

Article

Application of Spent Coffee Grounds (SCGs) as a Fuel and Alternative Reducer of Slags from the Copper Industry

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Abstract: This article presents the results of a study on metallurgical slag reduction using biomass such as Spent Coffee Grounds (SCGs). The proposed solution is a new aspect of searching for alternatives to standard reducers used in pyrometallurgical processes of metal production. Its gasification yields significant amounts of hydrocarbons, which are excellent reducing agents in such processes. The research results of copper slag reduction with the use of SCG biomass indicate this process is characterised by lower carbon dioxide emissions compared with the process using solid fuels such as coke and coke breeze. The addition of SCG as the reducer ensures the decrease in copper content in the slag to 0.32 wt.%, which corresponds to the increase of so-called relative decopperisation degree even up to 96.9%. As the decopperisation degree of slag increases, significantly more intense reduction in lead oxides during the reduction process is observed. The smallest lead content in waste slag of 0.91 wt.% was obtained for the slag reduction process with 7.56 wt.% of SCG as the reducer and the process duration of 1.5 h.

Keywords: reduction; spent coffee grounds; metallurgical slag



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1. Introduction

In recent years, we have experienced a markedly growing interest in new solutions concerning technologies of metal production using both secondary and waste metalliferous raw materials. The main reason is depletion of primary raw materials and increasing costs of mining operations associated with their extraction. Slags are major waste materials resulting from metal production technologies based on pyrometallurgical processes. Their metal contents significantly vary. In the case of slags from the copper industry, copper contents range from 0.5 wt.% Cu up to 16 wt.% Cu. Such considerable amounts of copper in slags compared with ores have made them a very important raw material for copper recovery. In high-temperature copper slag processing operations, the basic technological additive is coke. It functions both as the fuel and the substrate in the Boudouard reaction which yields a gaseous reducer, i.e., carbon monoxide (CO). Due to a meaningful drop in coke production observed in the EU countries over the recent years, it is necessary to search for alternative raw materials as substitutes for coke. This activity includes attempts to utilise biomass in technological operations. Application of biomass in processes aimed at energy production requires the use of resources of plant or tree origin or wastes from food production [1,2]. The latter category includes, e.g., the nut blanching waste, sunflower husks, fruit seeds/stones, nut shells, or spent coffee grounds (SCGs). The literature contains data on the use of alternative materials in metallurgical slag reduction processes [3–8]. However, the literature does not refer to the application of solid biomass from food production. Moreover, there are no papers associated with the SCG use in processes of metal production. This kind of

biomass was studied for its application in biofuel production, extraction of organic acids, and activated carbon production [9–26]. In addition, it can be used as a source of sugars or a sorbent for pollutant removal from sewage [27–45]. To date, the methods of SCG utilisation have not ensured the full management of this waste, which confirms the need for further studies to develop new technological solutions for the SCG use in other industries.

This paper presents results of the research on copper slag reduction using the SCG additive as a reducer.

The chemical composition of coffee is very complex. Both before and after the roasting process, coffee contains (among others) folic acid and many vitamins from the E and B groups. Minerals only constitute approx. 4% of the bean composition. Coffee primarily contains magnesium, phosphorus, calcium, and potassium. In addition, there are smaller amounts of iron, sodium, nickel, zinc, copper, and cobalt. Before the roasting process, raw coffee contains large amounts of proteins, carbohydrates, and sugars. The content of the last component is approx. 40 wt.% on average. During preparation of coffee drinks, sugar compounds remain as a solid matter, i.e., waste. Following thermal processing, coffee beans may also contain many organic acids. The available literature data on the SCG chemical composition are presented in Table 1.

Table 1. Elemental and biochemical analysis of SCG [46,47].

Elemental analysis	Element, wt. %			
	Carbon	Oxygen	Hydrogen	Nitrogen
	45–59.8	32–47	6–7.57	1.18–4
Biochemical analysis	Chemical substance, wt. %			
	Cellulose	Hemicellulose	Lignin	Protein
	8.6–15.3	31.7–41.7	22.20–33.60	13.00–17.54

Regarding technologies of non-ferrous metal production, copper pyrometallurgical practice is a particularly important issue. It should be noted that natural raw materials, such as ores, contain approx. 1.5 wt.% Cu while processing operations involve enriched concentrates with 25% to 30% of copper. One of waste products is slag which may contain 0.7 wt.% up to 16 wt.% Cu depending on its generation stage. As mentioned before, the contents of copper in slags resulting from various processes greatly vary. For instance, copper contents in slags from one-stage processes range from 11 wt.% Cu to 16 wt.% Cu and from 5.5 wt.% Cu to 8 wt.% Cu in processes of copper matte converting. It should be emphasised here that the amount of slag in a particular process mainly depends on the copper content in the concentrate being processed. In the case of rich concentrate smelting, significantly less slag is generated compared with so-called poor concentrates due to considerable amounts of iron and waste rock. Processes of copper slag reduction are not only aimed at recovery of metals but also at production of secondary waste slag which can be safely recycled or stored in accordance with applicable laws and regulations.

While analysing the process of copper recovery from slags, we should remember that copper in the slag being an ionic liquid appears in the form of Cu^+ cations [48] (which bond to silicate anions) or in the form of Cu_2O particles. Reduction in copper contained in the slag using carbon reducers (coke, coke breeze, anthracite, etc.) may proceed according to the following reactions:



When the analysed reduction process is accompanied by formation of hydrocarbons, they may participate in the reduction in copper oxides. The Gibbs free energy (enthalpy) values for the Cu_2O reduction reactions with such reducers as carbon, methane, and ethane

within 1200 °C to 1473 °C are presented in Table 2. The values were estimated using the thermodynamic data from the HSC database [49]. Based on the results presented in Table 2, it may be concluded that these are probable courses of all discussed reduction reactions from the thermodynamic perspective.

Table 2. The Gibbs free energy changes for selected Cu₂O reduction reactions.

Reaction	Temperature, °C				
	1200	1250	1300	1350	1400
	ΔG , kJ/mol				
$\text{Cu}_2\text{O} + \text{CO} = 2\text{Cu} + \text{CO}_2$	−96.72	−94.74	−92.73	−90.70	−88.65
$\text{Cu}_2\text{O} + \text{C} = 2\text{Cu} + \text{CO}$	−183.38	−189.94	−196.46	−202.94	−209.38
$2\text{Cu}_2\text{O} + \text{C} = 4\text{Cu} + \text{CO}_2$	−280.09	−284.68	−289.19	−293.65	−298.04
$4\text{Cu}_2\text{O} + \text{CH}_4 = 8\text{Cu} + \text{CO}_2 + 2\text{H}_2\text{O}$	−567.13	−576.04	−584.80	−593.43	−601.92
$7\text{Cu}_2\text{O} + \text{C}_2\text{H}_6 = 14\text{Cu} + 2\text{CO}_2 + 3\text{H}_2\text{O}$	−1096.07	−1114.36	−1132.41	−1150.23	−1167.82

Assuming that each of the considered reactions takes place in a given direction when the following condition is achieved:

$$\Delta G < 0 \quad (4)$$

Therefore, analysing the data contained in Table 2, it can be concluded that from the thermodynamic point of view all the discussed reduction reactions are possible.

