# The Role of Natural Succession in the Reclamation of Mining Waste Disposal Facilities

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## Abstract

*The mining industry is related with the production of waste, which are generated during the preperatory works, exploitation and processing of minerals. The type and quantity of generated waste result directly from the type of obtained mineral raw material (minerals), geological conditions of the deposit and the mining and processing technologies used. The changing approach to waste related to the circular economy model means that more and more waste is used economically. However, due to the different physicochemical properties of mining waste and the limited possibilities of its use, some waste is still deposited in mining waste landfills. Depending on the type of mining waste deposited, environmental and economic aspects, the landfill may be a source of raw materials (anthropogenic deposit) that may be exploited now or in the future. Some of this type of mining waste landfills are reclaimed and may be an important elements of the local landscape, as well as positively affect biodiversity through the development of specific natural habitats. The paper presents the concept of landfill reclamation of waste from hard coal mining, taking into account the importance of the phenomenon of natural succession in the formation of ecosystems in reclaimed landfills.*

**Keywords:** *waste facility, mining waste landfills, anthropogenic deposit, circular economy, reclamation, biological tests*

## 1. Introduction

Getting mineral raw materials, inter alia: fossil fuels, metal ores, minerals used in chemical and building industry involves producing wastes. These are mainly mining wastes made in the processes of searching, identifying and mining of minerals from their deposits, as well as their processing. Most mining wastes are a result of the construction and maintenance of excavations, often called sterile rock. Processing wastes are wastes in a solid or silt-like form, which are formed after processing of minerals, i.e., getting useful components through mechanical, physical, biological, thermal or chemical processes. The kind and quantity of the produced mining wastes directly depend on the kind of the mineral, geological conditions of the deposit and the applied technologies of mining and processing. According to the catalogue of wastes, they belong to the first group of wastes [1, 2]. In Poland, the largest quantity of produced wastes is connected with the mining of coal, copper, zinc, lead, and aggregates. These are three kinds of wastes:

- wastes from the flotation enrichment of the ores of non-ferric metals, code 01 03 81, formed during the processing of the ores of copper, zinc and lead;
- wastes formed during panning and rinsing minerals, code 01 04 12. These are mainly wastes from the processing of coal and rock aggregates;
- wastes from mining minerals other than metal ores, code 01 01 02. These wastes arise during mining of coal and rock aggregates (so-called sterile rock).

Over the recent years, the mentioned above kinds of wastes were produced in the quantities 69.5 to 60.8 million tonnes per year, which was 54–56% of all the industrial wastes produced in Poland (table 1). From 37 to 41 per cent of wastes were recovered. In 2016, 40.5 million Mg of mining wastes were deposited in the waste facility (WF), while in 2020 it was 35.8 million Mg, which was 59% of the mass of the produced wastes.

In mining industry, depending on the kind of the mineral, specifics of the processing and the applied technologies, also other industrial wastes are produced, which can be deposited. In case of some hard coal mines, flotation is applied during the processing, and the remains from the enrichment of coal make the post-flotation wastes. These are wastes classified pod in code number 01 04 81 – other than the mentioned in 01 04 80 wastes from the flotation enrichment of coal. Another kind of wastes characteristic for underground mines are wastes made as a result of treating mine waters, which are sent to the decantation ponds on the surface. In the decantation ponds solid particles are sedimented and their code is 19 13 06 – sludges from groundwater remediation other than those mentioned in 19 13 05. Among the mentioned above wastes, characteristic for hard coal mining wastes of code numbers: 01 01 02, 01 04 12 and 19 13 16, and in some mines also code 01 04 81.

