Archives of Mining Sciences 46, 4 (2001) 451–468

JAN SZLĄZAK*

THE DETERMINATION OF A CO-EFFICIENT OF LONGWALL GOB PERMEABILITY

WYZNACZANIE WSPÓŁCZYNNIKA PRZEPUSZCZALNOŚCI ZROBÓW ŚCIAN ZAWAŁOWYCH

This paper presents a method for the determination of a co-efficient of permeability in a caving zone formed by different kinds of roof rock mass. On the basis of a great number of mining examinations, the co-efficient of permeability was calculated and its change depending on the distance from a longwall face was taken into consideration. The value of the co-efficient of permeability is dependent on the kind of roof rock mass forming the caving zone. The rocks are characterised by their stratification resistance, which is a decisive factor in whether a rock is susceptible to caving. Determining the co-efficient of permeability is of great significance as far as the estimation of fire hazard in gob is concerned. Knowledge of the co-efficient of permeability allows theoretical calculations of airflow in a caving zone to be made.

Key words: ventilation, co-efficients of gob permeability, spontaneous fires, safety

W artykule przedstawiono sposób wyznaczenia wartości współczynnika przepuszczalności strefy zawału tworzonego przez różnego rodzaju skały stropowe. W oparciu o obszerne badania kopalniane dokonano obliczeń współczynnika przepuszczalności i uwzględniono jego zmianę w zależności od odległości od frontu ściany. Wartość współczynnika przepuszczalności uzależniono od rodzaju skał stropowych tworzących strefę zawału. Skały scharakteryzowano ich oporem rozwarstwienia, który decyduje o skłonności skał do przechodzenia w zawał. Wyznaczenie współczynnika przepuszczalności ma istotne znaczenie przy ocenie zagrożenia pożarowego w zrobach ścian. Znajomość współczynnika przepuszczalności pozwala na prowadzenie obliczeń teoretycznych związanych z przepływem powietrza przez strefę zawału.

Słowa kluczowe: wentylacja, współczynniki przepuszczalności zrobów, pożary endogeniczne, bezpieczeństwo

* WYDZIAŁ GÓRNICZY, AKADEMIA ORNICZO-HUTNICZA, 30-059 KRAKÓW, AL. MICKIEWICZA 30

1. Introduction

As a result of strata dislocation a rubble heap and fracture zone are formed in the space created by the excavation of the longwall face. In order to consider phenomena taking place in longwalls it is necessary to know the co-efficient of permeability (Litwiniszyn 1949; Szlązak 1980). The caving area of a longwall is filled with a roof rock mass whose structure is in a process of change. The very loose packing of grains in the face zone becomes tighter and tighter, as the distance from the longwall face increases. Little rock grains fill the gob between bigger ones and the latter, being supported non-uniformly, crumble under the stress in the rock mass, filling the gob tighter and tighter.

2. The method for determining the co-efficient of permeability

The examinations conducted in mines (Klebanow 1957; Mileticz 1962; Uszakow 1956; Szlązak 2000,) showed that for a "U-advancing" longwall ventilation system airflow in gob similar to laminar one takes place already in the distance above 25 m from a longwall face. The exponent characterising this airflow ranges form 0.68 to 1.19. However in the segment located 25 m from a longwall, short-term airflow takes place and the exponent ranges from 1.7 to 2.0. The transition from turbulent to laminar airflow is accords to a standard pattern.

If we take into consideration a U-advancing ventilation system, as presented in Fig. 1, assuming that laminar airflow takes place in the gob, this airflow can be described by means of the dependence (Szlązak, Szlązak 1987a):

$$\Delta p = R \cdot \Delta Q \text{ [Nm}^{-2}\text{]} \tag{1}$$

where:

R — aerodynamic resistance of gob along the line of airflow [Nsm^{-5}],
ΔQ— volumetric rate of airflow in the gob [m^3s^{-1}],
Δp — differential pressure drop between points located at entry points [Nm^{-2}].