It should be noted, however, that a metal alloy which forms during copper slag reduction very commonly appears in the form of spheroid particles suspended in the slag. When alloy droplets are very small (a few micrometres), they can float on the surface of liquid slag [50]. With the copper content of 0.3 to 0.7 wt.% Cu in the secondary slag, it is usually assumed that about a half amount of this metal is present in the form of oxides while the other appears as suspended metal droplets. The level of copper loss in the secondary slag depends on its temperature and physicochemical properties, mainly its viscosity and surface tension. From the technological viewpoint, slag decopperisation should be carried out in conditions which ensure the most rapid separation of the liquid metal phase from the slag phase. The process is far more rapid when the liquid slag is stirred [51,52]. This is possible with the CaCO₃ additive which decomposes and releases CO₂, ensuring the movement of liquid slag. Considering the above, SCG proposed as a reducer for the process of slag decopperisation is a beneficial solution influencing its efficiency because this material, when exposed to temperature, releases hydrocarbons [53] which intensify the slag stirring process and participate in processes of reduction in metal oxides contained in the slag. The proposed solution is a new aspect of searching for alternatives to standard reducers used in pyrometallurgical processes of metal production.

The main purpose of undertaking research in this area was an unconventional approach to the process of metal recovery from waste oxide materials generated in the pyrometallurgical process. This approach consisted of replacing natural carbon raw materials such as coke or anthracite with plant-derived materials. It is particularly interesting in the field of non-ferrous metallurgy, as the literature practically lacks a comprehensive description in terms of the applicability and effectiveness in reduction processes.

Increasing emphasis on greenhouse gas emissions as well as the use of various types of waste in other areas of the economy has resulted in an increased search for raw materials that are conducive to environmentally friendly use. This type of raw materials from human social and living sources can be a natural resource used for production in the metallurgical industry. However, the use in high-temperature processes entails high requirements of both physical form and chemical composition. This entails the need for continuous analysis and determination of the possibilities of use depending on the source of origin of this type of waste and even taking into account the season in which they become available. All these

factors make it necessary to enrich databases characterizing biomaterials so that in the event of exhaustion or limitation of one, others can be used. The effect of the conducted research is the possibility of extending the experiments to a semi-technical scale, which enables the selection of the most advantageous variants of the use of this type of materials on an industrial scale.

2. Materials and Methods

To verify the SCG physicochemical properties that condition its application in the process of metal oxide reduction, a series of experiments were conducted to characterise this material. The assumed cycle of experiments included:

1. SCG degasification tests using the thermogravimetric method;
2. SCG pyrolysis;
3. Slag reduction tests.

As part of the preliminary tests, the SCG chemical composition and its heat of combustion were determined.

2.1. Equipment and Research Methodology

The thermogravimetric analysis was carried out using an STA 449 F3 Jupiter analyser, Netzsch. The F3 Jupiter analyser is a device which enables series of measurements with the use of thermal analysis methods. It contains a graphite furnace which works in a protective atmosphere (argon and helium) and facilitates measurements at up to 2000 °C. The device and is presented in Figure 1.

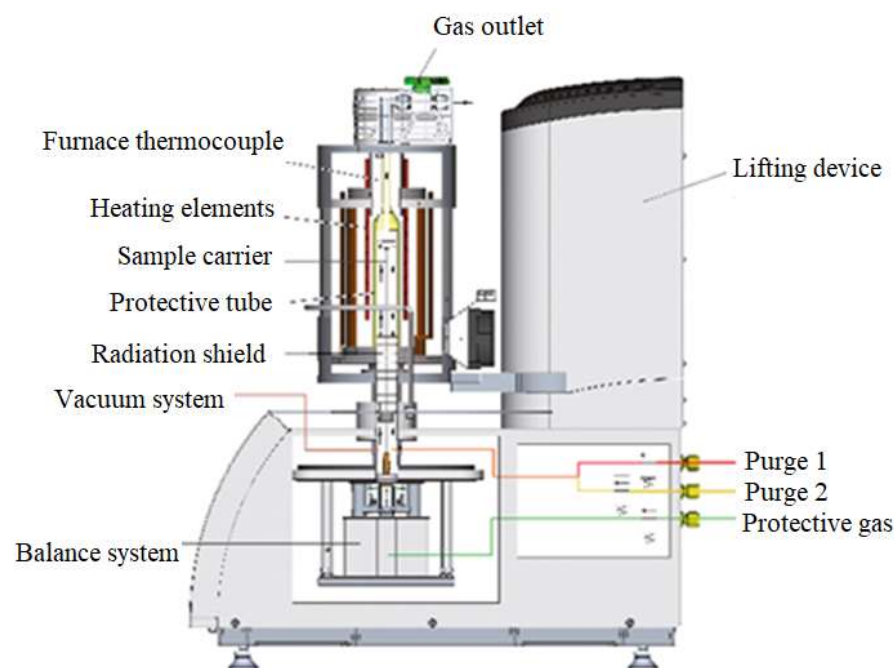


Figure 1. A diagram of the STA 449 F3 Jupiter thermal analyser.

Before the experiment, an SCG sample of a particular weight (approx. 200 mg) was placed inside a small DTA/TG Al_2O_3 crucible which was then attached to the measuring head in the working chamber of the analyser. The measurements were performed in the argon atmosphere with hydrogen addition. The assumed programme of sample heating consisted of three essential stages: the first stage involved sample heating up to 1200 °C (20 °C/min); next, the sample was isothermally held for 30 min, and then it was cooled down to 800 °C. The amount of volatile matter in the tested material corresponded to the loss of sample mass recorded during its heating as part of the experiment.

Measurements of the heat of combustion were carried out using a KL-12 Mn calorimeter, Precyzja-BIT. The values of heat of combustion were measured in the following way: an SCG sample was entirely burnt in the oxygen atmosphere under pressure in a calorimetric bomb immersed in water and the water temperature increment was determined. The heat of fuel combustion was automatically calculated. The accuracy of temperature increment measurement was 0.001 °C. The calorimetric measurements of the heat of combustion for the SCG pellet sample were carried out for three 1.5 g samples.

