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The use of fly ash for filling the shallow underground ore mine works on the example of the mine reclamation area in Piekary Śląskie

Introduction

Metal ore mining in shallowly bedded carbonate rocks is inseparably bound with forming of underground voids of considerable volumes. Mining works, which took place in the area of Piekary Śląskie probably from Roman times (however the first written evidence comes from the 12th century) up to beginning of the 20th century (Molenda 1963; Strzałkowski and Preidl 2016) resulted in the creation of post-mining areas, degraded to a state, which nowadays eliminates their economic usage.

To the main reasons of the economic usefulness of areas degraded by mining operations belongs the possibility of discontinuous ground deformations appearance, which manifests mainly in the form of sinkholes and elongated fractures or faults, named as aerial and linear deformations respectively (Popiołek 2009). Such deformations are also emerging on urban areas located on historical mining fields, which had been developed without previous undertaking of protective measures.

In aim to prevent the occurrence of such deformations on urban areas, as well as for the reclamation of post-mining areas, ground surface has be secured, most successfully through the elimination of underground voids by their filling (Strozik et al. 2016). Voids of relatively small dimensions as those, which occur in loose, porous grounds, most often are to be filled

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by injection methods, whereas voids of large volumes, such as mine works, should be liquidated by their backfilling (Pilecki 2009; Stryczek and Gonet 2000).

To achieve the effective reclamation of a post-mining area, among others an issue of the assortment of fill material and the technology of filling, as wells as the possibility of the assessment the degree of the threat to a given area from the side of underground voids, considering its level both before and after the fill operation, are of great importance (Dziewański et al. 2005).

1. Historical mining of metal ores and its effects on the contemporary development of the Kocie Górki post-mining area in Piekary Śląskie

The opencast and shallow underground mining operations conducted among others in the Piekary Śląskie area heavily affected the value of significant areas within the city limits of Piekary Śląskie.

Acquiring areas for new development including: industrial infrastructure, housing estates, and urban infrastructure in general, is a fundamental requirement for the sustainable development of a contemporary city. Meanwhile, degraded post-mining areas are not useful for building development without their preliminary protection, among others against the appearance of discontinuous deformations. The area of Kocie Górki is an example of a far-reaching transformation project in the south-west part of Piekary Śląskie. This area,

Fig. 1. Landscape forms after the mining of lead-zinc ores in the area of “Kocie Górki” in Piekary Śląskie (author’s photo)

Rys. 1. Formy krajobrazu pogórniczego po eksploatacji rud ołowiowo-cynkowych na terenie Kocich Górek w Piekarach Śląskich (fotografia Autora) due to the neighbourhood of the main communications ways and industrial estates, constitutes a perspective area for the development of economic activity (Strozik and Jendruś 2017). The current landscape of this area has been illustrated in Figure 1.

Practically the entire surface of the area is covered with heaps of Quaternary and Triassic debris and ore processing waste, excavations and ditches. Numerous hollows associated with collapses and destruction of shallow shafts and underground works also occur between them. All of them are remnants of the mining of metal ores, which was carried out within this area from the half of 18th to the beginning of the 20th century (Pilecki and Popiołek 2000).

Sinkholes and troughs on the ground surface can be the result of both sudden roof falls into the free spaces of mine works as well as karst and suffusion phenomena connected with the free migration of waters in fractured rock mass made up of carbonate rocks (Pilecki and Popiołek 2010).

Excerpts of maps of the ore mining in the area of Piekary Śląskie coming from about 1912, depicted in Figure 2, show the scope of the conducted mining works. Nowadays these maps deliver valuable information on potential threats to the area from the side of old mine works (Maciaszek 2010).

