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ELEMENTAL COMPOSITION OF FLY ASH: A COMPARATIVE STUDY USING NUCLEAR AND RELATED ANALYTICAL TECHNIQUES

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Abstract: Epithermal neutron activation analysis along with ICP-OES, LA ICP-MS, and XRF were used to determine the elemental composition of coal fly ash from the Malta coal power station in the Mpumalanga province of South Africa. A total of 54 major, trace and rare earth elements were obtained by the four analytical techniques. The results were compared and the discrepancies discussed to show the merits and drawbacks of each of the techniques. It was shown that the elemental content of this particular coal fly ash are of the same order as the NIST standard reference material Coal Fly Ash 1633b.

Keywords: coal fly ash, epithermal neutron activation analysis, X-ray diffraction, inductively coupled-optical emission spectroscopy, and laser ablation inductively coupled-mass spectroscopy

Introduction

Coal fly ash (CFA) is the major waste generated from coal combustion in thermal power station to produce electricity. Worldwide huge amounts of CFA are generated in order to meet energy demands, and about 70% of CFA is disposed as waste [1]. CFA disposal is of great concern globally due to the environmental issues arising from the disposal methods that are currently employed [2-4]. CFA is considered a highly contaminating medium because the toxic trace elements in coal are accumulated in higher concentrations in the combustion by product [5]. Thus, various environmental risks may be linked to the disposal of CFA air, soil, surface- and groundwater [6-8].

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CFA has been studied extensively to understand the environmental impacts associated with its disposal, management and reuse [6, 9-13]. Research of CFA compositions has shown that the chemical composition of fly ash comprises major (> 1 wt. %), minor (1-0.1 wt. %), and trace (< 0.1 wt. %) elements [14]. Elemental analysis have also revealed that rare earth elements (REEs) [15, 16], toxic elements [17, 18] and radionuclides [19] are present in CFA.

The analytical methods widely used in determining the elemental compositions of CFA are X-ray Fluorescence (XRF) spectroscopy [9, 20]; inductively coupled plasma - optical emission spectrometer/Mass Spectrometry (ICP-OES/MS) [18, 19]; Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) [21] and instrumental neutron activation analysis (INAA) [15, 22].

In South Africa millions of tons of CFA are generated annually by coal-fired power plants in order to meet the large demand for industrial and domestic energy and the disposal methods currently employed are raising a lot of environmental issues [23, 24]. In the management of CFA the focus should not only be on the prevention of environmental pollution, but also on methods that can be used to produce or manufacture value-added products from disposed fly ash. In order to achieve these objectives an accurate method of determining the chemical composition of CFA is fundamental in the qualitative and quantitative analysis of the elements of toxicity and value in fly ash. Instrumental epithermal neutron activation analysis (ENAA), X-ray fluorescence spectroscopy (XRF), inductively-coupled Plasma-Optical Emission Spectroscopy (ICP-OES) and Laser Ablation Inductively Coupled Plasma-Mass Spectrometry (LA ICP-MS) are used to determine the elemental composition of CFA. The results obtained will be used in understanding the method that is best suited for determining the different categories of elements that are contained in CFA. This knowledge will assist in the effective valorisation and management of CFA.

Materials and methods

Sampling

The CFA samples used in this study were collected directly from the hoppers of Matla coal power station in the Mpumalanga province in South Africa. The fresh CFA samples were put in sealed plastic bags devoid of air to avoid external contamination. The sealed plastic bags were labelled accordingly and stored in a dark, cool cupboard away from any heat source, direct sunlight or fluctuating temperatures.

Experimental procedures

Epithermal Neutron Activation Analysis

The analysis was carried out at the reactor IBR-2 in Frank Laboratory of Neutron Physics (FLNP), Joint Institute for Nuclear Research (JINR), Dubna. For short irradiation, 100 mg of the CFA sample were heat-sealed in polyethylene bags. For long irradiation, same amount of the CFA were packed in aluminium cups. To determine short-lived isotopes, the CFA samples were irradiated for 60 sec. After irradiation two gamma-spectrometric measurements were performed; the first one for 3 minutes after 2-3 minutes of decay, and the second for 15 minutes after 9-10 minutes decay. Long-lived isotopes were determined after irradiation for

100 hours in the cadmium-screened channel 1. After irradiation samples were re-packed into clean containers and measured after 4-5 and 20-23 days for 30 minutes and for 1.5 hours, respectively. Gamma spectra were registered as described elsewhere [25]. The elemental content of a NIST Certified Reference Material 1633 b was also determined by ENAA. The results obtained were then compared to the certified values [26].

