Fire hazard in coal waste dumps – selected aspects of the environmental impact

Zenon Różański
Faculty of Mining and Geology, Silesian University of Technology, Akademicka 2, 44-100 Gliwice, Poland
zenon.rozanski@polsl.pl

Abstract. In areas of coal basins all over the world, wastes are produced along with the process of coal exploitation. Formerly, the wastes were deposited to waste dumps in large amounts. The presence of coal waste dumps at the surface is strictly related to their environmental impact. One of the more significant problems related to the environmental impact is constituted by spontaneous fires. This paper presents the selected aspects related to the negative impact of spontaneous fires on the environment. Based on own experience and scientific literature, the causes and the mechanism behind the formation of fires as well as the factors impacting the development of fires were presented. The paper also concerns the environmental impact resulting from the process of leaching of contaminants from the wastes to surface and ground water as well as fire-related dust and gas emissions to atmosphere. It has been found that the emission of substances to the atmosphere is the most disturbing to the environment. The emissions include significant amounts of toxic substances and greenhouse gases.

1. Introduction
Underground exploitation of mineral resources and the production of significant amounts of waste rock that are extracted to the surface are inseparable. In hard coal mining, the wastes are constituted by barren rock accompanying coal seams. The wastes which are produced alongside the exploitation and processing of coal are commonly called mining wastes, although the name encompasses also some power production wastes, that is, wastes produced in the process of coal combustion. These wastes include i.a. ashes, slags and fly ash.

Due to the high output of numerous mines in coal basins, enormous amounts of mining wastes were produced, and the problem of neutralising these wastes emerged. It was only at the end of the previous century that large-scale activities aimed at the use of the mining wastes were taken up. Beforehand, a larger part of the wastes was deposited at the surface. Numerous dumps were established by the coal mines or in the nearest vicinity of the mines, where enormous amounts of barren rock and often other kinds of waste materials were deposited.

There are hundreds of objects constituting the location of coal mining waste in the coal basins around the world [1, 2]. There are approx. 250 such objects in Poland, yet there are countries in which this number is even higher. For example, in China, the number of dumping grounds on which gangue from bituminous coal mines was deposited exceeds 1700, and their presence constitutes a significant environmental problem [3].
Besides the mining dumps’ disadvantageous impact on the landscape, the dumps may have a negative impact on the environment. Their chemical composition and the possibility of leaching of substances are a source of pollution of surface water, ground water and soil [4, 5, 6, 7]. Certain amounts of fine-grained material contained therein may be easily transported by wind thus contributing to the increased dust levels in the atmosphere. Their most disturbing effect is, however, exhibited upon the emergence of fire in these objects. Fires of mining waste dumps are a typical and common phenomenon. Such fires constitute a source of emissions of gas substances to the atmosphere and increase the dust levels in air. Due to the high temperatures accompanying the fires, they contribute to the general safety hazard posed to people present within the outline of the dumps [8, 9, 10, 11, 12, 13, 14, 15]. The main cause of the fires is the spontaneous process of low-temperature oxidation of coal and pyrite contained in the wastes from Carboniferous deposits. This process is accompanied by an increased production of heat and increased temperatures. Most of the old cone-shaped dumps, where the wastes were built by free deposition, have formerly been subject to spontaneous combustion. In some of the dumps, the thermal activity continues since several dozen years until now.

The article presents selected environmental aspects related to the presence of mining waste dumps and the occurring fires thereof. Own research results and the results obtained by other researchers were used in the paper.

2. Causes of fires of coal waste dumps

The waste material deposited in waste dumps consists mainly of gangue. However, it also contains substantial amounts of combustible constituents. Along with gangue, coal is deposited in waste dumps in the form of bands or as a constituent of rocks that coexist with coal seams, such as coal clay or shale. A significant constituent of coal waste is also pyrite [16]. Both coal and pyrite are chemically active in relation to oxygen, and the reactions they go into are exothermic. Moreover, other combustible materials may also be deposited together with gangue in waste dumps: fragments of conveyor belts, wooden components of mine supports, etc.

The presence of significant amounts of combustible materials in coal mining waste dumps is the main cause of the occurrence of fires at these sites. Depending on the cause of fire occurring in waste coal deposition sites, fires may be classified as:

- exogenous,
- endogenous.

Exogenous fires arise as a result of external heat coming from sources such as bonfires, grass burning, welding operations, hot ash disposed on the dump with other mining waste, etc. Such fires may be prevented relatively easy by avoiding the activities mentioned above. Lack of awareness makes the common practice of grass burning a frequent cause of waste dump fires.