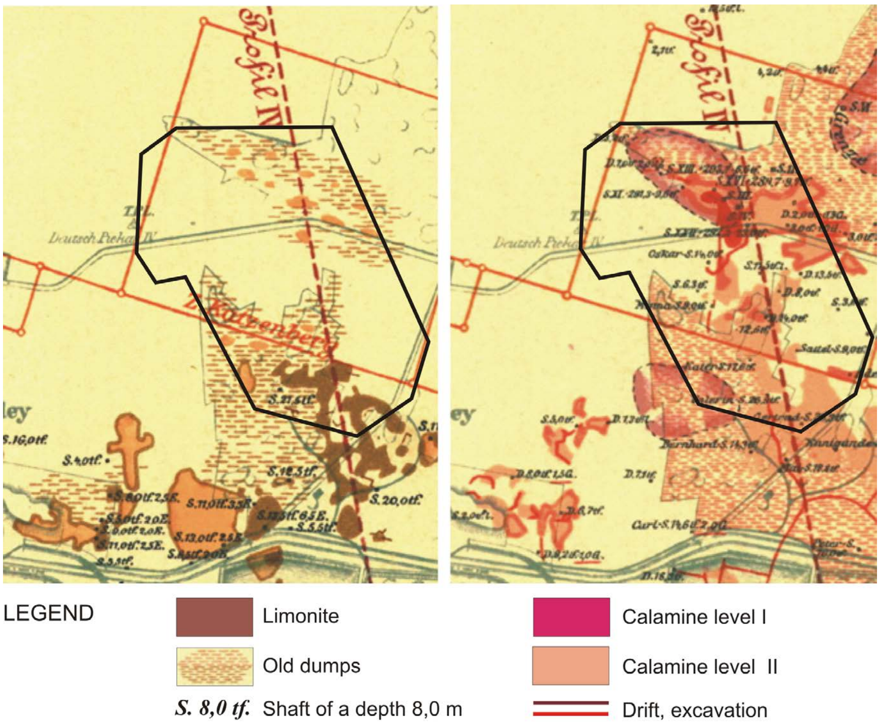

Fig. 2. Excerpts from ore mining maps of Kocie Górki in Piekary Śląskie.
On the left – iron ore, on the right – zinc ore (Map 1912)

Rys. 2. Fragmenty map eksploatacji rud metali obszaru Kocich Górek w Piekarach Śląskich.
Po lewej – ruda żelaza, po prawej – ruda cynku (Mapa 1912)

The zinc-lead mineralization in the considered area is appearing in the range of depth from 0 m (outcrops of Triassic strata) to about 50 m, wherein metalliferous layer most often lies in the range of the depth from about 20 m up to 30 m.

Quaternary soft sedimentary rocks occur (mainly represented by sands and clays) above the roof of the Triassic rock mass, wherein deposits of the limonite (a poor iron ore, being an object of the historical mining) are also present in its floor (Pszonka 2007).

Maps in Figure 2 illustrate the range of the conducted extraction of limonite – on the left and calamine zinc ore on the right.

The considerable number of shallow mineshafts with depths of approximately 2 m to 26 m, wherein the majority of them does not exceed 20 m is characteristic for the analysed area. As a rule, short underground works accompanied the shafts. Even at the time of printing the maps from Figure 2, the location of these works had been considered as already largely unknown.

Black lines mark the area, on which geophysical examination was conducted in order to determine places of appearing of the discontinuities in the structure of shallow layers of the rock mass (Strozik and Jendruś 2016).

2. Forecasting to the surface from shallow underground voids

The primary factor determining the probability of collapse of the roof rocks in an underground void, which may lead to the creation of a discontinuous deformation on the ground surface, is the relation between the heights of the collapsed and fractured rock zones and the thickness of the native rock mass (Triassic formation) above the roof of a void.

One of the attempts to solve the problem of probability evaluation of the appearance of the discontinuous deformations over shallow mining in carbonate rocks is a method proposed by Janusz and Jarosz (Popiołek and Pilecki 2005; Chudek 2010). Its authors assumed that an underground void present at the depth H, with the width L and the height w is located in the vicinity of the roof of solid rocks mass of thicknesses w_g, overlaid by loose overburden of thicknesses h, which reaches the surface of the ground, as in Figure 3.

Due to the mechanical properties of the rock mass, if the rocks are not sufficiently strong to withstand increasing stresses, then the roof rocks above an underground working or void tend to collapse. After the fall of the roof rocks, two zones of distorted rock structures may be distinguished: the caving zone, where the rocks are disintegrated and displaced, and the fractured zone where the rock structure is disturbed by fracturing and eventually erosion.

On the base of numerous observations it can be concluded that in conditions of shallow Triassic deposits of zinc and lead ores, the maximal height of a caving (rubble) zone $h_{z\max}$, which comes into existence as a result of total self-filling of a void can be formulated as (Popiołek and Pilecki 2005):

$$h_{\ \max} = w\left[\frac{}{\pi(\quad - \quad)} + 0,25\right]$$

↳ k_r – coefficient of rocks loosening.

The coefficient of loosening of collapsed rocks k_r is a quotient of the volume of the rocks volume in caving zone to the initial volume of rocks in intact rock mass, which underwent collapsing. On the basis of observations, for Triassic carbonates its average value is about $k_r = 1.25$.

