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Waste management in the mining industry of metals ores, coal, oil and natural gas - A review

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ABSTRACT

Waste generated due to mining activity poses a serious issue due to the large amounts generated, even up to 65 billion tons per year, and is often associated with the risk posed by its storage and environmental management. This work aims to review waste management in the mining industry of metals ores, coal, oil and natural gas. It includes an analysis and discussion on the possibilities for reuse of certain types of wastes generated from mining activity, and discusses the benefits, disadvantages and the impact of waste management on the environment. The article presents current methods of waste management arising during the extraction and processing of raw materials and the threats resulting from its application. Furthermore, the potential methods of mining waste management are discussed through an in-depth characterization of the properties and composition of various types of rocks. The presented work addresses not only the issues of more sustainable management of waste from the mining industry, but also responds to the current efforts to implement the assumptions of a circular economy, which is aimed at closing the loop. The methods of recycling by-products and treating waste as a resource more and more often not only meet environmental expectations, but also become a legal requirement. In this respect, the presented work can serve as a valuable support in decision-making about waste management.

1. Introduction

Currently, in the world, open-pit and underground mines actively operate to extract valuable metallic and energy resources (Radić et al., 2016). This paper focuses on six raw materials: copper, lead, zinc (metallic raw materials) and coal, crude oil, and natural gas (energy raw materials). The work focuses on analyzing the discussed raw materials relative to five countries that are recognized as leaders in terms of resources and production of a given raw material. For copper, these are Chile, Peru, China, USA, and the Democratic Republic of Congo (DRC) (Flanagan, 2019; Kotarska et al., 2018); for zinc: China, Peru, Australia, USA, and India (Maghfouri et al., 2018). Most lead is mined in China, Peru, the USA, Mexico, and Russia (Mymrin et al., 2020). Oil and gas are mined in the USA, Russia, Saudi Arabia, Canada, the United Arab Emirates, Iran, Canada, and China (Ismail et al., 2017). Among these countries, only in the United States there are located all of the above-mentioned raw materials. However, China is also at the forefront in terms of owned resources and their extraction, except for crude oil.

Naturally, the large variety of raw materials found in the USA and China result from the massive area of both countries, amounting to over 9 million km^2 (Brown et al., 2020). The wide range of latitude and longitude determines a broad climatic spectrum for those countries, which is conducive to the conditions for the formation of raw materials in the past and now. Equally crucial for the formation of the discussed raw materials were tectonic movements and the formation of the surface due to geological processes (Drachev et al., 2010; Mann et al., 2005). It is worth emphasizing that the United States is situated on active tectonic plates, e.g., the San Andreas Fault, which runs through western and southern California, which is characterized by rich sources of oil and natural gas (Mann et al., 2005).

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In the case of China, the most active are 3 tectonic faults: Webschuan, Pengguan, Baichuan, causing cyclical shocks (4000 movements in 15

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years), contributing to mineralization and filling in the resulting void spaces in rocks (Song et al., 2018).

Peru is rich in copper, zinc and lead, while Russia has the largest reserves of lead, oil and gas. However, Russia is situated on one of the most stable tectonic plates - Eurasian, which reduces the further mineralization of ores in this region of the world. Therefore, oil and gas originate there from the existing geological formations. Other countries are the leaders for one or two of the raw materials. Significant deposits of oil and gas are observed in the Arab states. In turn, in Australia and India, the geology is characteristic of the presence of metalliferous elements (Drachev et al., 2010; Flanagan, 2019).

Figs. 1–6 presents countries with the largest deposits and the largest amounts of extracted raw materials. The amount of produced waste was estimated based on the literature data. The data in the graphs represent the resources that have been estimated and reported in geological journals and texts (Bakalarz, 2019; Dudeney et al., 2013; Flanagan, 2019) for the country concerned. The annual extraction of the raw material in a given country was presented on the basis of data presented by the plants that extract the given raw material. Data on the annual extraction of raw materials are also made public in official reports (Brown et al., 2020). The amount of waste produced was estimated on the basis of data that includes the amount of metal or raw material in the deposit and on the basis of reports that refer to the ratio of the amount of raw material extracted to the amount of waste produced, expressed as a percentage (Çoruh et al., 2012).

The largest copper deposits are located in Chile (209 mln tones) and Peru (68 mln tones), wherein the annual extraction in Chile is more than twice that of Peru. The remaining countries, i.e., the Democratic Republic of the Congo, China, and USA have resources ranging from 20 to 35 million tons, with annual production 77% lower than that of Chile. Since the amount of raw material extracted is closely correlated with the amount of waste generated during the extraction process, the presented values indicate, why Chile produces 400% more waste than the Democratic Republic of Congo.

In Europe, Poland is the leader in extraction and production of copper. The biggest Polish producer, KGHM Polish Copper, extracts up to 702 thousand tons of raw material per year in total. With an average copper content of about 2% in Polish deposits, and extraction of 566 thousand tons, over 28 thousand tons of copper ore flotation tailings are formed (KGHM, 2020). During mineral enrichment, on average 94% of the material is treated as waste (Kotarska, 2012). Annually, Chile extracts about 60 times more copper than Poland and as much as 99% is waste. Both countries stockpile similar amount of flotation tailings, constituting 60–70% of the primary raw material (Łuszczkiewicz, 2000; Steliga and Uliasz, 2012).

The highest zinc deposits are located in Australia (68 mln tones) and China (44 mln tones). Despite China deposits are around 35% less, it extracts about 3 times more than Australia. Similarly, to Peru, which has less than 3.6 times zinc deposits than Australia but extracts 7% more. The largest amount of waste from the zinc extraction processes is generated by China, reaching around 81.7 million tons, which is 307% more than in Peru, being second on the list (Amy C. Tolcin, 2020; Brown et al., 2020).

The largest lead mineralization occurs in China, where the deposit's potential is 18 million tons and is approximately 2.8 times greater than the deposits in Russia or Peru and 3.2 times greater than in the other countries. China is the undisputed leader, when it comes to mining of lead, since it brings it out 700% more than other countries. Similarly, as in the case of the aforementioned metalliferous raw materials, China is also an inglorious leader in terms of waste generated from the lead mining process (Yin et al., 2020).

Coal deposits found in the United States are estimated at around 250,000 million tons, while smaller resources, ranging from 105,000 million tons to about 150,000 million tons, are in India, China and Australia ("Coal and lignite production," 2019). Annually, Chinese coal production is about 4000 million tons, while other forefront countries extract 85% less. This is related not only to smaller coal deposits, but also to climate policy. However, coal waste accounts for approximately 46% of the annual output for each of the leaders (Fečko et al., 2013).

The majority of crude oil extraction is carried out by Arab countries, such as the United Arab Emirates, which has 97,800 tcm (trillion cubic meter) and Saudi Arabia having less than half of the deposits of the United Arab Emirates. However, despite having the biggest resources, these countries are not producing the most. The leader is the United States, which despite having 92% smaller oil deposits than the United Arab Emirates, extracts it up to 415% more ("Crude oil production," 2019).

Russia has the largest natural gas reserves in the world, estimated at 38 tcm, which is 16% more than the estimated natural gas deposits in Iran. Similarly, to the crude oil, despite not having the biggest resources, the USA is the largest producer of this raw material. Iran, Canada and China produce similar amounts, despite large differences in their resources. Compared to the US, annually they extract around 77% less ("Natural gas production," 2019). Charts with regard to global extraction, resources and waste from metals, and energy raw materials are presented in the appendix (Figs. I and II).

Data on resources and annual production (Figs. 1–6) show what sizes of raw materials individual countries have. The distribution of the share of the distinguished countries has been similar so far, as it corresponded to the resources held. However, the situation has recently changed due to the prevailing pandemic. As a result of sanitary restrictions and people infected with covid-19, the efficiency of mines decreased due to the limited number of working personnel. In some countries, mining activities have been reduced or terminated, such as South Africa, where the shutdown of the mining process led to the closure of mines and the dismissal of workers. The restrictions led to the suspension of many industrial and construction productions, which led to a dramatic drop in demand for metals. There has been a decline in the prices of metals and minerals, mainly aluminum (down 15%), copper (down 14%), gold, lead and nickel, thereby putting the incomes of countries based on exploration of raw materials at risk (Laing, 2020).

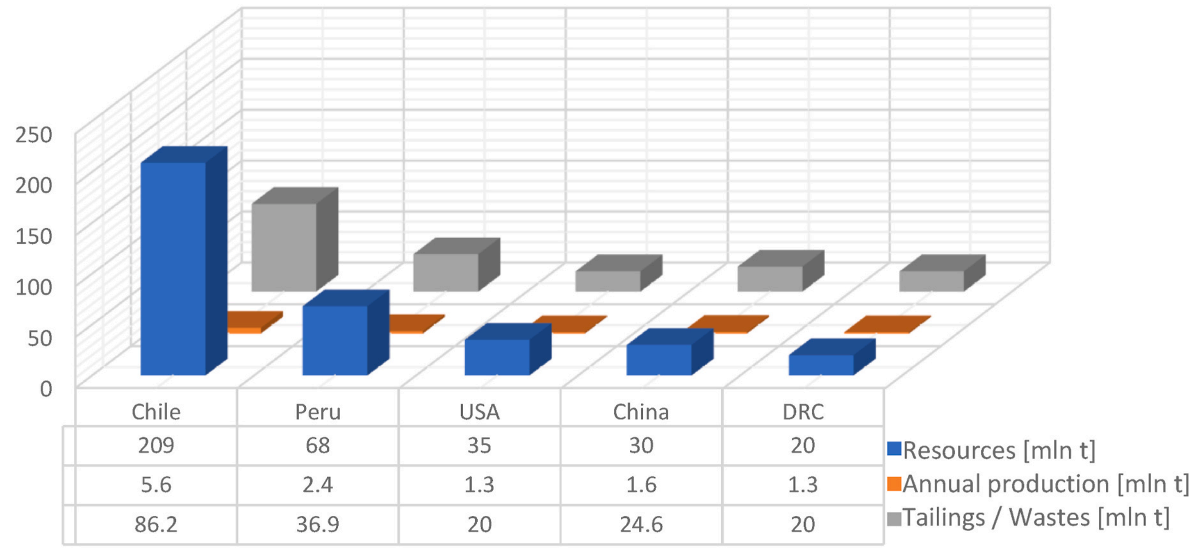
The introduced restrictions related to movement affected the transport sector, including aviation, and this in turn affected the fuel market. These sectors accounted for 60% of the oil demand. As a result of the pandemic, demand decreased from 100 million barrels in January 2020 to less than 75 million barrels in April 2020. The International Energy Agency (IEA) predicted that global demand for natural gas in 2020 will decrease by 4%. From December 2019 to June 2020, the number of drilling and gas rigs in the US decreased from 805 to 265.

Downtime caused by the pandemic contributed to the lack or problems with the availability of certain materials on the market, and this also contributed to a sharp increase in the prices of metal raw materials as well as oil and gas (Moore et al., 2020; Nyga-Łukaszewska and Aruga, 2020; Zanoletti et al., 2021).

This work aims to review waste management in the mining industry of metals ores, coal, oil and natural gas. It includes an analysis and discussion on the possibilities for reuse of certain types of wastes generated from mining activity, and discusses the benefits, disadvantages and the impact of waste management on the environment.