Endogenous fires are the result of natural low-temperature process of the oxidation of a carbonaceous or other substance, e.g. pyrite. Oxygen access to the bulk of the dump promotes oxidation of carbonaceous substances, which is accompanied by heat generation. The mechanism of initiating endogenous fires is similar to that of an underground fire [17]. The conditions that must occur simultaneously for a fire to start include:

- appropriate amount of substance chemically active in contact with oxygen in air,
- access of air to the bulk of the dump,
- heat accumulation inside the dump (amount of heat generated in exothermic reactions exceeds the amount of heat given off to the environment).

2.1. Mechanism of initiation of endogenous fires

Despite many years of research, the process of coal self-heating, which is the main cause of coal waste dump fires, has still not been fully comprehended. According to Banerjee and Pone, oxidation of carbonaceous substances proceeds in four stages [18, 19]:
1) physical adsorption of oxygen, initially accompanied by a rise in temperature (by 30 to 50°C);
2) chemical absorption (temperature above 50°C), which leads to the formation of unstable, oxidized hydrocarbon compounds and the so-called peroxygen complexes,
3) decomposition of oxidized hydrocarbons and peroxygen complexes to provide additional oxygen amounts at subsequent stages of oxidation (temperature range above 70°C),
4) process acceleration, temperature increase to ignition point above 150°C (ignition point depends on coal rank).

These processes may lead to temperature increase to even above 1000°C. In the meanwhile oxygen consumption is accelerated and gaseous products are released violently.

The course of self-heating and spontaneous ignition of coal is shown in figure 1. In the first stage of fire development, self-heating of coal (waste material) proceeds and the temperature slowly rises. This period is called the induction (or incubation) period. When temperature reaches critical value ($T_{cr}$ = ca. 60-80°C), the rate of reaction increases rapidly. When the conditions listed above are met, temperature increases to ignition temperature $T_i$ (the value of which depends on the type of coal) at which ignition occurs and in consequence fire starts. If critical temperature is not reached or if conditions change to promote heat abstraction, then a cooling period starts. The self-heated coal undergoes weathering.

![Figure 1. Course of the process of spontaneous ignition of coal [17].](image-url)

Thermal phenomena result from many reactions of the constituents of the waste material or of secondary products of reactions that take place inside the coal waste dumps. These reactions include exothermic reactions that cause temperature increase, and endothermic reactions which, however, result in products that participate in subsequent exothermic reactions. The most important of them are listed in Table 1 along with enthalpy differences $\Delta H$ that are a measure of emitted (−) or absorbed (+) heat.

Due to the latent nature of the initial phase of endogenous fires, detecting them is difficult, and consequently combating them is more complex.
Table 1. Basic chemical reactions occurring during the self-heating of coal waste.

| Chemical reaction                                      | Enthalpy difference $\Delta H$ (kJ mol$^{-1}$) |
|--------------------------------------------------------|-----------------------------------------------|
| $\text{C + H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}$ | +118.5                                        |
| $\text{CO + H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2$ | −42.3                                         |
| $\text{CO} + 3\text{H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O}$ | −206.0                                        |
| $\text{C} + 2\text{H}_2 \rightarrow \text{CH}_4$             | −87.5                                         |
| $2\text{C} + \text{O}_2 \rightarrow 2\text{CO}$              | −123.1                                        |
| $\text{C} + \text{O}_2 \rightarrow \text{CO}_2$              | −406.0                                        |
| $\text{C} + \text{CO}_2 \rightarrow 2\text{CO}$              | +159.9                                        |
| $2\text{FeS}_2 + 7\text{O}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{FeSO}_4 + 2\text{H}_2\text{SO}_4$ | −2544.0                                       |

2.2. Factors influencing the fire hazard

There is a number of factors that have an effect on the probability of occurrence and intensity of thermal phenomena associated with self-heating. These can be classified into two groups:

- internal factors - which determine the reactivity of the waste material in relation to oxygen of air at low temperatures,
- external factors - related to ambient conditions or to features of the waste dump that have an effect on filtration capacity and the heat balance.

Reactivity of waste material depends on its physicochemical properties. The most important of these is material composition, which determines the content of combustible materials in the waste, in this case mainly coal and pyrite.