In the case when the maximum height of the caving zone $h_{z\max}$ exceeds the thickness of solid rock strata ($h_{z\max} > w_g$), the arising of a sinkhole on the ground surface is highly probable. The sinkhole can also appear in a case in which the height of the fractured zone over the caving zone is greater than the thickness of the durable rocks strata over the roof of a void ($h_{s\max} > w_g$).

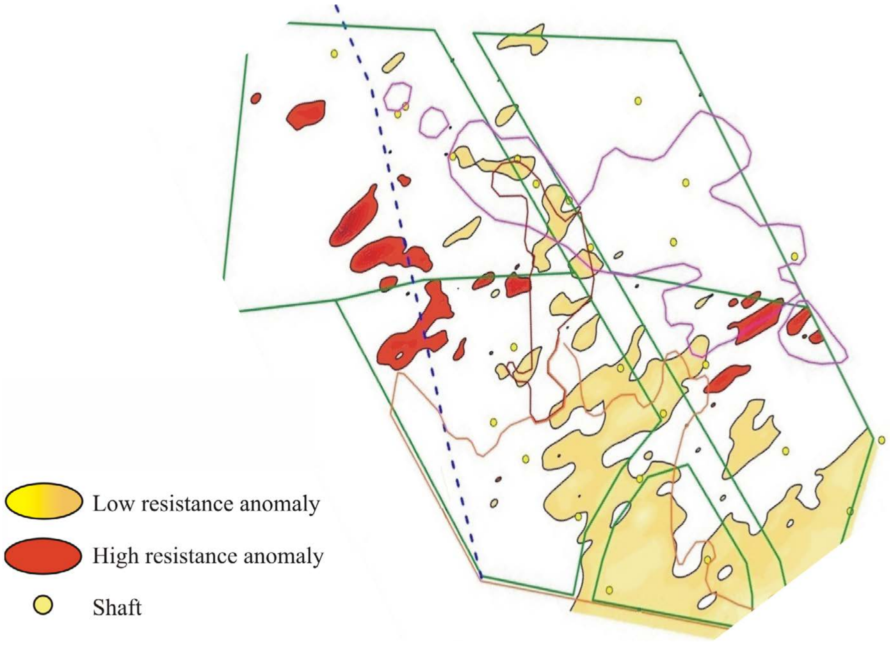

Fig. 3. The development of a sinkhole resulted from a roof collapse in a shallow underground void (Chudek 2010)
A – mineral bed layer, B – limestone, C – Quaternary sediments overburden,
D – caving zone, E – fractured zone, F – sinkhole

Rys. 3. Powstawanie zapadliska na skutek zawału stropu płytkiej pustki podziemnej (Chudek 1010)
A – wybrana warstwa złoża, B – wapień, C – nadkład osadów czwartorzędowych, D – strefa zawału,
E – strefa spękań, F – zapadlisko

One may assume that in the conditions of shallow zinc-lead ore beds in the area between Tarnowskie Góry and Piekary Śląskie, the height of fractured zone h_s achieves values up to a maximum of 2.5 times the height of the caving zone.

Observation of other post-mining areas after the shallow ore mining in similar mining-geological conditions show that if the thickness of solid rock strata is larger than the height of the caving zone but smaller than the height of the fractured zone ($h_{z\max} < w_g < h_{s\max}$), when the collapse of the roof most certainly ended with the appearance of a sinkhole, as long as the thickness of the soft overburden h is smaller than 10 m (Chudek 2010). If value of h lies between 10 m and 30 m, then occurrence of a discontinuous deformation is probable and its shape on the ground surface depends on the thickness, structure, and properties of the overburden. In the case in which the overburden is thicker than 30 m, the collapse of the roof and self-filling of a void may result in a relatively smooth continuous deformation of the surface, likely in shape of a shallow trough. The graph in Figure 4 illustrates the dependence of the height of a void (mine working) on the height of caving and fractured zones $h_{z\max}$ and $h_{s\max}$.

For example, a void located at the depth of 20 m and 10 m below the roof of carbonate rocks would not create a threat for the ground surface if its height does not exceed about 0.85 m.

For growing values of the height of a void, the probability of a discontinuous deformation appearance is continuously increasing (the fractured zone penetrates the overburden strata, but caving zone does not reach the roof of native carbonate formation). When the height of a void exceeds 1.25 m, the creation of a discontinuous deformation on the ground surface becomes unavoidable, because the maximal height of the caving zone exceeds the height of solid carbonate rock roof.