Low-temperature pyrolysis tests were performed to determine chemical compositions of fractions resulting from SCG thermal decomposition. The tests were carried out in a research stand outlined in Figure 2.

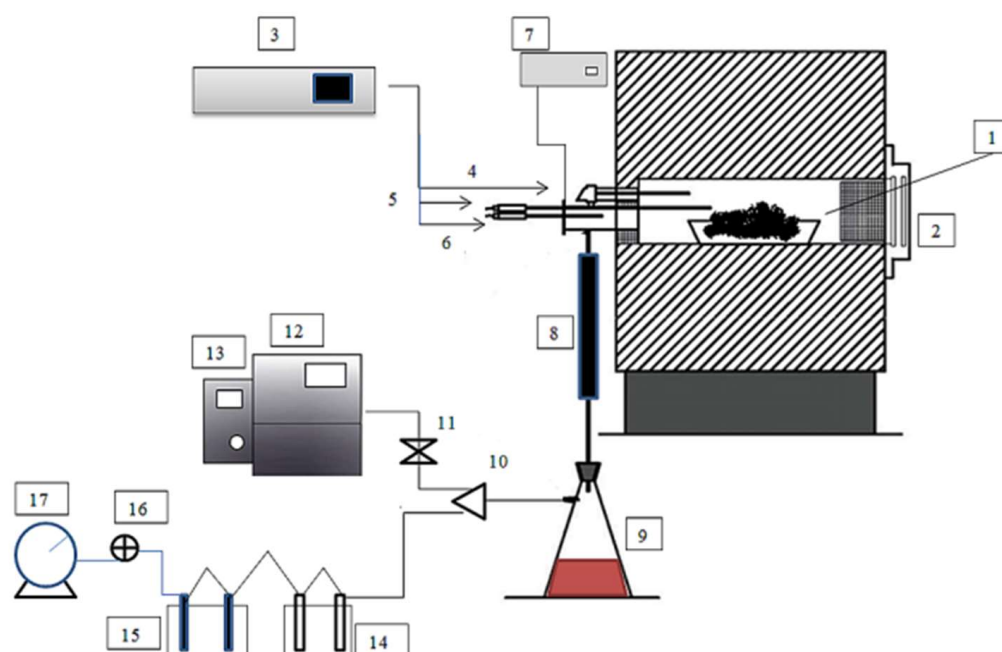


Figure 2. A diagram of the biomass pyrolysis system used in the research: 1: the pyrolysis chamber; 2: the material feeding zone near the furnace pyrolysis chamber; 3: the temperature recorder; 4: the furnace chamber thermocouple; 5: the sample thermocouple; 6: the process gases thermocouple; 7: the measurements of gas pressures in the pyrolysis chamber; 8: the water cooler; 9: the filtering flask with pyrolysis oil drain; 10: the gas separator; 11: the filter; 12: the measurements of gas compositions; 13: the measurements of O₂ content in the gases; 14: the water scrubbers; 15: the absorption tubes with XAD-2 and activated carbon; 16: the pump; 17: the gas meter.

The low-temperature pyrolysis experiments were carried out on 500 g SCG material. The test sample was placed in the furnace pyrolysis chamber (1) and, following tight sealing of the measuring system, the carrier gas (argon) was delivered at 6.1 L/min. After several minutes, the furnace pyrolysis chamber was heated to the measurement temperature of 600 °C. This process was initiated when the O₂ content in the gas leaving the reactor (13) was less than 0.1%. The pyrolysis process started when smoke in the filtering flask (9) was observed, and CO appeared in the measuring system (12). This moment was assumed to be the beginning of thermal decomposition of the sample. The resulting process gas was cooled down using the water cooler (8). The pyrolysis oil drops migrated from the cooled gas into the filtering flask (9) below the cooler. Following its cooling, the process gas was delivered to the water scrubbers (14) and the absorption tubes (15) with the activated carbon and XAD-2 deposit. The aim of the research was to determine the amounts of hydrocarbons that formed during the pyrolysis process. In addition, CO, CO₂, and O₂ levels in the process gases were measured by the analyser (12) until CO and CO₂ were absent from the measuring system. The measurement ended when the argon flow to the reactor was cut off and the reactor heating system was shut down.

The processes of slag reduction smelting were carried out in a PT 40/1300 pit-type resistance furnace, Czylok. The maximum working temperature of the furnace is 1350 °C. The application of this furnace in laboratory experiments facilitated crucible feeding during the experiment. An overview of the PT 40/1300 the schematic diagram of the research stand for reduction experiments is presented in Figure 3.