Grain size distribution in the material is also important. It depends on the origin of the waste material. Waste originating directly from mining or sorting operations contain coarse grains, or even large chunks. Mechanical processing and coal cleaning processes yield fine-grained material. Disposal of coal waste directly onto dumps by belt conveyors and rail cars, without any fire-preventive processing, which was a general practice in the past, caused the so-called grain segregation, which promoted self-heating [20]. When waste is disposed on the dump, fine grains tend to accumulate in the top and middle parts of the dump, while the coarse grains slide down the slope and gather in the bottom part of the dump or around it. The thus formed structure of the dump (figure 2) creates advantageous conditions for air penetration into the bulk of the dump, and consequently for initiating oxidation of carbonaceous materials. Fine waste from processing plants may cause partial self-sealing of the dump. This may help reduce air penetration into the dump, but on the other hand, processing waste contains more combustible constituents.

Susceptibility to spontaneous ignition of coal contained in waste also depends on carbon content (rank of coal). According to W. Gabzdyl [21] the study of the natural susceptibility of coal to spontaneous ignition requires, in the first place, the analysis of macerals. Vitrinite is the most susceptible to spontaneous ignition, whereas in the Upper Silesian Coal Basin the susceptible low-rank coals contain more than 30% of fusinite and semifusinite, that is macerals of the inertinite group. An important feature (in addition to petrographic composition) is carbon content (rank of coal) and macrostructure of the seam from which coal is derived.
Figure 2. Structure of cone-shaped dumps that promotes air penetration.

Low-rank coals containing thick-bedded vitrite are considered to be the most susceptible to spontaneous ignition. Susceptibility to spontaneous ignition depends on the content of mineral matter, particularly of sulphides (pyrite).

Higher rank coals, despite having higher carbon content, are characterised by lower susceptibility to spontaneous ignition. This is due to lower specific surface area and low volume of micropores [22], which reduces surface adsorption of oxygen. Coal rank also determines the composition of volatile components of coal, which has an effect on the ignition temperature of coal. Higher rank coals contain more highly aromatic hydrocarbons (with higher ignition temperature), and the volatile matter of lower rank coals contain more aliphatic compounds of lower ignition temperature. For the reasons listed above, spontaneous ignition is rare in coal waste dumps of coking coal mines in the Jastrzębie region.

Important external factors that affect the susceptibility to spontaneous ignition of waste dumps include the applied haulage, dumping and fire prevention methods. They have an effect on the air tightness of the waste dumps. As mentioned before, dumps formed in an uncontrolled manner have an unfavorable structure as regards fire hazard. The applied methods of dumping and fire prevention must ensure the highest possible compaction of the deposited waste material. It is assumed that the minimum value of the compaction factor when banks of coal waste are formed is $I_s = 0.95$ [23]. Waste dumps formed nowadays are much less susceptible to the occurrence of thermal phenomena. Dumping of waste material now does not consist in uncontrolled deposition, but rather in planned construction of dumps with elimination, or at least minimization, of factors that promote self-heating and spontaneous ignition. Factors that affect the filtration capacity of a waste dump, which also result from the manner of dump formation, include its shape and height. This is related to the action of wind on the slopes of the dump. The most exposed to fire hazard are slopes of the dump that are high, steep and situated on the windward side. For this reason, at particular risk are the slopes of conical dumps of significant height and of high angle of slope, due to both wind action and grain segregation described before. In Upper Silesia (particularly in the Rybnik Coal Area) there are many examples of conical waste dumps that have already burned out or that have been thermally active for several dozen years (Figure 3).

Waste tips that are level with the ground, and therefore have no slopes, are much less susceptible to self-heating because of the reduced surface exposed to air penetration induced by winds. Self-heating is also affected by other weather factors. Solar radiation causes heating of the uppermost layers of waste material, which affects the heat balance of the waste dump. Rains, particularly heavy rainfalls, cause damage to the slopes by forming fissures, furrows or breaches which facilitate air access to the bulk of the dump [20]. Atmospheric pressure variations (decrease, increase) cause a phenomenon that is called baric aeration [24]. Increased pressure forces air into the bulk of the dump. Under lower pressure air moves in the opposite direction.
Figure 3. Examples of cone-shaped waste dumps in Poland – local absence of snow cover is an evidence of thermal activity of waste material.

The scope and manner of applying fire prevention is a very important factor influencing the susceptibility of waste dumps to spontaneous ignition. At present, waste dumps are constructed in a planned manner and methods and means are applied to effectively reduce the risk of spontaneous ignition. Methods of prevention depend on the conditions determining the probability of fire occurrence mentioned before. They are based mainly on reducing the concentration of combustible matter in the deposited material by adding inert material, on reducing the capacity to accumulate heat and on cutting off oxygen access to the bulk of the dump.

