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CAULKING OF GOAFS FORMED BY CAVE-IN MINING AND ITS IMPACT ON SURFACE SUBSIDENCE IN HARD COAL MINES

The impact of caulking of goafs after mining exploitation of a hard coal seam with caving is expressed as the change in value of a a exploitation coefficient which, as defined, is the quotient of the maximum reduction in the surface height of a complete or incomplete trough to the thickness of the exploited seam. The basis for determining the value of the exploitation coefficient was geological and mining data combined with the results of the measurement of subsidence on the surface – measuring line 1222-1301 – of the Ruda mine. There, mining was carried out between 2005 and 2019, with a transverse longwall system and the caulking of goafs. The research team used two methods to determine the impact of the caulking applied in the goafs on the value of the exploitation coefficient. In the first method the goafs are filled evenly along the whole longwall, and in the second method unevenly and on a quarterly basis. The determination of the values of the exploitation coefficients for selected measuring points was preceded by the determination of the parameters of the Knothe-Budryk theory, which was further developed by J. Białek.

The obtained dependencies are linear and the values of the correlation coefficients fall between –0.684 and –0.702, which should be considered satisfactory in terms of experimental data. It is possible to reduce the value of the exploitation coefficient by caulking the goafs by about 18%, when filling the goafs to 0.26% of the height of the active longwall.

Keywords: mining, caulking of goafs, surface subsidence, exploitation coefficient

1. Introduction

Caulking goafs by means of hydraulic backfilling is a technique used in Polish coal mines to combat the endogenous fire hazard caused by the high susceptibility of these seams to self-combust (Mazurkiewicz, 1990) (Plewa et al., 2008). For approximately thirty years, an emulsi-

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fier has been used as backfilling material. Its main components are dusts and ashes from power plants, which is later mixed with water.

Another equally important aim of using an emulsifier as a caulking material is the reconsolidation of cave-in rubble. The reconsolidation of goafs is necessary in the case of a thick coal bed in order to extract the deposit without leaving a thick coal ledge. The reconsolidated rubble of the upper layers then forms a direct roof for the mining of the subsequent, higher layer of the seam.

The caulking of rock rubble may potentially cause subsidence of the surface and proportional decrease of the remaining deformation indicators: inclination, curvatures and horizontal deformation (Mazurkiewicz, 1990; Zych et al., 1993; Strzałkowski, 1995; Plewa et al., 2008).

In the case of the exploitation of bedded deposits (e.g.a hard coal deposit), when the size of the exploitation field is sufficiently large when compared to the depth of the operation (longwall mining) and when the roof over the exploited area is lowered to a certain constant value – w_{max} – the value of the a exploitation coefficient and the thickness of the exploited bed or its g layer determine the level of subsidence of the mining area.

The value of the exploitation coefficient is defined on the basis of the analysis of the measurements of subsidence and the recorded geometry of conducted mining activity that has caused subsidence in the mining area.

In the literature analysed for this study, no clues could be found that would enable the estimation of the impact that the volume of the caulking mixture (emulsifier) has on the values of the exploitation coefficients (Knothe, 1984; Whittaker & Reddish, 1999; Bialek, 2003; Kratzsch, 2008; Kowalski, 2020).

Recently published attempts to estimate the impact of the backfilling of goafs on the surface deformation were related to the partial mining of seams based on drilling many parallel drifts (Zhang et al., 2016; Zhu et al., 2018; Kowalski, 2020).

In 2019, the problem of the impact of caulking goafs after longwalls mining with caving on surface subsidence in hard coal mines was discussed in PhD thesis by T. Rutkowski (Rutkowski, 2019).

A description of surface deformation in the mining area was presented in the publications in the Archives of Mining Sciences in 2019-2020 (Polanin et al., 2019) and (Jiang et al., 2020).

This paper presents a method to determine the impact of the caulking of goafs in cave-in longwalls on the values of the exploitation coefficient based on geodetic measurements of the surface subsidence of the mining area, the recorded geometry of the goafs and the recorded volume of fly ash fed to the excavations. The research used mining and geological data from the area of the Ruda coal mine located in the Upper Silesian Coal Basin in Poland (Piecha et al., 2019; Rutkowski, 2019).

The relationships determined between the volume of the fly ash from power plants and the value of the a exploitation coefficient may be useful for other hard coal mines with geological and mining conditions that are similar to those in KWK Ruda.

2. Mining operation based on roof caving with backfilling caulking and surface subsidence

Fig. 1 shows a schematic representation of the course of the caulking process, where the backfilling mixture (emulsifier) is fed into the longwall excavation. The right part of the figure shows partially sealed goafs (the height of the mixture is much lower than the height of the gobs), while the left part shows fully sealed goafs.
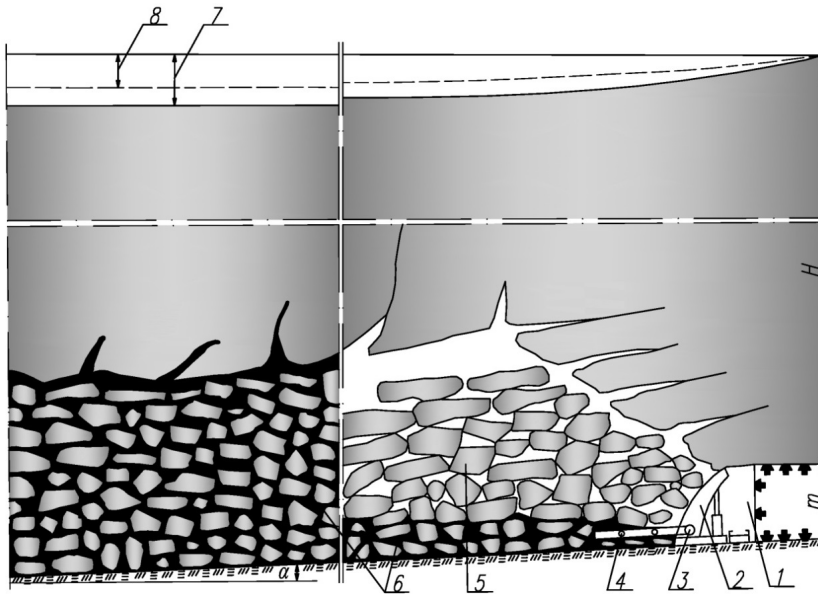
Fig. 1. Course of the caulking of goafs (Mazurkiewicz 1990). 1 – working space of the longwall, 2 – powered roof support, 3 – pipeline, 4 – perforated outlet connector, 5 – cave-in rubble, 6 – suspension filling the voids, 7 – w_{max} forcave-in operation, 8 – w_{max} forcave-in operation with caulking