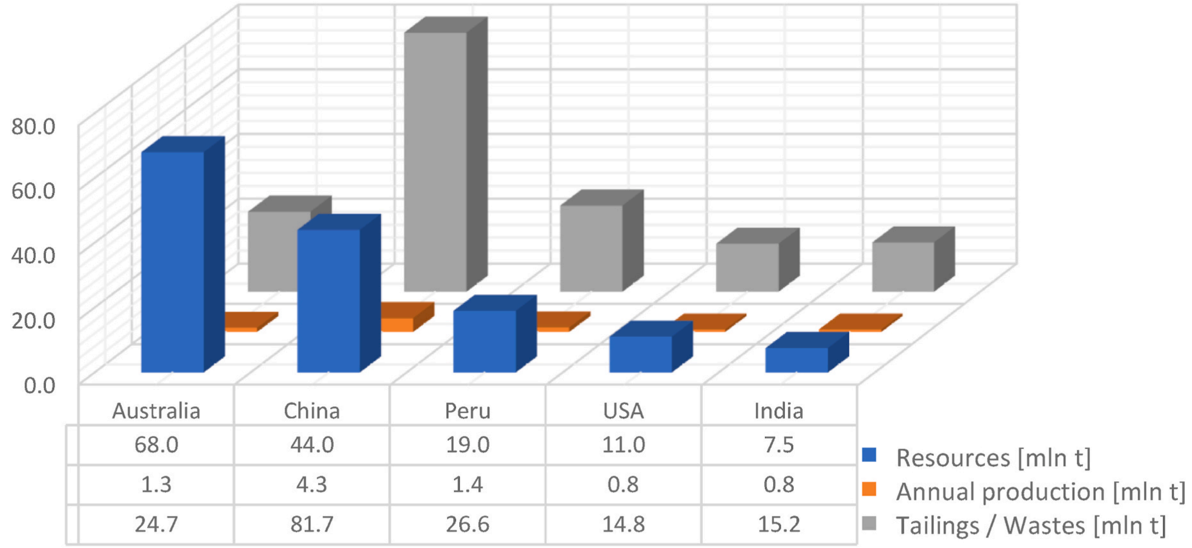
To meet the goal and to discuss waste management according to its characteristics, the research begins with the review on the properties and composition of metal-bearing ores and energy rock resources. Furthermore, it compares it with the variability in mineralogical composition of the wastes generated during processing and production. This knowledge and understanding of the technology of wastes acquisition allows estimating the amount generated, the variability between particular processes, and evaluate best and most environmentally friendly way of its future re-use and management.

The literature reviewed and placed in this paper, was selected in such a way as to present the world resources, annual extraction of selected metals and energy raw materials, and estimated amounts of produced waste, in order to show the scale of the amount of waste produced and



	Chile	Peru	USA	China	DRC
Resources [mln t]	209	68	35	30	20
Annual production [mln t]	5.6	2.4	1.3	1.6	1.3
Tailings / Wastes [mln t]	86.2	36.9	20	24.6	20

Fig. 1. Countries with the largest resources of deposits, annual production and the average amount of waste produced from copper.



	Australia	China	Peru	USA	India
Resources [mln t]	68.0	44.0	19.0	11.0	7.5
Annual production [mln t]	1.3	4.3	1.4	0.8	0.8
Tailings / Wastes [mln t]	24.7	81.7	26.6	14.8	15.2

Fig. 2. Countries with the largest resources of deposits, annual production and the average amount of waste produced from zinc.

the related management possibilities. The authors focused not only on published data in articles, but also on information that is available in individual mines and companies. Furthermore, a literature review was carried out on the geological basis of metals and energy raw materials, and mineralogical and phase composition of mine waste. These compositions vary according to the publication dates of the manuscripts. These differences result from technological changes in individual mining and material processing plants. Therefore, the authors chose the latest publications. On this basis, current data on the management of the above-mentioned waste and new possibilities of their use were presented.

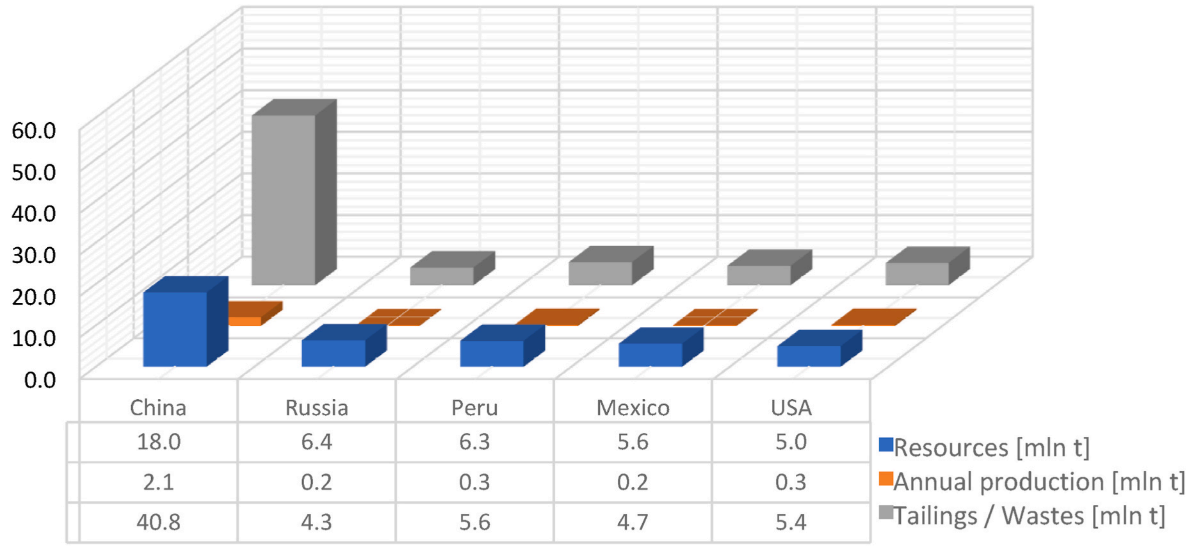
2. Geological aspects

A comprehensive analysis of the raw materials discussed in this paper is important as the aim is to analyze both the waste and the structure of the base component, which contain valuable minerals that end up in the waste. Due to their value, the raw material and accompanying rocks should be managed as best as possible, for example to produce a new product (concretes, coatings, pavements), but also to reduce possible environmental toxicity.

2.1. *Copper, zinc and lead*

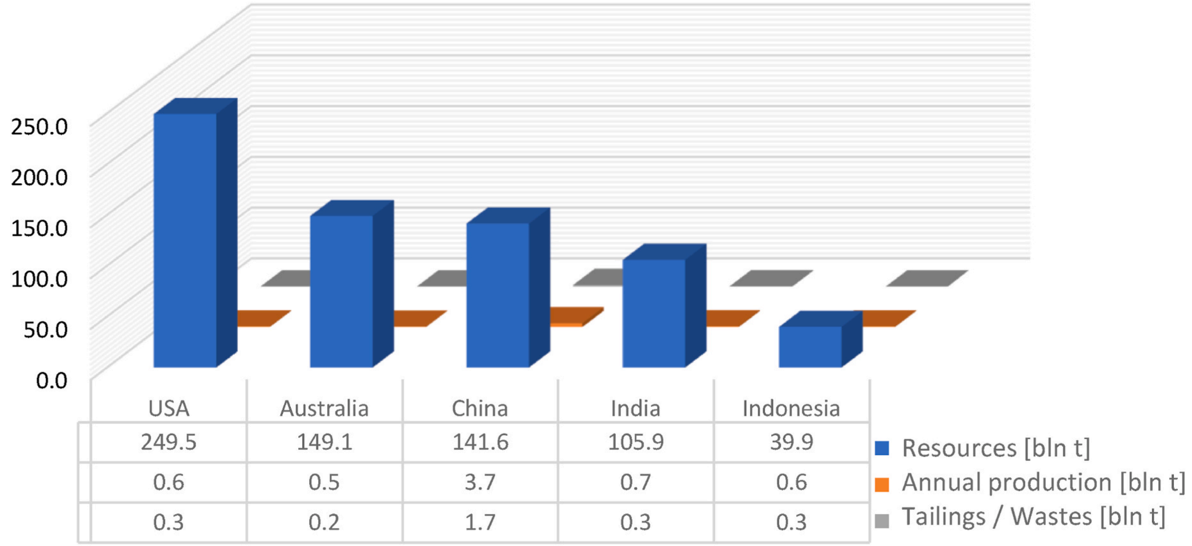
Copper is a metalliferous raw material obtained from rocks. It is extracted over 87–90% from sulphide ores and up to 9–12% from metal oxides ("Przeróbka kopalin miedziowych," 2008). Zinc and lead are also obtained from rock ores.

Acquiring raw materials for copper, zinc and lead requires mining them along with the rock in which they are contained. The raw material is extracted from the rock by means of flotation, whereas the remnants are considered as useless waste. Native copper ore deposits are extremely rare and constitute only about 1% of all its mineral deposits ("Copper alliance," 2018, "Informator Metale Nieżelazne," 2005). The mineralogical compound of rock waste results from the types of geological layers that may vary from region to region. The compound of copper ores for selected types of rocks are presented below. The main constituent is a gangue, which accounts for over 90% by weight, while copper minerals are less than 1 wt%. In Fig. 7 and Fig. 8, copper is indicated in the "other" group along with other compounds of metallic



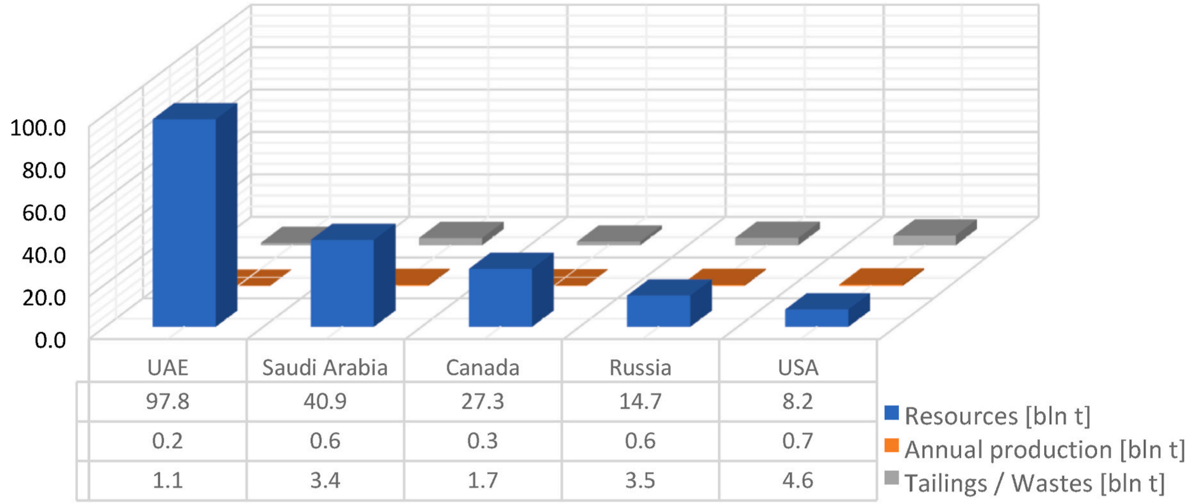
	China	Russia	Peru	Mexico	USA
🟦 Resources [mln t]	18.0	6.4	6.3	5.6	5.0
🟧 Annual production [mln t]	2.1	0.2	0.3	0.2	0.3
⬜ Tailings / Wastes [mln t]	40.8	4.3	5.6	4.7	5.4

Fig. 3. Countries with the largest resources of deposits, annual production and the average amount of waste produced from lead.



	USA	Australia	China	India	Indonesia
🟦 Resources [bln t]	249.5	149.1	141.6	105.9	39.9
🟧 Annual production [bln t]	0.6	0.5	3.7	0.7	0.6
⬜ Tailings / Wastes [bln t]	0.3	0.2	1.7	0.3	0.3

Fig. 4. Countries with the largest resources of deposits, annual production and the average amount of waste produced from coal.