The evaluation of the simultaneous effect of the factors mentioned, consisting in assigning numerical weights to these factors, may form a basis for assessing fire hazard in coal waste dumps [20, 23]. A modified method of assessing fire hazard developed by the Central Mining Institute (GIG) takes into account the following factors [23]:

- type of dump,
- susceptibility of waste to self-ignition,
- scope and frequency of monitoring,
- compaction factor,
- physical properties of waste (compactibility).

At present, of the 250 or so objects formed of coal waste in Polish coalfields, at least a dozen or more manifest thermal activity. This results in adverse environmental effects.

3. Environmental impact of burning coal waste dumps

The existence of coal waste dumps is in itself a source of environmental impact. This is manifested by affecting the soil and water environment and the air surrounding the objects.

Waste deposited in dumps is a source of contaminants that are washed out into surface and ground waters [25, 26, 27].

In the case of managing coal waste on ground surface (which includes waste dumps), the results of the analysis of water extracts thereof are compared with the permissible values specified in the Ordinance of the Minister of Environment of 24 July 2006 on the conditions of discharging wastewater to waters and soil and on substances particularly harmful to aqueous environment [28].

Analysis of water extracts of coal waste in the Upper Silesian Coal Basin [27] has shown that the determined basic ions (sodium, potassium, chlorides, sulphates) are washed out in quantities much lower than those permissible for wastewater discharged to soil or waters and specified in the Ordinance of the Minister of Environment (table 2). Some mining waste, however, when used in the environment, due to chlorides content, may have an adverse effect on vegetation growth and may lead to contamination of surface waters, or even of ground waters.
Table 2. Mean and maximum results of the determination of pH and composition of water extracts of waste from mines of the various regions of the Upper Silesian Coal Basin [27] and permissible values [28]

| Region                  | Concentration | pH  | Na⁺ | K⁺  | Cl⁻ | SO₄²⁻ |
|-------------------------|---------------|-----|-----|-----|-----|-------|
|                         |               |     | mg dm⁻³ |     |     |       |
| Central                 | mean          | 8.27| 56.0| 2.8 | 62.3| 9.8 |
|                         | maximum       | 9.15| 161.0| 5.5 | 255.9| 32.5 |
|                         | medium        | 8.11| 99.6| 4.9 | 134.7| 25.5 |
|                         | maximum       | 9.24| 435.0| 13.4| 867.0| 52.7 |
| East                    | mean          | 8.28| 38.0| 3.8 | 24.9| 6.3 |
|                         | maximum       | 8.92| 63.0| 6.1 | 72.2| 25.9 |
|                         | medium        | 8.74| 69.0| 2.4 | 68.6| 11.2 |
|                         | maximum       | 9.06| 102.0| 4.2 | 110.2| 14.8 |
| Bytom                   | mean          | 8.28| 38.0| 3.8 | 24.9| 6.3 |
|                         | maximum       | 8.92| 63.0| 6.1 | 72.2| 25.9 |
|                         | medium        | 8.28| 66.6| 3.5 | 77.1| 13.7 |
|                         | maximum       | 9.24| 435.0| 13.4| 867.0| 52.7 |
| Rybnik-Wodzislaw        | mean          | 8.74| 69.0| 2.4 | 68.6| 11.2 |
|                         | maximum       | 9.06| 102.0| 4.2 | 110.2| 14.8 |
| Total                   | mean          | 8.28| 66.6| 3.5 | 77.1| 13.7 |
|                         | maximum       | 9.24| 435.0| 13.4| 867.0| 52.7 |
|                         | permissible   | 6.5-9.0| 800| 80 | 1000| 500 |

Leachates that form in mining waste deposits constitute a real threat for the soil environment and for ground waters because of high loads of heavy metals (table 3).

The processes of leaching water soluble components proceed at varying rates that depend on physicochemical transformations that occur in Carboniferous rocks. Physical, chemical and biochemical weathering of waste gathered in the dumps is of high importance in this process. The content of components in freshly deposited waste is relatively low. Much higher quantities of contaminants arise in the physicochemical process of waste weathering [29].

