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Review

The Mechanisms of Endogenous Fires Occurring in Extractive Waste Dumping Facilities

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Abstract: The processes of hard coal extraction and processing are accompanied by the generation of a considerable amount of post-mining extractive waste, which in most cases is deposited on the ground surface. In the past, such waste was disposed of by deposition in bings and spoil piles of various kinds. The application of modern technologies makes it possible to recycle, reuse or reclaim extractive waste in engineering works or as a substitute of natural aggregates used for the construction of different kinds of banks and embankments. Regardless of whether the waste is deposited or reused, the basic target method of waste management consists of depositing it on the ground surface. This form of extractive waste management is always associated with the risk of the occurrence of coal self-heating phenomena, which may consequently lead to an endogenous fire. Therefore, it is of critical importance to apply appropriate technologies for the construction of coal waste embankments on the one hand, and on the other hand to recognize the mechanisms responsible for the occurrence of fires in extractive waste dumps, which constitutes the subject matter of this paper.

Keywords: extractive waste; endogenous fire; fire prevention; self-ignition

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1. Introduction

In recent years, the restoration and reclamation of land where extractive waste has been deposited is becoming more and more common. Areas that have been so far recognized as degraded, after the rehabilitation may perform new functions, most frequently as industrial [1,2] or public transportation facilities [3,4], but also commercial or recreational ones [5,6]. In many cases, due to their location, such areas represent a large potential for future development. However, the prospective developers who are interested in post-mining areas expect that these areas will be ecologically safe. With regard to the areas where extractive waste has been deposited, the possibility of self-ignition constitutes the most serious environmental threat. In addition, there is a lack of effective routine procedures for the assessment of endogenous fire hazards.

The extant literature on the occurrence of fires in the locations where extractive waste is deposited deals with several research areas [7–9]. In most of the papers, the authors discuss the methods of fire prevention aiming at preventing the self-ignition of discard dumps [7,10–12], as well as the methods and technologies for extinguishing the existing fires [13–15]. Many papers present methods used for the thermal monitoring of extractive waste dumping sites [16] and facilities [17,18], the results of monitoring research [19–21] and practical experience concerning the handling of fire phenomena [11,12,15,22,23]. Another significant area of research is determining the mechanisms responsible for the occurrence of fires in coal spoil piles [24–26], including the initiation process of the phenomenon, its development and the course of the whole process [27,28], as well as the factors contributing to the self-ignition of waste [14,19,29]. Since the second half of the 20th century, there have been research studies focusing on the development of effective methodology for forecasting and assessing fire hazards occurring in the areas of extractive waste sites. The research concerns both the development of expert methods consisting in assessing the fire hazard on the basis of a number of site-specific criteria and the character of the deposited waste [29–31]. The studies also discuss laboratory methods by means of which the propensity to self-ignition is assessed based on tests and observations of extractive waste in installations or research stands under laboratory conditions [14,27,29,32]. Some of the laboratory methods are dedicated to assessing the self-ignition of bituminous coals and are then adopted to the assessment of extractive waste self-ignition without any modifications.

There is another group of methods which are focused on mineral and petrographic analysis, where the assessment is carried out by means of the analysis and observation of minerals that are components of the extractive waste and the coal macerals contained in the minerals; the assessment of the tendency to self-ignition can also be made using the derivatographic method [27,32]. The noxiousness of burning coal spoil piles and the ever-growing environmental awareness have contributed to the development of technologies dedicated to decreasing or eliminating fire hazards connected with the deposition of extractive waste on the ground surface. Highly developed countries of Western Europe as well as the USA and Australia have been pioneers in terms of the activities aimed at combating the fires of coal spoil piles [33,34]. In Great Britain, the first attempts at creating legal regulations concerning the depositing of extractive waste prone to self-ignition were made in the aftermath of growing protests of local residents living close to burning spoil piles as early as in the 1930s [34]. The activities were intensified in the post-war period and in the 1970s there already existed legal instruments regulating the environmental requirements regarding the handling and management of extractive waste in Germany, France [34,35] and Great Britain [36,37]. As a consequence, the mining sector was compelled to take measures with the aim of eliminating the existing seats of fire as well as designing and implementing environmentally safe technologies of waste disposal. Adjusting the legislature to the requirements of the European Union, Poland developed appropriate procedures and legal instruments for the purpose of assessing the standards of ground quality in terms of the excessive contents of chemical elements and substances as well as in terms of the leaching of contaminants and their transmission to surface and ground waters [38,39]. However, in the case of the disposal of extractive waste in which the most serious environmental threat is the possibility of self-ignition, there are no effective routine procedures for assessing the hazard of endogenous fire occurrence.