Inductively-Coupled Plasma-Optical Emission Spectroscopy

The digestant for total acid digestion of the solid CFA sample selected included hydrofluoric acid (HF) and aqua regia (HCl and HNO₃ mixed in the ratio of 3 : 1 respectively). The digestion was carried out according to [27]. 0.25 g of the Matla CFA sample was weighed into a Teflon cup. 2 cm³ of concentrated HF and 5 cm³ aqua regia were added. The Teflon cup was put in a digestion vessel (Parr bomb), sealed and heated to 200°C for 2 hours in an oven. The Parr bomb was removed from the oven and allowed to cool down. 25 cm³ of H₃BO₃ was added to the sample in order to prevent the formation of sparingly soluble in the sample. The digestate was filtered through 0.45 µm membrane filter and made up to 100 cm³ with ultra-pure water (ELGA Pure lab UHQ). The procedure was triplicated.

The solution obtained from the total acid digestion experiments was analysed for major and trace concentration using Varian 710-ES ICP Optical Emission Spectrometry. The sample was introduced through a high sensitivity glass, single-pass cyclone spray chamber and conical nebulizer using argon gas. It was then passed through axially oriented plasma. The wavelength released by different analytes was detected with a CCD detector and auto integrated using ICP Expert II software. The ICP-OES instrument was calibrated before analysis with three calibration standards and a blank (2% HNO₃). The certified standards used in calibrating and checking the accuracy of the instrument was supplied by Industrial Analytical. The certified standards were Spectrascan SS-1256 for Si, SS-1206 for Ca, SS1242 for Na, SS-9415S for multiple elements and SS- 028321 for REEs. Three replicates were run for each sample in order to check the reproducibility of the analysis.

X-Ray Fluorescence Spectroscopy

CFA samples were crushed into a fine powder (particle size < 100 µm) with a jaw crusher and milled in a tungsten zib mill (to prevent contamination from trace and REE) prior to the preparation of a fused disc for major element and trace analysis. The jaw crusher and mill were cleaned with uncontaminated quartz after analysing each sample to avoid cross contamination. Pressed powder pellets were prepared for XRF analysis using 8 g of the sample and a few drops of MOVIOL (a brand of polyvinyl alcohol) was added for binding. The composition was then determined by XRF spectrometry on a Philips 1404 Wavelength Dispersive spectrometer. The spectrometer was fitted with an Rh tube and with the following analysing crystals: LIF200, LIF220, LIF420, PE, TLAP and PX1. The instrument is fitted with a gas-flow proportional counter and a scintillation detector. The gas-flow proportional counter uses 90% argon and 10% methane gas mixture. Trace elements were analysed on a pressed powder pellet at various kV and mA tube operating conditions, depending on the analysed element. Matrix effects in the samples were corrected for by applying theoretical alpha factors and measured line overlap factors to the raw intensities measured with the SuperQ Philips software. Control standards that were used in the calibration procedures were NIM-G (Granite from the Council for Mineral Technology,

South Africa) and BHVO-1 (Basalt from the United States Geological Survey, Reston). The XRF technique reports concentration as % oxides for major elements and ppm [mg/kg] for minor and trace elements. The elements reported as mass % oxides were converted to ppm of the elements using element conversion software downloaded at [28].

Laser Ablation Inductively Coupled Plasma-Mass Spectrometry

The instrument was set by connecting a 213 nm laser ablation system connected to an Agilent 7500ce ICP-MS. The CFA sample was coarsely crushed and fusion disks were made by an automatic Claisse M4 Gas Fusion instrument and ultrapure Claisse Flux. A chip of sample was mounted in a 2.4 cm round resin disk. The mounted sample was then polished for analysis. The sample was ablated using He gas and then mixed with Ar after coming out of the ablation cell. The sample was then passed through a mixing chamber before being introduced into the ICP-MS. Trace elements were quantified using NIST 612 for calibration method and 29 Si as internal standard. Three replicate measurements were made on each sample. The calibration standard was run after every 12 samples. A quality control standard was run in the beginning of the sequence as well as with the calibration standards throughout. Both basaltic glass, BCR-2 or BHVO 2G were certified reference standards produced by USGS (Dr Steve Wilson, Denver, CO 80225) that were used for this purpose. A fusion control standard from certified basaltic reference material (BCR-2, also from USGS) was also analysed in the beginning of a sequence to verify ablation on fused material. Data was processed using Glitter software.