	UAE	Saudi Arabia	Canada	Russia	USA
🟦 Resources [bln t]	97.8	40.9	27.3	14.7	8.2
🟧 Annual production [bln t]	0.2	0.6	0.3	0.6	0.7
⬜ Tailings / Wastes [bln t]	1.1	3.4	1.7	3.5	4.6

Fig. 5. Countries with the largest resources of deposits, annual production and the average amount of waste produced from oil.

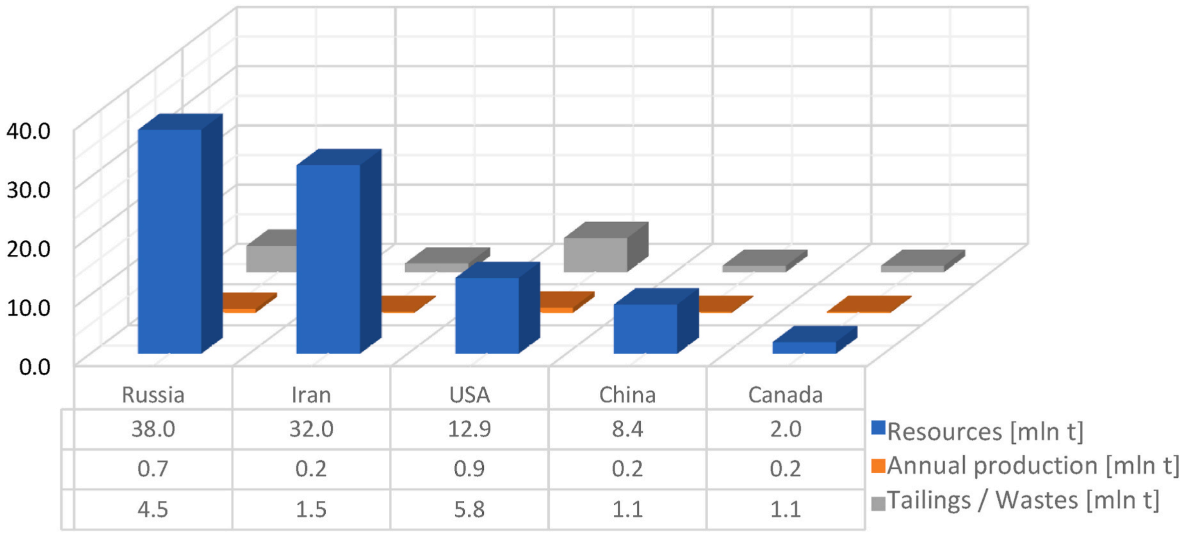


Fig. 6. Countries with the largest resources of deposits, annual production and the average amount of waste produced from gas.

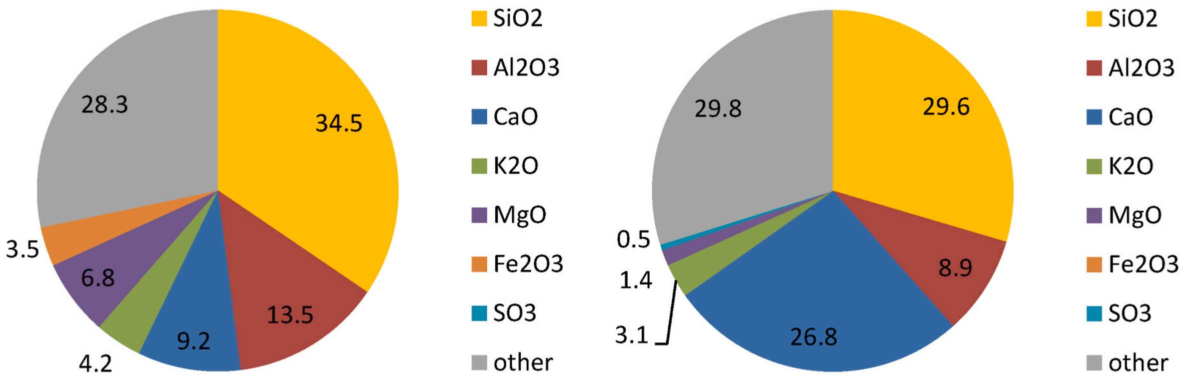


Fig. 7. Mineralogical compound of shale rocks (left) and marls (right) containing Cu minerals.

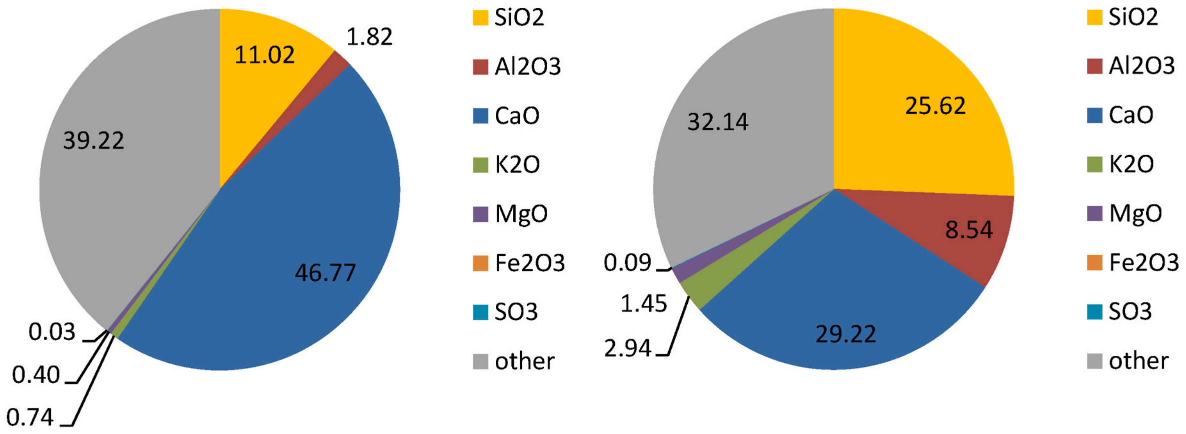


Fig. 8. Mineralogical compound of Zechstein limestone (left) and spotted marls containing Cu minerals.

origin in small amounts (Matlakowska et al., 2014).

Copper mineralization is observed in various types of rocks. Copper compounds are contained in igneous and sedimentary rocks of the Sierra Gorda deposit - the largest copper-molybdenum ore deposit in the world, located in the Atacama Desert in Chile. Copper occurs there in the form of sulphides and oxides in granodiorite, granite and monzodiorite rocks. Due to the large area of the deposit, the mineralization of the raw material also took place there in volcanic rocks, mainly in tuffs and andesites, and mudstones and claystones of sedimentary rocks (López and Ristorcelli, 2011; Pieczonka et al., 2017; Ristorcelli, S., Ronning, P., Fahey, P. and Lustig, 2008). Copper compounds in sedimentary rocks are also found in Polish copper deposits, which have been mineralized in shales, dolomites and sandstones. (Kibort and Małachowska, 2018; Konopacka and Zagożdżon, 2014).

Copper is also contained in Chinese sandstone deposits in the Chuxiong Basin. Sandstones are the result of the formation of geological features in the Cretaceous. Copper mineralization is visible in rock deformations (faults, anticlines, crevices) and in places that contacted with water. A shale zone is also distinguished there, which is consistent with the Permian copper shale from the European region. Copper minerals are mainly observed in the form of lenses and dominant thin lamination (Chen et al., 2000; Hsi-chi et al., 1968; Huang et al., 2019).

The quantity of the extracted raw materials is influenced by the rock texture of the sediment deposits, in which the raw material occurs. Thus, it is important to consider the texture when analysing the potential of any resources for production (Kibort and Małachowska, 2018). Copper in rocks can occur in different forms, what is graphically presented in Fig. 9: it occurs as dispersed or finely dispersed, filling rock spaces, e.g., in sandstones, – mineralized veins, usually occurring according to the location of the rock layers (shales), and – irregular sockets, known as lenticular, characterized by an oval shape observed in the form of lenses and dominant thin lamination (Chen et al., 2000; Hsi-chi et al., 1968; Huang et al., 2019, Kibort and Małachowska, 2018; Onuaguluchi and Eren, 2012).

Zinc and lead are most often found in the form of a single ore and are mostly extracted from sulphide ores. In the recent years zinc has been obtained by the hydrometallurgical method using electrolysis (Cabała, 2010). In its native state, zinc does not occur naturally. The main minerals of zinc are zinc blende (sphalerite - zinc sulphide) and smithsonite (zinc carbonate). Zinc blende is the most important zinc ore, containing also large amounts of cadmium, lead and even silver, indium and gallium (Kołodziejczyk, 2019). Cadmium accompanies almost all zinc ores.

The most important lead ores are galena (PbS - lead (II) sulphide) and anglesite ($PbSO_4$ - lead (II) sulphate). Galena is found in igneous and sedimentary rocks. It is accompanied by compounds of antimony, bismuth, zinc, copper, silver, gold and iron. Most often it contains only a few percent of lead, while pure lead sulphide may contain it up to 86%. In the case of zinc and lead, similar forms of occurrence are observed as in the case of copper, and the mineralization and distribution depend on the hydrogeological and thermal conditions. The presence of zinc and lead minerals in carbonate rocks is associated with hydrothermal processes of transfer of compounds from lower geological formations to the higher layers containing sulfur compounds, forming compounds with zinc and lead. Another source is the deposition of lead zinc in carbonate layers as a result of entering the cooler layers, preventing dissolution of the elements and further penetration (Van der Graaf, 2018). In Fig. 10 are mineralogical compound of dolomite containing zinc minerals and marls containing lead minerals with the minerals Zn and Pb being classified in the group "other". Zn and Pb content did not exceed 1 wt% (Biernacka et al., 2005).

The largest zinc mineralization was observed in dolomite sedimentary rocks and smaller in igneous rocks (Abu-Hamatteh and Al-Amr, 2008; Höller and Gandhi, 1997). To a lesser extent, the mineralization of zinc and lead is observed in metamorphic gneiss in the form of