On the basis of formula (1) an average aerodynamic resistance of the caving segment can be determined, having Δp i ΔQ. Gob resistance for laminar airflow, which can be determined on the basis of the equation of linear filtration in a porous medium:

$$v = K \cdot \frac{dp}{dy} \tag{2}$$

or after transformation:

$$\frac{\Delta Q}{S} = \frac{k}{\mu} \cdot \frac{dp}{dy} \tag{3}$$

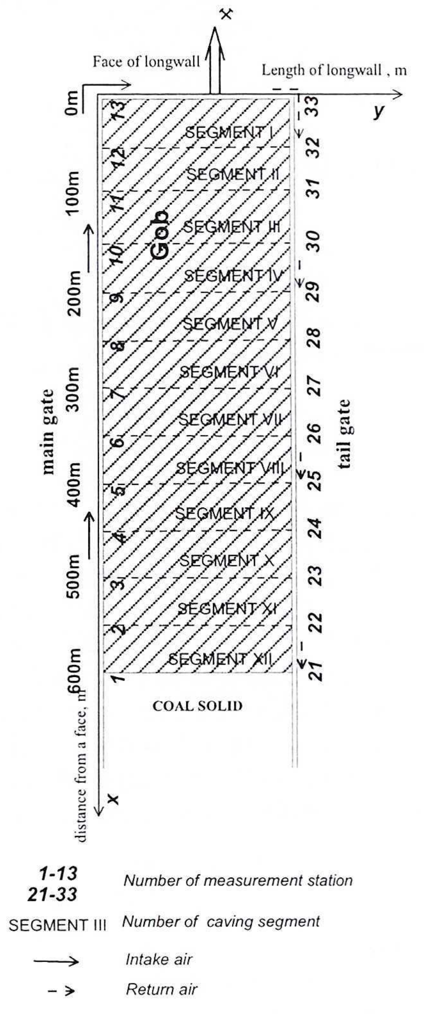

Fig. 1. U-advancing ventilation system of a longwall

Rys. 1. Schemat rozmieszczenia stacji pomiarowych wokół zrobów

where:

K — co-efficient of permeability [m^2],

μ — co-efficient of absolute viscosity of air [Nsm^{-2}],

S — cross-sectional area of airflow [m^2].

For longwall gob $\frac{dp}{dy}$ can be replaced by an approximate value:

$$\frac{\Delta p}{L} \approx \frac{dp}{dy} \tag{4}$$

where:

L — distance of air filtration [m],

Δp — the differential pressure drop [Nm^{-2}].

Then from dependence (1) after substitution the following formula is obtained:

$$\Delta p = \frac{\mu}{k}\frac{L}{S}\Delta Q \tag{5}$$

The dependence thus derived is equivalent to (1). Therefore, the co-efficient of permeability may be expressed in the following form:

$$k = \mu \frac{L}{S}\frac{\Delta Q}{\Delta p}\ [m^2] \tag{6}$$

It is difficult to determine the area of airflow S because it is dependent on the composition and structure of the roof rock-mass. The authors dealing with this problem have assumed that airflow takes place in a cross-section, equal to three (Chudek 1976; Szlązak 1980) or four times the thickness of a mining seam or layer. In the work by Szlązak J. (1980) it is assumed that the vertical height in which airflow takes place is determined by the extent of caving. Caving takes place in the roof rock mass to a height of up to 3 m (Kidybiński 1982). Moreover the area of a particular longwall affects the airflow. Therefore a height of 4 m is assumed. However, taking into consideration the fact that average subsidence of the roof above the exploited area falls by 0.5–0.6 m. Therefore the cross sectional area of airflow can be expressed by the following formula:

$$S = 3.5\ \mathrm{m}\, x_1\ [m^2] \tag{7}$$

where:

m — thickness of a mining seam or layer [m],

x_l — length of gob calculated along entries [m].

From dependence (3) it can be concluded that the value characterising the kind of gob is the quotient of co-efficient of absolute viscosity and of permeability. Inserting values into dependence (6) $S = 1$ [m^2], $L = 1$ [m], $\Delta Q = 1$ [m^3s^{-1}] and $\Delta p = 1$ [Nm^{-2}] the gob permeability with a cross-sectional area of airflow equal to 1 [m^2] and a unitary distance of airflow of 1 [m] during gas airflow of viscosity μ [Nsm^{-2}] the following is obtained.

Value "*k*" is the co-efficient of gob permeability and is will be used to compare gob formed by different kinds of roof rock mass. The value of this co-efficient is not dependent on the type of gas flowing.

However, it should be borne in mind that the co-efficient of permeability determined in this way is constant along the whole co-ordinate y (along the line of longwall L) and at the height of the airflow zone in the gob (along co-ordinate z).