Results and discussion

The results obtained on the elemental content in Matla CFA using ENAA, ICP-OES, LA ICP-MS, and XRF are presented below. A total of 54 elements were determined and are summarized in three tables (Tables 1-3).

To demonstrate the accuracy and reliability of ENAA as the most powerful primary analytical technique [29], NIST Standard Reference Material 1633b (bituminous coal fly ash) was used. The results are given in Tables 1 and 2, subdivided according to the level of certification (certified and non-certified values).

The major elements in fly ash with concentrations > 1 wt. % are presented in Table 3, whilst the minor (1-0.1 wt. %), and trace (< 0.1 wt. %) elements [14] are presented with the REEs in Table 4 and the other trace elements in Table 5. The techniques and principles on which these analytical methods are based are different and each of these techniques has its own merits and demerits which may affect the outcome of the CFA analysis. The composition of the elements in the Matla CFA sample shows that it is Class F since the sum of SiO₂, Fe₂O₃ and Al₂O₃ is greater than 70% [30, 31]. Class F is produced from the burning of bituminous coal and anthracites. Thus the elemental composition of the Matla CFA can be compared to the given concentrations of the elements in SRM 1633b-NIST (bituminous).

ENAA

Quality Assurance

To assure the quality of ENAA the NIST Certified Reference Material 1633b was used. The concentrations of the elements in the NIST SRM 1633b determined by ENAA in

Dubna (present value) are compared to the known concentrations of the NIST SRM 1633b (certified value).

Table 1
Elemental concentrations in the NIST SRM 1633b determined by ENAA in Dubna and the certified values [26]

Elements	NIST certified value [mg/kg]	ENAA present value [mg/kg]	Minimum detection limit [mg/kg]	RSD [%]
Al	150500	151000	179	-0.33
As	136.2	133	0.507	2.35
Ba	709	708	21.4	0.14
Ca	15100	15100	691	0.00
Cr	198.2	198	33.3	0.10
Cu	112.8	71.9	662	36.26
Fe	77800	77700	518	0.13
K	19500	20400	4910	-4.62
Mg	4820	4810	176	0.21
Mn	131.8	132	2.8	-0.15
Na	2010	2090	38.5	-3.98
Ni	120.6	121	23.4	-0.33
Se	10.26	9.83	1.39	4.19
Si	230200	230000	334000	0.09
Sr	1041	1040	32.4	0.10
Th	25.7	27.4	0.108	-6.61
U	8.79	8.49	0.286	3.41
V	295.7	312	14.4	-5.51

It can be seen from Table 1 that there is a strong agreement between the results obtained by ENAA of the NIST SRM 1633b and the certified values of this standard. Except Cu (36.26%) the RSD% values of the analysed certified SRM were below $\pm 10\%$. The RSD is used to test for the accuracy of the instrument in order to determine the reliability of the instrument in the analysis of each element. The acceptable range for RSD value is about $\pm 10\%$. The RSD% was calculated as follows:

$$\frac{\text{Expected value} - \text{Analytical value}}{\text{Expected value}} \cdot 100\%$$

Expected value = value of the certified standard; Analytical value = value obtained when certified was analysed.

In Table 2, the noncertified values of some elements in the NIST SRM 1633b are compared to the amounts determined by ENAA in Dubna. Except for Gd (-109.23%) and Zn (-107.62%), there is a good agreement between the two values. The RSD% of the analysis is also below $\pm 10\%$, however the RSD% values Gd (-109.23%) and Zn (-107.62%) clearly shows that their determined amounts in the NIST SRM 1633b are inaccurate and unreliable.

Table 3 presents the concentrations of major elements in the Matla CFA determined by ICP-OES, XRF, and ENAA. The major elements were not determined by the LA ICP-MS technique due to unavailability of suitable standards. The results reveal that the major elements analysed in the Matla CFA were Si, Al, Fe, Ca, Mg, Na, K, P, Ti, Mn and S. The ENAA technique did not report the concentration of P.