These wastes are characterised by various physical and chemical properties, which determine further processes of their management (e.g., chemical composition, granulometric composition, mechanic properties, the content of coal, humidity) [8-12]. The influence of wastes on the environment is also significant, e.g., through the presence of heavy metals, as well as leachability of salts, such as sulphates and chlorides in the amounts exceeding the highest acceptable levels. Thus, these wastes are used in various manners – in the building

Tab. 1. Production and management of mining wastes in Poland [3-7]

Tab. 1. Wytwarzanie i zagospodarowanie odpadów górniczych w Polsce [3-7]

| Year | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|
| | million tons | | | | |
| Generated waste - total | 128.3 | 113.8 | 115.3 | 114.1 | 109.5 |
| Generated waste - Mining and quarrying | 69.5 | 62.3 | 61.4 | 63.7 | 60.8 |
| Waste recovery - Mining and quarrying | 28.4 | 23.2 | 24.1 | 25.6 | 24.4 |
| Landfilled waste - Mining and quarrying | 40.5 | 38.0 | 36.9 | 37.5 | 35.8 |

Tab. 2. Production and management of wastes by the hard coal mines in Poland [3-7]

Tab. 2. Wytwarzanie i zagospodarowanie odpadów przez kopalnie węgla kamiennego w Polsce [3-7].

| Year | Waste generated during the year [mln tonnes] | | | | |
|---|---|---|---|---|---|
| | 2016 | 2017 | 2018 | 2019 | 2020 |
| Grand total | 32.4 | 28.5 | 28.1 | 30.2 | 27.8 |
| Recovered | 25.0 | 20.9 | 21.2 | 22.7 | 21.4 |
| Landfilled | 7.4 | 7.1 | 6.8 | 7.2 | 6.3 |
| Waste landfilled (accumulated) so far (as of the end of the year) | 434.6 | 421.4 | 426.9 | 424.2 | 430.1 |

construction, road construction, energy industry, mining, land reclamation and agriculture [9-11, 13,14]. Nevertheless, due to large quantities of these wastes, lack of local customers, economical aspects, both in the past and nowadays, they are deposited or accumulated on the waste facility (WF), such as heaps or decantation ponds. According to recent data [7], in 2020 hard coal mining industry in Poland produced 27.8 million tonnes of wastes, among these 6.3 million tonnes were deposited, and by the end of 2020, 430.1 million tonnes of wastes were deposited on WF in total (table 2).

Such large quantities of wasted deposited on WF located near mines have direct and indirect impact on the environment. This impact is usually considered negative, nevertheless, with time, industry attempts to improve damage by reclamation of waste repositories, their liquidation by retrieving the wastes, or – what can be noticed in recent years – allowing the formation of new habitats through natural succession.

The article presents new trends, which can be observed in the approach to the management of WF which, depending on the kind of deposed wastes and estimated impact on the environment, can be treated as the reservoir minerals that can be obtained in the future. This can refer to e.g., wastes containing valuable components, which – due to previously applied technologies and economical aspects – were not retrieved in a satisfactory extent. Such objects can make anthropogenic deposits and their renewed mining gains increased interest. In case of WF where mining wastes of no environmental threat were deposed, it is possible to „leave the object to nature", after previous „technical reclamation od the object". In the repositories of this type, often due to natural succession valuable habitats are formed. At the same time these habitats are adjusted to local environmental conditions.

## 2. The Characteristics of Waste Facility

Disposal of mining wastes causes numerous changes in the environment, starting from the impact on fauna and flora, soil and water environment or visible changes on the surface of the terrain. For many years of the activities of mining industry anthropogenic forms of relief were made. There area, height and shape varied. This was mainly because of the properties of the deposited wastes and techniques of the disposal or the location of a specific landfill. Thus the existing repositories of mining wastes can be divided according to various criteria [15]: size and shape (terrace, table, ridge, dome and cone), situation referring to the ground (over-ground, underground, partially over-ground and underground and lateral), situation referring to the mining enterprise (near the mine, central, involving several mines), aquatic conditions (drainage, non-drainage) or the degree of vegetation cover (reclaimed, partially reclaimed, not reclaimed).

The legal status of the existing WF depends on many factors connected with the subject managing such an object and activities conducted in the area. Usually the subjects managing the waste repositories are mining enterprises, enterprises dealing e.g., with wastes recycling or the State Treasury. One can distinguish active WF, where mining wastes are still disposed, partially closed (disposal is conducted only in parts of the objects) and closed. Closing WF is usually a result of achieving its planned height, defined by the area, volume and height parameters. Another reason for the closure of WF can be the lack of the possibilities or the lack of the permission from the administration to increase its volume, as well as ceasing the activities of the mining enterprise. In the framework of the process of closing the object of mining wastes neutralisation, often an object is constructed. Such works are based on the construction project and the construction permit. Scarps are built and the crown of the object are built. Mining wastes are often use for this purpose. Once the construction works are finished, reclamation and area management are carried out in such a way that a proper state from utilitarian and ecological point of view is restored, especially soil quality, wildlife and flora, natural habitats, systems of fresh water and landscape [16].