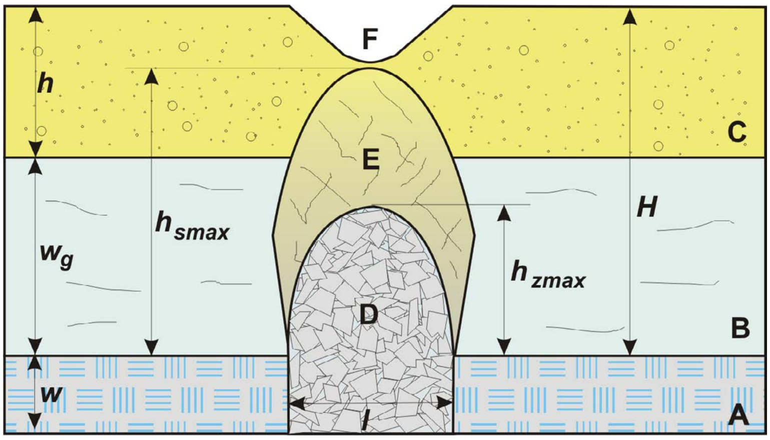

Fig. 4. Dependency of the height of the void on the height of caving zone $h_{z\max}$ and fractured zone $h_{s\max}$ including reference to a sample working described in text

Rys. 4. Wpływ wysokości pustki na zasięg strefy zawału $h_{z\max}$ i spękań na $h_{s\max}$ z odniesieniem do przykładowego wyrobiska opisanego w tekście

The majority of voids lying most shallowly, characterized by the highest probability of the roof fall, likely already underwent self-filling process. The results of these processes can be seen on the surface of the ground as already existing, numerous sinkholes and faults as shown in Figure 1.

In view of the above, intact or only partially filled underground voids may still exist on the post-mining areas like Kocie Górki , which initial probability of roof collapsing was low and medium. However, as a result of numerous phenomena affecting the weathering and weakening of roof rocks, the activation of these old voids is still possible (Popiołek and Pilecki 2005) and the probability of sinkhole occurrence increases with time. Therefore within the framework of the rehabilitation of post-mining areas, those still existing underground voids should be filled up to enable development and safe use of regained areas.

3. Filling of underground voids with fly ash

Materials for filling underground voids must meet a lot of conditions, out of which, from the point of the view of safety of the ground surface, the most important include the following (Shen et al. 2017):

- ability to penetrate and fill tightly both dimensionally large (e.g. caverns) and small (e.g. spaces between collapsed blocks of rocks) voids,
- low compressibility,
- low water permeability,
- resistance to eluviation, decalcification, and other erosive processes,
- compliance with requirements of environmental standards.

Fly ashes from hard coal combustion in power plants belong to the frequently used materials for filling the underground voids (Evans and Whysner 2017). Underground voids can be filled up with them in dry conditions using pneumatic transportation (fresh ashes), wet state (ashes from settling ponds or landfills) with the use of high pressures or in a form of fly ash – water mixtures, usually prepared from fresh fly ashes, which demonstrate chemical binding properties.

The height of caving and fractured zones over a void in the case of a roof fall depends on the degree of filling and compressibility of a fill material, which will be revealed after its loading with the weight of fallen down roof rocks (Sharma et al. 2015).

The achieved final degree of the filling of an underground void often reaches less than 100%, because of e.g. placement of the fill pipeline outlet below the maximum height of a void, its complex geometry, presence of obstacles reducing the range of flow of a fill mixture in a void and other reasons.

The compressibility of a fill material depends on its physical properties, which could be strongly differentiated, and the load applied on its surface (Plewa and Mysłek 2001). Within the considered conditions, where underground works occur at the depth of about 20 m, the pressure of the rocks mass, which is acting on the roof of underground voids may be assumed as about 0.5 MPa.

The highest compressibility exhibit dry, fresh fly ash, being delivered into the voids pneumatically. Its compressibility in such a case is between 20% and 50%, even by small loads applied by the roof rocks, mainly due to large difference between the densities of loose fly ash in bulk and after its initial compaction (Sear ed. 2011). In the case of wet ashes, the density of the grains structure, which varies in dependence of water content is crucial for their compressibility (Sha and Pal 2012). Wet fly ashes without binding properties, by maximal bulk density, which are dependent on the kind of ash and moisture content (in a range from a dozen or so to about 30%), demonstrate compressibility between 8% and 20% under a pressure of 0.5 MPa (Plewa et al. 2011).

In fly ash – water mixtures their compressibility under small pressures depends on their load carrying capacity (LCC), which increases during the cure of a portion of the mixture. The cure time required by a mixture to withstand a load of 0.5 MPa without the deformation of its surface is considered as a parameter describing LCC, in accordance with Polish standard PN-G-11011:1998. Correctly composed fly ash – water mixtures could be considered as incompressible under a pressure of 0.5 MPa in about two days after placement in a void.