The value of the co-efficient of gob permeability can be determined on the basis of measurements carried out along longwall gobs. To determine this, measurement stations must be set up along entries. The positioning of measurement stations is presented in Fig. 1. The distance between measurement stations does not matter and the greater the distance, the more accurate are the values of the co-efficient of gob permeability are obtained. Using dependencies 6 and 7 the formula for the co-efficient of permeability is obtained in the following form:

$$k = \mu \frac{L}{3.5\,\mathrm{m}\, x_1} \frac{\Delta Q}{\Delta p}\ [\mathrm{m}^2] \tag{8}$$

Therefore, in order to determine the co-efficient of gob permeability it is necessary to apply the parameters from formula (8), ie:

- fall in pressure along entries,
- airflow velocity at particular measuring points and their cross-sections,
- dry and wet temperature of air.

3. The characteristics of the longwalls examined

Only straight longwalls ventilated by means of a U-advancing system were examined. For further examinations six longwalls were selected whose roof rock mass consisted of soft, medium-hard and hard rock formations. The characteristics of mining and the geological parameters of the longwalls examined are listed in Table 1. The measurement points were located in the entries of the longwalls investigated and their positioning is depicted in Fig. 1.

Figs. from 2 to 7 present graphically the changes in the co-efficient of gob permeability in relationship to the distance from a longwall face.

The co-efficient of permeability attains its highest value behind a longwall face. As the distance from a longwall face increases the value of the co-efficient of permeability decreases. In the distance of approximately 2/3 of the current line of face-advance the co-efficient of permeability increases. The change in the value of the co-efficient of permeability results from the fact that where a longwall begins, a pillar was present, on which the roof rock mass was supported. As time passes, which is directly related to the time of commencement of the longwall exploitation, the value of the co-efficient of permeability of this zone decreases.

4. Estimation of the influence of the roof rock mass on the change in the co-efficient of permeability

The quantity of airflow in gob depends mainly on the kind of roof rock mass forming the caving, that is, on the value of the co-efficient of gob permeability. The character of caving formed by roof rock mass depends on its compactness and thickness, which is on separation resistance. Thinly stratified rocks are more liable to caving. The support for

TABLE 1

Characteristic of parameters of longwalls where changes in the co-efficient of gob permeability were examined

TABLICA 1

Charakterystykę parametrów górniczo-geologicznych badanych ścian

No	Specification		Symbol	Unit	No. of longwall					
					465	405	170	220	660	765
1	2		3	4	5	6	7	8	9	10
1.	Longwall width		L	m	140	180	175	165	224	180
2.	Longwall height		m	m	2.0	2.2	1.65	1.3	2.1	2.3
3.	Line of longwall		l	m	600	650	750	745	600	600
4.	Average rate of advance		p	m/m-th	25	40	20	60	80	55
5.	Inclination of seam			deg	9.0	5.0	12.0	10.0	5.0	6.0
6.	Seam		—	—	411/1	414/2	502	506	501	502
7.	Type of roof rock mass		—	—	mudstone with water intrusion	sandy shales	sandstone	sandstone	friable sandstone	sandstone
8.	Roof rocks separation resistance		R_{rrs}	N/m^2	$2.5 \cdot 10^6$	$4.0 \cdot 10^6$	$6.0 \cdot 10^6$	$6.7 \cdot 10^6$	$4.5 \cdot 10^6$	$6.5 \cdot 10^6$
9.	Element. Resistance	of entries	$R_1 + r_2$	Ns/m^9	0.00202	0.00360	0.00460	0.00152	0.00128	0.00061
		of a longwall	r_s	Ns/m^9	0.00160	0.00222	0.00343	0.0025	0.00090	0.00129
10.	Quantity of air at the intake of	entry	Q	m^3/s	14.96	11.05	13.89	25.00	29.00	33.33
		longwall	Q_s	m^3/s	11.49	6.63	5.52	11.90	18.72	13.92

the main roof, within a certain proximity to the longwall face, is susceptible to unpredictable collapse. Therefore the co-efficient of gob permeability is dependent on the bed separation resistance of the roof rock mass.

A bed separation resistance of the roof rock mass caving was assumed for the analysis of gob permeability. Bed separation resistance is an expression of the rock's tensile strength measured in a perpendicular direction to the area of stratification. Consequently the tensile strength is a decisive factor in its susceptibility to caving. Bed separation resistance for the roof rock mass should be calculated on the basis of the following formula:

$$R_{rrs} = \frac{\sum_{i=1}^{n} R_{rri} m_i}{\sum_{i=1}^{n} m_i} \ [\mathrm{N/m^2}] \tag{9}$$

where:

R_{rrs} — bed separation resistance of roof ,
R_{rri} — bed separation of the i-layer,
m_i — thickness of the i-layer [m].