Thermal processes occurring during self-heating and fires of waste dumps are also significant. The degree of thermal conversion of waste has an effect on metal leachability. As shown by the example of waste dump no. 4 at the Nowy Wirek Coal Mine, much more elements (Al, Co, Cr, Cu, Ni) are leached from samples of deeply thermally transformed samples (sinters) than from samples of thermally intact (unburned) waste and moderately thermally transformed (burned out) waste. This is due to the presence of significant amounts of glaze in sinters, such glaze being subject to devitrification and release of metals contained therein [30].

Table 3 shows results of determination of trace elements in samples of soil taken in the vicinity of a waste dump where the deposited material had undergone deep transformation as a result of thermal processes associated with fires. The table also shows similar results for water samples taken from a lagoon formed after excavation of part of the waste material. For most of the listed elements, the content thereof in water from the lagoon is several-fold higher than the values reported for surface waters in the region of Ruda Śląska [31]. As concerns the soil studied, limits (specified in the Ordinance of the Minister of Environment of 9 September 2002 on soil and ground quality standards) have not been exceeded, with the exception of Ba and Zn. However, the values determined were much higher than those of the background specified in the Geochemical Atlas of the Upper Silesia for the following elements: Ba, Co, Cr, Cu and Ni.

Table 3. Content of trace elements in soil and water samples taken in the vicinity of the waste dump in Ruda Śląska [32].

| Content of the elements | Al  | As  | Ba  | Cd  | Co  | Cr  | Cu  | Fe  | Ni  | Pb  | Zn  |
|-------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| in soil                 | nd  | <2  | 282 | 1120| <0.5| 5.39| 50  | 1.57| 5.96| nd  | 14  |
|                         | <2  | 1.0 |     |     | 0.031| 0.57| 0.157| 0.294|     | 0.217| nd  |
| in water                | 0.045| 0.559| 0.423| -   | 0.031| 0.057| 0.157| 0.294| 0.217| nd  | 0.921|

nd - no data (analysis not performed)
Another environmental component that is exposed to the impact of coal waste deposits is air. Adverse effects are related to emissions of dust, greenhouse and toxic gases [8].

Waste dumps contain fine-grained material which is carried away by wind and causes particulate pollution in air. This can easily be abated by biologically reclaiming the waste dumps. However, there are still many objects that have not been reclaimed at all or that have been reclaimed to an insufficient extent only.

If fires occur in waste dumps, pollutant emissions to air increase substantially. Dust content in air may attain grievous levels. Because of increased temperature and intensified evaporation, the material in the waste dump is freed of moisture. Dry particulates levitate in air more easily. If in the course of a fire, coal contained in waste is transformed into ash, the tendency to be carried away by wind is intensified, particularly during operations associated with combating fire, removal and transportation of burned material or reclamation works (figure 4).

Dust from mining waste dumps does not only affect human health, but can also contaminate the adjacent soil. Bianhas studied such impact of waste dumps on the soil. An increased content of Cu, Pb, Cd, Cr and Zn was exhibited in the soil in vicinity of a mining waste dump that was on fire, even at a distance of 100 m from its slopes [3].

![Figure 4. Dusting in waste dump during fire combat and other operations.](image_url)

Gases evolving during a fire are emitted from the surface of the thermally active waste dump into the atmosphere (figure 5). The number and amount of emitted pollutants depend on many factors, among them:

- chemical composition of the waste,
- oxygen and water access to the bulk of the dump,
- stage of fire development and depth,
- temperature of waste material,
- gas transport in the interior of the dumping ground,
- weather factors, e.g. atmospheric pressure, wind etc.

The main gaseous substances emitted during endogenous fires are the products of reactions listed in table 1. These include: CO₂, CO, water vapour, CH₄, H₂. However, there are many other products resulting from other heat-induced reactions. As the waste material contains sulphur, sulphur dioxide SO₂ and hydrogen sulphide H₂S are emitted. Evidence of that is yellow efflorescence on the surface of the waste dump (figure 6).
Figure 5. Gases emission from the surface of burning waste dumps.

Figure 6. Sulphur efflorescence in gases outflow places.

Example results of chromatographic determination of main gas concentrations in samples taken from the fire-infested area of the Wrzosy dump of Rydułtowy-Anna Coal Mine are shown in Table 4. Concentration of toxic carbon monoxide above the surface of the waste dump within its thermally active area was above the permissible limits.