Table 2

Elemental concentrations in the NIST SRM 1633b (noncertified values [26])
and those determined by ENAA in Dubna

Elements	NIST Non certified value [mg/kg]	ENAA Present value [mg/kg]	Minimum detection limit [mg/kg]	RSD [%]
Br	2.9	2.72	0.454	6.21
Ce	190	190	8.16	0.00
Co	50	47.7	0.326	4.60
Cs	11	11	0.17	0.00
Dy	17	16.2	4.85	4.71
Eu	4.1	4.1	0.776	0.00
Gd	13	27.2	0.718	-109.23
Hf	6.8	8	0.414	-17.65
La	94	92.3	1.43	1.81
Nd	85	157	36.6	-84.71
Rb	140	140	1.84	0.00
Sb	6	5.26	0.0519	12.33
Sc	41	41	0.198	0.00
Sm	20	20	0.0907	0.00
Ta	1.8	1.84	0.038	-2.22
Tb	2.6	2.6	0.0651	0.00
Ti	7910	7920	1760	-0.13
Tm	2.1	1.98	0.353	5.71
Yb	7.6	7.61	1.03	-0.13
Zn	210	436	9.27	-107.62

Table 3

Concentrations of major elements in Matla CFA determined by ENAA, ICP-OES, and XRF
[number of determinations = 3]

Elements	ENAA	ICP-OES	XRF
	[mg/kg]	[mg/kg]	[mg/kg]
Si	176000 ± 11314	176760 ± 0.981	225683 ± 0.044
Al	129500 ± 707	62040.13 ± 0.413	163495 ± 0.22
Fe	33100 ± 1453	9201.59 ± 0.074	19661 ± 0.027
Ca	38233 ± 493	17211.72 ± 0.048	47983 ± 0.083
Mg	29233 ± 503	896.19 ± 0.023	12807 ± 0.04
Na	25376 ± 93	21032.51 ± 0.858	4101 ± 0.009
K	6640 ± 464	116.3956 ± 0.008	6985 ± 0.009
P	Nd	2539.08 ± 0.025	3873 ± 0.013
Ti	9383 ± 500	9558.16 ± 0.066	7553 ± 0.016
Mn	290 ± 10	132.412 ± 0.002	155 ± 0.0004
S	1420 ± 473	Nd	77.58 ± 0.0024

Nd = Not detected

From Table 3, the concentration value of the major elements in the Matla CFA obtained using XRF and ENAA were in better agreement when compared to the certified SRM (1633b-NIST) in Table 1. Also, from Table 3 it is observed that the concentrations of the major elements (Al, Fe, Mg, and K) in the Matla CFA obtained using ICP-OES were more than an order of magnitude lower than the concentrations obtained using XRF and ENAA whereas XRF results of Na were two orders of magnitude lower than ICP-OES and ENAA. However the elemental abundances of these elements seemed to be proportional.

The lower concentrations determined by ICP-OES might be attributed to the sample preparation involved in the technique or matrix effects. The ICP-OES/MS is mostly used in determining the concentration of elements in CFA. However, its main disadvantage is that the CFA has to be digested before analysis [32-34]. An acid digestion required for ICP-OES of fly ash may result in either loss or contamination of the sample from the acid and the subsequent dilution technique [35-37]. The Matla CFA was digested prior to ICP-OES and that process may have resulted in the lower elemental concentrations detected in the Matla CFA [38].

Table 4
Concentrations of trace elements in Matla CFA determined by ENAA, ICP-OES, LA ICP-MS and XRF
[number of determinations = 3]