Formula (9) takes into consideration the influence of the thickness of particular rock layers on roof susceptibility to caving. Bed separation resistance of particular rock layers can be calculated on the basis of the values obtained by means of a hydraulic exploratory drilling (Instrukcja 1976).

Caving formed by roofs with different bed separation resistances creates different conditions for airflow. When analysing the results of measurements (presented in Figs. 2 to 7), it can be seen that as bed separation susceptibility of the rock mass increases (Table 1), both the co-efficient of gob permeability and the airflow through the gob increase. The measurements were carried out for bed separation resistances ranging from 2.5 to 7.0 [MPa].

Obtained values of the bed separation resistance of the roof rock mass are dependent on the kind of rock layer and its thickness. On the basis of the measurements taken, it can be concluded that the most frequently encountered roof rock-types are characterised by the following bed separation resistances:

- sandstone (fine-, medium- and coarse-grained) — (5.5–7.0) [MPa],
- arenaceous shale — (3.0–4.5) [MPa],
- Mudstone — (1.5–3.0) [MPa].

5. Analysis of changes in the co-efficient of gob permeability

The co-efficient of gob permeability is one of the main factors deciding about the quantity of air lost by flowing through the gob. The comparison of gob permeability of particular longwalls is complicated by factors such as the volume of caving and the fall in air pressure along the airways through the gob. Therefore when analysing gob permeability a co-efficient of permeability with area of 1 [m^2] and airflow way of 1 [m] must be applied.

On the basis of the analysis of the results of measurements and calculations it can be concluded that the co-efficient of gob permeability decreases as the distance from a longwall increases (Figs. 2 to 7). The greatest value of the co-efficient of gob permeability is obtained close to a longwall face and lowest at a distance of approximately 2/3 of the line of longwall. After falling to the minimum, the co-efficient of permeability increases to the place of the longwall commencement. As the line of longwall advances, the co-efficient of permeability in the place of the commencement decreases. However it is always bigger than the minimum value at a distance of approximately 2/3 of the line of longwall. As the rate of longwall advance increases, the segment of gob with a small co-efficient of permeability increases as well.

The gob for which bed separation resistance is lowest is characterised by the smallest values of the co-efficient of permeability. As the bed separation resistance of the roof rock mass increases, the co-efficient of gob permeability also increases. It can be observed in figures from 2 to 7, which are the result of the measurements taken for different values of bed separation, the resistance of the roof rock mass increases.

On the basis of the measurements taken and of the analysis, it may be concluded that the co-efficient of gob permeability is dependent on the distance from the longwall face and the values of the bed separation resistance of the roof rock mass (the kind of roof rock mass). As the distance from the longwall face increases, the co-efficient of gob permeability decreases. Different authors describe the change in co-efficient of gob permeability assuming a linear filtration using different formulae.

The dependencies presented by J. Litwiniszyn (1949) and F.S. Klebanow (1957) were used in order to describe the changes in the co-efficient of permeability:

$$k(x) = k_0 e^{-bx} \tag{10}$$

by K.Z. Uszakow (1956):

$$k(x) = k_0 e^{-bx^2} \tag{11}$$

by A.F. Mileticz (1962):

$$k(x) = \frac{\mu}{r_0 + ax^{b_1}} \tag{12}$$

where:

$r_0,\ a,\ b,\ b_1$ — empirical co-efficients dependent on mining and geological conditions of caving,

$k_0 = \frac{\mu}{r_0}$ — the co-efficient of permeability of caving behind a longwall face [m^2],

x — the distance from the a longwall face [m].

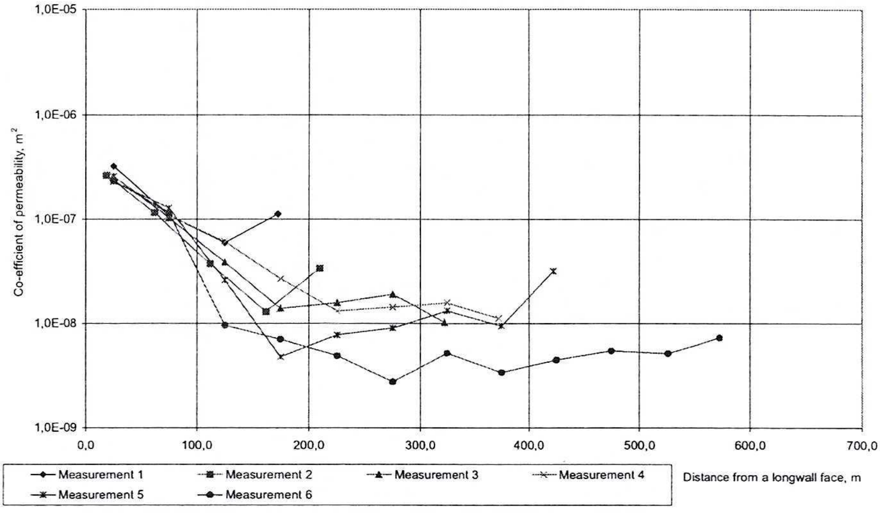

Fig. 2. Change in co-efficient of permeability of caving zone depending on the distance from a longwall face 465