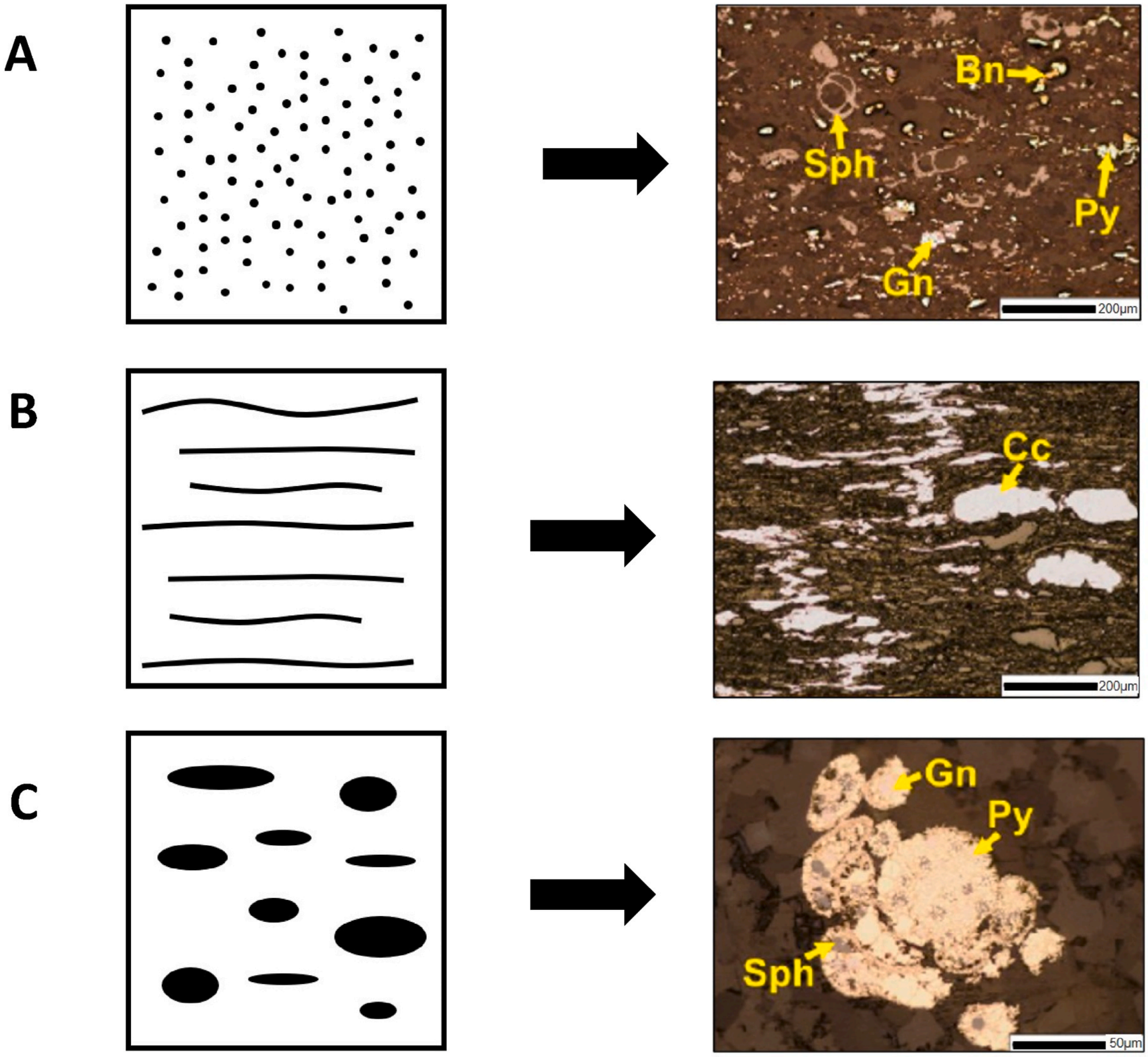


Fig. 9. Forms of copper: A - dispersed, B – mineralized veins, C – lenses.

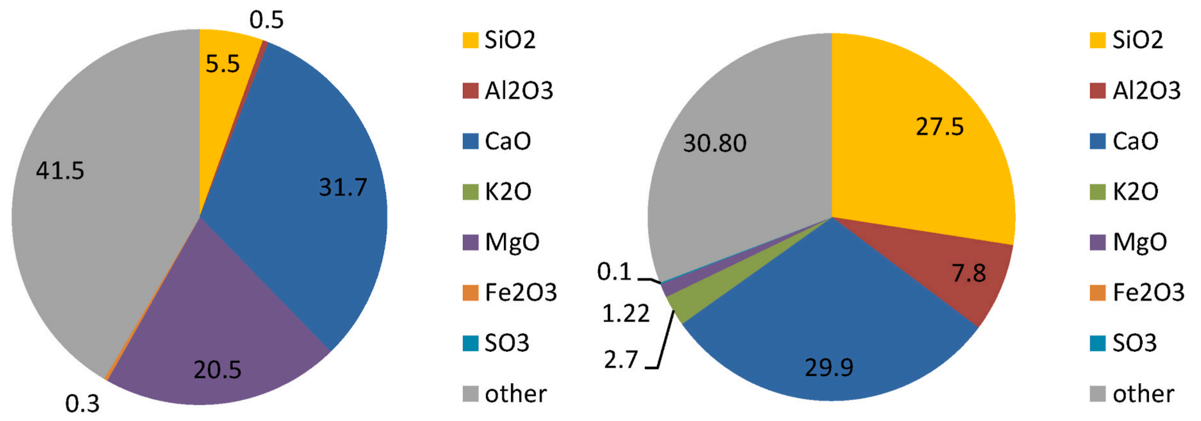


Fig. 10. Mineralogical compounds of dolomite (left) containing Zn minerals and marls (right) containing Pb minerals.

sulphide ores of the Ramura-Agucha deposit and graphite-mica-sillimanite shales (Kumar, 2013). A similar situation of mineralization is observed in the Barney Creek Formation in Australia, where zinc and lead deposits are mostly found in dolomite and shale rocks (Haines, P.W., Pietsch, B.A., Rawlings, D.J., Madigan, T.L., Findhammer, 1993; Hughes, 1990; Page et al., 2000). The mineralization of zinc and lead compounds is observed in an overhang of gneiss strands of the Rampura-Agucha deposit in the form of sphalerite and galena. They are in the form of fine to coarse grains with inclusions of feldspar, quartz, sillimanite and chlorite (Kumar, 2013).

A similar condition occurs in the European region with zinc and lead, referred as MVT deposits (Mississippi ValleyType). The name results from the similarity of the properties of the deposit to the compounds found in the Mississippi River Valley. The largest European zinc-lead region is located in Poland and is characterized by the presence of raw materials in carbonate rocks, the mineralization of which dates back to the period from the Devonian to the Jurassic. According research (Gałkiewicz and Śliwiński, 1983), the mineralization of zinc and lead follows tectonic structures (PIG-PIB, 2020; Piwowarski and Żeglicki, 1977).

Zinc deposits associated with carbonate rocks are also observed in Iran, where they are found in the Dolomites and Lower Permian dolomitic limestones. A characteristic feature of this deposit is the absence of zinc sulphides. Below the layer of zinc-lead ore deposit, there are shales and sandstones, and above gypsum, sandstone and shale rocks (Maghfouri-Moghadam et al., 2009).

The forms of zinc and lead minerals are described as similar to those of copper. They fill gaps and tectonic breaches. The most common are lenticular forms, as well as nests, stockworks and lines, which occur according to the stratification of the ore deposit (Nieć et al., 2018; Piwowarski and Żeglicki, 1977).

2.2. Coal

Coal mining is associated with the acquisition of the raw material along with accompanying rocks. Occurring coal seams are characterized by a different geology and period of formation. Such condition can be observed in the Chinese layered coal seam structure, where the influence of the marine environment on the geology of accompanying rocks is undoubtedly visible. Those coal seams are mainly associated with sedimentary rocks including sandstones and to a lesser extent mudstones and bauxite. Lime inclusions also appear there (Fang et al., 2013; Jin et al., 2013). Carbon stratification by sedimentary rocks is also observed in the European region. An example is the Upper Silesian Coal Basin, in which sandstone may constitute from several to 70% of the accompanying rocks. Further west, the sandstone content is lower, while claystone and shale predominate (Galos and Szlugaj, 2010).

2.3. Crude oil and natural gas

The drilling sector is characterized by a wide spectrum of rocks extracted as a drilling waste, which is influenced by the location and depth of the drilling that may pass through several significant and minor geological strata. For example, the geology of oil and gas fields in the Gulf of Mexico is made up by an alternation of shales and sandstones at a depth of 5000–5300 m. Carbonate rocks also appear in the lower section of the well (approx. 6000 m) (British Petroleum, 2010; Dice, 2017). Further down, from about 6800 m to 7500 m, salt deposits are present ("bp Statistical Review of World Energy," 2020, "Natural gas production," 2019; Dice, 2017).

Sandstones and sandy clays constitute the rock layers of the Baltic hydrocarbon deposits. Quaternary clays also occur with them. Free rock spaces are most often filled with silt or organic material. The Northern Baltic Sea Basin is characterized by the transition of sandy rocks into clay, loams and mudstones Therefore, it can be concluded that the Baltic region consists of those four rock types (Sikora and Wojna-Dylag, 2010).

3. Properties of mining and processing waste

Mining and processing of rocks and metal ores generates large amounts of waste rocks, (gangue), from the extraction process, tailings (from flotation and enrichment) and metallurgical waste (from the smelter).

During metal processing in a smelter, a waste called slag is produced (Gorai et al., 2003). The extraction of copper in one mine generates an average of 2.3 million tons of waste per year (Çoruh et al., 2012). Similarly, in the case of zinc and lead, 1 ton of extracted metal generates 19 tons of flotation waste and gangue (Bouguermouh et al., 2018). Fig. 11 presents a general scheme of how metal raw materials are processed.

Processing of energy resources such as coal, oil or gas, as in the case of metals, produces liquid waste, and solid waste - drill cuttings. As a result of coal mining, a waste rock, in the case of coal constitute about 30% (Kopacz, 2015), and the rest of the generated waste are tailings containing gangue and large amounts of water, which is recycled in a closed circuit (Hudson-Edwards et al., 2011).

The oil and gas industry also produces specific waste, known as drilling (around one million tons) and cuttings. The extraction of raw materials generates waste rock, such gangue and drill cuttings (Huang et al., 2018) as well as drilling and fracturing fluid. A general diagram of waste generation during the extraction of crude oil and natural gas is shown in Fig. 12.

3.1. Copper, zinc and lead

The extraction of copper, zinc and lead ores as well as the processing

Fig. 11. Diagram of the extraction of metal raw materials.

of these raw materials affects the quality of the environment. Mines produce a large amount of waste because the metal-containing ore is a small fraction of the total volume of material extracted. The waste material is generated in the processes of mining, extraction, processing and further treatment, and its quantity depends on a number of factors related to the geological structure of the rock mass, the quality of the deposits, methods of excavation and enrichment technology (Baic and Witkowska-Kita, 2011; Galos and Szlugaj, 2014; Tumidajski et al., 2008).

Mining waste constitutes mainly gangue, which is removed at the stage of deposit preparation, and waste from the extraction and processing of the raw material. The amount of the waste depends on the type of a mine: whether it is underground or open-pit. The waste from mining and preparatory works includes those generated, among others, while drilling new shafts. They are characterized by high variability of petrographic composition. The share of clay, sandstone, mudstone and overgrowth is varied. The grain composition of this material is in the range of >300 mm. In open-pit mines, the surface material is called an overburden, which is used to backfill the place, where the raw material was mined.

The waste from processing operations includes coarse-grained scrubber waste, grain class 20–200 mm; medium-grain waste from jigs, grain class 2–20 mm and fine-grain waste from spirals, grain class 0.5–2.0 mm. The content of organic parts in the waste material ranges from 42% in the case of jigs to 60% in the case of spirals. The mineral content ranges from 58 to 40%, respectively. The processing waste also includes sludge waste. They come from a chamber and belt presses. These are very fine-grained waste with a grain size of less than 0.5 mm. In terms of petrography, they are characterized by a significant share of clay and coal.

3.2. *Coal*

Coal mining, in relation to the production of other raw materials discussed in this study, generates the least amount of solid waste, which is managed through landfilling. The generated waste mainly comes from accompanying rocks that are separated in the froth flotation process. The waste from flotation can be further subjected to an enrichment (Melo and Laskowski, 2006). Wei and Peng, 2015 (Wei and Peng, 2015), used a diesel collector for coal flotation, while methyl isobutyl carbinol (MIBC) was used as a frother, while Peng 2015 used N-dodecane and 2-octanol as a collector and frother. From the literature review it is seen that oily reagents are commonly used, despite they should be neutralized before storage.

3.3. *Oil and gas*

The extraction of crude oil and natural gas involves drilling. Wastes from oil and gas extraction are mainly drill cuttings from drilling holes, contaminated drilling mud to facilitate production operations. The chart below shows an example of the cuttings mineralogical composition, which is the average value for ten depths within the range from 2500 to 5000 m. The main minerals of cuttings are quartz, feldspar, calcite and clay minerals. The content of each of them ranges from about 21 to 26%. Dolomite has the lowest content equal to 4.1%.

