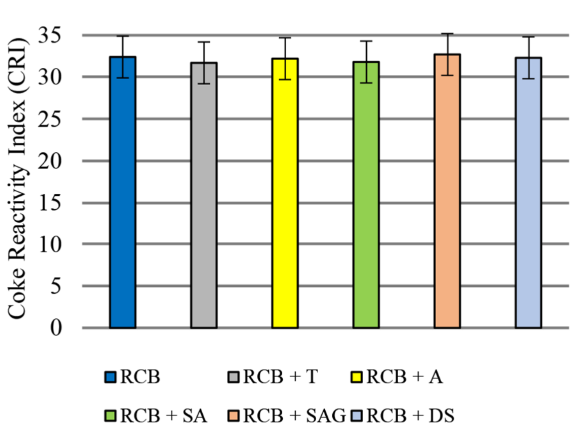

Figure 12. Influence of the chemical additive on the CRI of cokes

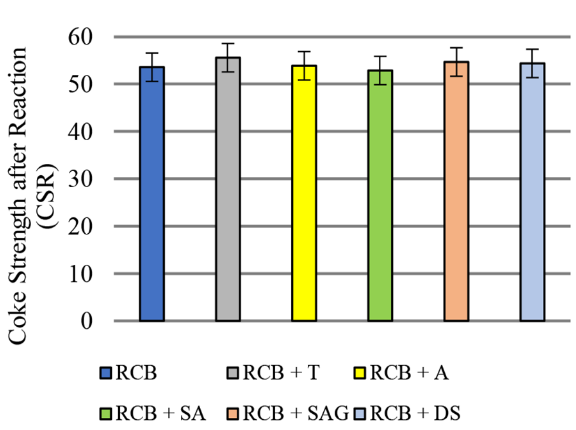

Figure 13. Influence of the chemical additive on the CSR of cokes

verify the performance of the selected additives under real operating conditions. Such investigations should assess not only the durability of the strengthening effect but also the influence of the additives on each stage of the technological process, including dosing, homogenisation, transport and storage of the coal blend, operation of the coal tower, stamping, charging, carbonisation, and the performance of coke oven by-product recovery systems.

The results of this study indicate that improving the mechanical integrity of stamped coal cakes may provide benefits extending beyond the technological performance of the coke-making process. Increased coal cake strength reduces the risk of structural failure during handling and charging, thereby limiting process disturbances, material losses, and fugitive emissions associated with coke production. In particular, preventing coal cake disintegration may reduce the release of untreated coke oven gas as well as the generation of coal dust, contributing to improved air quality, reduced occupational exposure, and lower diffuse emissions from coke plants.

Enhanced mechanical stability also promotes more efficient utilisation of coal resources by enabling more complete chamber filling, reducing coal losses caused by spillage and dust entrainment, and improving process continuity. This is particularly important for stamp-charging technology, which enables the use of lower-quality coking coals while maintaining the required coke quality, thereby reducing dependence on scarce premium coking coals.

The environmental performance of the proposed approach is further supported by the selection of commercially available water-based binders and industrial by-products. The investigated polymer binders were supplied as aqueous dispersions free of organic solvents, eliminating additional volatile organic compound (VOC) emissions during preparation of the coal blend. Furthermore, the potential reuse of coke-making by-products as functional binders is consistent with the circular economy principles by promoting the valorisation of internally generated process streams and reducing the consumption of virgin auxiliary materials.

An additional opportunity offered by chemical binders is the potential reduction of coal blend moisture while maintaining adequate mechanical strength of the stamped coal cake. Lower moisture content would reduce the amount of water introduced into the coking process, decrease wastewater generation, lower the energy required for water evaporation during carbonisation, and consequently reduce indirect CO_2 emissions associated with heating the coke oven battery. Although these environmental benefits should be confirmed under full-scale industrial conditions.

CONCLUSIONS

Based on the laboratory investigations, the following conclusions can be drawn:

1. The addition of the investigated substances had no significant effect on the bulk density of the stamped coal cakes. The observed variations in bulk density were relatively small and remained within the range of the expanded measurement uncertainty, indicating that the improvements in mechanical strength resulted primarily from enhanced interparticle bonding rather than changes in the degree of compaction.
2. Several of the investigated additives significantly improved the mechanical strength of the stamped coal cakes. The highest increases in compressive strength were obtained for additives T (18.6%), SA (16.7%), and A (16.4%). Particularly noteworthy is that additives A and SA achieved comparable strengthening effects at a dosage of only 0.3 wt.%, whereas additive T required 1.0 wt.% to obtain similar performance. This indicates that low-dose polymer binders may represent an efficient solution for improving coal cake stability while minimising the consumption of auxiliary materials.
3. The investigated additives did not significantly affect the coking behaviour of the reference coal blend. The values of the Roga Index, Free Swelling Index, Arnu-Audibert dilatation parameters, and maximum contraction remained within the normal range of experimental variability. A moderate increase in maximum Gieseler fluidity (F_{max}) was observed for additives T, SAG, and DS, suggesting that these substances may slightly modify the thermoplastic behaviour of the coal blend without adversely affecting the coking process.
4. No significant changes were observed in the quality of the produced coke. The values of the CRI and CSR remained comparable with those of the reference coke, confirming the neutral effect of using additives for amounts <1%. This finding

is particularly important from the perspective of blast furnace operation, as maintaining stable CRI and CSR values should contribute to stable and efficient process performance.

5. From a technological perspective, the obtained results indicate that selected chemical binders may improve the operational reliability of stamp-charging technology. Increasing the mechanical strength of the stamped coal cake can reduce the risk of cracking during handling and charging, thereby limiting production disturbances, incomplete chamber filling, and losses of coal associated with cake disintegration.
6. The investigated approach may also provide environmental benefits. Improved coal cake integrity has the potential to reduce fugitive emissions of coal dust and raw coke oven gas during charging operations. Moreover, the use of water-based binders and selected industrial by-products is consistent with the principles of resource efficiency and circular economy. The possibility of achieving the desired strengthening effect using very low additive dosages (0.3–1.0 wt.%) further supports the environmental and economic feasibility of the proposed solution.

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