Rys. 2. Zmiana współczynnika przepuszczalności strefy zawału w zależności od odległości od frontu ściany 465

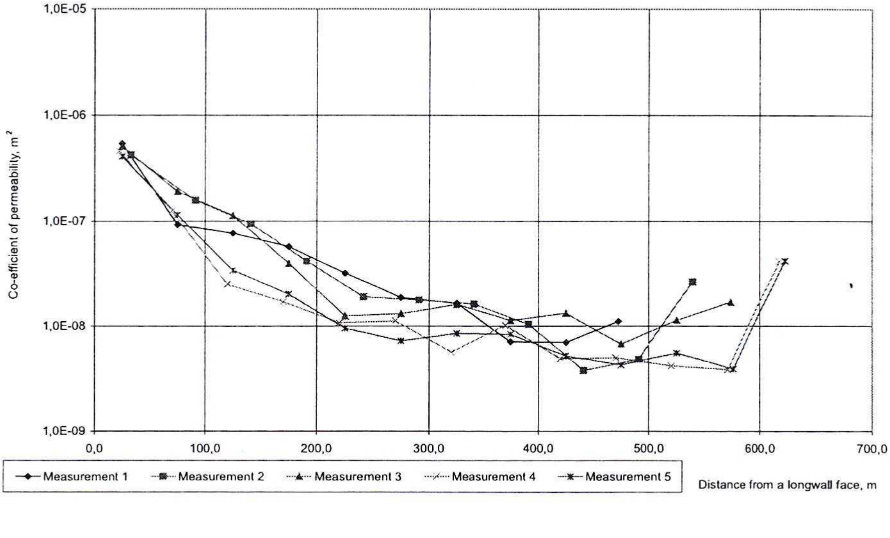

Fig. 3. Change in co-efficient of permeability of caving zone depending on the distance from a longwall face 405

Rys. 3. Zmiana współczynnika przepuszczalności strefy zawału w zależności od odległości od frontu ściany 405

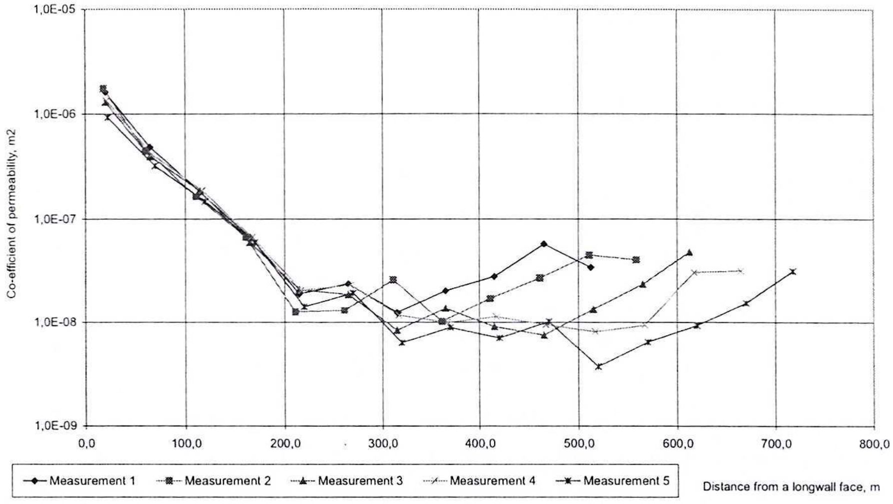

Fig. 4. Change in co-efficient of permeability of caving zone depending on the distance from a longwall face 170

Rys. 4. Zmiana współczynnika przepuszczalności strefy zawału w zależności od odległości od frontu ściany 170