Elements	ENAA [mg/kg]	ICP-OES [mg/kg]	LA ICP-MS [mg/kg]	XRF [mg/kg]
V	120 ± 6	ND	154.31 ± 3.49	64.91 ± 6.24
Cr	177.33 ± 19.09	76.09 ± 0.009	183.01 ± 2.41	89.36 ± 2.29
Ni	72.27 ± 2.98	169.62 ± 0.024	49.54 ± 1.80	88.97 ± 6.41
Co	25.90 ± 0.1	2.364 ± 0.001	17.30 ± 0.49	16.08 ± 6.89
Zn	250.33 ± 148.38	26.56 ± 0.002	45.25 ± 2.67	64.61 ± 4.41
As	21.97 ± 4.88	64.22 ± 0.011	Nd	20.07 ± 2.68
Nb	Nd	519.75 ± 0.041	42.97 ± 1.35	51.50 ± 1.80
Se	1.44 ± 0.64	20.12 ± 0.038	Nd	Nd
Br	0.55 ± 0.05	Nd	Nd	Nd
Rb	46.67 ± 0.92	0.24 ± 3.29E-06	55.46 ± 2.20	72.48 ± 0.89
Sr	1900 ± 34.64	110.22 ± 0.007	2137.02 ± 81.70	3495.55 ± 5.63
Ag	1.05 ± 0.36	Nd	Nd	Nd
Cd	5.56 ± 2.25	0.11 ± 0.00005	Nd	Nd
In	0.39 ± 0.12	Nd	Nd	Nd
Sb	2.51 ± 1.03	Nd	Nd	Nd
Cs	10.5 ± 0.1	Nd	14	Nd
Ba	1823 ± 65	Nd	2372.11 ± 32.01	2079.31 ± 12.80
Hf	14.53 ± 0.15	Nd	8.63 ± 0.57	Nd
Ta	3.46 ± 0.02	Nd	2.69 ± 0.11	Nd
W	9.01 ± 0.19	Nd	Nd	Nd
Cl	73 ± 5.82	Nd	Nd	Nd
Au	0.0083 ± 0.004	Nd	Nd	Nd
Th	50 ± 0.44	Nd	35.44 ± 1.53	46.60 ± 3.33
U	12 ± 0	11.43 ± 0.0132	13.38 ± 0.38	63.28 ± 2.43
Cu	Nd	44.45 ± 0.0026	61.84 ± 0.96	117.26 ± 3.38
Mo	Nd	4.81 ± 0.0001	10.45 ± 0.33	Nd
Pb	Nd	22.45 ± 0.006	69.00 ± 1.78	100.25 ± 4.02
Zr	Nd	258.93 ± 0.022	313.94 ± 19.57	787.73 ± 3.35

Nd = Not detected

The trace element composition of the Matla CFA determined by ENAA, ICP-OES, LA-ICP-MS and XRF is presented in Table 4. The ICP-OES and XRF techniques reported 15 trace elements in the analysis of the Matla CFA while 17 and 23 trace elements were reported by the LA-ICP-MS and ENAA techniques, respectively. Cd is not determined by

XRF analysis. Also, As and Cd were not obtained by LA ICP-MS, while it is impossible to determine Pb by ENAA. However As, Cd, Pb were obtained by ICP-OES. These elements are of major environmental concern due to their toxicity. The amounts of the trace elements in the Matla CFA obtained using the LA-ICP-MS and ENAA were in better agreement in abundance when compared to the certified SRM (1633b-NIST).

Table 5
Concentrations of REEs in Matla CFA determined by ENAA, LA ICP-MS, ICP- OES, and XRF
[number of determinations = 3]

Elements	NAA	ICP-OES	LA-ICP-MS	XRF
	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]
Sc	33.80 ± 0.79	0.83 ± 0.0001	24.94 ± 1.46	Nd
Y	Nd	Nd	52.3 ± 3.47	103.71 ± 1.46
La	92.23 ± 29.88	0.196 ±	81.66 ± 4.31	111.45 ± 6.51
Ce	247.33 ± 6.66	20.31 ± 0.004	189.78 ± 4.13	226.02 ± 30.00
Sm	18 ± 0	3.72 ± 0.003	11.93 ± 0.56	Nd
Eu	3.11 ± 0.12	1.238 ± 0.0006	2.35 ± 0.13	Nd
Gd	27.57 ± 0.45	1.163 ± 0.001	10.40 ± 0.82	Nd
Tb	2.26 ± 0.19	Nd	1.60 ± 0.12	Nd
Dy	35.23 ± 1.77	0.44 ± 0.001	9.5 ± 0.56	Nd
Tm	1.89 ± 0.72	Nd	0.77 ± 0.06	Nd
Yb	7.64 ± 1.96	Nd	5.27 ± 0.47	Nd
Lu	1.26 ± 0.51	0.3 ± 0.0002	0.72 ± 0.042	Nd
Nd	88.40 ± 5016	Nd	63.50 ± 1.78	Nd
Pr	Nd	9.53 ± 0.004	18.35 ± 0.60	100.32 ± 2.45
Ho	Nd	Nd	1.97 ± 0.19	Nd
Er	Nd	4.3 ± 0.004	5.38 ± 0.28	Nd