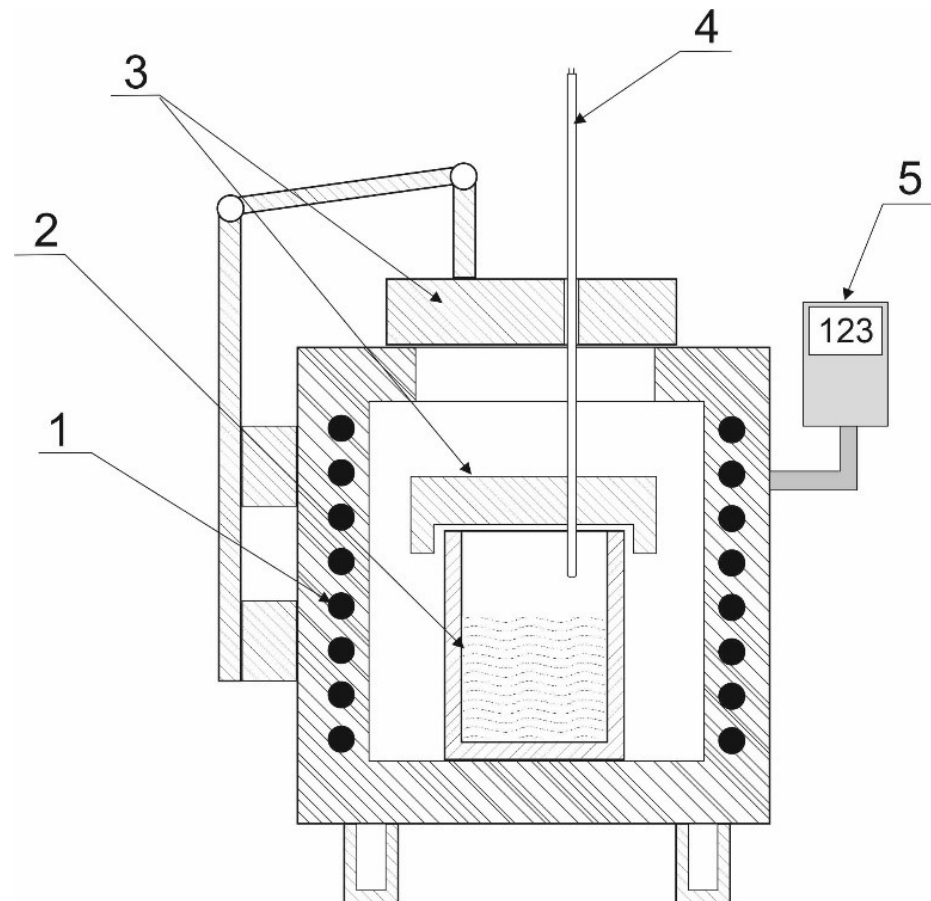


Figure 3. A schematic diagram of the research stand for slag reduction experiments: 1: electric resistance furnace; 2: crucible with the tested sample; 3: ceramic cover; 4: thermocouple; 5: device controlling the furnace operation.

The reduction process was carried out in alundum crucibles at 1300 °C. This temperature was found optimal based on the findings of preliminary tests. The slag weight was 100 g. The variable parameters were the SCG reducer weight and duration of the reduction process. The amount of smelted metal and the weight of secondary slag were determined after each experiment. Both the metal and the slag were analysed for copper, lead, and iron contents. The chemical composition of the alloy was analysed using the wavelength dispersive X-ray fluorescence (WDXRF) spectroscopy with direct exposure of the sample to X-rays. The elemental composition was analysed with the use of the programme for semi-quantitative (SQX) analysis. Before the analysis, the sample was thoroughly ground in a planetary mill with a zirconium dioxide (ZrO_2) grinding chamber. The final grain size was <0.2 mm, which constituted an analytical sample. Next, 2.0000 g (± 0.0001 g) of the sample was weighed and transferred to the weighing container where it was blended with 2.0000 g (± 0.0001 g) of the binding agent, i.e., anhydrous crystalline cellulose (ACS grade). The mixture was pressed in an HTP 40 hydraulic press, Herzog. The yielded pellet was analysed for its elemental composition by means of the Primus II X-ray fluorescence spectrometer. For the measurements, laboratory analytical programmes for

quantitative and semi-quantitative (SQX) analyses included in the analytical software of the spectrometer were applied.

Determination of carbon content in SCG was obtained by burning an SCG sample in an Eltra carbon analyser model CS2000. The contents of other elements, such as oxygen, hydrogen, and nitrogen, were obtained as a result of semi-quantitative analysis using X-ray fluorescence spectrometry (XRF) on the ZSX Primus—WDXRF (Rigaku) spectrometer.

2.2. Research Materials

Copper slag and spent coffee grounds (SCGs) following the drying process were used for the research. The slag chemical composition is presented in Table 3. The amounts of basic SCG components are listed in Table 4.

Table 3. The amounts of basic copper slag components used in the research.

Slag Component	Cu	Pb	Fe	SiO ₂	CaO
Component amount, wt. %	10.3	2.25	11.1	34.5	14.1

Table 4. The amounts of basic SCG components used in the research.

SCG Component	Carbon	Oxygen	Hydrogen	Nitrogen
Component amount, wt. %	47.2	50.0	6.17	3.11

3. Results and Discussion

3.1. Thermogravimetric Analysis

TG and DTG curves of the degasification process for the tested SCG sample are presented in Figures 4 and 5, respectively.

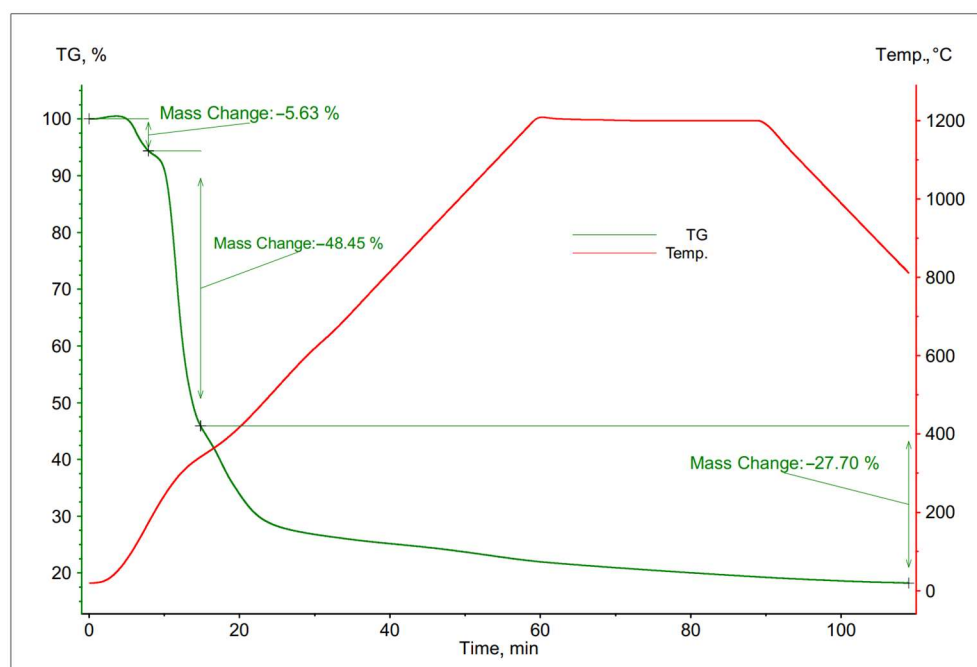


Figure 4. The TG curve for the process of spent coffee ground sample degasification.