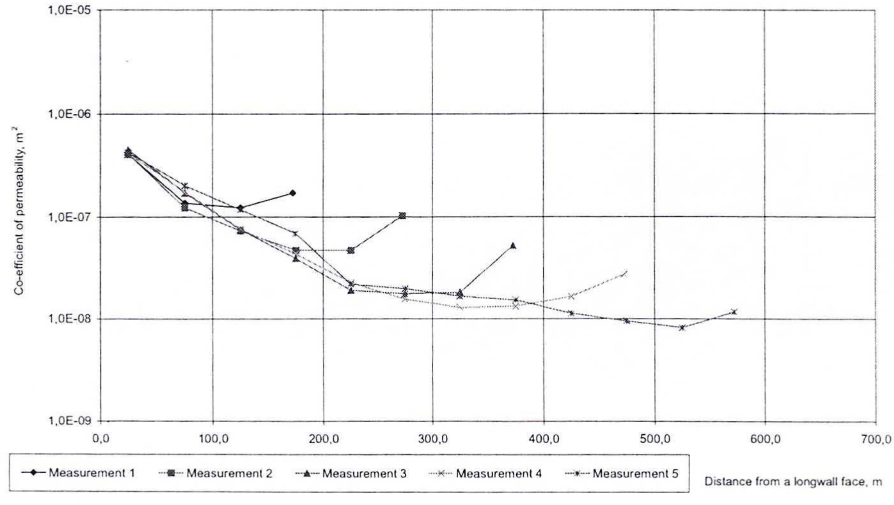

Fig. 5. Change in co-efficient of permeability of caving zone depending on the distance from a longwall face 660

Rys. 5. Zmiana współczynnika przepuszczalności strefy zawału w zależności od odległości od frontu ściany 660

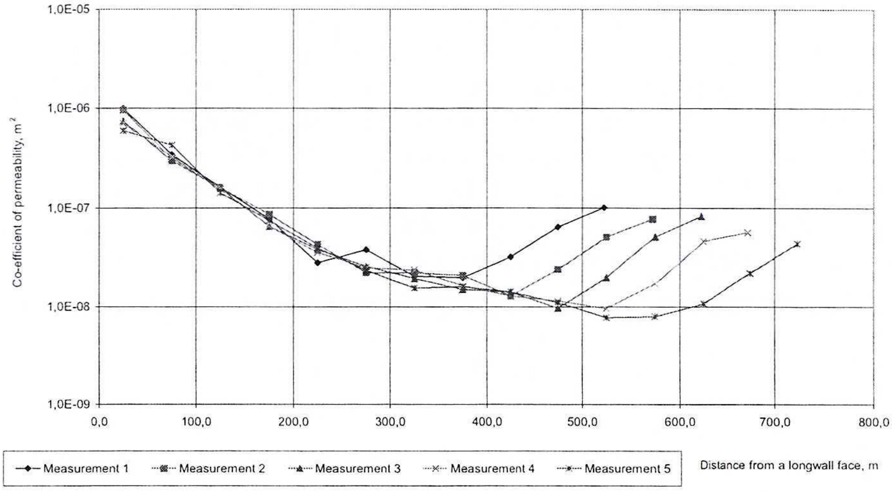

Fig. 6. Change in co-efficient of permeability of caving zone depending on the distance from a longwall face 220

Rys. 6. Zmiana współczynnika przepuszczalności strefy zawału w zależności od odległości od frontu ściany 220

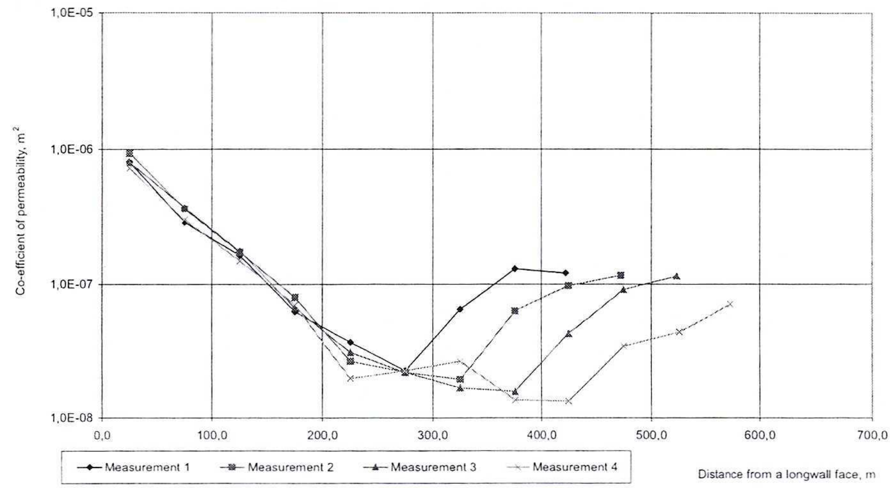

Fig. 7. Change in co-efficient of permeability of caving zone depending on the distance from a longwall face 765