There is also a range of other physical and chemical properties of fly ash – waters mixtures, which have to be considered by the filling of underground voids. Most of them depend strongly on origin of a fly ash (e.g. properties of particular coal and desulphurization technique being in use in a power plant where the fly ash comes from) and solids to water ratio (Plewa and Mysłek 2001; Gruchot et al. 2014). However, one should keep in mind that fly ash – water mixtures exhibit great variability of binding process in time (Sear ed. 2011).

In aiming to assess the influence of compressibility of fly ash on the reduction of sinkhole occurrence hazard generated by shallow underground voids, three types of fly ashes have been investigated in the Laboratory of Ecological Materials for Mining in the Institute of Mining Technology at the Technical University of Silesia. Three types of fly ash representative for hard coal fired power stations in Poland have been selected for tests: sample SD-A and SD-B – fly ash from vessels with semi-dry desulphurization method in power plants ”A” and “B”, and sample FD-B – fly ash from fluidal bed vessel in power plant “B”. The most important physical properties and parameters obtained from measurements of these fly ashes are collected in Table 1.

The results of the tests show that the compressibility of the investigated fly ashes ranges from 19.6% for sample SD-B up to 30.4% for sample SD-A in result of compaction of dry fly ash under pressure of 0.5 MPa. The compressibility of wet fly ash under the same conditions ranges from 10.2% for sample SD-A up to 17.3% for sample FL-B. Fly ash – water mixtures made with the use of fly ash SD-A and FL-B reached load capacity of 0.5 MPa after 28 and 36 days respectively, as well as they solidified after 28 days of cure time and obtained uniaxial compressive strength Rc = 4.21 MPa and 0.68 MPa respectively. Due to their

Table 1. Compressibility and related parameters of selected types of fly ash

Tabela 1. Ściśliwość i związane z nią właściwości wybranych rodzajów popiołów lotnych

Parameter	Unit	SD-A	FL-B	SD-B
Density	kg/m^3	2 420	2 084	2 112
Bulk density	kg/m^3	1 253	925	1 133
Bulk density after compaction	kg/m^3	1 800	1 235	1 409
Cure time for load capacity 0.5 MPa	hours	28	36	–
Uniaxial compressive strength Rc after 28 days	MPa	4.21	0.68	0
Compressibility ◆ Dry fly ash ◆ Wet fly ash ◆ Solidified fly ash–water slurry (table spread R = 230 mm)	%	 30.4 10.2 0	 25.1 17.3 0	 19.6 14.8 –

Source: own research.

load ability and compressibility these mixtures do not undergo compression under the pressure of 0.5 MPa. A mixture made from fly ash SD-B in the same conditions did not pass the 0.5 MPa load ability test and did not solidify within the standard 28 days sure time. This means that this mixture remains in liquid form and is not able to act as a material for filling underground voids. Measurement results clearly show that the type of fly ash and fill technology implicate the variable compressibility of fill material, which in connection with the obtained level of filling, results in a differentiated variable reduction of caving and fractured zones heights.

The graph shown in Figure 5 presents a sample dependence of maximal height of caving zone $h_{z\ \max}$ on the height of the fill w_p, in a void of initial height of 2.0 m decreased by a value resulted from compressibility of SD-A fly ash in different methods of filling. The rock mass loosening factor value of k_r = 1.25 and vertical pressure of 0.5 MPa have been adopted.

The results of the calculations indicate that the height of a caving zone formed through collapsing of the roof above a void of a height w = 2.0 m will reach 15.8 m when no filling has been applied, however, if such a void would be entirely filled up, the caving zone height would achieve 4.7 m for a filling with dry fly ash, 1.6 m in the case of the use of wet ash, and 0.0 m by filling with a fly ash – water mixture respectively. The heights of the fractured zones would amount to 23.7 m, 7.1 m, 2.4 m and 0.0 m respectively.