Table 4. Concentrations of gases in the thermally active area measured at the outlets of boreholes and 0.5 m above the surface of the Wrzosy waste dump of the Rydułtowy-Anna Coal Mine.

| Measurement location | Average fire gas concentrations, (vol.%) | Interior temperature (°C) (depth) |
|----------------------|-----------------------------------------|----------------------------------|
| Borehole 1           | O₂ 12.45, CO₂ 6.15, CO 4.4, H₂ 1.185, CH₄ 0.728, C₂H₆ 0.095, N₂ 74.2 | 420 (1.0m)                      |
| Borehole 2           | O₂ 19.2, CO₂ 0.975, CO 0.2805, H₂ 0.0515, CH₄ 0.0515, C₂H₆ 0.01, N₂ 78.95 | 99.52                           |
| Borehole 3           | O₂ 12.9, CO₂ 5.01, CO 1.1, H₂ 0.226, CH₄ 0.226, C₂H₆ 0.07, N₂ 79.9 | 99.43                           |
| Borehole 4           | O₂ 13.6, CO₂ 6.345, CO 0.1495, H₂ 0.1665, CH₄ 0.1665, C₂H₆ 0.04, N₂ 78.9 | 99.37                           |
| Borehole 5           | O₂ 14.3, CO₂ 5.53, CO 0.5, H₂ 0.277, CH₄ 0.277, C₂H₆ 0.06, N₂ 78.55 | 99.49                           |
| Borehole 6           | O₂ 20.4, CO₂ 0.62, CO 0.005, H₂ 0.028, CH₄ 0.028, C₂H₆ 0, N₂ 78.9 | 99.98                           |
| 0.5m *               | O₂ 20.8, CO₂ 0.11, CO 0.005, H₂ 0, CH₄ 0, C₂H₆ 0, N₂ 78.9 | 99.82                           |
| 0.5m *               | O₂ 20.8, CO₂ 0.1, CO 0.006, H₂ 0, CH₄ 0, C₂H₆ 0, N₂ 78.95 | 99.81                           |
| 0.5m *               | O₂ 20.8, CO₂ 0.08, CO 0.005, H₂ 0, CH₄ 0, C₂H₆ 0, N₂ 78.5 | 99.39                           |
| 0.5m *               | O₂ 20.9, CO₂ 0.07, CO 0, CH₄ 0, C₂H₆ 0, N₂ 78.9 | 99.87                           |

* above surface of the dump

Investigations [9, 11] have shown that fire-infested waste dumps are a major source of fugitive emissions of greenhouse gases. Potential rate of these emissions has been determined on the basis of...
investigations of the amounts of gases emitted from a defined surface area and concentrations of CO$_2$ and CH$_4$ in the gas mixture formed. The obtained measurement results indicate that from 1 m$^2$ of a highly fire-infested waste dump (interior temperature more than 400°C), under the assumption that the intensity of thermal phenomena is constant, ca. 8 MgCO$_2$ and 0.2 MgCH$_4$ is emitted to the air every year [9]. When the global warming potential of methane (GWP100 = 23 according to IPCC) is taken into account, this corresponds to equivalent carbon dioxide of 12.6 Mg CO$_2$e.

Limited oxygen availability, presence of water in pores and elevated temperature make the processes that proceed inside the waste dump similar to those of low temperature carbonization (at lower temperature) or to coking (at higher temperature) of coal. This is accompanied by evolution of subsequent gaseous substances. Under such conditions, compounds having genotoxic, mutagenic and carcinogenic properties are formed. These include polycyclic aromatic hydrocarbons (PAHs). This was confirmed by research conducted by P. Kuna-Gwoźdźiewicz (GIG) [33]. Fire gases from one of waste dumps have been shown to contain two- and three-ring hydrocarbons, such as: naphthalene (Nap), acenaphthene (AcP), fluorene (Flu), phenanthrene (PA) and anthracene (Ant). The results of measurements are shown in table 5.

| PAH     | Concentration (mg·m$^{-3}$) | RCC* |
|---------|----------------------------|------|
| Nap     | 9.911                      |      |
| AcP     | 0.084                      |      |
| Flu     | 0.123                      |      |
| PA      | 0.129                      |      |
| Ant     | 0.004                      |      |
| Σ PAH   | 10.251                     |      |

*relative carcinogenic coefficient (in relation to benzo[a]pyrene) according to [34].

The emissions of the PAHs referred to above from thermally active dumps were also confirmed by research conducted by Howaniec [35]. Insignificant amounts of other carcinogenic substances such as Fluoranthene (Flu), Pyrene (Pyr), Chrysene (Chr) have also been found in the fire-related gas. Their average concentrations, however, did not exceed 1 μg·m$^{-3}$.