Rys. 7. Zmiana współczynnika przepuszczalności strefy zawału w zależności od odległości od frontu ściany 765

For the last measurement series, figures from 8 to 13 illustrate the changes in the co-efficient of gob permeability as a function of the distance from a longwall face for six longwalls with different bed separation resistances of the roof rock mass. The value of the co-efficient of permeability was plotted on a semi-logarithmic format. For these values, the approximation of the co-efficient of permeability by means of dependencies (10), (11) and (12) is also presented. On the basis of the figures it can be concluded that only dependence (12) approximates well the results of measurements along the whole line of the longwall. Therefore it was assumed that the co-efficient of gob permeability will be approximated by the following dependence:

$$k(x) = \frac{\mu}{r_0 + ax^2} \ [\mathrm{m}^2] \tag{13}$$

for $0 \le x \le \frac{2}{3} l$

where:

l — signifies the total line of the longwall [m].

However for value $x = \frac{2}{3} l$ the minimum value of the co-efficient of gob permeability is obtained. After reaching the minimum, the co-efficient of permeability increases until a longwall begins. Along the length where the co-efficient of gob permeability increases, an approximation was conducted by means of the following dependence:

$$k(x) = \frac{\mu}{r_0 + a\left(\frac{4}{3} l - x\right)^2} \ [\mathrm{m}^2] \tag{14}$$

for $\frac{2}{3} l \le x \le l$

However the values of co-efficients r_0, k_0, a and b are dependent on bed separation resistance of the roof rock mass located over a selected seam. Fig. 14 presents the dependence of changes in co-efficients $k_0 = \frac{\mu}{r_0}$ and a on the bed separation resistance of the roof rock mass.

As the bed separation resistance of the roof rock mass increases, the value of co-efficient k_0 also increases. The change in the co-efficient of caving permeability behind the longwall face was approximated by the following dependence:

$$k_0 = \frac{\mu}{6} 10^{-10} R_{rrs}^{1.74} \ [\mathrm{m}^2] \tag{15}$$

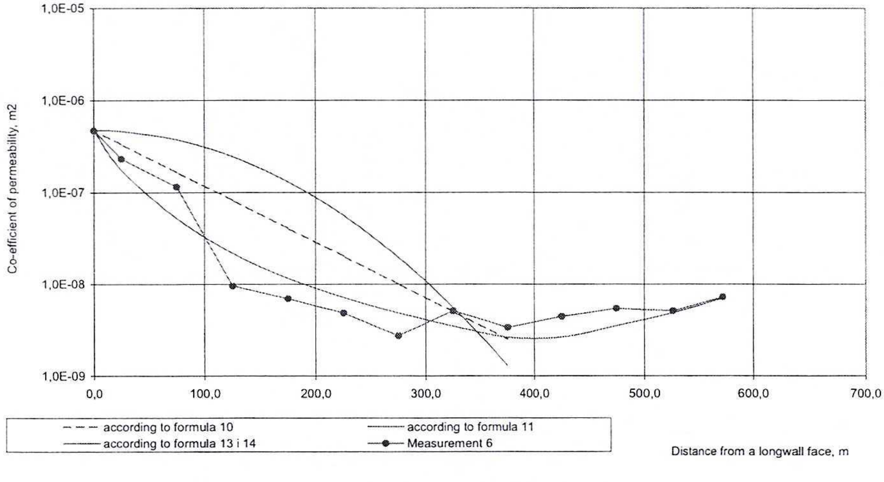

Fig 8. Change in co-efficient of permeability of caving zone for the last series together with approximation for longwall 465

Rys. 8. Zmiana współczynnika przepuszczalności strefy zawału dla ostatniej serii pomiarowej z aproksymacją tych zmian dla ściany 465