This paper presents a review of the global literature concerning the methods of assessing the risk of the occurrence of fire phenomena in areas where extractive waste is deposited, along with a review of the mechanisms responsible for the formation of fires.

2. Extractive Waste and its Management

There are two major types of extractive waste, namely mining waste and coal processing waste [40]. Mining waste is generated mainly during the opening-up phase, and it is characterized by a large variability of petrographic content. Waste generated during the extraction and processing of coal called extractive or mining waste is a mixture of rocks co-occurring with the seams of bituminous coal (claystones, mudstones, sandstones, shales and the like) and coal which was impossible to recover during the processing and enrichment of the extracted raw material [40]. Mining waste is generated during all stages of the mine development and extraction activities, starting with shaft sinking, through the opening out of the seams and finishing with all technological operations connected with the enriching and purification processes.

The granulation of the rock material is within the range of 0–500 mm. The content of combustible substance in this kind of waste is diverse and depends on the scope and character of mining activities. Coal processing waste, which accounts for the major waste stream (approximately 95%) on the ground surface, originates from enriching and purification processes using various technologies. Coal processing waste can be subcategorized into several principal groups including coarse grained and fine grained waste, flotation waste and coal sludge. These types of waste are characterized by a higher stability of chemical, mineral and petrographic content. The particular types of coal processing waste differ according to the contents of organic matter, sulfur and moisture. The content of coal substance in the processing waste ranges from 3% to 30% [40]. The average content of coal in coarse-grained waste equals approximately 8%; in fine grained waste the content of coal is about 10%; whereas in flotation waste it is about 20% [41]. According to Central Statistical Office data, 71.8 million tons of extractive waste (accounting for 55% of total industrial waste) was generated in Poland in 2014. Despite the fact that statistical data demonstrates that approximately 95% of extractive waste generated in Poland is recycled, in most cases it is deposited on the ground surface in the form of earthworks, earth structures, land leveling, engineering works and filling of the adversely transformed lands.

The differentiation between the types of waste is made only from the legal perspective, because from the technical point of view there are no major differences between the recycling and depositing of waste. This form of extractive waste management is characteristic for all major coal basins all over the world [31,32,35,42–47]. Currently, the accumulation of extractive waste in Poland accounts for over 550 million Mg [48]. According to the inventory of extractive waste dumping sites carried out within the framework of the project Management System of Eliminating CO_2 Emissions from Extractive Waste Piles [49], in the Upper Silesian Coal Basin there are 154 facilities of such a kind with a total area of 3800 ha. Considering the fact that the data do not incorporate the facilities located in the Lower Silesian and Lublin Coal Basins, and especially the areas where extractive waste has been utilized for the purpose of construction works, land subsidence leveling or land reclamation, the actual area of extractive waste deposition in Poland is much larger. For the purpose of comparison, according to the Ukraine Mining Ministry, only in the area of closing coal mines within the boundaries of three Ukrainian coal basins, 341 spoil piles were inventoried, 105 of which had seats of fire [44]. The authors of documentations prepared for the execution of the Joint Implementation Projects in Ukraine [5] concluded that the extractive waste piles of the Donbas Coal Basin cover an area ranging from 7 to 10,000 ha. In the coal basins of the People's Republic of China, 4.5 billion Mg of waste has been deposited in approximately 1600 facilities with an area of over 15,000 ha [14,50].