In the Polish miningindustry, laboratory and in situ tests have been carried out in order to estimate the value of the exploitation coefficient in cases where the cave-in zone is subjected to caulking. The authors (Zych et al., 1993; Strzałkowski, 1995) showed that thesealing of goafs makes it possible to reduce the value of the exploitation coefficient by approximately 20% in relation to the value of this coefficient when sealing is applied. However, these authors did not examine the relationship between the volume of ashes fed to the goafs and the change in the value of the exploitation coefficient.

The research carried out in Poland so far shows that the absorption of the goafs varies from 0.07 to 0.27 of the height of the exploited bed (Piotrowski & Mazurkiewicz, 2006). On the basis of the measurement of the water inflow to the goafs, which determines the water capacity of the goafs (porosity), it has been shown that their absorbency is between 0.25 and 0.30 for new goafs, and 0.2 for old goafs (Ślaski 2010).

T. Niemiec (Niemiec, 2011), when considering the possible density of the cave-in rubble, quotes the result of J. Kepler's hypothesis that the ratio of the sum of the volumes of spheres with identical diameters to the volume of space occupied by these spheres can reach a maximum value of 0.74. Thus, the sum of the voids between these spheres (the water volume of a model of cave-in rubble consisting of densely packed spheres) may constitute 26% of the total volume. In the case of the rockmass, the voids in the goafs may be potentially gradually reduced due to the clamping of the rock rubble.

(Popiołek et al., 2014) analysed, for LGOM data, the relationship between the volume of the subsidence troughs measured by the INSAR method and the volume of extracted copper ore. On the basis of these analyses they estimated that – at the time of the measurement of land

subsidence—the capacity of the existing voids constitutes approximately 30% of the capacity of the extracted mineral from this region.

Such a significant volume of voids results from the manner of conducting mining operation in a single copper ore deposit. There is incomplete exploitation of the seam, as a substantial amount of the deposit that has not been exploited remains, and the measured subsidence troughs are usually incomplete, as evidenced by the relatively small values of the exploitation coefficient $a \approx 0.5$.

3. Brief characteristics of the mining and geological conditions of the analysed area

The research team used geological and mining data obtained from the Ruda mine where the caulking of goafs has been conducted for many years and the subsidence of the mining area is measured using geodetic techniques. Due to the geological structure, where alternately layers of clay, silt, sandstone and hard coal are deposited, as well as the previously repeated exploitation of the mining deposit in the coal mined below (group 500), the analysed area may be considered typical for the Upper Silesian Coal Basin.

Fig. 2 shows the contours of the longwall zones exploited between 2005 and 2019, including four seams: 413/2 – green, 414/2 – blue, 416 – purple and 418 – brown. The depth of exploitation ranged from 350 m to 760 m, and the heights of the longwalls (exploitation thicknesses) ranged from 2.1 m to 2.7 m. Exploitation was carried out from the south to thenorth towards the
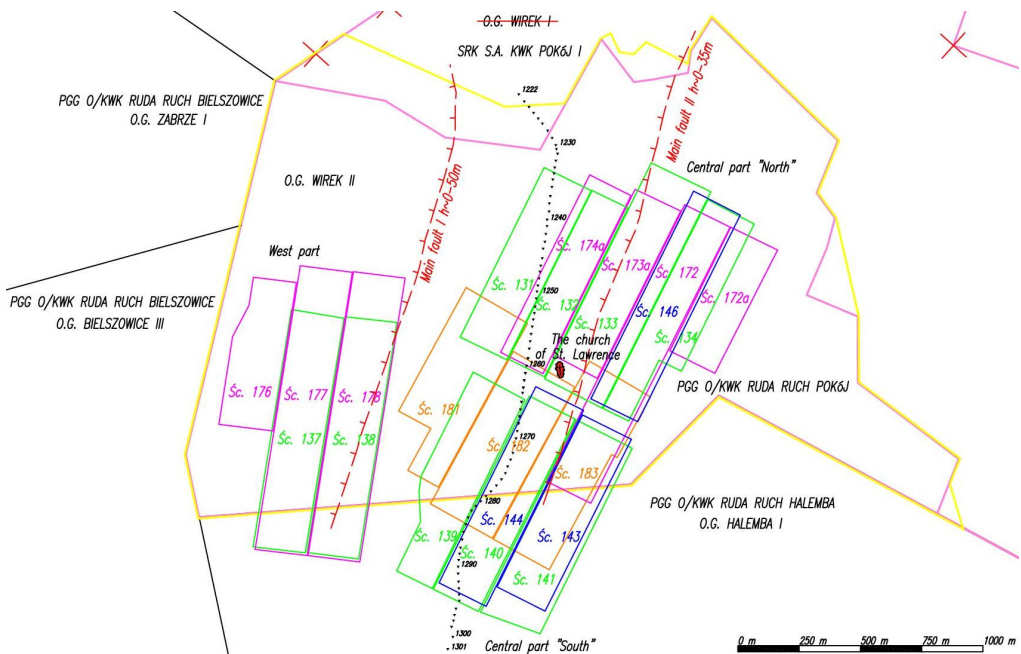

Fig. 2. Operating longwalls in the western and central part, sealed with ashes from power plants between 2005 and 2018, and the location of the measuring line 1222-1301

elevation, thanks to which the emulsifier flowed down in the direction of the goafs, which in turn made it possible to seal the goafs with ashes from power plants. The locations of the points of the measuring line 1222-1301 are marked against the background of longwalls edges.