Drill cuttings variability in composition may be the result of natural geological processes or the result of contamination with components of water or oil-based drilling fluids. The group of liquid contaminants also

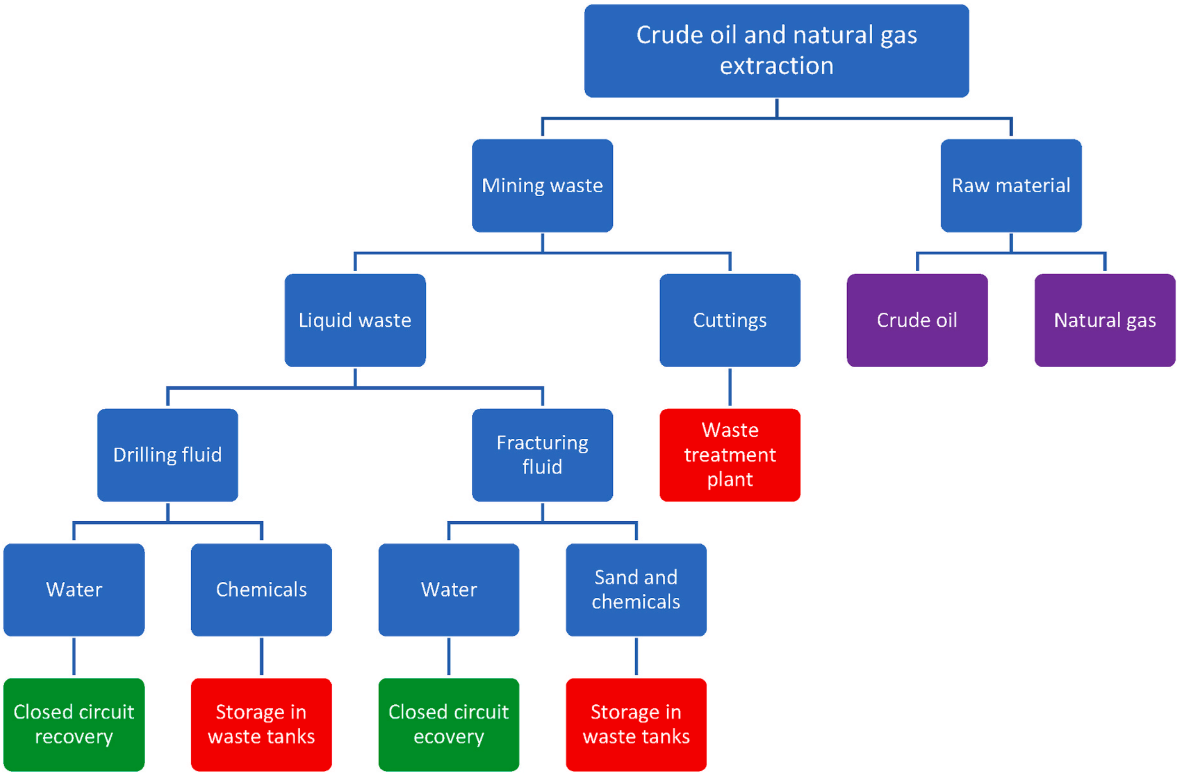


Fig. 12. Diagram of waste generation during the extraction of crude oil and natural gas.

includes the fracturing fluid consisting of 90–95% of water and chemical additives. To reduce the resource consumption, the flowback fluid from the fracturing process is treated and reused (Steliga and Uliasz, 2012).

Drilling works are carried out to the point of contact with the source hence the drill cuttings and drilling fluid are slightly contaminated with crude oil. This qualifies them as harmful to the environment and intended for disposal or neutralization. The chemical composition of drilling fluids can also contaminate solid and water wastes. There are three most popular types of drilling fluids: water-based, oil-based and pneumatic (Eldridge, 1996; Pereira et al., 2019), the compositions of which are shown in Fig. 13.

Water-based drilling fluids, such as synthetic ones, have a minimal impact on the environment and can therefore be disposed offshore. As most harmful and toxic drilling fluids are considered those based on oils. That type cannot be returned to the environment without purification and neutralization processes (Kujawska and Pawłowska, 2020). Types of drilling fluid is presented in Fig. 14 according to (Ismail et al., 2017). Similarly, as petroleum-based fluids, which are not permitted for offshore disposal and generated drill cuttings need to be cleaned prior to storage.

In turn, synthetic-based drilling fluids are preferred due to their technical characteristics and minimal environmental impact. An exemplary composition of the drilling fluid is shown in Fig. 15 (Ismail et al., 2015).

4. Composition of waste from mining activity

The composition of waste from raw material extraction was analyzed

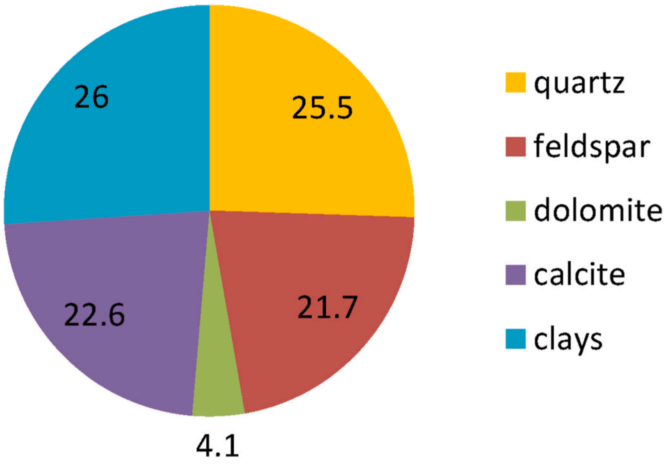


Fig. 13. Example of mineralogy of drill-cuttings.

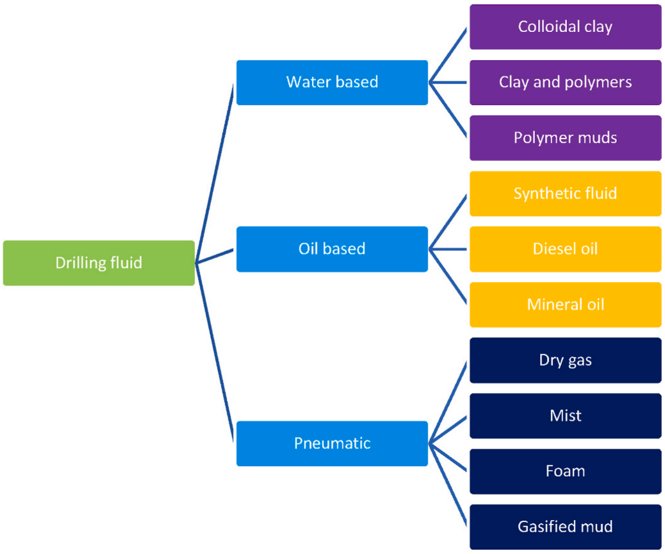


Fig. 14. Types of drilling fluid.

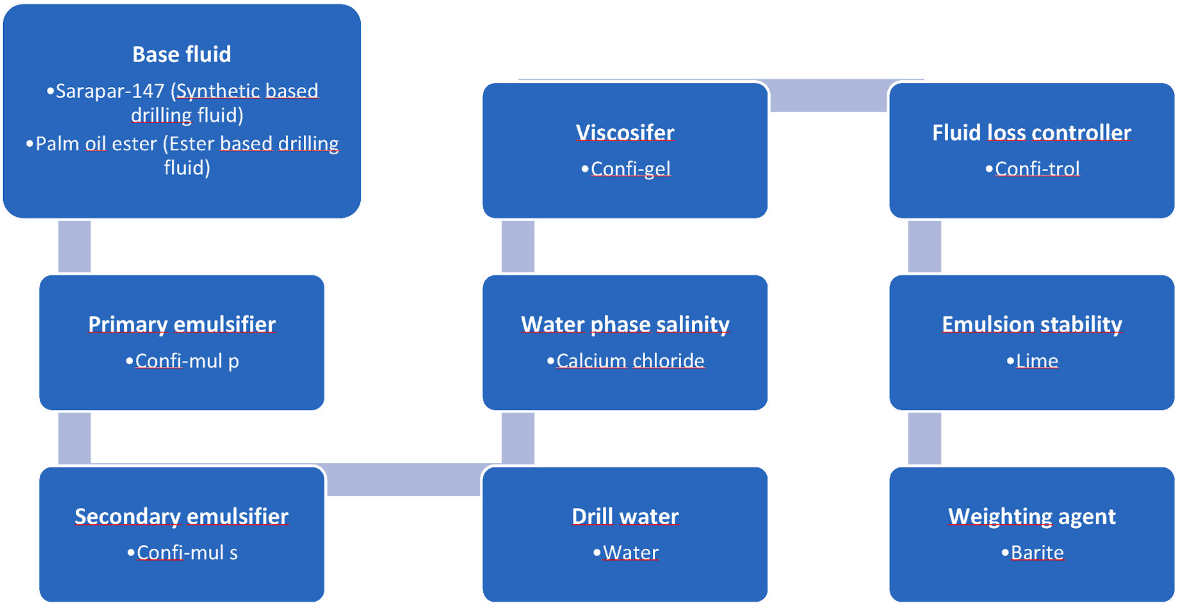


Fig. 15. An example of a drilling fluid.

in terms of the following compounds: SiO_2, Fe_2O_3, Al_2O_3, TiO_2, CaO, CuO, ZnO, PbO, PbO_2, Cr_2O_3, SO_3, K_2O and MgO.

The main components of flotation process of copper are silica (SiO_2), which comprises from 27% to 59%, and iron oxide (III), Fe_2O_3, representing from trace amounts up to 65% (Çoruh et al., 2012). The basic components of zinc and lead flotation waste are calcium oxide, CaO (up to approximately 26%), iron (III) oxide (approximately 12%), magnesium and sulfur oxides (around 11% each) and silicon dioxide (8.4%). Copper minerals constitute up to 1 wt%. while lead minerals up to approx. 0.3 wt%. In Fig. 12, both Cu and Pb are grouped as 'other'. Other compounds such as Al_2O_3, Na_2O, K_2O, TiO_2, P_2O_3, As_2O_2, PbO_2, ZnO, Cl are present in trace amounts (Bakalarz, 2019; Çoruh and Ergun, 2006; Grudinsky et al., 2020; Kowalczyk, 2019; Kozioł and Uberman, 1996; Liu et al., 2020; Nowak, 2008; Stanojlović and Sokolović, 2014; Steliga and Uliasz, 2012). Fig. 16 shows averaged data of the content of mineralogical compounds in the post-flotation tailings based on the analysis of literature data from (Lutyński and Szpyrka, 2010; Rad and Modarres, 2017) the recognized compounds comply with the deposit geology (Alp et al., 2008; Çoruh et al., 2012). The identified compounds are consistent with the previously described geology of copper, zinc and lead deposits. Depending on the occurrence of the rock formation, they may differ in the intensity (% content) of the occurrence of individual mineralogical compounds.

Post-flotation waste from the processes of obtaining zinc and lead was analyzed on the basis of two authors what is presented in Fig. 12 (Nowak, 2008; Śliwka et al., 2019). The average values indicate more even distribution of components than in the case of copper waste. Zinc and lead wastes are characterized by the highest CaO content, ranging from 26% to 29%, which is consistent with the typical geology of the deposit. A lower content was recorded for MgO (15%), Fe_2O_3 and SiO_2 (about 12% each) and SO_3 with a content up to 9%. There was no presence of CuO, PbO and Cr_2O_3. (Asadi et al., 2017; Muravyov and Fomchenko, 2018). Other compounds such as Al_2O_3, K_2O, TiO_2, P_2O_3, PbO_2 are present in trace amounts. Zn minerals constitute up to 3 wt%. while minerals Pb approx. no more than 0.3 wt%. Both Zn are Pb are presented in Fig. 12 as components of the "other" group.