3. Fires of Extractive Waste Dumps

The sites of extractive waste deposition may be characterized by exceeded standards of ground quality due to excessive contents of particular chemical elements or compounds. Frequently, contaminants such as chlorides and sulfates are leached from extractive waste and transferred to surface and ground waters [9,27,51,52]. Additionally, the sites, especially those that were not subject to land reclamation activities, may become a source of excessive emissions of dust. However, the most serious potential threat associated with the deposition of extractive waste is the possibility of self-ignition and the resulting endogenous fire of the dump [7,29,40]. The fires of waste dumps are long-lasting processes, which constitute considerable noxiousness to the natural environment as well as human health and adversely affect standards of living.

Fires of dumps and the increased thermal status have been recorded in coal basins all over the world [14,15,18], whereas the scale of the phenomena differs and most often depends on the attitude of national authorities towards the issues of environmental protection. In Datong, a Chinese coal basin located in Shanxi, a province neighboring Beijing, where 13 active coal mines produce over 120 million Mg of coal annually, until recently the fires of extractive waste dumps have been common phenomena [50]. The environmental impact of these processes was not monitored and no extinguishing or preventive activities were carried out. The gaseous products resulting from the fires had a significant impact on the state of atmospheric air in the neighboring Beijing. Only in 2008, before the Olympic Games, measures were undertaken to combat the thermal activity of the waste dumps in Datong Coal Basin. Before July 2009, the majority of extractive waste dumps in the region were densified and covered with a layer of soil, which contributed to the decrease of fire phenomena intensity [50]. Research conducted on waste dumps with thermal activity showed that the temperature of the surface may reach several hundred degrees Celsius, while the temperature inside the dump may even exceed 1000 °C [18,29,40]. The studies demonstrated that in the zones of intense thermal phenomena the temperatures may even reach 1400 °C. In addition, burning dumps are sources of dust and odors as well as the emissions of toxic gases such as carbon monoxide, sulfur oxides, nitrogen oxides, n-alkanes, polycyclic aromatic hydrocarbons, phenols and the like [14,26,27,53]. Research on the thermal state of the coal spoil piles in the Upper Silesian Coal Basin that has been conducted since the 1990s by the Central Mining Institute showed that the concentration of carbon monoxide in the atmosphere inside the thermally active dump may equal even a few percent [51]. Based on the measurements made on the premises of a dump located in Siemianowice Slaskie, Poland, Drenda et al. [19] found that the concentration of carbon monoxide immediately at the surface of the dump as well as at the height of 0.5 m above the ground in some places reached tenths of a percent. Pan et al. [14] discussed cases of explosions of gases emitted from thermally active sites along with eruptions of deposited waste. Such phenomena occurred inter alia in several coal mines in the People's Republic of China, especially in regions with long lasting heavy rainfall [14]. There is a case study describing an explosive ejection of 10,000 Mg waste over a distance of 100 m caused by the explosion of gasses emitted from a burning dump [14].

4. Factors Contributing to the Development of Fires

Studies concerning endogenous fires of extractive waste dumps indicate a number of factors contributing to the occurrence and propagation of the phenomenon. The factors fall into the following two categories (see Table 1).

Table 1. The factors that contribute to the occurrence and propagation of endogenous fires in extractive waste dumps.

No.	Factor Category	Type of Factors	References
1	Factors connected with the properties of the waste	The rank of coal	[27–30,47,52]
		The content of macerals	
		The percentage content of coal in the waste	
		The mineral content	
		The moisture content	
2	Factors connected with the place and the method of depositing the waste	The shape and height of the extractive waste dumping facility	[27,29,30,52]
		The volume, the surface area and the location as related to the surrounding land	
		The technology of forming the embankment and the method of odor neutralization	

4.1. Factors Affecting the Development of Fires Connected with the Extractive Waste Properties

All ranks of bituminous coal in contact with the atmosphere are subject to oxidation and weathering processes. Coal oxidation takes place even in low temperatures and is an exothermic process. Relatively low specific heat capacity of coal and a low thermal conductivity coefficient make the heat that is emitted during the oxidation process produce a high increase in temperature. If the produced heat is not effectively dissipated into the environment, the process of coal self-heating may be initiated and under favorable conditions it may result in an endogenous fire [32]. Examining under microscope the processes taking place during the natural oxidation of coal, Van Krevelen [53] found that in the conversion process on the external surface of the coal grain as well as along the fissures and cavities observed at the microscopic level the total reactive surface area exposed to oxidation is larger than the outer surface alone. Around such areas, an oxidation rim appears, which spreads with the progress of the oxidation process. The width of the oxidation rim at a given time and temperature is a measure of coal reactivity related to oxygen. It can be expected that low rank coals, coals with large surface area with micro-cracks, easily crushable coals and coals with a relatively high content of reactive macerals will demonstrate the highest reactivity [27,54–56].