The research was based onthe known mass and volume of ash fed to the excavations; per unit of the surface of the exploited seam, expressed by the average height h[m] of the layer of ash,referring to the *g* thickness of the *h/g* seam.

Fig. 3 shows an example of the distribution of *h* heightof ash in longwalls 139÷141 in seam 413/2 in quarterly periods. The figure indicates that the quarterly heights of the dust layer are diversified, on average ranging from 0.1 m to 0.6 m.
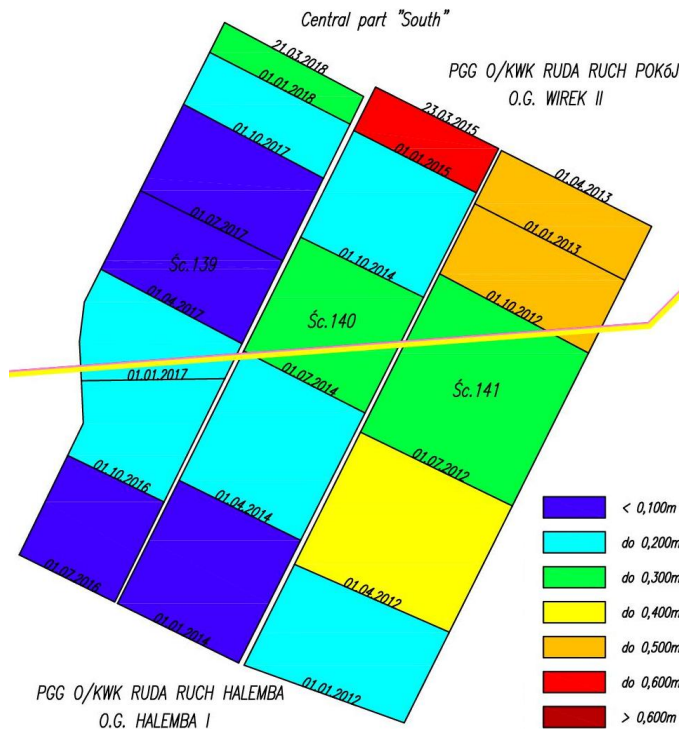

Fig. 3. Heights of the layers that would be formed by the ash backfill in the southern part of the central part in seam 413/2

4. Methodology and results

4.1. Test method

Cyclical measurements were conducted in the area of the mining exploitation, which, depending on the needs, can be carried out with a high frequency, Fig. 4.

On the basis of the analysis of the exploitation range, eight time intervals were selected between successive measurement cycles, in which the maximum increases in the observed sub-
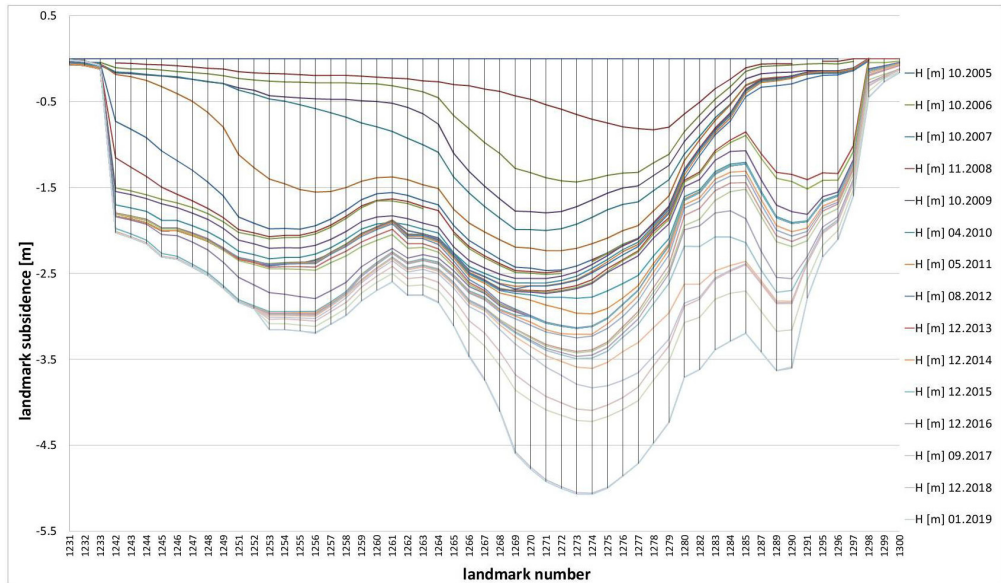
Fig. 4. Subsidence along the measuring line 1222-1301 in the period from October 2015 to January 2019

sidence caused by the exploitation of a single seam were close to the subsidence expected for a complete subsidence trough. The data from these timescales with the indication of the range of operation, and the position of the analysed sections in the measuring line are presented in Table 1.

In order to include the complex mining and geological conditions, and the fact that some subsidence troughs are partially complete, further analysis of subsidence was based on computer programmes from the EDBJ series (Białek, 2003) with implemented formulas of the Knothe and Budryk theory together with their extensions developed by J. Białek (Białek, 1991).