## 3. Waste Facility as Antropogenic Deposits

The model of economy in UE, changing from linear into circular model, introduced changes, which also referred to mining wastes [17]. Mining industry in greater and greater degree will have to limit the amount of the produced wastes, and – if already produced – treating them as raw materials to produce products of various kind. Moreover, economic factors more and more often wastes disposed in WF and repositories (e.g., wastes from metallurgy, post-flotation wastes from metal ores or wastes from energy industry) are treated as anthropogenic deposits, where raw materials can be obtained.

The mining of such a deposit contributes to the regaining of the accumulated wastes, which make substitute for natural deposits, thus we save natural resources, as well as reclaim the previously occupied area, which then can be used in diverse ways. The kind of potential resources collected in an anthropogenic deposit, their amount and quality depends on many factors connected with the source of wastes, the way of their disposal and the duration of time; these are the following: efficiency of the carried out previous methods of processing, the way of disposal (selective, not selective), kind and amount of deposited wastes, the age of the repository and physical and chemical changes in wastes, which took place inside the repository. Moreover, the mining of anthropogenic deposits also depends on other aspects, such as: profitability, new technologies of wastes processing to regain valuable raw materials, demand for the particular mineral, the impact on the environment of the liquidation of the repository, the role fulfilled by the object for the area or natural values. This the decision of the mining of the repository WF requires individual approach [18]. In case of the repositories of industrial wastes, usually retrieved minerals are metal ores, including valuable metals, rare-earth elements or critical raw materials, minerals used in chemical industry, scrap steel, cast iron and construction materials [19, 20]. The wastes deposited in WF by hard coal mines make potential source of energy and construction resources [21, 22]. According to the inventory [18], in Poland there are 259 objects, where hard coal mining wastes of different legal status in terms of the activities carried out are deposited (about 800 million tonnes). The estimated analysis contained in [21] indicates that in 1945–1989 120 million tonnes of coal silts were disposed in the objects like decantation ponds. The authors identified 59 objects where these wastes were disposed.

The exploitation of WF means taking wastes, usually with the use of excavators/loaders and processing them, depending on the kind of the retrieved wastes. The whole processing can take place in situ, in the facility located at WF or outside. In this case the product (waste) is transported in motor vehicles, railway or tape conveyors to the processing facility. Usually in the processing sieving, crushing and mincing are applied, as well as methods of gravity and flotation enrichment.

The obtained flammable fractions, depending on the calorific value and the size of grains, are used to produce energy for industry and households. The second significant raw materials are artificial aggregates – taken directly from the wastes repositories or being the remains after the processes of the recovery of the flammable fraction. Artificial aggregates make substitute for natural aggregates and they are usually used in construction industry, road construction and engineering. Regained wastes can make components of mineral fertilizers and stimulators of the development of plants [23].

As a result, old repositories, forming anthropogenic deposits are liquidated, the area can be reclaimed and brought back to agriculture or forestry use. It can also be used for economic purposes (the area for new service or production companies) and even converted to residential area.

**4. Reclamation of the Waste Facilitis From Hard Coal Mines**

Reclamation works can be carried out, provided that the legal status of the enterprise is regulated, including permit for wastes retrieval, permit to close the object of mining wastes neutralisation and, according to the legal regulations, so that they are safe for human health and life and did not have negative impact on the environment. Firstly, one should define the direction of reclamation, conduct the studies on geo-mechanic properties of the ground, water balance, as well as the range of land transformations. This is so-called preparatory reclamation, then a subsequent stage – basic reclamation – often called technical reclamation takes place [24].