Coal oxidation mechanisms that lead to self-ignition constitute a complicated process comprised of several characteristic stages widely discussed in the literature in terms of surface and underground coal fires in the coal mine. In [57], a critical review of the different techniques developed to investigate the susceptibility of coal to spontaneous combustion and fire is presented. In [58], the mechanism of self-heating, areas of spontaneous combustion, various factors influencing self-heating and different experimental studies to predict its occurrence are reviewed (in terms of the South African context). In [59], the authors presented an engineering classification system for coal spontaneous combustion. In [60], the authors provide a comparison of the intrinsic factors that affect spontaneous combustion (based on South African coal). In [61], a new way of preventing coal spontaneous combustion was presented. In [62], like in the previous case, the processes of spontaneous combustion of coal and ores were discussed. In [63], the application of thermogravimetric and infrared spectroscopic techniques in the spontaneous combustion characteristics of different pre-oxidized lignites was presented. In [64], the influence of various pyrite contents on the parameters of spontaneous combustion, such as index gases, temperature and released heat, was investigated. In the [65], the author studied the impact of several factors on spontaneous coal combustion. In [66], TGA and Fourier infrared-spectrum technology were used to analyze the change rules for the critical temperature and stage characteristics during the process of the coal spontaneous-combustion oxidation reaction.

According to Falcon [32], the process leading to coal self-ignition can be divided into four stages. Adsorption and oxygen chemisorption constitute the first stage, as a result of which coal increases in weight. This process requires a very small activation energy (3 to 4 kcal/mol), occurs most intensely up to the temperature of 70 °C and then continues up to 350 °C. In the second stage, above 80 °C, the adsorption complex undergoes decomposition and the weight of the coal decreases. Similarly, the second stage also requires a relatively small activation energy (6.5 kcal/mol) and because of that it frequently takes place in low temperature ranges, between 80 and 150 °C. As a result of the decomposition of this complex, carbon monoxide is produced, whereas inherent moisture is driven off between 100 and 150 °C. In the third stage, which occurs in the temperature range of 150–230 °C, further chemical reactions lead from an unstable adsorption–chemisorption complex to the formation of a stable chemical compound, oxygen–carbon compound oxycoal with an accompanying intense production of heat. This process requires a high activation energy (16 kcal/mol). In higher temperature ranges, the formation of oxycoal is stopped and the process of combustion is initiated. This reaction requires the activation energy of the order of 20 kcal/mol. With the rapid increase in temperature, there occurs a rapid decrease in weight connected with an excessive production of soot, whereas the coal substance begins to intensely oxidize.