The integral and geometric theory of influence by S. Knothe that describes the subsidence $w(P,...)_K$ of P point due to the exploitation of the S seam area, with g thickness and subsidence coefficient a may be recorded in the following manner:

$$w(P,...)_K = w_K = \iint_S \frac{-a \cdot g}{r^2} \exp\left(-\pi\left(\frac{L}{r}\right)^2\right) dS \tag{1}$$

Where: L – variable distance of the dS field element from P measuring point. Operational extension of the formula (1) proposed by J. Białek enables, among other things, the inclusion of the edge effect (Fig. 5), which follows (2):

$$w(P,...)_{teoret} = w_K - A_{obr} \cdot f\left(w_K, \gamma_{oct}, r, ...\right) \tag{2}$$

Where: γ_{oct} – octahedral form deformation – results of the extension of Knothe theory by Bialek. It describes volumetric changes in the rock mass which is deformed by mining exploitation (Bialek, [2]); r – Knothe theory parameter – radius of the main influence range; $A_{obr} \cdot f(w_K,....)$ – an alteration reducing the value of the subsidence in the area of the slopes of the subsidence

Determined values of the parameters of the theory for selected ranges of operation
on the basis of the observation of the subsidence on the measuring line

Item	Seam	Longwall No.	Period of exploitation	h/g	Section of measuring line 1222-1301, Measurement time	Determined parameters of the theory			σ_w [mm]
						a	$tg\beta$	A_{obr}	
1	413/2 414/2	139 140 143	07.2016-03.2018 01.2014-03.2015 11.2015-09.2016	0.078	1285-1301 (12.2013-09.2017)	0.78	2.49	0.01	32.7
2	413/2 414/2	139 140 143 144	07.2016-03.2018 01.2014-03.2015 11.2015-09.2016 11.2017-12.2018	0.084	1276-1301 (12.2013-01.2019)	0.80	2.41	0.09	25.9
3	413/2 416 418	131 133 174a 184	12.2007-01.2009 04.2009-07.2010 08.2007-08.2008 12.2010-08.2011	0.170	1232-1249 (03.2007-08.2012)	0.61	3.45	0.29	45.9
4	413/2 416	131 174a	12.2007-01.2009 08.2007-08.2008	0.184	1233-1244 (03.2007-04.2010)	0.59	3.24	0.28	38.7
5	418	182 183	10.2005-03.2007 05.2007-11.2008	0.100	1272-1297 (10.2005-10.2009)	1.05	1.97	0.22	54.9
6	413/2	132	03.2015-02.2016	0.211	1238-1258 (12.2013-03.2017)	0.60	1.78	0.00	21.7
7	414/2	144	11.2017-12.2018	0.103	1288-1301 (09.2017-01.2019)	0.86	2.58	0.16	10.9
8	413/2 414/2	139 144	07.2016-03.2018 11.2017–12.2018	0.083	1282-1301 (08.2016-01.2019)	0.97	2.38	0.09	10.7
Average values				0.127		0.78	2.54	0.14	30.2

troughs and in the area of the bottom of incomplete troughs, enabling a significant reduction of systematic error in the description of subsidence.

It should be emphasized that when a = constans takes the value of the w_{teoret}, it is directly proportional to the value of the coefficient of subsidence $a = a_{teoret}$ which was included in the calculations.

The programmes also allow temporal variations in size and the position of the exploited plots $S(t)$, and the observed time delays on subsidence to be included.

The explanation of the meaning of the parameters in formulas (1) and (2) for the model of a subsidence trough – when its formation is caused by mining activity in the shape of a half-plane (Fig. 5) – is determined by formulas (3) to (7).

$$a = \frac{W_{\max}}{g} \tag{3}$$
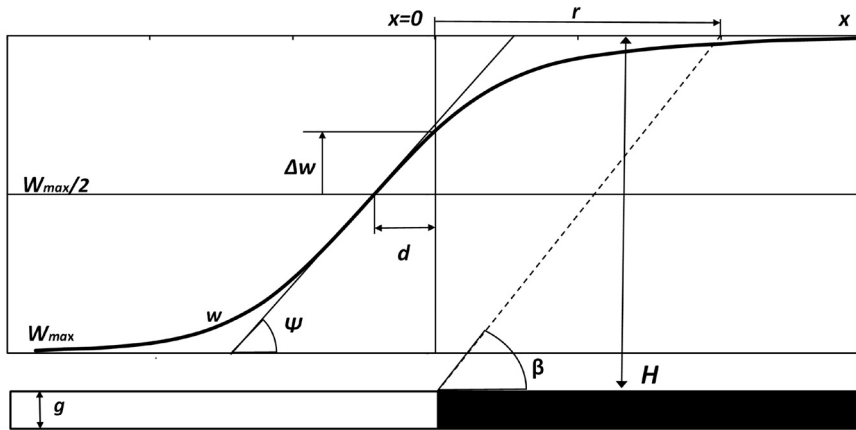
$$r = \frac{H}{\tan\beta} \tag{4}$$

Fig. 5. Explanation of the terms used in the example of a subsidence trough formed in the area of the exploitation edge in the shape of a half-plane

$$\tan \beta = \frac{H \cdot T_{\max}}{W_{\max}} \tag{5}$$

$$A_{obr} = \frac{-\Delta w(x=0)}{W_{\max}} = \frac{0.5 \cdot W_{\max} - w(x=0)}{W_{\max}} \tag{6}$$

$$d \cong A_{obr} \cdot r \tag{7}$$

where: $W_{\max}$ – the value of the maximum reduction of the bottom of a complete subsidence trough (CST).

Here, one can distinguish the maximum value of the subsidence in the incomplete subsidence trough – $w_{\max}$ – from the w subsidence at any P point of the trough.

$T_{\max} = \tan\psi$ – the tangent line to the subsidence at its inflection point.

The parameters of formulas (3)-(7) should be determined on the basis of measurements of CST, as only then are their values relatively stable and can be used for predicting the deformation of a mining area. For example, the value of the maximum subsidence of an incomplete subsidence trough may vary in the range $0 \leq w_{\max} \leq W_{\max}$, hence the value of the subsidence coefficient determined based on the formula $a = W_{\max}/g$ may change in the range $0 < a \leq w_{\max}/g$. The values of the remaining parameters are less susceptible to the impact of the extent of mining area.

With a time-dimensional description of the geometry of the conducted operation and a description of the position of the bench marks of the measuring line together with the increased values of measured subsidence in the analysed time periods, the research team determined the values of the parameters of the theory (1) by S. Knothe – a, $\tan\beta$ – and the A_{obr} parameter included in the formula (2) determining the influence of the edge (voids in the rock mass over the goafs along their borders). The method of least squares (LS) was applied which minimized the mean σ_w error between the values of subsidence calculated from the $w(P, S, a, \tan\beta, A_{obr}\ldots)_{teoret}$ model and the w_{pom} subsidence measured. The values of the determined parameters and average error values are presented in Table 1.