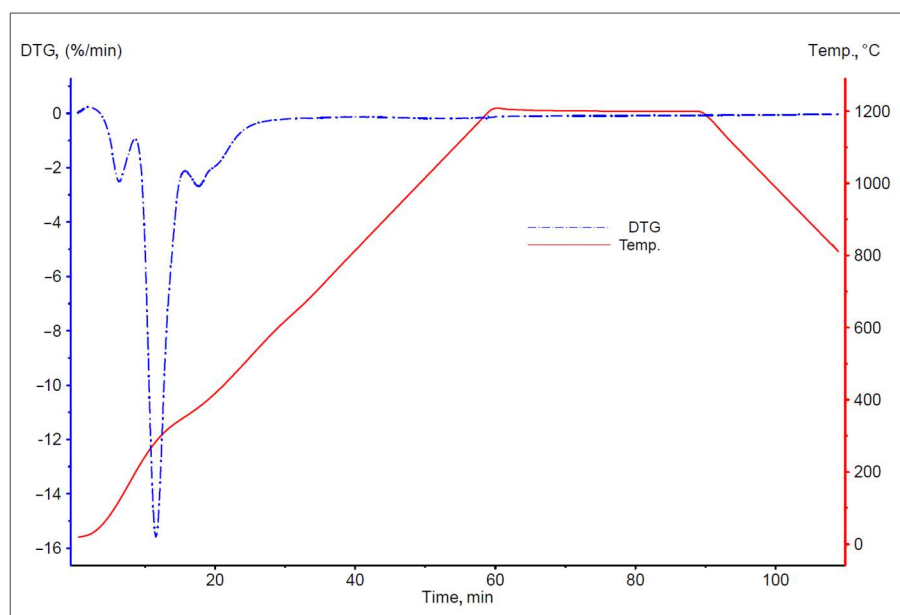


Figure 5. The DTG curve for the process of spent coffee ground sample degasification.

While analysing the curve shown in Figure 5, three distinct temperature ranges with significant differences in mass loss values are observed. Their characteristics are presented in Table 5. Based on the known chemical composition of the test material and the temperature ranges for the particular mass losses, the potential courses of characteristic reactions during sample heating were determined. The first mass loss recorded for the sample was associated with vaporisation of water. The next mass loss was related to the loss of so-called volatile matter. The last sample mass loss, occurring at the highest temperatures, was associated with thermal decomposition of the SCG chemical compounds. The average rate of the sample mass loss during the heating phase was 0.046 mg s^{-1} .

Table 5. Recorded mass losses of the particular samples.

Sample Mass Loss	Loss I [%]	Loss II [%]	Loss III [%]
	5.63	48.45	27.70
Temperature range for the particular loss: °C	20–200	200–370	370–1200
Mass loss rate: mg s^{-1}	0.0094	0.1047	0.0064

3.2. Calorimetric Analysis

The values of the heat of combustion for the SCG samples (mean values from three measurements), determined based on the experiments, are listed in Table 6. For comparison, the values of the heat of combustion for other biomass types from the food production processes are also included in the table [54–56]. For SCG, the Q_{mean} was 21.09 kJ kg^{-1} . It should be noted that the value of the heat of combustion for spent coffee grounds was higher than those for most biomass types.

Table 6. Tabularised results of combustion heat measurements for spent coffee grounds (SCGs) and selected biomass types [53–55].

No.	Sample	C	H	O	N	Mean Heat of Combustion Q _{mean} , kJ/kg
		[%w/w]				
1	Almond shells	44.98	5.97	42.27	1.16	19.38
2	Walnut shells	49.98	5.71	43.35	0.21	20.18
3	Peanut shells	46.30	6.59	41.66	0.50	17.35
4	Peanut shells, pellet	40.84	5.44	38.39	0.86	16.74
5	Peach stones	53.00	5.90	39.14	0.32	20.82
6	Sunflower husks, pellet	52.08	6.06	37.94	0.75	20.49
7	SCG	47.2	6.17	50.0	3.11	21.09

3.3. Analysis of SCG Pyrolysis

The basic parameters of spent coffee ground sample pyrolysis are presented in Table 7. The duration of the process was 90 min. It started when the sample temperature reached approx. 105 °C. The SCG pyrolysis results are presented in Table 8.

Table 7. SCG pyrolysis parameters.

Pyrolysis duration	[min]	90
Argon flow	[L/min]	6.1
Beginning of the process		
Furnace temperature		174.8
Sample temperature	[°C]	104.7
Gas temperature		24.4
End of the process		
Furnace temperature		603.3
Sample temperature	[°C]	594.5
Gas temperature		129.6

Table 8. Weights of the SCG pyrolysis products.

Sample Weight for the Process	Biochar	Sample Mass Loss during the Process	Solid Fraction Percentage	Oil	Liquid Fraction Percentage	Volatile Fraction	Volatile Fraction Percentage
[g]		[%]		[g]	[%]	[g]	[%]
500.0	127.0	74.6	25.4	189.0	37.8	184.0	36.8

The data in Table 8 show that the total loss of tested SCG sample mass during pyrolysis was 74.6%, which may be associated with removal of the volatile matter from the sample. The process yielded products including approx. 25% of biochar, almost 38% of pyrolysis oil, and approx. 37% of the volatile fraction. A graphic presentation of percentages of the particular fractions formed during the SCG sample pyrolysis is shown in Figure 6. Concentration changes for the gaseous phase components (O₂, CO₂, and CO) which accompany the process of pyrolysis and the temperature changes recorded during the pyrolysis process are presented in Figures 7 and 8, respectively.

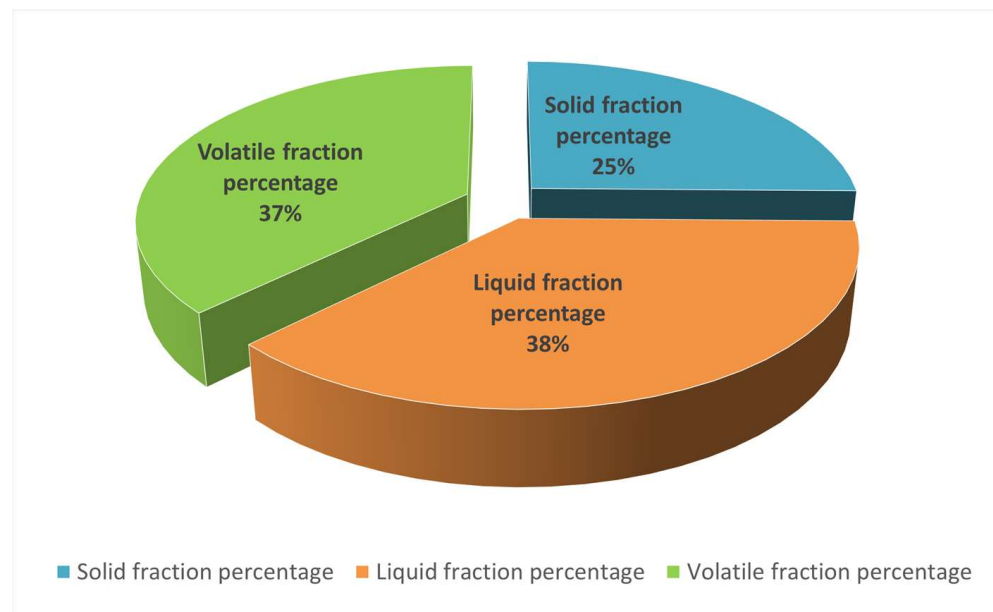


Figure 6. Percentages of the particular fractions resulting from pyrolysis.