Research conducted all over the world showed that younger coals with a lower degree of carbonization demonstrated a larger tendency to self-ignition [13,27,52]. This results from the fact that they are characterized by a bigger content of vitrinite macerals, which are more susceptible to the oxidation and self-heating processes [27,28,32,51]. The petrographic characteristic of coal also has an impact on its tendency to self-ignite [28]. There are four basic petrographic types of bituminous humic coal: vitrain (bright coal), clarain (moderately bright coal), durain (moderately dull coal) and fusain (dull fibrous coal). It was proven that powder coals (fusain) as well as easily crushable coals (vitrain) are most prone to self-ignition, while coals that are not easily crushable have a smaller tendency to self-ignite. Numerous studies indicate that mineral substance inclusions, especially iron sulfides (pyrite and marcasite) may have a significant impact on the processes of the self-heating of coal [13,14,27,51,54]. The inherent moisture of coal as well as ground water levels, humidity and rainfall play an equally important role in the coal self-heating processes [13,48,54]. The presence of a sufficient amount of moisture favors the exothermic decomposition processes of both the organic compounds and the mineral ones (e.g., pyrite). The probability of the occurrence of coal self-ignition significantly increases in the case of large differences in coal moisture by its alternating drying and wetting [14,32]. In order to examine the impact of moisture on the occurrence of coal self-ignition in extractive waste dumps, Pan et al. [14] developed an experimental platform to research the interactions between the deposited waste and water inside the dump. Under laboratory conditions, the prism of extractive waste was heated by means of an external source of heat and wetted with water mist. The research was carried out for various simulated weather conditions including rainfall or lack of it. The results demonstrated that the moisture of the waste dump block constitutes an important factor causing waste self-ignition incidents. Continuous wetting of the block generated differences in the high temperature range as well as differences in the rate of self-heating, which in turn produced the chimney draft effect and increased air convection in the high temperature range. In this way, the combustion process intensified. The transfer of water to high temperature zones contributed to the formation of water vapor, which provides substances for the reaction of water and gas in the high temperature zone. As a result, large amounts of combustible gases are produced, including carbon monoxide and hydrogen; in comparison to rainless weather conditions, the amount of the gases increases to even achieve the level of explosive concentrations. Grewer [55] stated that during the coal oxidation, self-heating and self-combustion processes, various organic compounds such as methane, ethane, ethylene or polycyclic aromatic hydrocarbons and phenols are produced apart from carbon monoxide and hydrogen.

4.2. Factors Affecting the Development of Fires Based on the Place and the Method of Depositing the Waste

Long-time monitoring of extractive waste dumps with thermal activity demonstrated that besides the natural propensity to self-heating resulting from the physical and chemical properties of the waste, there exist other factors that may have an impact on increasing the fire hazard, for example air and moisture supply as well as the possibility of heat accumulation inside the dumping facility [27,32,40,56]. These factors largely depend on the shape and height of the extractive waste facility, the volume and the surface area, as well as its location as related to the surrounding land, and especially the technology of forming the embankment and the method of odor neutralization. In Table 2, the possible types of facilities for the deposition of extractive waste are presented [29].

Table 2. Types of facilities for the deposition of extractive mine waste.

No.	Type of Facilities	Examples
1	Below ground level facilities	Open cast excavations filled with waste up to the elevation of the surroundings areas, leveling of mining-induced land subsidence etc.
2	Above ground level facilities	Bings, waste banks, civil engineering facilities, earth structures etc.
3	Below-and-above ground level facilities	Facilities in which the waste is both deposited below the ground level of the surrounding area and partially above the level forming an elevated massif.

Gogola et al. [29,30] proposed a simplified classification of extractive waste facilities, which comprises facilities with scarps (above ground level, below-and-above ground level and partially filled below ground level facilities) or without scarps (below ground level facilities). Table 3 presents the classification of fire hazard in extractive waste dumps proposed by Gogola et al. (2012) [29,30].

It was proven that the development of fire phenomena occurs much more frequently in facilities with scarps than in ones below ground level [30]. This is associated with the fact that below ground level facilities are characterized by a much smaller area of contact between the air and the extractive waste and because they are to a smaller degree exposed to weather conditions such as winds, rainfall and erosion, which have an impact on the self-heating processes of waste [28,29,52]. In the case of the above ground facilities, the shape plays a significant role in regard to the hazard of endogenous fire.

The facilities that have scarps with considerable inclination are especially liable to the development of thermal activities. Cone dumps where the inclination angle is also the angle of the natural waste chute may be an illustrative example [52]. It was demonstrated that the fire hazard increases with the increasing height of the facility, whereas the thermal processes are more frequently recorded on scarps positioned transversely to the typical direction of winds occurring in a given area [27,28,52].

Table 3. Classification of fire hazard in extractive waste dumps.