Table 1 shows that the determined values of parameters are as follows:
– exploitation coefficient average $a = 0.78$, from 0.59 to 1.05;
– rockmass parameter average $\tan\beta = 2.54$, from 1.78 to 3.45;
– exploitation edge average $A_{obr} = 0.14$, from 0.00 to 0.29;
– error of the surface reduction adjustment was 30.2 mm.

Moreover, Table 1 shows that the height of thewaste from the power plant, in given groups of operating longwalls, varied from 0.078 to 0.211 h/g, with an average of 0.127 h/g.

In order to achieve the aim of the work, it was of key importance to determine (on the basis of geodetic measurements and accepted ranges of exploitation) the values of the a_{pom} subsidence coefficient and h heights of fly ash distributed on the floor of goafs of individual longwalls andcorresponding to these operating ranges. Since the distribution of such ash on the floor is not uniform, the research team applied a certain substitute and relative (related to the g thickness of the seam) indicator of the ash backfilling intensity $X(P)_{(h/g)}$ described by formula (10). Its value at different heights of ash is variable, depending on the position of the P_j measuring point.

The research team used the J set of P_j measuring points located in the central regions of the subsidence troughs – each of the points with the values of the a_{pom_j} subsidence coefficient and the corresponding values of the $x_j = X(P_j)_{(h/g)}$ index – and applied the method of the least squares (LS), to calculate the a_0, $a_{h/g}$ estimators of the regression function defined by the formula:

$$a_j = a_o + a_{h/g} \cdot x_j \tag{8}$$

where: a_j – theoretical (expected) value of the subsidence coefficient for P_j point.

The a_0 parameter is defined using the value of the exploitation coefficient that would be recorded when no caulking of goafs is applied. The $a_{h/g}$ parameter indicates the impact of the caulking of goafs on the value of the exploitation coefficient.

4.2. Determination of the value of the a_{pom_j} exploitation coefficients on the basis of the measured subsidence of individual points in the bottom part of subsidence troughs

A set of values of the a_{pom_j} subsidence coefficients individually determined at particular P_j measuring points is required to estimate the parameters in the regression function (8).

It is not possible to apply the values of the determined a exploitation coefficients listed in Table 1, as they are average values for the whole set of measuring points in each analysed period and do not include the diversified effect of the variable quantity of ash on the value of the subsidence coefficient at individual measuring points.

If an extensive CST formed on the surface and was measured, it would be possible to determine the values of the exploitation coefficients at particular measuring points located at the bottom of the its surface, directly by using formula (3). In addition, differences in the determined values of the a_{pom_j} parameter could be assigned to a variable amount of the fly ash fed to the goafs. Currently, in the conditions of the USCB where the exploitation of coal seams is carried out at medium and large depths, it is almost impossible to meet the CST conditions, therefore the analysis required the observations of troughs which only approximately meet the criteria for complete troughs.

Formulas (1), (2) well describe both complete and incomplete subsidence troughs when $w_{max} > 0.7\ w_{max}$. The effect of the size of the field in use on the increase of the maximum reduction is modelled quite precisely.

If we want the calculated $w(P_j)_{teoret}$ subsidence to be equal to the measured w_{pom_j} subsidence, from the condition of the proportionality of the subsidence calculated to the value of the subsidence coefficient with the other parameters unchanged, its value can be calculated by the formula:

$$a_{pom\_j} = \frac{w_{pom\_j} \cdot a_{teoret}}{w(P_j)_{teoret}} \tag{9}$$

where: a_{teoret} – value of the subsidence coefficient was included in the calculations (its value was entered in the exploitation database, most often $a_{teoret} = 0.8$); $w(P_j)_{teoret}$ – theoretical subsidence calculated by formulas (1) and (2).

The authors further assumed that the result of the measured w_{pom} subsidence, and therefore the value of the subsidence coefficient (9), could have been affected by the height of the introduced backfilling mixtures.

4.3. Backfilling ratio (BR)

Fig. 3 shows the quantities of fly ash fed to the goafs of the subsequent longwall located in seam 413/2. It is evident that the average quarterly h heights of the ash layers varied from ~0.1 m to ~0.6 m.

If any P point of the mining area is considered, it is simultaneously affected by the $w(P)_g$ caused by mining the parcels located at the g height and by total $w(P)_h$ "counter-subsidence" caused by the backfilling of some fragments of these parcels that differ in h height of the fly ash. The relationship of these theoretical interactions is referred to as generalized backfilling ratio (BR) and is described as $X(P)_{(h/g)}$ at P point

$$X(P)_{h/g} = \frac{w(P)_h}{w(P)_g} \cdot a_{teoret} \tag{10}$$

where: $w(P)_g$ – subsidence calculated by formulas (1) and (2) when the quotation includes g seam thickness and values of a_{teoret} subsidence coefficient, as in formula (9); $w(P)_h$ = subsidence calculated by formulas (1) and (2) when the quotation includes the value of the $a = 1.0$ subsidence coefficient in all parcels, and h height of the fly ash instead of g thickness.

The $X(P)_{(h/g)}$ parameter has the following characteristics:
– When the thickness of the seam is g = constans and ash layer height is h = constans, the $X(P)_{(h/g)} = h/g$ in any point of the mining area.
– When the heights of the dust layers are variable (at g = constans), the $X(P)_{(h/g)}$ expression will take a weighted value depending on the position of the P calculation point relative to the S backfilled field and the dimensions of the field.

These are properties that enable the use of the generalized backfilling ratio as an argument of a function that describes the effect that the diversified height of fly ash has on the value of the subsidence coefficient.