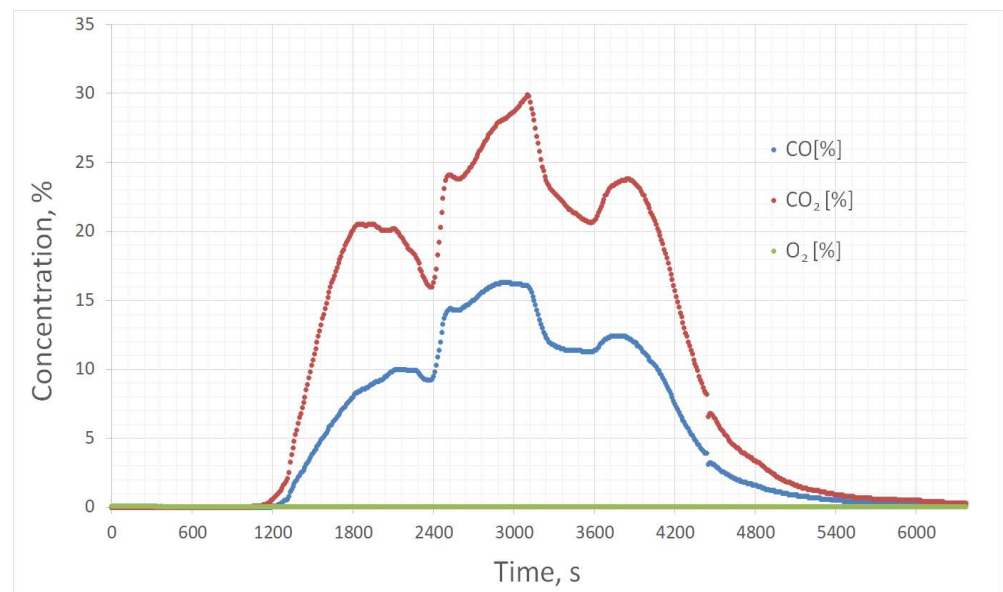


Figure 7. Composition of the gaseous phase during SCG pyrolysis.

The analysis of the chemical composition of biochar produced during SCG pyrolysis showed significant amounts of carbon and oxygen: 78 wt.% and 13 wt.%, respectively. In addition, the biochar contained potassium, chlorine, calcium, magnesium, and phosphorus: 1 wt.% to 3 wt.%. The carbon content in the biochar was much higher than that in the starting material (an increase from 47 wt.% to 78 wt.%). This confirms that SCG can be used in processes of reduction in copper oxides in slag.

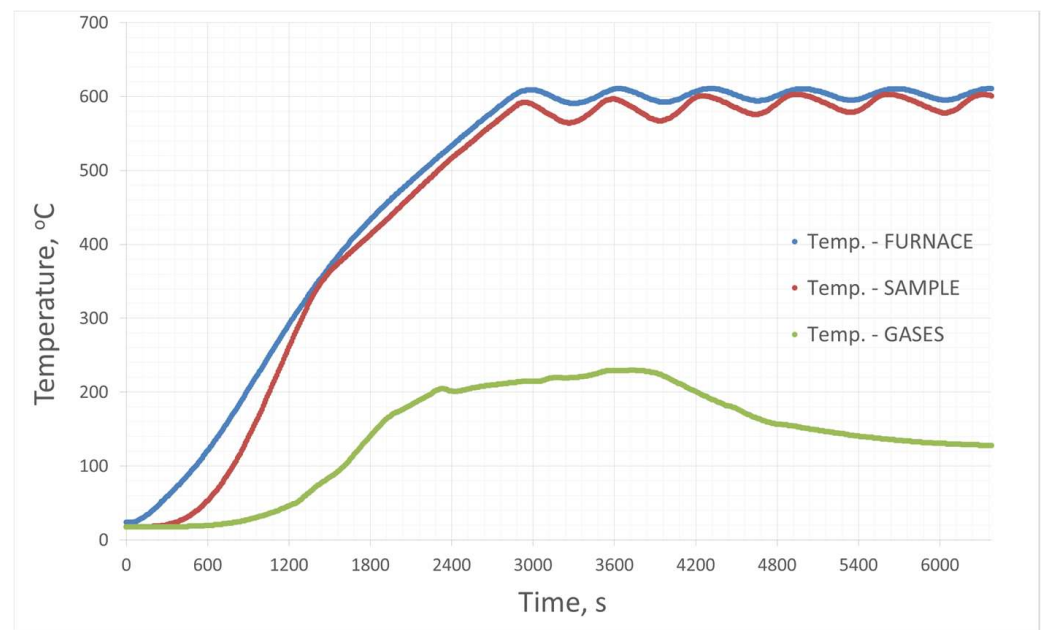


Figure 8. The temperature distribution during spent coffee ground pyrolysis.

3.4. Slag Reduction Process

Based on the experiments of liquid copper slag smelting with the SCG additive as an alternative reducer to coke, data on the effects of reducer mass percentage and the process duration on its efficiency were obtained. Results of copper slag reduction smelting with the SCG additive as a reducer are listed in Table 9. In addition to the data referring to the amounts and types of feeding materials used in the particular experiments, the table presents the test findings, i.e., the weights of smelted copper alloy and waste slag as well as their chemical compositions (contents of copper, lead, and iron) for the particular measurement series.

Table 9. Results of slag reduction using the SCG additive.

No.	Feeding Components, g		Reduction Time, h	Alloy Weight, g	Waste Slag Weight, g	Chemical Composition of the Waste Slag, wt.%			Chemical Composition of the Cu–Pb–Fe Alloy, wt.%		
	Slag	SCG				Cu	Pb	Fe	Cu	Pb	Fe
1		5.67	1	8.95	89.13	1.19	2.22	11.85	92.92	2.29	0.07
2		7.56	1	13.61	85.81	0.50	1.04	12.39	91.02	7.77	0.06
3		5.67	1.5	12.17	89.82	0.91	1.87	11.93	94.61	4.46	0.01
4		7.56	1.5	13.02	85.94	0.45	0.91	11.72	90.70	7.06	0.07
5		5.67	2	11.53	87.99	0.79	1.71	11.61	91.18	7.34	0.03
6	100	7.56	2	12.12	86.91	0.41	1.27	12.06	93.51	5.35	0.05
7		5.67	3	10.04	88.68	1.41	2.46	11.10	96.84	1.90	0.07
8		7.56	3	11.40	86.59	0.63	1.37	11.45	92.38	4.95	0.15
9		5.67	4	10.57	89.62	1.03	1.94	11.22	95.66	3.31	0.03
10		7.56	4	11.26	86.23	0.67	1.56	11.94	93.58	5.37	0.11
11		10	3	12.11	92.05	0.49	1.15	11.60	77.66	19.82	0.31
12		12	3	13.15	90.04	0.32	0.98	12.55	89.48	8.06	0.20

While analysing the results for changes in the slag chemical compositions, a high degree of oxide reduction was observed for copper. The waste slag contained less than 1.2 wt.% Cu after one hour of the reduction process and even less than 0.4 wt.% Cu after 4 h. In the case of lead, the smallest amount of this metal in the post-process slag was 0.91 wt.%.