In the framework basic reclamation, engineering works are done, including earth works connected with shaping the scarps and top of the repositories, earth works connected with reclamation cover, works regulating water balance and building access roads. Like in construction works, during reclamation, the mentioned above hard coal mining wastes are used in the amount connected with the technical way of reclamation. Due to the fact that the wastes of codes 01 01 02 and 01 04 12 are characterised by large size of grains and are often mixed with fine-grained wastes of code 01 04 81 to increase the isolation of the layer by fulfilling the inter-graine space (e.g., 10% participation). Earth works are connected with the shape of the top and scarps of the repositories, have also the purpose of securing the crown and scarps of the repositories from water and wind erosion. An example of earth works technology is distributing, levelling and compacting the wastes making the layer of thickness 1-1.5 m and density index Ismin = 0.95. After shaping the top and scarps of the waste repository, reclamation cover is made. Its thickness depends on planned plantations. If mining wastes are used, the participation of waste 01 04 81 increases e.g., to 20%, additionally, other wastes, such as concrete and brick debris (waste of code 17 01 07), soil and earth (waste of code 17 05 04), stabilised municipal sludges (waste of code 19 08 05) can be used.

Then, on the layer of reclamation cover, the earth layer of the thickness of e.g., 0.3 m is put, with the use of wastes from coal burning (e.g., slag, ash and dust from the boilers – waste of code 01 01 01), as well as soil and earth coming from construction works, renovation and demolishing of constructions and road infrastructure (waste of code 17 05 04), earth from digging (rocks from deepening – code of waste 17 05 06) or soil and earth coming from gardening (waste of code 20 02 02). After these measures biological reclamation is conducted.

Biological reclamation, also known as detail reclamation, is the third phase of the reclamation process. Biological stage of reclamation is a key stage. Its purpose is regeneration of biological activity of soil. Biological reclamation is a set of engineering and agrotechnical measures, a significant role is played by biological processes taking place in the upper layer of the ground, reshaping biocoenotic structure on degraded soils. The purpose of this stage of reclamation ma is first of all the protection from erosion, biological protection of the top and slopes and initiating and stimulation of soil-forming processes. Vegetation cover formed in the reclaimed area fulfils many functions, inter alia, causes the limitation of dust, increases the retention, which also limits leaching inside the profile, also fulfils the phyto-melioration function, sanitation, and remediation function (bioremediation and phytoremediation). Additionally, the vegetation cover forms microclimate and fulfils the protection function for the adjacent areas [25- 28].

The selection of the direction of biological reclamation is determined by many conditions. Firstly, the direction of reclamation must comply with the plan of the spatial management of a given area, as well as habitat conditions. Formal and legal, technical, hydrogeological, cultural conditions are important, as well as the kind and accessibility of infrastructure, the degree of urbanization of a given area and ecological factors [29, 30]. Natural succession in the reclaimed area must be considered [31].

Fig. 1. Spontaneous vegetation with the black locust (Robinia pseudoacacia) in a fine coal landfill
Rys. 1. Spontaniczna wegetacja z udziałem szarańczy czarnej (Robinia pseudoacacia) na składowisku węgla drobnego

Fig. 2 Spontaneous succession in the area of closed hard coal mines
Rys. 2. Sukcesja spontaniczna na terenie nieczynnych kopalń węgla kamiennego

The efficiency of biological reclamation depends on the properties of the reclaimed grounds. The reclamation measures are influenced by the pH, the amount of accessible nutrients, the content of humus, which significantly influence the sorption complex and retention properties, as well as the granulometric composition of the ground. Thus the condition of the revival of biological activity of soil is providing optima conditions for the development of plants and soil microorganisms, which also allow spontaneous succession of the adapted organisms.