4.4. Test results

The analysis includes observation points which in the analysed periods were lowered w_{pom_j} by more than 60% of the W_{max} subsidence. This enabled the limiting of the impact of the error in the determination of A_{obr} and $\tan \beta$ values determined by formula (9) used to calculate the subsidence coefficient, since in incomplete subsidence troughs, especially when including points near the operating edge and outside the exploitation field, the value of the a_{pom_j} subsidence coefficient significantly correlates with the values of the other parameters.

In order to check the impact of the quarterly reduction of the quantity of the backfill on the parameters of the formula (8), the research team applied two methods that differ in terms of the way they include the amounts of fly ash fed to the goafs.

Method 1 – a uniform distribution of backfilling mixtures averaged for lengths of selected longwalls. This is different in individual longwall areas.

Method 2 − assumed quarterly (as shown in Fig. 3) changes in the amount of the backfilling mixture.

For each of the P_j, measuring points selected in this way, using the algorithm described in sections 4.1, 4.2 and 4.3, the value of the a_{pom_j} subsidence coefficient was calculated (formula 9), as well as two values of the $x_j = X(P_j)_{(h/g)}$ backfilling ratio (BR) corresponding to even and uneven distribution of fly ash along the entire length of the longwalls.

Using the EXCEL and Statistica programmes, based on the LS method, the values of a_0, $a_{h/g}$ linear regression parameters were determined (8).

The calculation also includes data filtering by rejecting the outliers. The research team assumed, also using the results from Table 1, that the values of the determined exploitation coefficient should fall between 0.65 and 0.95.

a. Even distribution of the backfilling mixture in each longwall (method 1)
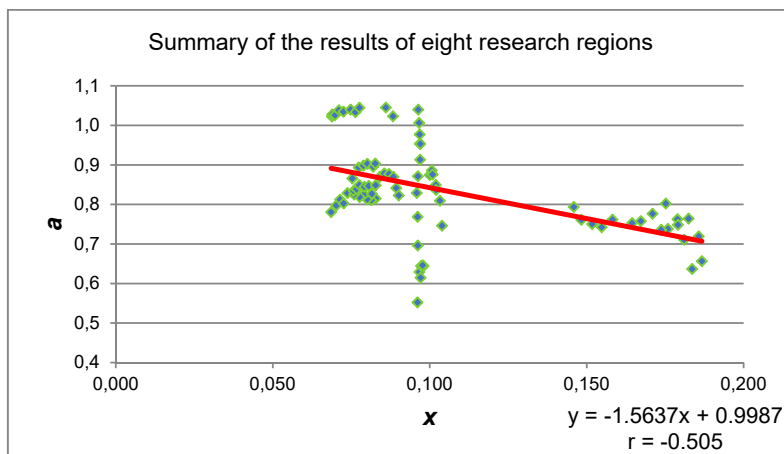

Fig. 6. The dependence of the value of the subsidence coefficient for cave-in mining with backfill caulking for all points and parcels where even distribution of backfilling material along the length of selected parcels for method 1 was assumed

Fig. 6 shows the dependence of the a exploitation coefficient on the height of the backfill converted to the thickness of the bed. All analysed measuring points were taken into account and it was assumed that the dust is evenly distributed along the subsequent longwalls. In the author's opinion, the value of the $a_{h/g} = -1.56$ parameter determining the influence of backfilling on the decrease of the a subsidence coefficient is too high in this case. From a physical point of view, if, even before the falling of cave-in rocks, the dusts formed a hard layer of h thickness, they could have a similar effect to that of reducing the operational g thickness by h, which would result in a decrease in the subsidence coefficient by h/g, thus the maximum possible value is $|a_{h/g}| \leq 1.0$. The determined value was $|a_{h/g}| > 1.0$ due to the fact that the analysed dataset included points that substantiality deviated from the regression line, therefore the next analysis does not include the measuring points in which $a_{pom\_j} < 0.65$ and $a_{pom\_j} > 0.95$. After this filtration, a regressive relation (11) was obtained for which the value of the correlation coefficient was r = –0.684.

$$a = 0.9213 - 0.9672x \tag{11}$$

Dependency (11), including the specified confidence interval of 95% for the determined regression relationship, is illustrated in Fig. 7.
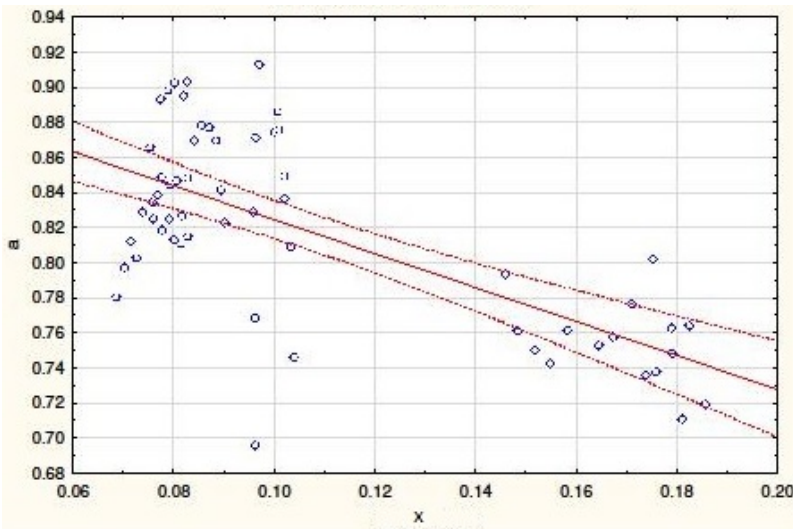

Fig. 7. The dependence of the value of the subsidence coefficient for cave-in mining with backfill caulking for all points and parcels where even distribution of backfilling material along the length of selected parcels for method 1 after the filtration of data (rejecting some points from Fig. 6) was assumed

The figure proves that rejecting the outliers substantially improves the results. The correlation coefficient increased from r = –0.505 to r = –0.684, and the determined values of the parameter of formula (11) can be considered acceptable thanks to their physical meaning.

b. Uneven distribution of the backfilling mixture in individual longwalls, evenly in quarterly periods (method 2)