Fig. 17 shows the results of the average mineralogical compound of coal flotation waste are the average value based on the results presented by research groups (Lutyński and Szpyrka, 2010; Piszcz-Karaś et al., 2019; Rad and Modarres, 2017). The highest content was recorded for silica (39%–60%) and Al_2O_3 (c.a. 17.5%). The content of the remaining components was ranging from 1.5% to about 5%. The compounds like CuO, ZnO, PbO, PbO_2, Cr_2O_3 were not recorded in the composition of coal waste.

The mineralogical compound of waste and drill cuttings obtained as a result of oil and gas extraction works varies depending on the existing geological layers, what is shown in Fig. 18 (Chen et al., 2000; Çoruh et al., 2012; Hsi-chi et al., 1968; Huang et al., 2019; Kibort and Małachowska, 2018; Konopacka and Zagożdżon, 2014; Longarini et al., 2014; López and Ristorcelli, 2011; Nowak, 2008; Pieczonka et al., 2017;

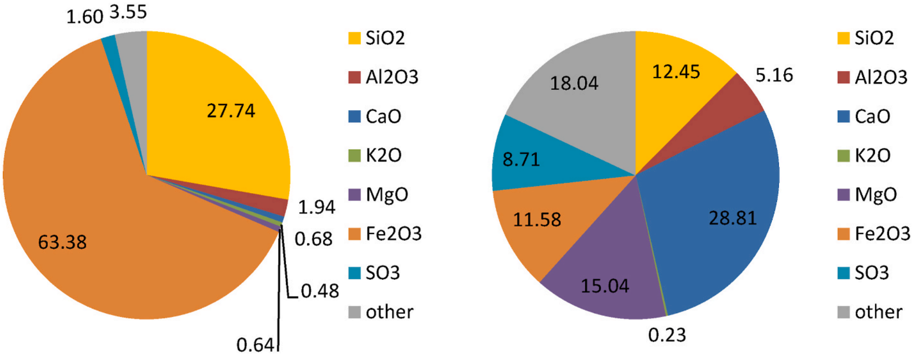


Fig. 16. Mineralogical compounds of post-flotation waste from Cu ores (left) and Zn and Pb ores (right).

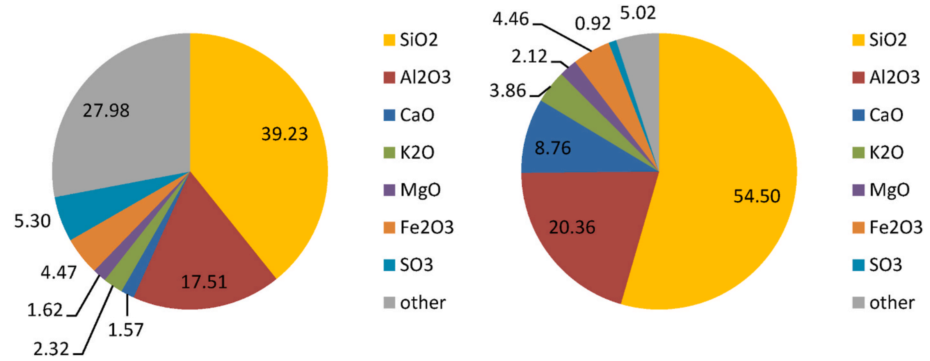


Fig. 17. Mineralogical compounds of coal post-flotation waste (left) and coal ash (right).

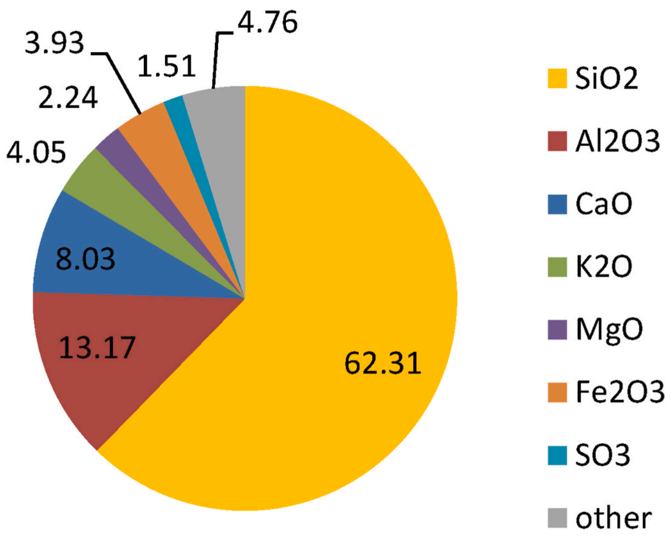


Fig. 18. Mineralogical compounds of cuttings from oils & gas sector.

Ristorcelli, S., Ronning, P., Fahey, P. and Lustig, 2008). Wastes from oil and gas extraction are mainly rocks contaminated with components of drilling fluid. Drilling waste compounds were analyzed on the basis of 4 literature sources by (João et al., 2017; Köse, 2019; Piszcz-Karaś et al., 2019; Rykusova et al., 2020). The average result of drilling wastes shows that the silica content was over 60%, Al_2O_3 was 13% and CaO was 8%. The content of Fe_2O_3, K_2O, MgO and SO_3 ranged from 1.5 to 4%. The remaining components were characterized by the content below 1%, except for PbO and PbO_2, which were not present.

5. Waste management

5.1. The current state of post-mining waste management

The most popular method of post-flotation waste management is ground storage in waste neutralization tanks. In Europe, the largest landfill and a facility for neutralizing copper flotation waste is the “Żelazny Most Mining Waste Treatment Plant”, owned by KGHM Polska Miedź, located in the Lower Silesia in Poland. The facility, where the waste is stored, is limited by the embankment, which is designed to prevent the waste from scattering. There is a pipeline in the upper part of the shaft to transport sewage by water. When waste is deposited, it spontaneously segregates: coarse-grained material falls close to the discharge point to form a beach, and water and dust flow to the landfill to form a sedimentation basin. Recycled water from the drained sediment is used in the flotation process (Çoruh and Ergun, 2006; Grudinsky et al., 2020; Kowalczyk, 2019) In the Żelazny Most also liquid flotation waste (sewage) from copper extraction is stored. Table 1 presents the parameters of the Żelazny Most waste treatment facility, the current state and assumptions for the coming years (Grabas and Pawlik, 2017).

Table 1
Parameters of the ‘żelazny most’ mining waste treatment plant.

Parameters	Size	
	Present	Future
Total area [km^2]	16	22
Total collected waste [mln m^3]	560	969
Length of embankments [km]	14.3	–
Maximum dam height [m]	36–62	over 100
Poolarea [km^2]	7.5–8	–
Beach area [ha]	794	–

In appendix are photos of the largest places disposal of post-flotation waste (Fig. IV). The areas of the reservoirs range from about 8 up to 20 km^2. For economic and logistical reasons, they are located in the vicinity of the mine.

A good pro-environmental solution is afforestation of brownfield sites. The literature is rich in research on the use of plant cover as a method of reviving such sites. The use of specific types of trees can have very good effects on people and the environment (Ciarkowska et al., 2017; Ciarkowska and Hanus-Fajerska, 2008; Mleczek et al., 2016).

Selected species of trees and plants can contribute to the increase in the content of organic matter in the soil and the development of a soil system capable of meeting the nutrient and water needs of other plants and microorganisms. Hence, the introduction of specific trees might be also an effective tool in reducing the risk of damaging dams prior to surface water migration.

Waste from coal mining is managed, however only in 44%. Among the waste related to coal mining and processing, the following types of waste are distinguished: flotation, slag, bottom ash and fly ash. Post-flotation waste may be subjected to the enrichment process; slag - can be used in construction as a material used in civil engineering (road construction), it can also act as a sealing material. Bottom ash is a good filter material or, after appropriate transformation, can be used as fertilizer or granulate for plants, while fly ash is mainly used in construction. Researchers (Lazutkina and Buler, 2003) proposed the use of carbon ash (an aluminosilicate material) mixed with borax to create glass coatings on steel surfaces in order to protect the steel from deformation at high temperatures.

Fly ash is deposited in ash dumps in Australia and half of this is processed into beneficial products such as concrete (“Unearthing Australia’s toxic coal ash legacy,” 2019). The global average of coal ash reuse is 53%, wherein India reuses 61%, the UK 70% and Japan 97%. In turn, in China waste constitutes 10–15%, and only 69% is managed, which gives about 535 million tonnes of unused waste (Maiti and Pandey, 2020; Pacholewska et al., 2007). Waste from coal processing and coking plants may contain valuable components. Pavlovich et al. (2004) proposed the use of phthalic anhydride, present in post-processing waste, as a raw material for the production of anti-corrosion and abrasion-resistant products.

One common method of mining waste management is underground storage, used among others for backfilling workings and sealing goafs, when there is too much waste from current production, which cannot be used otherwise. Waste management through underground storage is used mainly in the extraction of natural aggregates, where can be used to neutralize mine drainage and post-flotation sewage (Meggyes et al., 2008).

In order to manage drilling cuttings and mining waste, similarly as in the case of post-flotation waste, a landfilling is used. However, this method requires the pretreatment of drill cuttings, since they can contain heavy metals in an amount exceeding the permissible levels regulated by applicable law (Announcement of the Marshal of the Sejm of the Republic of Poland of October 8, 2020 on the publication of the uniform text of the Act on mining waste, Dz. U. 2020, pos. 2018, 2020; Europejski and Unii, 2006). Otherwise, storage of untreated drill cuttings in designated areas or agricultural areas may result in the release of undesirable components into the soil and groundwater, causing contamination. On average, one well can produce about 1000 m^3 of solid waste – drill cuttings, and from 800 to 1200 m^3 of liquid waste (Kujawska et al., 2016; Steliga and Uliasz, 2012). In selected European countries, such as in Poland, gangue - drill cuttings, is managed in 86%, however mainly by landfilling.

Based on the types of contamination, there are 3 options for the disposal of drilling waste:

- disposal at sea,
- land disposal,
- re-injection into the drilling field, reconstruction of the well.

Waste treatment methods differ among countries. Almost always, disposal at sea or on land is restricted by regulations and most often is associated with additional restrictions as to the storage of hazardous substances on unsecured areas. Drilling cuttings, in the form of solid waste, require treatment of oily substances and storage in adapted landfills. Solid and toxic waste need storage in special, sealed tanks. Re-injection of drill cuttings into the well is a favorable disposal option, if the drilling waste is not contaminated and has been subjected to pretreatment process (Permata and McBride, 2010).

5.2. Closed water circuit

Proper management of water used in the flotation process and the extraction of raw materials is a very important element from economic and environmental point of view. Due to the potential risk of soil contamination, and thus the negative impact on plants and animals, researcher carry out studies on the biological purification and treatment of water and its reuse in technological processes related to mining (Daldoul et al., 2019; Shengo and Mutiti, 2016). The flotation process can be used for water treatment, as shown in the article (Rubio et al., 2002).

The quality of the water used in the flotation, as well as pH and the content of dissolved solids, are of great importance for the process efficiency. To obtain optimal conditions, it is recommended to use both recycled water and water from the network (Farrokhpay and Zanin, 2012; Lin et al., 2020). However, water recycling in a closed loop is also desirable and considered as capable of reduction the number of reagents, decrease in Na_2S content, and consequently a reduction in water consumption by as much as 34.62%.

The biohydrometallurgical method, using post-flotation water, can recover valuable cobalt (Dudeney et al., 2013; Parbhakar-Fox et al., 2018). Monitoring the quality of unused post-flotation water is a very important for assessing the stability of the structure of reservoirs and dams, in which these wastes are collected (Retka et al., 2020).