The effects of reduction duration on the contents of lead and iron in the waste slag are illustrated in Figure 9. The changes in the Cu–Pb–Fe alloy chemical composition during the process are presented in Figure 10.

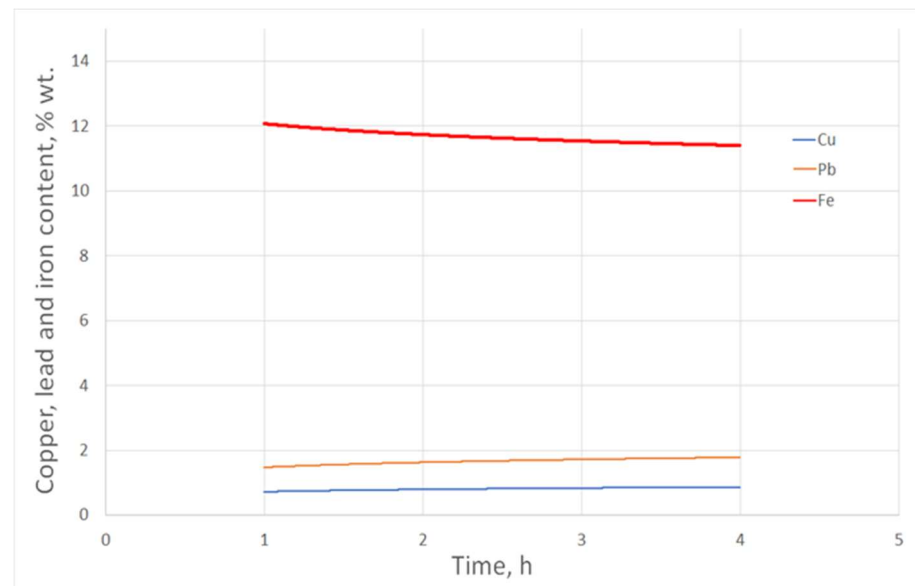


Figure 9. Changes in copper, lead, and iron amounts in the waste slag.

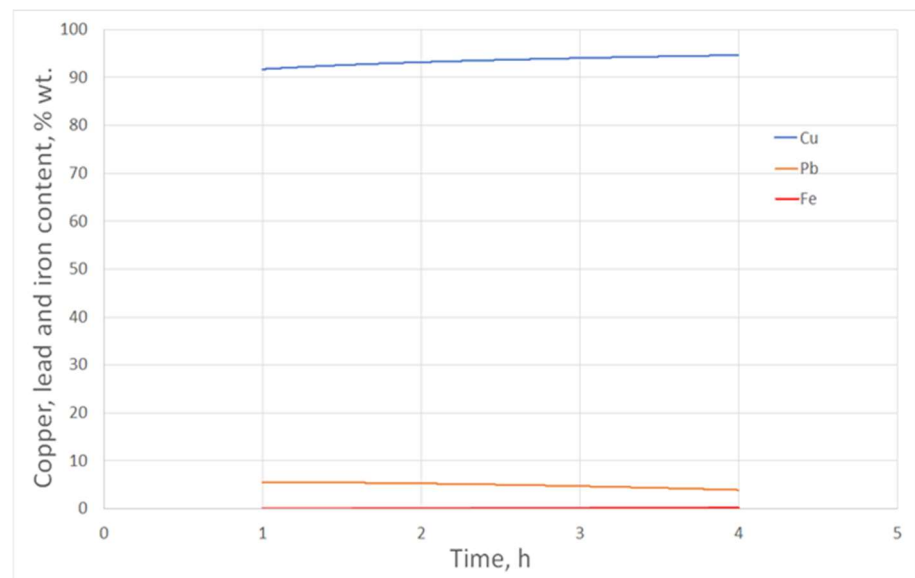


Figure 10. Changes in copper, lead, and iron amounts in the Cu–Pb–Fe alloy.

When the amount of the reducer (SCG) increased, larger amounts of the resulting Cu–Pb–Fe alloy and lower contents of copper in the waste slag were observed. These findings are graphically presented in Figure 11.

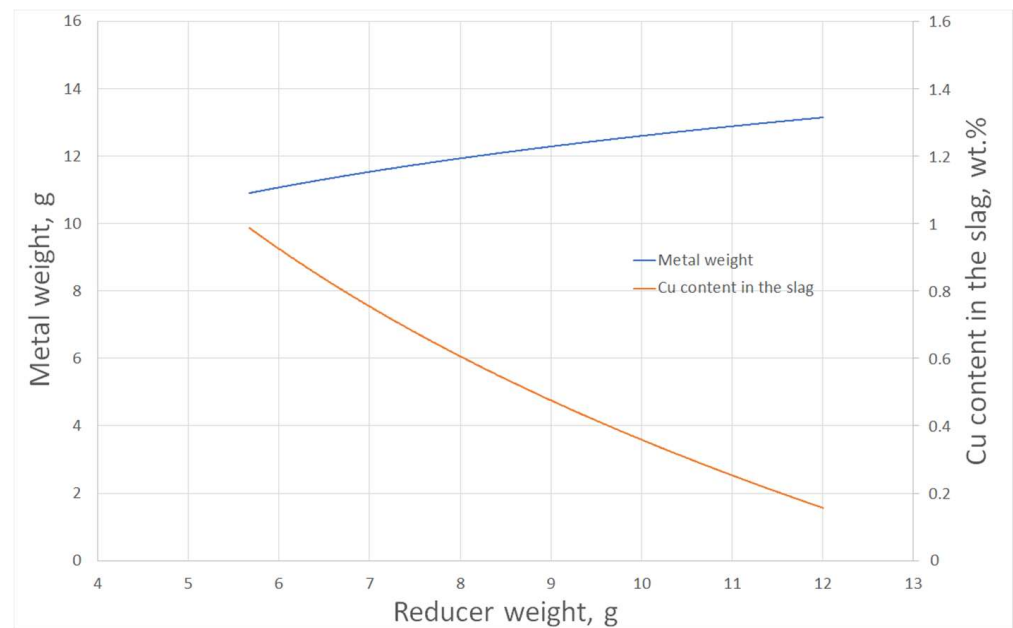


Figure 11. Effects of the added reducer on the amounts of smelted Cu–Pb–Fe alloy and on the final copper content in the waste slag.