Graph 8 presents the results of the analysis performed taking into account quarterly changes in the amount of the backfilling material. Comparison of Fig. 6 and Fig. 8, show a fundamental extension of the range of values of the $x = h_{zast}(P)/g$ variable, which is obvious as Fig. 6 shows dust heights averaged for the whole lengths of the longwalls.
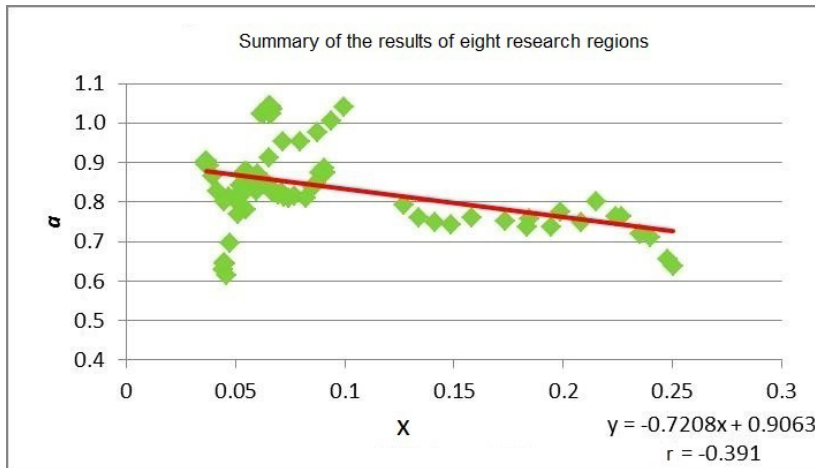

Fig. 8. The dependence of the value of the subsidence coefficient for cave-in mining with backfill caulking for all points and parcels where uneven distribution of backfilling material along the length of selected parcels for method 2 was assumed

It should be emphasized that without any data filtering, the determined values of the parameter in formula (8) fall within the range of acceptable values due to the physical meaning of this formula.

The distribution of the points presented in Fig. 9 was developed by rejecting the measuring points in which $a_{pom\_j} < 0.65$ and $a_{pom\_j} > 0.95$. This decomposition can be described by the introduction of regression (12), which is characterized by a relatively high value of the correlation coefficient – $r = -0.702$.

$$a = 0.8773 - 0.62x \qquad (12)$$

5. Discussion of the results

Table 2 compares the values of the correlation coefficient (column 5) that show the dependence of the exploitation coefficient on the value of the backfilling ratio for methods 1 and 2. In addition, it shows the ranges of exploitation coefficients (column 2) and reliability ranges of exploitation coefficients (columns 3 and 4).
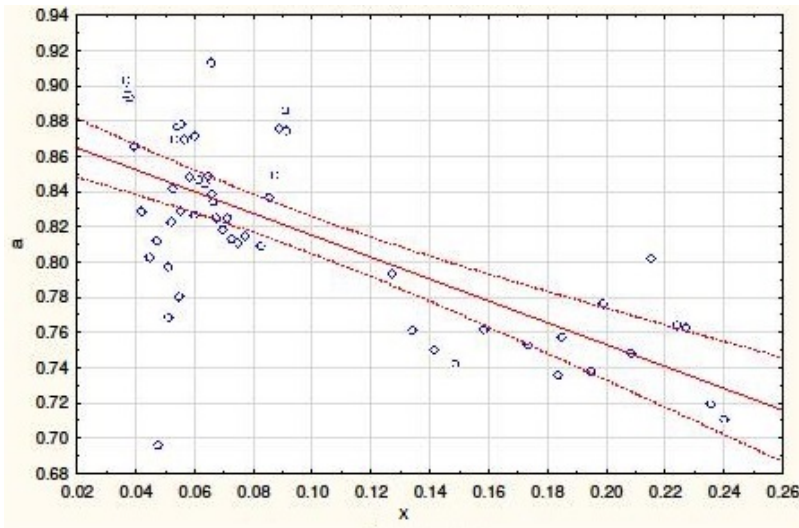
Fig. 9. The dependence of the value of the subsidence coefficient for cave-in mining with backfill caulking for all points and parcels where uneven distribution of backfilling material along the length of selected parcels for method 2 after the filtration of data was assumed (rejecting some points from Fig. 8)

TABLE 2

Comparison of the values of exploitation coefficients and the correlation of their dependence
on the degree of caulking of goafs (cave-in mining)

Method of determining the relationships	Determined values of exploitation coefficients	Determined reliability range of the share of backfilling material in goafs	Determined reliability range of the exploitation coefficient	Values of the correlation coefficient	Average ash layer height (for given period)
1	2	3	4	5	6
Method 1	0.63-0.92	from 0.10 to 0.12	$0.8 < a < 0.83$	−0.684	Exploitation of the longwall field
Method 2	0.69-0.88	from 0.08 to 0.11	$0.8 < a < 0.83$	−0.702	Quarterly

Table 2 shows that:
– The determined values of the correlation coefficient (column 5) indicate that statistically it is a strong correlation with a significant dependence (Stanisz, [17]).
– The comparison of the results obtained without taking into account the quarterly variability of the amount of fly ash (variability in individual longwalls) – Fig. 6 and 7 (formula 11) – with the results in which the quarterly variability of such fly ash is taken into account – Figures 8 and 9, formula (12) – show that that including the quarterly variability of the fly ash layer height increases the value of the correlation coefficient in the formula (12), and the results obtained, even without data filtering, are completely acceptable thanks to their physical significance. This proves that the height of the fly ash layer reduces the subsidence coefficient and consequently impacts the deformation of the mining area.

   – In terms of the filtering of the test results, it is proposed that the dependence (12) be used. Here, if the share of the backfilling material in the goafs falls between $0.0 < h/g < 0.26$, it will be possible to reduce the exploitation coefficient from 0.88 to 0.72 (18%), by having goafs filled with a backfill up to the height of $0.26g$.