Waste management in the Oil & Gas sector largely relies on the water treatment used for drilling. As a result of contact with highly saline water and the shale itself in the fracturing zone, the drilling fluid is enriched with chlorides and barium salts. Contaminated water from drilling works in the production of crude oil and natural gas is circulated. Very often it can be reused up to 100%, for example, the United States recycles more than 90% of polluted water. Contaminated water from drilling processes can be returned to the surface, cleaned with vibratory screens, centrifuges, hydrocyclones, etc., and reused for further drilling purposes. It is assumed that more than 90% of the flowback fluid is recycled at the well stations and used for subsequent drilling processes. The rest of the polluted water is directed for disposal (Steliga and Uliasz, 2012). In order to recover a significant amount of the fracturing fluid, in other words flowback fluid, consisting of 90–95% of water and chemical additives, the fluid undergoes a treatment procedure (Steliga and Uliasz, 2012).

The exploration and drilling site is usually protected by lining with cement slabs and foil to minimizes the risk of toxic compounds getting into the soil and surface waters (Dudeney et al., 2013). Example of the storage sites is Łebień drilling rig which is shown in Fig. VI, in the appendix.

5.3. The impact of waste management on the environment

Metal mining is a key part of the economy for many countries. Many countries decide to explore small deposits of raw materials for which the demand is growing every year. As a consequence, the amount of waste produced also increases (Bamigboye et al., 2021; Nikolić et al., 2019).

It is practically impossible to prevent the generation of post-mining waste. Tailings are troublesome to handle due to their high abundance, properties, and difficulty in removal. As a result, long-term processes are used to minimize negative environmental and socio-economic consequences. The generated waste is either sent for recovery or neutralization, wherein neutralization most often means disposal in dedicated landfills.

The literature review is rich in examples showing that wastes from flotation process can be slightly toxic. It is confirmed by studies of plants and water that have come into contact with them, therefore their storage is not the most beneficial solution because it affects the environment and occupies a very large area, and also distorts the landscape (Behera et al., 2020).

A lot of papers present research (Ciarkowska et al., 2017; Kasowska et al., 2018; Mendez and Maier, 2008; Śliwka et al., 2013) in which plants, mainly trees, were planted on copper tailings to examine the accumulation of metals. The aim of using plants, known as phytostabilization, is to reduce the risk of metal migration to deeper soil layers. The experiments showed that some plants contained a critical amount of copper, which thereby confirmed high copper content in the waste, and inefficiency of the flotation process. Permissible lead levels were exceeded. The obtained results showed the best accumulation properties of metals for fungi. Additionally, an increased content of heavy metals, especially copper, was detected in pine needles.

Jakovjevica K. and Mišlejenović et al. 2020 (Jakovljević et al., 2020), carried out a study to determine the toxicity level of plants growing in 4 soil samples taken from different parts of the post-flotation tank. The highest concentration of toxic elements (As, Sb, Zn) was determined in samples from the vicinity of the closed Stolice mine in Serbia (Zn–Pb polymetallic deposit, a flotation basin), and from Zn–Pb tailings near the Ibar River. Even though the mine was closed in 1987, it still poses a threat. The waste that was generated still contains potentially toxic elements. The greatest accumulation of these elements is near the river; therefore, they can potentially get there, polluting the river and aquatic organisms.

On the other hand, a water study carried out at the closed Jerada mine in Morocco, where 15 to 20 million tons of waste is currently stored, showed an increase in sulphate content to over 700 mg/l, with an average level of around 300 mg/l. The increase was observed during the rainy season, indicating that surface water migration has an impact on pollution levels.

Studies of the abandoned tailings from a mine in Mexico, revealed that the oxidation of chemicals was less intense in the settling tank than in the dam. The pH was low in the oxidized zone (down to 2.7), and was increasing with the depth, indicating that the H^+ ions are consumed by dissolving the aluminosilicate minerals. This results in the precipitation of iron oxides which in the presence of form cement layers in the dam. The waste contained high level of heavy metals easily washed away by water (As and SO_4^{2-}). The concentration and mobility of the toxic elements is controlled by precipitation, sorption and desorption (Romero et al., 2007). In studies on the toxicity of tailings from mines in Norway, it was concluded that tailings from a mine, where no process chemicals were used, had the greatest toxicity. This means that properly selected chemicals in the flotation process is a very important factor that can minimize the toxicity of a generated waste (Brooks et al., 2019) It was also shown that the ion exchange process can be effective in purifying water after the zinc and lead ore flotation process (Woynarowska et al., 2011).

Being aware of the risk to the environment coming from generated waste and landfilled tailings, more effective methods are needed to reduce negative impacts on air, soil, and water. It is a challenge; hence the role of innovation is very crucial here. It is important to protect the waste from migration and to ensure the geotechnical stability of disposal site. In order to reduce the impact of waste on the environment, various techniques are applied, among others physical methods that create a barrier to the migration of pollutants, e.g. geotextile separators - functioning as barrier between the ground and the stored waste, multi-layer coverings - protecting from external weather conditions, or the aforementioned biological methods, like phytostabilization or hydroseeding, in which a mixture of fertilizer, seeds and water is sprayed onto the ground to make the grass grow. It is important to protect the waste from migration and to ensure the geotechnical stability of disposal site (González-Alday et al., 2008; Karczewska et al., 2017).

Additionally, to provide support for environmental protection legal regulations are applied. In the EU, European Commission has introduced directives related to waste management, which among others regulate waste from extractive industries (Directive, 2006/21/EC), control of major-accident hazards involving dangerous substances (Directive, 2012/18/EU) and protection of groundwater against pollution and deterioration (Directive, 2006/118/EC). Additionally, in accordance with Directive 2006/21/EC, Joint Research Centre provided Best Available Techniques Reference Document for the Management of Waste from Extractive Industries (MWEI BREF) (Garbarino et al., 2018). MWEI-BREF, which is a technical document, aimed at minimizing the environmental impact connected with extraction of mineral resources, includes among others generic and risk-specific BAT conclusions, generic and risk-specific objectives, information about management, as well as emerging techniques to prevent environmental deterioration coming from extractive industry (Garbarino et al., 2020).

Extraction of resources, which is inherent in the production of waste, to ensure short-term and long-term safety, requires following a predetermined plan, considering life cycle assessment, risk assessment, and waste deposition plan so to minimize the adverse effects on the environment and eventually human health. Additionally, it should also include a planning for closure of extraction and disposal facility, including rehabilitation, reclamation, remediation, after-closure procedures, and subsequent monitoring (Garbarino et al., 2018).

6. New methods of waste management

6.1. Copper, zinc and lead

The potential of the use of tailings has been discussed for many years. Already in 1996, an article was published on the possibility of using mining and energy waste in the construction of expressways and highways (Kozioł and Uberman, 1996). It was found that waste from rock mining can be used as a road aggregate for the construction of road foundation.

Due to the chemical and phase composition, the most frequently considered solution for the management of tailings, other than neutralization in tanks, is using it as an additive to cement (Gao et al., 2020; Gou et al., 2019; Guo et al., 2016; Liu et al., 2018; Muravyov et al., 2012; Onuaguluchi and Eren, 2012; Wang et al., 2017; Yi and Cao, 2014; Zheng et al., 2015). According to the European standard (EN 197-1:2012. *Cement. Part 1: Composition, specifications and conformity for common cements, European Standards.*, 2012), additives added in the amount of up to 40% of the cement mass improve some functional properties. The greatest economic benefit resulting from the use of flotation waste in the building materials industry is the saving of cement, which can be replaced by waste, even in a small percentage (Mikula et al., 2021).

Chinese scientists (Guo et al., 2016) checked the pozzolanic activity of tailings generated in the process of pyrite flotation. An X-ray fluorescence analysis was performed to identify the main components of the waste. Pozzolanic materials are characterized by a high content of SiO_2 and Al_2O_3. This was also in the case of examined waste, which additionally contained small amounts of alkali. The optimal amount of waste was determined at the level of 20% of the cement mass. This amount of waste causes that the concrete has still good workability.

Coal tailings can also be used as pozzolanic material. This was shown in the research: (Yagüe et al., 2018). Very fine samples had the best properties, however they required thermal activation treatment (Qiu et al., 2011).

The use of dry copper tailings may increase the yield point, which is an undesirable effect, however the use of pre-moistened waste has reduced this disadvantage. The samples showed a higher initial water absorption rate and resistance to chloride penetration and acids (Onuaguluchi and Eren, 2012).

Concrete mixes with the addition of tailings are characterized by water resistance and better hydrophobicity than traditional cement mortar (Liu et al., 2017). The addition of tailings from reverse flotation can significantly improve the watertightness of cement mortars. The mixture prepared for self-compacting concrete showed high resistance to freezing and thawing, and it can be classified as XF4 concrete exposure class. Scientists from the University of Nis (Ristić et al., 2019) showed that the addition of copper tailings, in the amount of about 40% of the cement mass, did not significantly affect such parameters as air content or segregation.

Low air content and high bulk density are more suitable for laying bricks (Fontes et al., 2016). The composite made of zinc and lead tailings and fly ash is a good solution for backfilling workings, however appropriate proportions of mixtures need to be kept, preventing their secondary liquefaction (Jarosiński et al., 2007; Jarosiński and Madejska, 2008).

Alexander Karamanov et al. (2007) investigated the use of flotation waste as an ingredient in the production of glass-ceramics. They found that flotation wastes alone are not enough to create high-quality glass, and mixes with various additives are better. No visible air bubbles were observed in the obtained glasses. After thermal treatment, the material became homogeneous, which increased its strength. The grinding made the material similar in texture to granite.

Another example of using tailings is building ceramics. Mymrin V. (2020) et al. (Mymrin et al., 2020) created mixtures containing lead ore flotation tailings, foundry sand and a mixture of sand and clay. The 10% addition of waste increased the compressive strength by 8%. The SEM images showed the formation of a new amorphous glassy phase that covered all surfaces of the ceramics and closed the porous space, thus strengthening the samples (Alekseev et al., 2019; Bhardwaj and Kumar, 2019; Hossiney et al., 2018; Mackay et al., 2020; Sua-iam et al., 2019).

Applying even a small amount of tailings to concrete is beneficial since it reduces environmental impact and contribute to land remediation (Onuaguluchi and Eren, 2012). Summary of advantages and disadvantages of using flotation waste as building materials is presented in Fig. 19.

Flotation waste is also used to recover many valuable elements. There are many studies and publications showing that the elements copper, zinc, lead and can be obtained from waste. However, these processes also generate wastes that are even more difficult to handle. These wastes are free of key elements and contain foaming additives and chemical solvents. Over the years, the amount of exploited metal, coal, oil and gas deposits decreases, hence it is expected that the flotation process will be even more effective, and thus the post-flotation waste will have a different chemical composition, less harmful to the environment. Reducing the number of deposits and extraction from deposits of lower quality will contribute to an increase in the amount of waste.

6.2. *Oil and gas extraction*

Historically, a number of non-biological methods have been used to remove drill cuttings, including backfilling pits, landfills and reinjection wells, chemical stabilization and solidification, as well as thermal treatments such as incineration and thermal desorption. The results of the research showed that drilling waste that is not classified as hazardous, due to its high pH, could be used for the remediation of land degraded by acidification, e.g. located in the vicinity of open pit sulfur mines or on heaps of mining waste containing acid minerals, e.g. pyrite (Ball et al., 2012) The confirmation of such development is also presented by Kujawska and Pawłowska (2020) (Kujawska and Pawłowska, 2020), proposing the remediation of acidic, barren and degraded soils. Another example is the use of the drill cuttings as construction aggregate, the formation of granules or burning and creating a natural fertilizer for plants.

Depending on properties, solid waste, cleaned from oily substances, can be used in construction. Leonard et al. (Leonard and Stegemann, 2010) presented the possibility of using two types of waste to produce Portland Cement (CEM I). One component were the stabilized and solidified drill cuttings and the second was the residue from coal combustion, i.e., fly ash with high carbon content as additional component of organic pollutants.