Category	Hazard	Sub-Category	Minimum Scope of Preventive and Corrective Activities
I	Low	-	Activities specific for a given facility
II	Average	a	Monitoring of the facility, improvement of monitoring procedures or other specific activities
		b	Sealing or densifying of the banks
III	High	a	Monitoring of the facility, improvement of monitoring procedures, sealing or densifying of the banks
		b	Graining improvement with appropriate fraction materials, sealing or densifying of the banks
		c	Monitoring of the facility, improvement of monitoring procedures, graining improvement with appropriate fraction materials, sealing or densifying of the banks
IV	Very high	-	Monitoring of the facility, improvement of monitoring procedures, graining improvement with appropriate fraction materials, sealing or densifying of the banks, constructing and insulation cover or, alternatively, dismantling/redevelopment of the facility

Yet another important factor connected with the geometry of the extractive waste facility is the cubic capacity of the structure and the associated capacity of heat accumulation. Above ground level facilities of solid structure and large cubic capacity of the order of several hundred thousand cubic meters are not able to effectively dissipate the heat generated by the processes occurring inside the facility or the heat coming from solar radiation [12,52].

5. The Assessment of the Thermal Conditions of Areas with Extractive Waste Deposition

In the second half of the 20th century, there occurred a significant development of technologies dedicated to minimizing hazards associated with the fires of extractive waste dumps along with the development of thermal activity monitoring systems to control the quality of conducted works and the rapid detection of thermal anomalies in order to prevent the development of the seats of fire. In the 1970s, a method for assessing the thermal conditions of extractive waste piles was developed [67]. The method was based on previous procedures applied to coal heaps [68]. According to this method, the thermal condition of the facility was determined on the basis of the site inspection and in situ measurements of characteristic physico-chemical parameters, such as surface temperature and the temperatures and the concentrations of oxygen, carbon dioxide and carbon monoxide inside the facility taken at the depth of approximately 1 m. In the original method, the temperature was measured by means of resistance thermometers, whereas gas concentrations were measured using calorimetric detection tubes [67]. With the development of measuring techniques, infrared devices (pyrometers) started to be applied to measure the temperature, while portable gas analyzers were used to determine the concentrations of gases [51]. The advancement of thermal imaging technology along with the application of thermo-vision cameras contributed to the improvement of the accuracy of temperature measurements; see Figure 1 [15,69]. In recent years, airborne and satellite photography have been used to assess the thermal condition of the facilities; see Figure 2 [70].

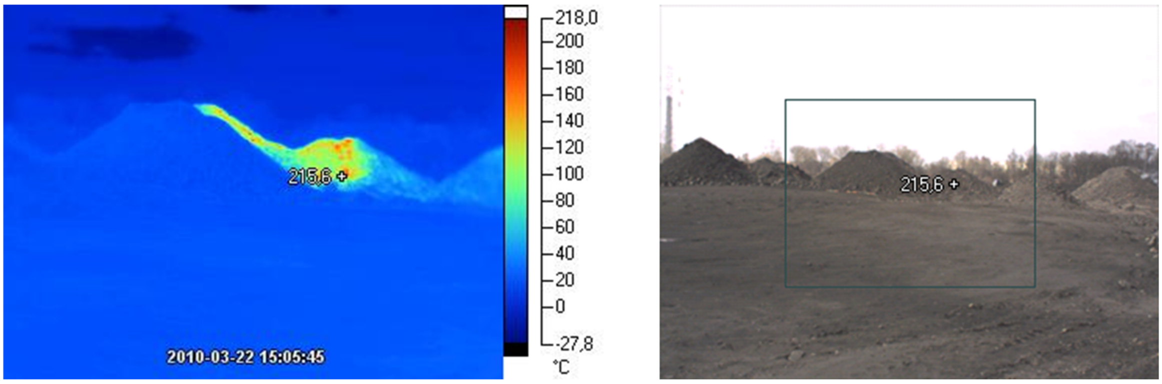

Figure 1. Thermogram imaging the surface temperature of extractive waste facility juxtaposed with a visible range photo.