Examples of changes in the slag decopperisation degree depending on the reduction duration are presented in Figure 12. The values of this parameter were estimated based on the following equation:

$$S_{\text{Cu}} = (C_{\text{Cu}}^0 - C_{\text{Cu}}^t) / C_{\text{Cu}}^0 \cdot 100\% \quad (5)$$

where: C_{Cu}^0 and C_{Cu}^t are the initial content of copper in the slag and the content of copper in the slag after time t , respectively.

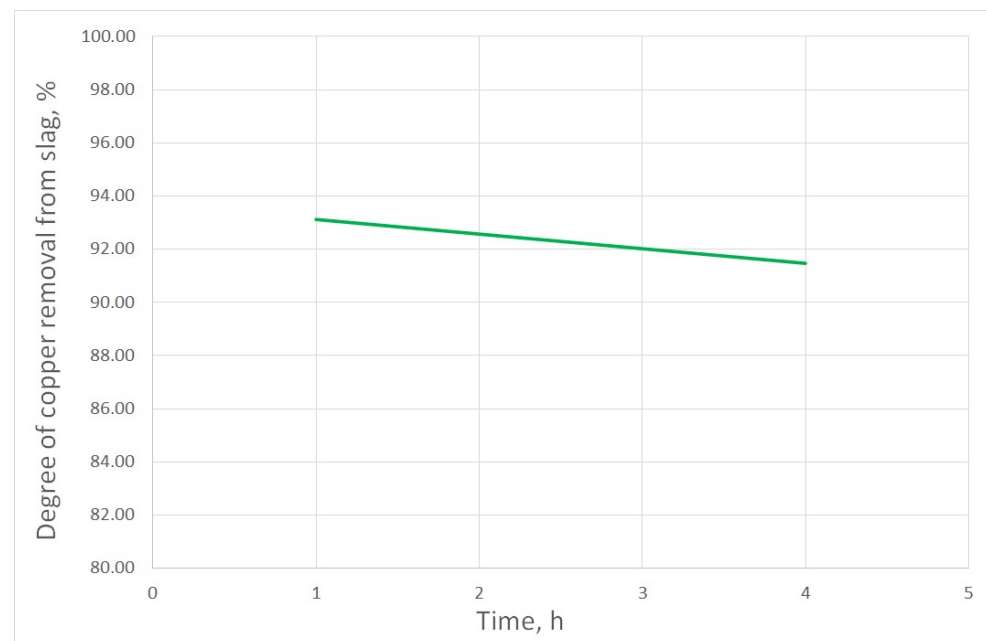


Figure 12. Changes in the slag decopperisation degree depending on the reduction duration.

Based on the results, very high values of this parameter are seen for all experiments.

The relationship between contents of lead and copper in the waste slag for selected reduction tests is presented in Figure 13. It shows that reduction in lead oxides is more

intense when the copper amount in the slag decreases. The experiments of copper slag reduction with the SCG reducer demonstrated a small degree of iron transformation to the metal alloy.

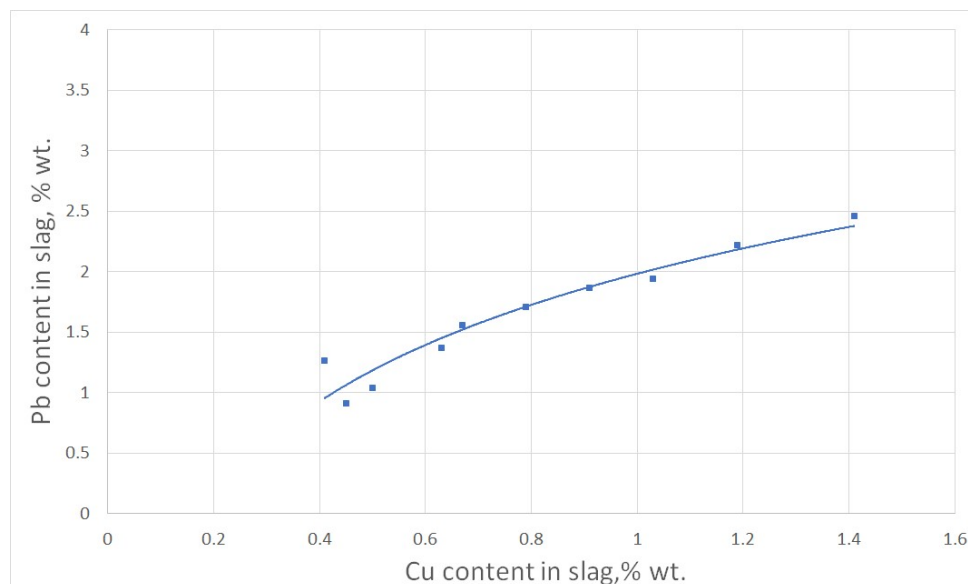


Figure 13. The relationship between lead and iron contents in the waste slag.

4. Conclusions

Based on the research on the application of SCG for reduction in slag from the copper industry, the following conclusions were formulated:

- The results of SCG pyrolysis show the potential for production of biochar containing 78 wt.% of elemental carbon, which means that SCG may be a good reducer in the process of copper slag reduction;
- The assumed research parameters of copper slag reduction process and the addition of SCG as the reducer from 5.67 wt.% to 12 wt.% ensure the decrease in copper content from 10.3 wt.% to 0.32 wt.%, which corresponds to the increase in so-called relative decopperisation degree from 88.4% to 96.9%;
- The slag reduction process with 7.56 wt.% of SCG as the reducer and the process duration of 1.5 h resulted in the smallest lead content of 0.91 wt.%;
- When the amount of SCG reducer increased from 5.67 wt.% to 12 wt.%, a higher percentage of the resulting Cu–Pb–Fe alloy and decreased amounts of copper in the waste slag from 1.41 wt.% to 0.32 wt.% were observed;
- When the content of copper in slag decreases, significantly more intense reduction in lead oxides during the reduction process is observed;
- The assumed research parameters and the amount of SCG added as the reducer do not demonstrate any major effects on the degree of iron transformation to the metal alloy;
- The process of copper slag reduction with the use of SCG biomass is characterised by lower carbon dioxide emissions compared with the process using solid fuels such as coke and coke breeze.

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