6. Conclusion

1. The proposed research method as well as the obtained geological and mining data combined with the results of the measurements of surface subsidence (database) made it possible to determine the relationship between the exploitation coefficient and the height of ash fed to the goafs.

2. For practical applications, however, it is proposed that dependence (12) be used. Here, if the share of the backfilling material in the goafs falls between $0.0 < h/g < 0.26$, it will be possible to reduce the exploitation coefficient from 0.88 to 0.72 (18%), by having goafs filled with a backfill up to the height of $0.26g$.

3. The results of the research can be used for designing mining operation based on cave-in and the caulking of goafs with ashes in the case of mines with geological and mining conditions similar to those prevailing in the Ruda mine.

4. The research presented in the paper does not fully cover the broad range of this problem, but the results indicate that there are possible methods to reduce surface deformation by using ash from power plants.

References

[1] J. Białek, *Opis nieustalonej fazy obniżeń terenu górniczego z uwzględnieniem asymetrii wpływów końcowych*. Zeszyty Naukowe Politechniki Śląskiej (1), 1991.

[2] J. Białek, *Algorytmy i programy komputerowe do prognozowania deformacji terenu górniczego*. Wydawnictwo Politechniki Śląskiej 2003.

[3] Y. Jiang, R. Misa, K. Tajduś, A. Sroka, *A new prediction model of surface subsidence with Cauchy distribution in the coal mine of thick topsoil condition*. Archives of Mining Sciences **65** (1), 147-158 (2020), doi: 10.24425/132712

[4] S. Knothe, *Prognozowanie wpływów eksploatacji górniczej*. 1984 Wydawnictwo Śląsk, Katowice.

[5] A. Kowalski, *Deformacje powierzchni terenu górniczego kopalń węgla kamiennego*. 2020 Wydawnictwo Głównego Instytutu Górnictwa, Katowice.

[6] H. Kratzsch Bergschadenkunde, 2008 Deutscher Markscheider-Verein e.v., Bochum.

[7] M. Mazurkiewicz, Z. Piotrowski, *Grawitacyjne podsadzanie płytkich zrobów zawiesiną popiołów lotnych w wodzie*. Ochrona Terenów Górniczych **66**, 6-8 (1984).

[8] M. Mazurkiewicz, *Technologiczne i środowiskowe aspekty stosowania stałych odpadów przemysłowych do wypełniania pustek w kopalniach podziemnych*. Zeszyty Naukowe AGH, Górnictwo nr 152, (1990).

[9] T. Niemiec, *Porowatość zrobów a współczynnik eksploatacyjny*. Sbornik referatu XVIII, Konference SDMG, 161-167 (2011).

[10] W. Piecha, S. Szewczyk, T. Rutkowski, *Ochrona powierzchni dzielnicy Wirek w świetle dokonanej i prowadzonej podziemnej eksploatacji górniczej*. Przegląd Górniczy (2) 55-66, (2019).

[11] Z. Piotrowski, M. Mazurkiewicz, *Chłonność doszczelnianych zrobów zawałowych*. Górnictwo i Geoinżynieria **30** (3), 37-45 (2006).

[12] F. Plewa, Z. Mysłek., G. Strozik, *Zastosowanie odpadów energetycznych do zestalania rumowiska skalnego*. Polityka Energetyczna **XI** (1), 351-360 (2008).

[13] P. Polanin, A. Kowalski, A. Walentek, *Numerical simulation of subsidence caused by roadway system*. Archives of Mining Sciences **64** (2), 385-397 (2019), doi: 10.24425/1286090

[14] E. Popiołek, Z. Niedojadło, P. Sopata, T. Stoch, *Możliwości wykorzystania pogórniczych niecek obniżeniowych do oszacowania objętości pustek w zrobach poeksploatacyjnych*. (2014).

[15] T. Rutkowski, *Ocena wpływu podsadzania zrobów zawałowych na obniżenia powierzchni terenu w warunkach górnośląskiego zagłębia węglowego*. Główny Instytut Górnictwa, praca doktorska, Katowice, 2019.

[16] R. Ślaski, *Warunki zatapiania kopalni „Morcinek”*. Materiały konferencyjne SITG Oddział Rybnik. Ochrona środowiska na terenach górniczych podziemnych i odkrywkowych zlikwidowanych zakładów górniczych w subregionie zachodnim województwa śląskiego, (2010).

[17] Subsidence Engineers' Hand book, National Coal Board Mining Department, 1975.

[18] A. Stanisz, *Przystępny kurs statystyki z zastosowaniem STATISTICA PL na przykładach z medycyny (1)*. Statystyki podstawowe, StatSoft Polska, 2006, Kraków.

[19] P. Strzałkowski, *Doszczelnianie zrobów zawałowych a deformacje powierzchni terenu*. Materiały Konferencyjne Szkoły Eksploatacji Podziemnej. Centrum Podstawowych Problemów Gospodarki Surowcami Mineralnymi i Energią PAN, 27-40 (1995).

[20] D.N. Whittaker, D.J Reddish, *Subsidence*. Occurrence, Prediction and Control, 1989 Elsevier, Amsterdam, Oxford, New York, Tokyo.

[21] J. Zhang, Q. Sun, N. Zhou, J. Haiqiang, D. Germain., S. Abro, *Research and application of roadway backfill coal mining technology in western coal mining area*. Arab J. Geosci. (**9**:558), 1-10 (2016).

[22] H. Zhu, F. He, S. Zhang, Z. Yang, *An integrated treatment technology for ground fissures of shallow coal seam mining in the mountainous area of southwestern China a typical case study*. Gospodarka Surowcami Mineralnymi-Mineral Resources Management (34), 119-138 (2018), doi:10.24425/118641

[23] J. Zych, R. Żyliński, P. Strzałkowski, *Wpływ doszczelniania zrobów zawałowych na wielkość deformacji powierzchni*. Materiały Konferencji naukowo-technicznej II Dni Miernictwa Górniczego i Ochrony Terenów Górniczych, 307-311 (1993).