The heights of caving and fractured zones for a void being filled up to 75% of their initial height 2.0 m, determined for each kind of fly ashes and fill technologies present graphs in Figures 6, 7, and 8. As it can be seen, in result of the collapse of a roof over a 2 m high void, which was previously filled up to 1.75 m with use of dry fly ash, a sinkhole on the ground

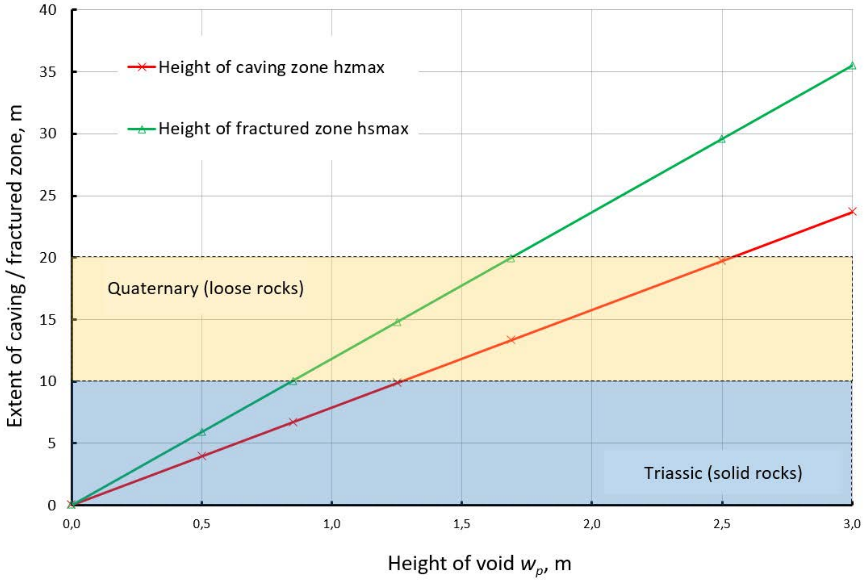

Fig. 5. Maximal height of the caving zone over a 2 m high void, in the dependence of fill level and the technology of filling for fly ash SD-A

Rys. 5. Maksymalna wysokość strefy zawału nad pustką o wysokości 2 m w zależności od stopnia i technologii wypełnienia dla popiołu lotnego SD-A

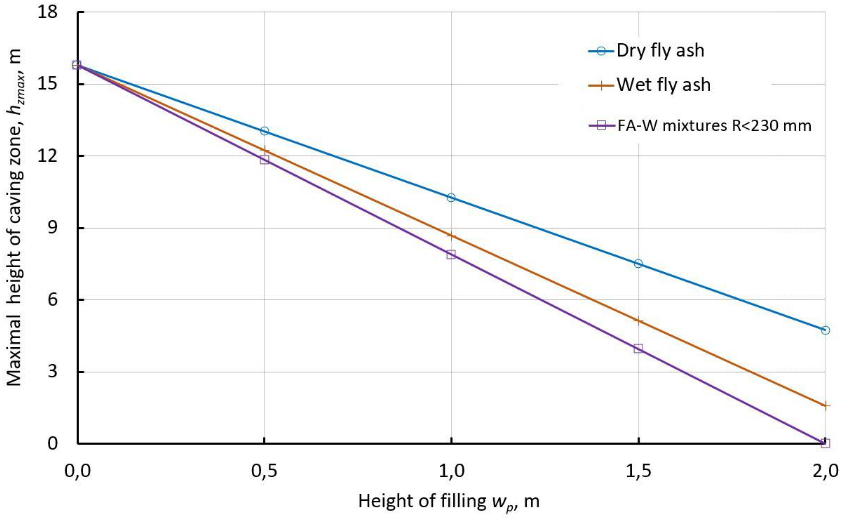

Fig. 6. The height of the caved and fractured zones for a 2 m high void filled up to 75% of its height with fly ash SD-A in dependence on fill technology

Rys. 6. Wysokości stref zawału i spękań dla pustki o wysokości 2 m wypełnionej w 75% popiołem SD-A w zależności od technologii wypełniania

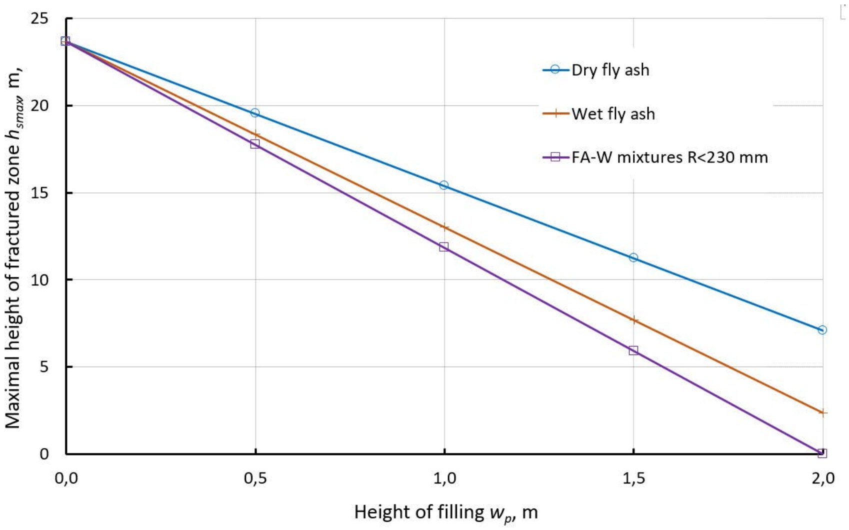

Fig. 7. The height of the caved and fractured zones for a 2 m high void filled up to 75% of its height with fly ash SD-B in dependence on fill technology