Over years various concepts of biological reclamation in the degraded areas have been formed. The concept by Skawina considered the role of pioneer plants introduced in the reclaimed area. The role of pioneer plants was the initiation of soil-making process and activation of biological processes. Pioneer plants could be commercially used, nevertheless their basic function of the stimulation of soil-making processes before the final (permanent) species are introduced. To initiate soil-making processes and the enrichment of soil in nitrogen, Fabaceae (Papilionaceae, leguminous plants) are used. Due to the symbiosis with Rhizobium bacteria the Fabaceae can use atmospheric nitrogen and do not require mineral fertilizers. The species of pioneer plants also produce large amount of surface biomass and have strongly developed and draining root system. Often, apart from leguminous plants, various grass species are introduces, acting against erosion (the timothy (Phleum pratense), red fescue (Festuca rubra), orchard grass (Dactylis glomerata) In the area reclaimed in the forest direction the function of pioneer plants fulfil the species of trees and shrubs, such as: the black alder (Alnus nigra), grey alder (Alnus incana), silver birch (Betula verrucosa), Scotch pine (Pinus sylvestris) and various species and varieties of willow (Salix sp.). Non-native species with the features of pioneer plants were also introduced, but these were invasive species posing threat to native biodiversity, such as: the black locust (Robinia pseudoacacia), Siberian peashrub (Caragana arborescens) [Fig.1]. Other model of biological reclamation (Polish Academy of Science model) assumed intensive mineral fertilization in the first years of the reclamation, putting in doubt the significance of the organic substance. Direct introduction of final species was recommended, and then intensive mineral fertilization of plantation took place, which posed a significant risk of the eutrophication of water streams and water bodies. In practice often final species were replaced by various species of herbaceous plants, which spontaneously entered nitrogen-rich soils and overgrew the plantations. [32].

**5. Natural Succession in the Degraded Areas**

Devastated and degraded post-industrial areas include (among others): repositories of solid wastes from mining, metallurgy, energy industry, chemical and municipal wastes, decantation lagoons and the areas of soils strongly transformed by chemical substances. Depending on the degree and kind of degradation, technical formation of such a deposit, local climatic conditions, water and ground conditions and the properties of earth material, spontaneous development of vegetation is common. Spontaneously entering plant species usually come from the adjacent areas. In case of deposits rich in nutrients the biomass of a given plant species exceeds the biomass of the same plant species growing in normal conditions. Similarly, the content of macro and micro components in the biomass of these plants varies significantly. Plant communities on waste repositories and degraded grounds are communities of a high degree of hemeroby, characterised by high specialisation and pioneer character. The most common species belong to poly-hemerobes and meta-hemerobes [33]. Often plants growing in the degraded areas, especially in several decades old waste repositories, characterised by large content of heavy metals and low content of nutrients and unfavourable water conditions form defensive mechanisms, protecting them from environmental factors. Plants growing in such extreme conditions make quite rich phytocoenoses, which Wierzbicka called heap populations. Plant species of heap populations often morphologically vary from plants of

Fig. 3. Yellow iris (Iris pseudoacorus) position near the fine dust yard
Rys. 3. Stanowisko irysa żółtego (Iris pseudoacorus) w pobliżu placu drobnego pyłu

the same species, growing in natural conditions can also higher tolerance to heavy metals [33-36].

Due to the differentiation of post-industrial habitats, in terms of relief, hydrological conditions, content of various factors, including toxic elements and granulometric composition of the ground, the areas of this type have very differentiated ecological niches, possible to be populated by various species, and due this they have high potential of ecological remediation [37] [Fig.2].

Observed in the repositories mining wastes, often characterised by theoretically unfavourable conditions for vegetation (e.g., salinity, high temperature), after several years, dense vegetation cover is found. Through natural succession, these apparently hostile formations are colonised by plants of high adaptation abilities. The formed habitats are valuable objects of studies referring to the succession of adaptation mechanisms to unfavourable environmental conditions. Mining leads to the formation of ecological niches, which are often populated by valuable species, protected by law or regionally threatened. On the heaps of the gangue, covered with vegetation as a result of spontaneous succession nearly 600 species of vascular plants were identified, including several species protected by law. Most species are connected with ruderal and segetal habitats [38] [Fig.3]. Scientific studies carried out on the repositories of mining wastes, which underwent spontaneous succession, show much higher so-called biotic novelty index compared to forests grown in natural habitats. Observations are promising in the context of the reclamation and revitalisation of this type of objects, however, a factor which works against such solutions is the time of the formation of such ecosystems through the spontaneous succession place [39].