Another type of drill cuttings is from the oil sands in Canada and represents one of the most difficult challenges for the mining sector. Oil sands are cleaned using the so-called Thermo-Mechanical Cuttings Cleaner. The waste is heated to a temperature high enough to evaporate the oil and water, which are then transferred to the liquid phase in separate condensers. The by-product is a very fine quartz powder that can potentially be used as a filler material in the production of cement materials (Aboutabikh et al., 2016; Boudens et al., 2016; Huang et al., 2015; Loganathan et al., 2015).

7. Results and discussion

A review of the world literature shows increasing interest in a mining waste management. Innovative solutions are constantly searched for, which will allow waste management not only through storage, but also efficient use, striving to reduce CO_2 emissions and improving the quality of environment. Table 2 summarizes methods of managing individual types of waste, indicating the numerous possibilities of post-flotation and mining waste management.

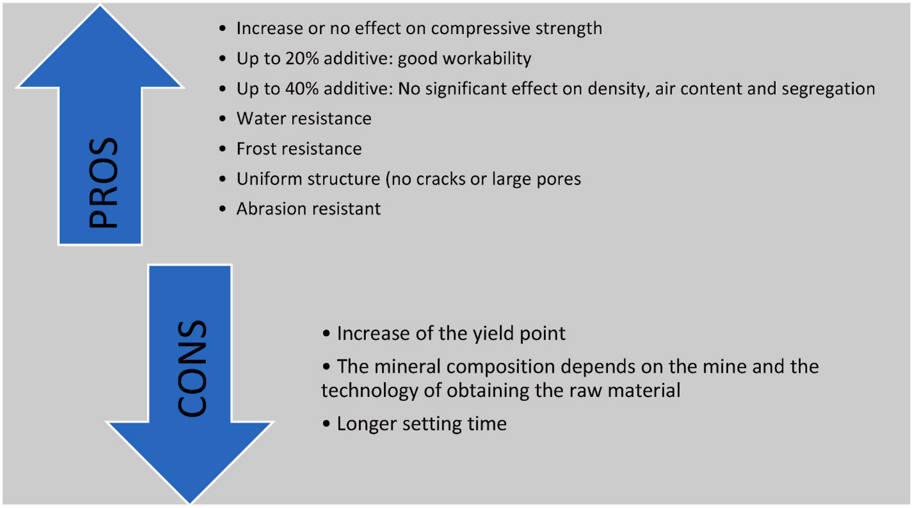
The article presents many advantages and additional possibilities of using flotation tailings as a partial replacement of aggregate or cement. However, one of the biggest disadvantages of post-mining waste is its chemical and thus mineralogical variability. Flotation tailings differ in their chemical composition, depending on the mined ores or whether oil or gas is being extracted. The waste may contain trace amounts of elements that may adversely affect the concrete structure, such as sulfur and iron compounds, as well as heavy metals.

Another issue to replace the materials used in the production of concrete is the fact that concrete plants and cement plants have a developed, proven system and do not necessarily want to retrain to new solutions.

In the past, the flotation waste, due to transportation problems and no development directions, was deposited in earth settlements, which degraded the natural environment, disfigured the landscape and increased the areas transformed by mining activities. Such approach led to environmental damage and exposed mines to huge losses due to waste of raw materials and fees for land use, etc. (Alwaeli M., 2009).

The biggest problem when using waste as components of building materials is the need to prepare the waste for use (Dash et al., 2016). Usually, the material should be additionally shredded or roasted (Kotwica et al., 2018). In order for the waste to be used effectively as an additive to building materials, additives are used such as alkaline activators (Ahmari et al., 2015). This means introducing additional chemical ingredients into the materials. All the above-mentioned activities generate costs related to the processing of waste so that it can be used.

Another common problem in the use of waste as components of building materials is the change in physical parameters of the material. With the use of waste, a decrease in strength (caused by the problem with the formation of appropriate tricalcium aluminates, silicates) and there are noted a decrease in the workability of concrete (high



- Increase or no effect on compressive strength
- Up to 20% additive: good workability
- Up to 40% additive: No significant effect on density, air content and segregation
- Water resistance
- Frost resistance
- Uniform structure (no cracks or large pores
- Abrasion resistant

- Increase of the yield point
- The mineral composition depends on the mine and the technology of obtaining the raw material
- Longer setting time

Fig. 19. Summary of advantages and disadvantages of using flotation waste as building materials.

Table 2
Waste management options according to waste characteristics.

Source	Type of waste	Parameters	Method of waste management	References
Copper	Waste rock and overburden	- Compressive strength [MPa] - Chemical composition [%] - Graining [%] - Water absorption [%]	• aggregate in concrete and road construction • the backfilling of mined headings/workings and post-mining voids as a material for dry filling, • the backfilling of the voids that were formed as a result of mining as the material for supplemental sealing • the backfilling of the headings that require strengthening and stabilization • the hardening of underground mine roads • source recovery • recovery of chemical elements	(Henne et al., 2018; Kotarska et al., 2018; Lidelöw et al., 2017; Rossetti et al., 2019)
	Flotation Tailings	- Chemical composition [%]	• chemical precipitation • reuse of water in the flotation process • purification of water from metals and sulfates • for the production of mineral binder	(Nariyan et al., 2017; Rajczyk, 2017; Shengo and Mutiti, 2016)
	Smelter and tailing slag	- Compressive and flexural strength [MPa] - Chemical composition [%] - Graining [%] - Friction [N] - Water absorption [%]	• aggregate in concrete and road construction • source recovery • for the production of mineral binder • the hardening of underground mine roads • reaction catalyst	(Esmaeili and Aslani, 2019; Kiventerä et al., 2020; Li et al., 2018; Mikula et al., 2021; Muleya et al., 2020; Nikolić et al., 2019; Paiva et al., 2019)
Zinc	Flotation waste	- Compressive strength [MPa] - Chemical composition [%] - Water absorption [%]	• as proppant • reuse of water in the flotation process • source recovery • hydrophobic surface	(Azevedo et al., 2018; Muravyov and Fomchenko, 2018; Pietrzykowski et al., 2018; Wang et al., 2017)
	Waste water	- Chemical composition [%]	• reuse of water in the flotation process	(Azevedo et al., 2018; Kyzas and Matis, 2019)
Lead	Flotation waste	- Compressive strength [MPa] - Chemical composition [%] - Water absorption [%]	• as proppant • as a component of the ceramics industry roofing material • source recovery	(Kudełko, 2018; Larachi et al., 2019; Romero-García et al., 2019; Woźniak and Pactwa, 2018)
	Waste water	- Chemical composition [%]	• coagulation with the application of lime carbide residue • reuse of water in the flotation process	(Azevedo et al., 2018; Kyzas and Matis, 2019)
Coal	Flotation coal enrichment	- Chemical composition [%]	• flooring	(Gupta et al., 2017; Wang et al., 2020)
	Bottom ash	- Compressive strength [MPa] - Chemical composition [%] - Graining [%] - Water absorption [%]	• incinerating/fertilizer for plants • the backfilling of the voids that were formed as a result of mining as the material for supplemental sealing • ceramics materials • phosphorus adsorbent • aggregate	(Muthusamy et al., 2020; Namkane et al., 2017; Rani and Jain, 2017; Zhou et al., 2019)
Oil & Gas	Cuttings, Sludges waste, Scales waste	- Compressive and flexural strength [MPa] - Graining [%] - Water absorption [%]	• land application and landfilling • discharge to surface • recycling • as proppant/road construction • incinerating/fertilizer for plants • aggregate • surface of tennis courts	(Ayati et al., 2019; Davarpanah et al., 2018; de Almeida et al., 2017; Hu et al., 2021; Hussain et al., 2017; Reuben et al., 2018; Stuckman et al., 2018)
	Waste water	- Chemical composition [%]	• surface impoundment • underground injection • waters source reduction • simple and enhanced separation • dissolved air flotation • evaporative treatment • deep well • recovery water to the process	(Abdullah et al., 2017; Adham et al., 2018; Robbins et al., 2020)

absorbability of e.g., ash) (Capasso et al., 2019). Another problem is the reduction of adhesion or discoloration of the material (e.g. in ceramic tiles, glaze layers cannot be applied) (Rahman et al., 2020).

When considering the use of waste in the building materials industry, in chemical aspects, there is a problem with heavy metals and their potential leachability from finished products (Dell'Orso et al., 2012). However, there are studies and publications (Yu et al., 2005) that show that cement materials do not leach dangerous amounts of heavy metals, because they have been incorporated into the structure of the hardened composite.

The last threat arising from the use of waste in the building materials industry is the law and standards. For safety reasons, European standards for cement, concrete and other building materials are very strict. Therefore, the condition of waste and finished building elements should be properly examined and monitored so that their use does not turn out to be harmful and dangerous, as it turned out in the case of asbestos.

To summarize the risks of using waste in the building materials industry, there are many obstacles and a financial effort is needed to prepare the waste for use in construction. However, as shown in the article, there are many more advantages and positive aspects to continue developing the waste utilization processes.

8. Conclusions

Mining is still a key part of the economy for many countries, and it is practically impossible to prevent the generation of post-mining waste. That is why in this work authors selected the most key resources in the mining industry, which are metals ores, coal, oil and natural gas, and focused on best solution for the generated waste to be safely managed or re-used. The proposed methods for handling with produced waste present both benefits and disadvantages, and additionally include environmental aspects that conditions a more sustainable waste management.

Mining wastes are high in abundance, properties, and difficult in removal. The generated waste is very often sent for recovery or neutralization, wherein neutralization most often means disposal in dedicated landfills, which is ground storage in waste neutralization tanks. Currently, this is the most popular method of post-flotation waste management, even though it is known that continuous collection of massive amounts of wastes may eventually result in disastrous environmental degradation. The waste, especially those untreated, may contain toxic and harmful elements, hence it is important to store it far from rivers and farmlands to minimize the risk of pollution of rivers and soils as well as groundwaters. However, it is not only storing and possibility of leakage to the ground, which pose a threat to the surrounding area, but also the ash that may be released from the storage tanks, which very often are not well covered. Some additional risk may arise, when wastes like for example drill-cuttings need to be pre-treated, which will involve additional waste generating processes.

Since the current waste management in the mining industry is very often far from being sustainable, this paper includes an overview of waste management practices that are more environmentally friendly and presents alternative methods of waste management. At the same time, this review covers data on properties and composition of mining and processing waste, aiming at identifying the unused benefits of improper waste management and handling.

Environmental concerns related to the management of mining waste are growing every year, which eventually leads to the need to recycling and reusing this waste. Due to the characteristic chemical composition, as shown in this article, the recycling of post-flotation and mining waste has the potential to be used in the building materials. Innovative solutions are constantly searched for, which will allow waste management not only through storage, but also efficient use, striving to reduce CO2 emissions and improving the quality of environment.

The article contains a detailed review of the literature on geology and the current management of by-products generated in the processes of extraction and processing of raw materials. The amounts, chemical compositions, and forms of occurrence of metal ores of copper, zinc, lead, as well as coal, crude oil and natural gas deposits are discussed in detail. Waste management methods and their potential possibilities are presented and discussed.

Based on the literature results, new waste management options are proposed, which consider the recycling of already stored material and waste generated from current production. It has been shown that the current management of the above-mentioned waste, by depositing it in waste disposal facilities, is one of the less effective activities, and has negative impact on the environment, especially in a case of surroundings of the tanks.

A deeper look into the conditions and possibilities of waste management may result in drawing the attention of specialists in the fields of environmental protection and the building materials encouraging them to the use by-products from mining processes. The greater the knowledge about the possibilities of using post-flotation waste, the more effective the solutions to meet today’s challenges.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.114239.

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