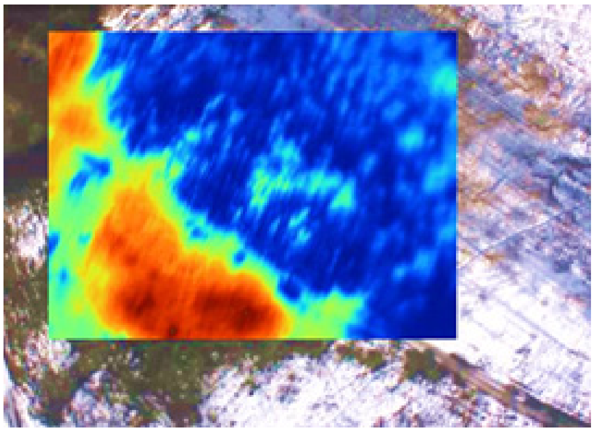

Figure 2. Airborne infrared photograph of extractive waste dumping facility.

The application of electro-resistivity and conductometric methods constitutes a promising tool for the assessment and imaging of the thermal conditions of extractive waste dumping. In their research, Kotyrba et al. [71] confirmed the strong dependence of electrical resistivity and electrical conductivity of extractive waste on temperature.

6. Appropriate Methods for the Construction of Waste Dumps to Minimize the Risk of Fires

Minimizing the hazard of endogenous fires constitutes one of the priorities in the currently applied technologies of extractive waste deposition. The embankments made of extractive waste are constructed in a controlled manner including mechanical compacting and the application of layers that are 0.4–0.6 m thick. Special attention is placed to ensure that the moisture of the deposited waste approximates the optimal one and that each formed layer is mechanically compacted by means of vibrating or static rollers to the required compaction ratio [15,16,29,72]. The selection of appropriate granulation of the material ensuring the right compaction ratio plays an important role [29,30]. Based on experience, the minimum required waste compaction ratio should be Is $\geq$ 0.95 [29,30,73]. In the case when the land is intended to serve as a venue for economic activity, it is recommended that the ratio be higher, i.e., Is = 0.97 $\div$ 1.0. It is also essential that the extractive waste first be crushed if it is coarse-grained and contains grains of a size exceeding one third of the formed layer. During the construction work, the compactness of each formed layer is constantly monitored [29,30,73]. Another significant factor that decreases the risk of endogenous fires is the use of different antipyrogenous additives, such as the side products of fuel combustion from energy plants (CBPs), materials which do not contain combustible matter or substances which inhibit the occurrence of thermal processes [49,52,70,72,74]. Additional factors are successive land reclamation by means of covering the dump by a soil layer [33,52,75,76]; depositing the waste in separate cells [15]; and the continuous monitoring of the thermal conditions [15,29,30,67,71].

7. Appropriate Technologies and Strategies for the Prevention of Fires in Extractive Waste Dumps

The techniques and technologies for combating endogenous fires in extractive waste facilities fall into the following seven categories [9,72]: injection technologies; fire extinguishing and cooling the site with inert gases; technologies with antipyrogenous additives; earth works technology (encasing, dismantling, etc.); shielding technology using absorption trenches; controlled burn through (afterburning) technology; and correlated technologies in which the combination of two or more of the above is applied.

Injection technologies consist of the injection of fire-extinguishing agents (most often a mixture of fine-grained material and water) into the extractive waste dump through a system of previously drilled wells [72,77]. In these technologies, cased (perforated tubes) and partially cased wells [10,11,50,72] as well as bose pipes are used [50,72]. Within the framework of the technology, deep insulation shields whose task is to cut off the burning zones from the areas without thermal activity are constructed [72,77]. In addition, the technology uses surface insulations made by means of drilling a network of shallow wells into the subsurface layer of the dump, through which the extinguishing agents are injected.

In the injection technologies, CBP water-based suspensions constitute the most frequently used extinguishing agents, which are sometimes combined with different kinds of additives and improvers. Janik and Kuś [78] developed and implemented extinguishing agent formulas including selected silt materials for the insulation of hot spots. In fire extinguishing works taking place in the area of an extractive waste dump belonging to a former Rymer coal mine, a CBP water-based suspension with stabilizing and setting agents was applied [76]. Additionally, numerous formulas for fire extinguishing and preventive mixtures aimed at eliminating the fires of extractive waste dumps and reducing fire and greenhouse gases emissions were developed, patented and implemented [49]. The formulas provide for the admixtures of liquefying agents, carbon dioxide binding agents and additives improving the mixture properties.