Rys. 7. Wysokości stref zawału i spękań dla pustki o wysokości 2 m wypełnionej w 75% popiołem SD-B w zależności od technologii wypełniania

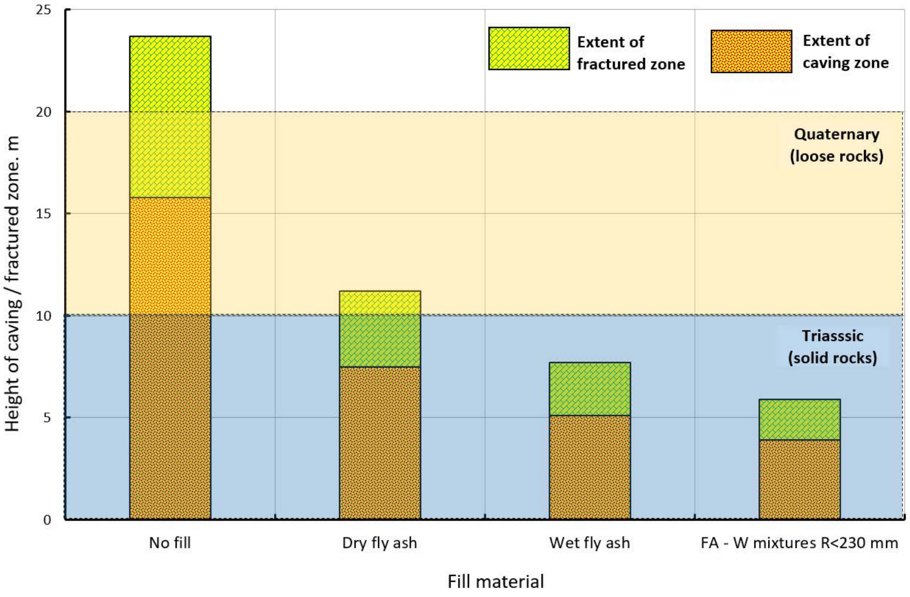

Fig. 8. The height of the caved and fractured zones for a 2 m high void filled up to 75% of its height with fly ash FL-B in dependence on fill technology

Rys. 8. Wysokości stref zawału i spękań dla pustki o wysokości 2 m wypełnionej w 75% popiołem FL-B w zależności od technologii wypełniania surface must appear in the case of fly ash SD-A (Fig. 6) and on a smaller scale in the case of fly ash FL-B (Fig. 8). Filling the void with wet ashes without binding properties eliminates the penetration of fracture zone into the soft overburden for all three investigated fly ashes. Filling with fly ash – water mixtures made from fresh fly ash exhibiting binding properties (samples SD-A and FL-B), eliminates the occurrence of a sinkholes on ground surface and is more reliable than in the case of wet ashes.

Although in the case of fly ash SD-B (Fig. 7), which did not undergo solidification, the slurry liquid remained and did not create support for the roof of a void, this type of fly ash may be effectively used as dry or wet fill material. This case also shows that the measurements of the properties of fly ash must be carried out before its use for the filling of voids.

Summary

Certain areas of shallow metal ore mining, which were carried out in the past over the south-west part of Piekary Śląskie (e.g. Kocie Górki), have been degraded to a level, by which their development without mine land reclamation is impossible. The effective liquidation of shallow underground mine works, which still exist in Triassic carbonate rocks as remnants of historical mining operations, is crucial for the further use of affected terrains Within the range of reclamation works.

Both field observation and geophysical research indicate the presence of such underground voids and fractured zones, which are posing a threat to the ground surface by the occurrence of sinkholes and other deformations. As part of the reclamation works, all the voids existing on the considered areas must be identified and then effectively filled up.

The selection of a fill material and implemented technology of filling are decisive factors forthe effective elimination of roof collapses and displacements of rock masses in underground voids, which may result in the occurrence of discontinuous deformations of the ground surface.