Nd = Not detected

In Table 5 the REEs composition of the Matla CFA determined by ENAA, ICP-OES, LA-ICP-MS and XRF are presented. Ten REEs were determined by ICP-OES, whilst only three REEs were determined by XRF technique. LA-ICP-OES and NAA allowed determination of 16 and 12 REEs, respectively. Sc, La, and Ce were the only REEs determined by XRF technique due to unavailability of a suitable standard for calibrating the REEs. Moreover, the XRF cannot compete with other well established techniques such as INAA and ICP-MS [39]. The concentrations of the REEs in the Matla CFA obtained by ICP-OES were also much lower compared to the REE concentrations obtained when the Matla CFA was analysed using XRF, LA-ICP-OES and ENAA. This lower concentration of REEs may also be attributed to the sample preparation used for the ICP-OES as it was observed for the major element concentrations. The concentration of the REEs in the Matla fly ash samples obtained by LA-ICP-MS and ENAA are proportional to the given concentrations of REEs in the SRM. Hence LA-ICP-MS and ENAA may be considered as better techniques than ICP-OES or XRF analysis in determining the REE concentrations in coal fly ash.

Conclusions

For the first time a total of 54 elements, among them 16 rare earths, were determined in the Matla CFA using ENAA, ICP-OES, LA ICP-MS, and XRF techniques. The

concentration level of the major elements in the CFA determined by ENAA and XRF is very similar apart from Na and correlates well with that of the certified SRM NIST 1633b. Determination of trace and REEs content obtained by the ENAA and LA ICP-MS techniques is more reliable than their determination by the XRF or ICP-OES techniques. CFA can be considered as a potential source for extraction of REEs for industrial use. The hazardous impact of heavy metals such as Cd, Pb, As, Sr, U, Th, in particular, observed in the studied CFA should be monitored in the reuse of fly ash in agriculture and construction materials.

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References

- [1] Haynes RJ. [Reclamation and revegetation of fly ash disposal sites - Challenges and research needs](#). J Environ Management. 2009;90:43-53. DOI:10.1016/j.jenvman.2008.07.003.
- [2] Fulekar M, Dave J. [Disposal of fly ash-an environmental problem](#). Intern J Environ Studies. 1986;26:191-215. DOI: 10.1080/00207238608710257.
- [3] Jankowski J, Ward C, French D, Groves S. [Mobility of trace elements from selected Australian fly ashes and its potential impacts on aquatic ecosystems](#). Fuel. 2006;85:243-256. DOI: 10.1016/j.fuel.2005.05.028.
- [4] Sushil S, Batra S. [Analysis of fly ash heavy metal content and disposal in three thermal power plants in India](#). Fuel 2006;85:2676-2679. DOI: 10.1016/j.fuel.2006.04.031.
- [5] Gitari W, Petrik L, Etchebers O, Key Dm, Okujeni C. Utilization of fly ash for treatment of coal mines wastewater: Solubility controls on major inorganic contaminants. Fuel. 2008;87:2450-2462. DOI: 10.1016/j.fuel.2008.03.018.
- [6] Dellantonio A, Fitz W, Custovic H, Repmann F, Schneider B, Grünewald H, et al. Environmental risks of farmed and barren alkaline coal ash landfills in Tuzla, Bosnia and Herzegovina. Environ Pollut. 2008;153:677-686. DOI: 10.1016/j.envpol.2007.08.032.
- [7] Senapati M. Fly ash from thermal power plants - waste management and overview. Current Science. 2011;100(12):1791-1974.
- [8] Neupane G, Donahoe R. [Leachability of elements in alkaline and acidic coal fly ash samples during batch and column leaching tests](#). Fuel 2013;104:758-770. DOI: 10.1016/j.fuel.2012.06.013.
- [9] Adriano DC, Page PL, Elseewi AA, Straughan I. Utilization and disposal of fly ash and other coal residues in terrestrial ecosystems: A review. J Environ Qual. 1980;9(3):333-344. DOI: 10.2134/jeq1980.00472425000900030002x.
- [10] Asokana P, Saxena M, Asolekar S. Coal combustion residues - environmental implications and recycling potentials. Resources, Conservation and Recycling. 2005;43:239-262. DOI: 10.1016/j.resconrec.2004.06.003.
- [11] Dutta B, Khanra S, Mallick D. [Leaching of elements from coal fly ash: Assessment of its potential for use in filling abandoned coal mines](#). Fuel. 2009;88:1314-1323. DOI: 10.1016/j.fuel.2009.01.005.
- [12] Izquierdo M, Querol X. Leaching behaviour of elements from coal combustion fly ash: An overview. International J Coal Geol. 2012;94:54-66. DOI: 10.1016/j.coal.2011.10.006.
- [13] Blissett R, Rowson N. A review of the multi-component utilisation of coal fly ash. Fuel. 2012;97:1-23. DOI: doi.org/10.1016/j.fuel.2012.03.024.
- [14] Vassilev S, Vassileva C. Behaviour of inorganic matter during heating of Bulgarian coals 2. Subbituminous and bituminous coals. Fuel Processing Technol. 2006;87:1095-1116. DOI: 10.1016/j.fuproc.2006.08.006.
- [15] Smolka-Danielowska D. Rare earth elements in fly ashes created during the coal burning process in certain coal-fired power plants operating in Poland - Upper Silesian Industrial Region. J Environ Radioactiv. 2010;101:965-968. DOI: 10.1016/j.jenvrad.2010.07.001.