Shielding technology using absorption trenches is one of the most common methods of fire extinguishing activities conducted in extractive waste dumps in Poland. The method consists of insulating the burning zones and sealing the embankments by means of a network of deep trenches successively filled with fire extinguishing agents [9,12,72,76]. This technology uses basically the same fire extinguishing agents as the injection technology [72]. Most often, these are mixtures of water and CBPs, which while injected into the trench permeate to the inter-grain space of the adjacent embankments, decreasing their temperature and inhibiting the on-going thermal processes. In order to improve the geo-technical properties of the shield, an admixture of larger granulation materials is applied to the trench before the extinguishing agent solidifies [10,11,72]. In practice, while designing the fire extinguishing works, the injection and the shielding technologies are combined.

One of the most common globally used methods of combating extractive waste dump fires is the execution of earth works of different scope and character [9,23,77]. Such works include inter alia the construction of sealing or land reclamation covers made of incombustible materials [10,11,50], excavating the thermally active material, cooling it and re-depositing in the dump [72,76,77], airtight insulation of the embankments by means of a sarcophagus with the application of an incombustible material that separates the burning zone from the sarcophagus [9] as well as a complete dismantling of the extractive waste facility combined with recycling of the burned-through material and coal recovery from the unburned waste [72].

Buchwald and Korski [9] proposed the application of inert gases (a solution widely used in addressing fire hazards in underground mining goafs) to eliminate the thermal processes occurring in extractive waste facilities. Field tests carried out under the conditions of a burning extractive waste dump demonstrated that besides inhibiting the thermal processes by means of creating an anaerobic atmosphere, this method allows for the cooling of the deposited material [12]. However, so far this method has not been used on an industrial scale.

In research works and practical solutions concerning the elimination of fires in extractive waste dumps, more and more attention is placed on antipyrogenous additives, which decrease coal reactivity or inhibit the thermal processes if they have already been initiated. Combustion by-products (CBPs) are widely considered to be the basic antipyrogenous materials. Many years of experience and the monitoring of extractive waste facilities where CBPs were used, as well as laboratory research, demonstrated that they constitute an efficient anti-pyrogen. In the 1980s, in the former USSR coal basins, lime wash was applied to burning extractive waste dumps [78]. Yet another solution widely discussed in the field literature is addressing the problem of burning extractive waste dumps by means of controlled burn through (afterburning), sometimes combined with the recovery of the generated heat. Liu et al. [77] described a technology applied in the People's Republic of China in which the burning extractive waste dump is additionally aerated by means of a pipe system. The generated heat is recovered for economic activity, whereas the produced gases are captured and purified.

Barosz and Tabor [79] developed a technology in which the burning dump is encased with a sarcophagus, while the space between the sarcophagus and the burning zone is filled with coarse grain material facilitating the access of air and thus the advancement of the fire phenomena, which accelerates the burn through of the dump. Due to the fact that the technology does not involve the capture and purification of the gases generated in the process, the odor nuisance significantly increases.

8. Conclusions

In this paper, an analysis of the factors contributing to the occurrence and propagation of the endogenous fires of extractive waste dumps was presented. The literature review demonstrates that there exist two basic approaches to the problem of assessing the propensity of extractive waste to the self-ignition process. The first one relies on the so-called expert methods consisting of assessing the fire hazard on the basis of a number of site-specific criteria and the character of the deposited waste. The second approach is based on experimental methods by means of which the propensity of the waste to self-ignition is assessed using tests or observations of extractive waste in installations or research stands under laboratory conditions. The paper also discussed the development of technologies dedicated to minimizing hazards associated with the fires of extractive waste dumps as well as the development of thermal activity monitoring systems to control the quality of conducted works and rapid detection of thermal anomalies in order to prevent the development of the seats of fire.

Minimizing the hazard of endogenous fires constitutes one of the priorities in the currently applied technologies of extractive waste handling and management. Special attention is given to ensure that the deposited waste has a moisture level approximating the optimal one and that each formed layer is mechanically compacted by means of vibrating or static rollers to the required compaction rate.

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