**6. Conclusions**

The amount of the produced mining wastes is significant, taking into account the production of industrial wastes in Poland, as well as produced only in hard coal mines. More than half of these wastes end on the repositories. Depositing wastes is connected with high environmental nuisance, due to the landscape degradation, threat to the quality of surface and ground waters and air quality. Repositories of mining wastes used to be left without reclamation. They used to be treated as indispensable disfiguring element of landscape in the mining areas. Nowadays, according to the law, every repository, after the end of use must be remediated. The mentioned above old not cultivated repositories are overgrown with vegetation. Even in the areas of spontaneous succession where the conditions were and still are very unfavourable, vegetation appeared as a result of natural succession. This way very interesting and ecologically valuable ecosystems appeared quite often. The example can be Hałda Storczykowa in the commune of Złoty Stok where the wastes from arsenic ores were deposited. This heap is now an ecological utility due to the rich flora, including calamine grasslands and the early spring orchis (Orchis mascula). Overgrown with vegetation old heaps now make recreational areas for local residents. They can be managed of left as „wild" areas. More and more often educational paths are made there, the purpose of which, apart from recreation is getting the visitors familiar with the history of this area and drawing their attention to local nature.

Due to changing economic conditions and developing technological possibilities of retrieving useful minerals from wastes, often old repositories are treated as anthropogenic deposit and mined. This also refers to the heaps of hard coal mining. Nowadays, during energy crisis and expected shortage of fuels in Europe and their growing prices, the recovery of coal from wastes deposited on heaps was included in the governmental programme of the reclamation of post-mining areas, in the framework of which a pilot installation for coal recovery was made. Unfortunately, during the exploitation of the mining wastes repositories valuable ecosystems, which were formed on them are lost. However, one should remember that the mining of such an anthropogenic deposit allows obtaining the lacking minerals, preserving natural deposits and ecosystems in the areas where these deposits occur. Making decision a waste repository should be mined, one must take into account both economic and ecological conditions.

Newly formed repositories are filled with post-mining wastes which cannot be used now. These repositories are reclaimed. There are many methods of technical and biological reclamation, depending on the conditions in the repository and its destination. Thus, depending on architectural, environmental and social conditions, regarding the well-being of the residents and cultural factors, two ways of procedures should be taken. Some objects should be reclaimed in a specific direction, so that the area can be used again, but some objects can be left for the formation of new habitats, due to natural processes taking place in the natural environment, even the environment with a strong anthropogenic pressure (Kantor-Pietraga et al. 2021; Pu et al. 2017; Chen et al. 2019). In the repositories formed now, valuable ecosystems will be formed with time. New technologies, allowing economically profitable recovery of minerals from wastes can appear. This way a difficult decision if the new habitats should be preserved or the mining should start will have to be taken.

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## *Rola sukcesji naturalnej w procesie rekultywacji obiektów unieszkodliwiania odpadów wydobywczych*


*Działalność przemysłu wydobywczego wiąże się z wytwarzaniem odpadów, powstających głównie w trakcie prac udostępniających, eksploatacji jak i przeróbki kopalin. Rodzaj jak i ilość wytwarzanych odpadów wynikają wprost z rodzaju pozyskiwanego surowca mineralnego (kopaliny), z występujących warunków geologicznych złoża oraz stosowanych technologii górniczych i przeróbczych. Zmieniające się podejście do odpadów związane z modelem gospodarki o obiegu zamkniętym powodują, że w coraz większym zakresie odpady są gospodarczo wykorzystywane. Niemniej jednak ze względu na właściwości fizykochemiczne odpadów wydobywczych i ograniczone możliwości ich wykorzystania, powodują, że niektóre odpady są nadal składowane na obiektach unieszkodliwiania odpadów wydobywczych (OUOW). W zależności od rodzaju składowanych odpadów wydobywczych, aspektów środowiskowych i ekonomicznych OUOW stanowić mogą źródło surowców (złoże antropogeniczne), które obecnie lub w przyszłości będą mogły być eksploatowane. Część tego typu obiektów jest rekultywowana i może stanowić cenny element lokalnego krajobrazu, a także korzystnie wpłynąć na różnorodność biologiczną, poprzez wykształcanie się specyficznych siedlisk przyrodniczych. W artykule przedstawiona została koncepcja rekultywacji OUOW z górnictwa węgla kamiennego, uwzględniająca znaczenie zjawiska sukcesji naturalnej w kształtowaniu się ekosystemów na rekultywowanych obiektach.*



**Słowa kluczowe:** *obiekt unieszkodliwiania odpadów, składowiska odpadów wydobywczych, złoże antropogeniczne, gospodarka obiegu zamkniętego, rekultywacja, badania biologiczne*