- [16] Kashiwakura S, Kumagai Y, Kubo H, Wagatsuma K. Dissolution of rare earth elements from coal fly ash particles in a dilute H₂SO₄ solvent. *Open J Phys Chem*. 2013; 3:69-75. DOI: 10.4236/ojpc.2013.32009.
- [17] Davison R, Natusch D, Wallace J. Trace elements in fly ash dependence of concentration on particle size. *Environ Sci Technol*. 1974;13:1107-1113. DOI: 10.1021/es60098a003.
- [18] McNally D, Crowley-Parmentier J, Whitman B. Trace metal leaching and bioavailability of coal-generated fly ash. *Int Res J Environ Sci*. 2012;1(5):76-80.
- [19] Parami V, Sahoo S, Yonehara H, Takeda S, Quirit L. Accurate determination of naturally occurring radionuclides in Philippine coal-fired thermal power plants using inductively coupled plasma mass spectrometry and γ -spectroscopy. *Microchem J*. 2010;95:181-185. DOI: 10.1016/j.microc.2009.11.008.
- [20] Dogan O, Symsek Ö, Nuhoglu Y, Kopya M, Ertugrul M. Geochemistry, soil, and environmental sciences x-ray fluorescence spectrometry analysis of trace elements in fly ash samples of Kemerköy thermal power plants. *J Trace Microprobe Techniques*. 2001;19(2):289-295. DOI: 10.1081/TMA-100002218.
- [21] Spears D. The use of laser ablation inductively coupled plasma-mass spectrometry (LA ICP-MS) for the analysis of fly ash. *Fuel*. 2004;83(13):1765-1770. DOI: 10.1016/j.fuel.2004.02.018.
- [22] Rowe JJ, Steinnes E. Instrumental activation analysis of coal and fly ash with thermal and epithermal neutrons. *J Radioanal Chem*. 1977;37:849-856. DOI: 10.1007/BF02519396.
- [23] Hansen Y, Notten P, Petrie G. A life cycle impact assessment indicator for ash management in coal-based power generation. *The Journal of The South African Institute of Mining and Metallurgy*. 2002, July/August, 299-306.
- [24] Petrik L, White R, Klink M, Somerset V, Burgers C, Frey M. Utilisation of South African fly ash to treat acid mine drainage, and production of high quality zeolites from the residual solids. In: *Proceedings of the 2003 International Ash Utilisation Symposium*. University of Kentucky, USA, Paper no. 61. <http://www.flyash.info>.
- [25] Dmitriev AY, Pavlov SS. Automation of quantitative determination of elemental content of samples by neutron activation analysis at the reactor IBR-2 in FLNP JINR. *Physics of Particles and Nuclei Letters*. 2013;10(178):58-64. DOI: 10.1134/S1547477113010056.
- [26] National Institute of Standards and Technology (NIST). Certificate of Analysis, Standard Reference Material, 1633. 2008.
- [27] Jackson BP, Miller WP. Arsenic and selenium speciation in coal fly ash extracts by ion chromatography-inductively coupled plasma mass spectrometry. *J Analyt Atomic Spectrometry*. 1998;13:1107-1112. DOI: 10.1039/A806159I.
- [28] www.mariscigrp.org/elconv.html.
- [29] Bode P, Greenberg RR, De Nadai Fernandes EA. Neutron activation analysis: a primary (ratio) method to determine SI-traceable values of element content in complex samples. *Chimia*. 2009;63(10):678-680. DOI: <http://dx.doi.org/10.2533/chimia.2009.678>.
- [30] ASTM, Standard specification for fly ash and raw or calcined natural pozzolan for use as mineral admixture in Portland cement concrete. Pennsylvania: American Society for Testing and Materials; 1994.
- [31] McCarthy GJ. X-ray powder diffraction for studying the mineralogy of fly ash. *MRS Proceedings*, 1987;113:75-86. DOI: 10.1557/PROC-113-75.
- [32] Hou X, Jones B. Inductively Coupled Plasma/Optical Emission Spectrometry. In: *Encyclopedia of Analytical Chemistry*. Meyers RA, editor. Chichester: John Wiley & Sons Ltd; 2000; 9468-9485.
- [33] Chen M, Ma L. Comparison of three aqua regia digestion methods for twenty Florida soils. *Soil Sci Soc Am J*. 2001;65:491-499. DOI: 10.2136/sssaj2001.652491x.
- [34] Enamorado-Báez S, Abril L, Gómez-Guzmán J. Determination of 25 trace element concentrations in biological reference materials by icp-ms following different microwave-assisted acid digestion methods based on scaling masses of digested samples. *ISRN Analyt Chem*. 2013:1-14. DOI: 10.1155/2013/851713.
- [35] Hannaker P, Haukka M, Sen S. Comparative study of ICP-AES and XRF analysis of major and minor constituents on geological materials. *Chem Geol*. 1984;42:319-324.
- [36] Brown R, Milton M. Analytical techniques for trace element analysis: an overview. *Trends in Analyt Chem*. 2005;24(3):266-274. DOI: 10.1016/j.trac.2004.11.010.
- [37] Zhang Y, Jiang Z, He M, Hu B. Determination of trace rare earth elements in coal fly ash and atmospheric particulates by electrothermal vaporization inductively coupled plasma mass spectrometry with slurry sampling. *Environ Pollut*. 2007;148:459-467. DOI: 10.1016/j.envpol.2006.12.004.
- [38] Iwashita A, Nakajima T, Takanashi H, Akira Ohki A, Yoshio Fujita Y, Yamashita T. Effect of pretreatment conditions on the determination of major and trace elements in coal fly ash using ICP-AES. *Fuel*. 2005;85:257-263. DOI:10.1016/j.fuel.2005.04.034.