Fly ashes from hard coal combustion are applied for filling of underground voids most frequently, though their particular form and method of application result in a different degree of filling and compressibility of fills in voids. The analysis of processes of caving and fractured zones evolution in a rock mass over collapsing roof rocks prove that applying fly ash – water mixtures with binding properties provide the best conditions for the protection of the ground surface.

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ZASTOSOWANIE POPIOŁÓW LOTNYCH DO WYPEŁNIANIA PŁYTKICH WYROBISK PORUDNYCH NA PRZYKŁADZIE REKULTYWACJI TERENU POGÓRNICZEGO W PIEKARACH ŚLĄSKICH

Słowa kluczowe

pogórnicze tereny zdegradowane, wypełnianie pustek podziemnych,
zastosowania popiołów lotnych, deformacje nieciągłe powierzchnie terenu

Streszczenie

Na terenie Piekar Śląskich występują obszary, na których prowadzono eksploatację płytkich złóż rud metali, zalegających w pobliżu stropu warstw triasu. Są to tereny zdegradowane, między innymi na skutek występowania nieciągłych deformacji powierzchni terenu powodowanych przez nagromadzenie dużej liczby szybów oraz intensywną eksploatację rud metali, zarówno odkrywkową, jak i podziemną. Wyrobiska podziemne utrzymywane pod słabymi, spękanymi i zerodowanymi skałami tworzącymi strop warstw triasowych charakteryzują się podatnością na zawał skał stropowych i samopodsadzenie luźnymi utworami nadkładu, będącymi częstą przyczyną powstawania deformacji nieciągłych powierzchni terenu. Prawdopodobieństwo zawału stropu i samozasypania pustki podziemnej można określić dokonując oszacowania wysokości stref zawału i spękań, a następnie ich porównania z miąższością wapiennych skał stropowych i luźnego nadkładu czwartorzędowego.

Opierając się na modelu Janusza–Jarosza przeprowadzono analizę wpływu stopnia wypełnienia pustki podziemnej i rodzaju materiału wypełniającego na wysokość stref zawału i spękań powstających w wyniku opadu skał stropowych do niewypełnionej części objętości pustki oraz obniżenia stropu pustki wynikającego ze ściśliwości materiału wypełniającego. W analizie wzięto pod uwagę trzy technologie wypełnienia pustek za pomocą popiołów lotnych ze spalania węgla kamiennego, tj. pneumatyczne wypełnianie pustek suchymi popiołami lotnymi, ciśnieniowe wypełnianie pustek popiołami w stanie wilgotnym, pobranymi ze składowisk odpadów oraz hydrauliczne wypełnianie pustek mieszaninami popiołowo-wodnymi sporządzonymi z popiołów świeżych, wykazujących właściwości wiążące. Przeprowadzone analizy wykazały, że najlepsze rezultaty zapewnia zastosowanie mieszanin popiołowo-wodnych.

THE USE OF FLY ASH FOR FILLING THE SHALLOW UNDERGROUND ORE MINE WORKS ON THE EXAMPLE OF THE MINE RECLAMATION AREA IN PIEKARY ŚLĄSKIE

Keywords

post-mining areas, filling of underground voids, use of fly ash,
discontinuous ground deformations

Abstract

In city limits of Piekary Śląskie exist areas of intensively mined shallow deposits of metal ores, in the vicinity of the roof of Triassic carbonate rocks. These terrains constitute degraded areas, which development must be preceded by rehabilitation works. Degradation of the land has been contributed by substantial amount of shafts and mine workings, resulted from open cast and underground operations. Underground workings maintaining beneath weak, fractured, and eroded roof layer of Triassic and Quaternary sediments are strongly vulnerable to roof rocks collapsing and self-filling by loose overburden material. The latter leads to development of discontinuous deformations of the ground surface, which frequently take a form of sinkholes. Probability of roof collapse and self-filling of underground cavities may be assessed on the basis of the height of collapsed and fractured zones, in relation with the thickness of hard rock roof and soft overburden.

Janusz-Jarosz model of cavings formation in shallow underground voids has been used to analyse the influence of the degree of filling and type of fill material on the height of collapsed and fractured rocks zones, which develop over collapsed rest of the void volume, where also the effect of the compressibility of the fill material has been considered. The analysis focused on three filling technologies of voids with fly ash from hard coal combustion: pneumatic filling with fresh dry fly ash, pressurized filling with humid fly ash from ash ponds, and hydraulic filling of fresh fly ash – water binding mixtures. Results obtained from the analysis demonstrate that the best conditions for effective filling of the voids and elimination of deformation occurrence on the ground surface provide the use of fly ash – water mixtures.