4. Conclusions

Coal mining waste dumps affected by fires constitute a significant environmental problem in coal basins all over the world. The prevention of spontaneous fires is still relatively difficult and costly, especially in case of old dumps with large volumes and disadvantageous shapes. Due to the above, it is difficult to eliminate this disadvantageous phenomenon.

Dumps affected by fires exhibit an adverse impact on the nearest environment. It manifests itself by leaching of pollutants, which are transported to the surface and ground water as well as the soil. Usually, however, the allowable concentrations specified in legal regulations are not exceeded. The largest problem, however, is constituted by dust and fire gases which are emitted to the atmosphere. The emission of fire gases is highly burdensome to the citizens of areas directly neighbouring thermally active mining waste dumps. The concentration of CO in the areas of thermal activity may reach values that are hazardous to humans. Moreover, an intense odour nuisance is present in the area of the dump. Even if not exceeding the maximal allowable concentrations in the atmosphere, the sulphur compounds and hydrocarbons (PAH) are sensible even at very low concentrations in air, due to the very low odour threshold. Significant amounts of greenhouse gases are also emitted to the atmosphere during fires.
To eliminate the hazard posed to the environment by the dumps affected by fire, it is necessary to apply fire prevention that should consist in the monitoring of these objects. This would allow for an early detection of thermal phenomena and the commencement of preventive actions that would reduce the factors contributing to the further development of fire (e.g. the removal of the combustible material, cutting off the air supply or cooling the heated zones).

References

[1] Gawor Ł 2014 Coal mining waste dumps as secondary deposits–examples from the Upper Silesian Coal Basin and the Lublin Coal Basin Geology Geophysics and Environment 40(3) pp 285–9

[2] Zástěrová P, Marschalko M, Niemiec D, Durďák J, Bulko R and Vlček J 2015 Analysis of possibilities of reclamation waste dumps after coal mining Procedia Earth Planet. Sci. 15 pp 656–62

[3] Bian Z, Dong J, Lei S, Leng H, Mu S and Wang H 2009 The impact of disposal and treatment of coal mining wastes on environment and farmland. Environ. Geol. 58(3) pp 625–34

[4] Skarżyńska K M 1995 Reuse of coal mining wastes in civil engineering - part 1: Properties of minestone. Waste Management 15(1) pp 3–42

[5] Szczepańska J and Twardowska I 1999 Distribution and environmental impact of coal-mining wastes in Upper Silesia, Poland Environ. Geol. 38(3) pp 249–58

[6] Suponik T and Blank 2014 Removal of heavy metals from groundwater affected by acid mine drainage Physicochem. Probl. Miner. Process. 50(1) pp 359–72

[7] Pierzyna P, Popczyk M and Suponik T 2017 Testing the possibility of leaching salt debris obtained from underground excavations E3S Web of Conferences 18 EDP Sciences01033

[8] Sułkowski J, Drenda J, Różański Z and Wrona P 2017 Testing the possibility of leaching salt debris obtained from underground excavations E3S Web of Conferences 18 EDP Sciences01033

[9] Różański Z 2009 The potential gas emission from a thermally active coal waste dump Gospodarka Surowcami Mineralnymi 24(3/1)

[10] Różański Z and Wrona P 2010 The fires of mine waste dumps and connected hazard for the environment, Polish experiences Proceedings of ICCFR2 Second International Conference on Coal Fire Research 19-21 May 2010 Berlin pp 52–8

[11] Łączny M J and Ryszko A (Eds.) 2012 Praca zbiorowa w ramach projektu COOL’s: System zarządzania likwidacją emisji CO₂ ze zwałowisk odpadów powęglowych Central Mining Institute&Silesian University of Technology Katowice-Gliwice

[12] Fabiańska M J, Ciesielczuk J, Kruszewski Ł, Misz-Kennan M, Blake D R, Stracher G, and Moszumańska I 2013 Gaseous compounds and efflorescences generated in self heating coal waste dumps - a case study from the Upper and Lower Silesian Coal Basins (Poland). Inter. Journ. of Coal Geol. 116 pp 247–61

[13] Stracher G B, Prakash A and Sokol E V (Eds.) 2014 Coal and Peat Fires: A Global Perspective: Volume 3: Case Studies–Coal Fires Elsevier

[14] Smoliński A, Drobek L, Dombek V, Bak A 2016 Modeling of experimental data on trace elements and organic compounds content in industrial waste dumps Chemosphere 162 pp 189–98