- [39] Misra N. Total reflection X-ray fluorescence and energy-dispersive X-ray fluorescence characterizations of nuclear materials. *Pramana J Phys.* 2011;76(2):201-212. DOI: 10.1007/s12043-011-0046-y.

SKŁAD PIERWIĄTKOWY POPIOŁÓW LOTNYCH: STUDIUM PRZYPADKU Z WYKORZYSTANIEM METOD NUKLEARNYCH I ANALITYCZNYCH

Abstrakt: W celu określenia składu pierwiastkowego popiołów lotnych z elektrowni węglowej Malta w prowincji Mpumalanga w Republice Południowej Afryki wykorzystano epitermalną, neutronową analizę aktywacyjną oraz ICP-OES, LA ICP-MS i XRF. Za pomocą czterech techniki analitycznych oznaczono stężenia 54 głównych i śladowych pierwiastków oraz pierwiastków ziem rzadkich. Wyniki porównano, a także opisano różnice pokazujące zalety oraz wady każdej z wykorzystanych metod. Wykazano, że skład pierwiastkowy popiołu lotnego jest porównywalny ze składem standardowego materiału odniesienia NIST Węgiel Popiół Lotny 1633b.

Słowa kluczowe: popioły lotne z węgla, epitermalna neutronowa analiza aktywacyjna, dyfrakcja rentgenowska, optyczna spektroskopia emisyjna indukcyjnie sprzężona, ablacja laserowa indukcyjnie sprzężona ze spektroskopią masową