[15] Surovka D, Pertile E, Dombek V, Vastyl M and Leher V, 2017 Monitoring of Thermal and Gas Activities in Mining Dump Hedvika, Czech Republic IOP Conference Series: Earth and Environmental Science 92(1) p. 012060 IOP Publishing

[16] Skarżyńska K M 1995 Reuse of coal mining wastes in civil engineering - part 1: Properties of minestone. Waste Management 15(1) pp 3–42

[17] Strumiński A 1996 Zwalczanie pożarów w kopalniach głębinowych (Katowice: Wydawnictwo Śląsk)
[18] Banerjee S C 1985 *Spontaneous Combustion of Coal and Mine Fires* (Rotterdam: A.A. Balkema)

[19] Pone J D N, Hein K A A, Stracher G B, Annegarn H J, Finkelman R B, Blake D R, McCormack J K and Schroeder P 2007 The spontaneous combustion of coal and its by-products in the Witbank and Sasolburg coalfields of South Africa *Int. J. Coal Geol.* 72(2) pp 124–40

[20] Urbański H 1983 *Rekultywacja techniczna usypisk odpadów kopalnianych ze szczególnym uwzględnieniem zwalczania pożarów*. Training proceedings SITG Katowice Poland

[21] Gabzdyl W 1984 *Petrografija węgla* (Gliwice: Wydawnictwo Politechniki Śląskiej)

[22] Cygankiewicz J 2001. Wpływ zawartości wilgoci w węglu na przebieg samozagrzewania *Górnictwo i Geologia* 6(3) pp 37–47

[23] Gogola K, Bajerski A and Smoliński A 2012 Modyfikacja metody oceny zagrożenia pożarowego na terenach lokowania odpadów powęglowych *Prace Naukowe GIG Górnictwo i Środowisko* 2 pp 13–32

[24] Korski J, Henslok P and Friede R 2005 *Uwagi o przyczynach powstawania pożarów składowisk odpadów górniczych, zwalczaniu pożarów i profilaktyce przeciwpożarowej*. Seminary of The Strata Mechanics Research Institute of the Polish Academy of Sciences Kraków

[25] Szczepańska J 1987 *Zwałowiska odpadów węgla kamiennego jako ogniska zanieczyszczeń środowiskowego* (Kraków: AGH)

[26] Korban Z 2011 Problem odpadów wydobywczych i oddziaływania ich na środowisko, na przykładzie zwałowiska nr 5A/W-1 KWK „X” *Górnictwo i Geologia* 6(1) pp 109–20

[27] Bojarska K and Bzowski Z 2012 Wyniki badań wyciągów wodnych odpadów wydobywczych z kopalń węgla Górnośląskiego Zagłębia Węglowego w aspekcie wpływu na środowisko *Górnictwo i Geologia* 7(2) pp 101–13

[28] Rozporządzenie Ministra Środowiska z dnia 24 lipca 2006 r., w sprawie warunków, jakie należy spełnić przy wprowadzaniu ścieków do wód lub do ziemi, oraz w sprawie substancji szczególnie szkodliwych dla środowiska wodnego (Dz.U. Nr 137, poz. 984)

[29] Twardowska I, Szczepańska J and Witczak S 1988 *Wpływ odpadów górniczego na środowisko wodne. Ocena zagrożenia, prognozowanie, zapobieganie* (Wrocław: PAN)

[30] Nowak J 2011 Influence of thermal changes degree of the coal wastes on leaching substances into environment *Górnictwo i Geologia* 6(4) pp 59–70

[31] Atlas Geochemiczny Górnośląskiego Śląska 1995 (Warszawa: PI G)

[32] Hanak B and Nowak J 2010 Estimation of chosen metals concentration and components soluble in soils and water round of KWK Nowy Wirek *Górnictwo i Geologia* 5(4) pp 115–23

[33] Kuna-Gwoździewicz P 2013 Wielopierścieniowe węglowodory aromatyczne w gazach strefekshalacyjnych wybranego termicznie aktywnego składowiska odpadów wydobywczych z górnictwa węgla kamiennego *Journal of Sustainable Mining* 12(1) pp 7–12

[34] Nisbet I C T and LaGoy PK 1992 Toxic (TEFs) for polycyclic aromatic hydrocarbons (PAHs) *Reg. Toxicol. Pharmacol.* 16(3) pp 290–300

[35] Howaniec N, Kuna-Gwoździewicz P and Smoliński A 2018 Assessment of Emission of Selected Gaseous Components from Coal Processing Waste Storage Site *Sustainability* 10(3)