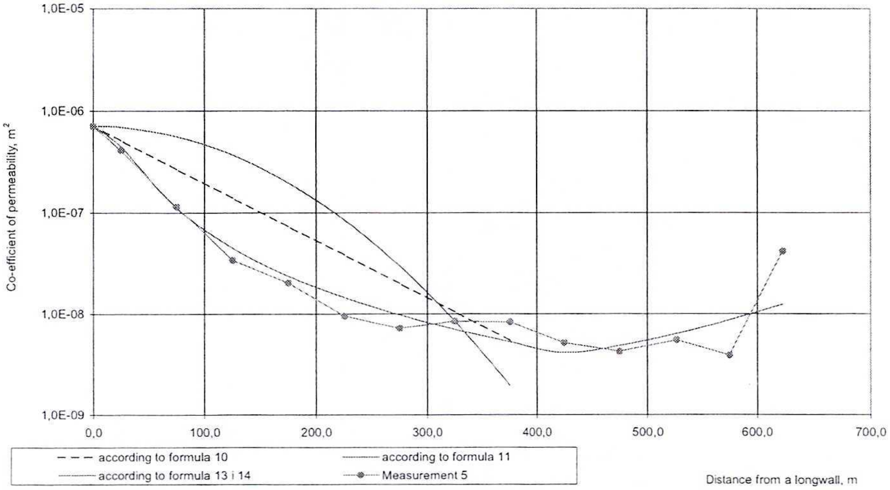

Fig. 9. Change in co-efficient of permeability of caving zone for the last series together with approximation for longwall 405

Rys. 9. Zmiana współczynnika przepuszczalności strefy zawału dla ostatniej serii pomiarowej z aproksymacją tych zmian dla ściany 405

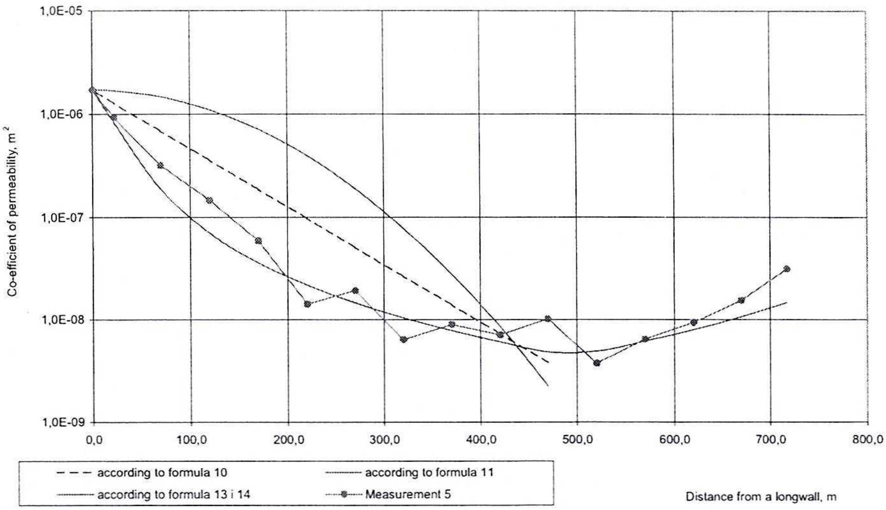

Fig. 10. Change in co-efficient of permeability of caving zone for the last series together with approximation for longwall 170

Rys. 10. Zmiana współczynnika przepuszczalności strefy zawału dla ostatniej serii pomiarowej z aproksymacją tych zmian dla ściany 170

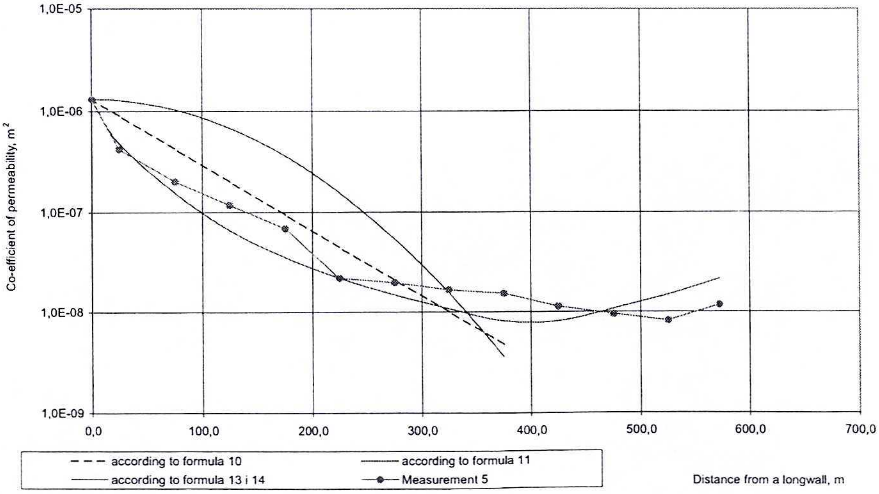

Fig. 11. Change in co-efficient of permeability of caving zone for the last series together with approximation for longwall 660

Rys. 11. Zmiana współczynnika przepuszczalności strefy zawału dla ostatniej serii pomiarowej z aproksymacją tych zmian dla ściany 660

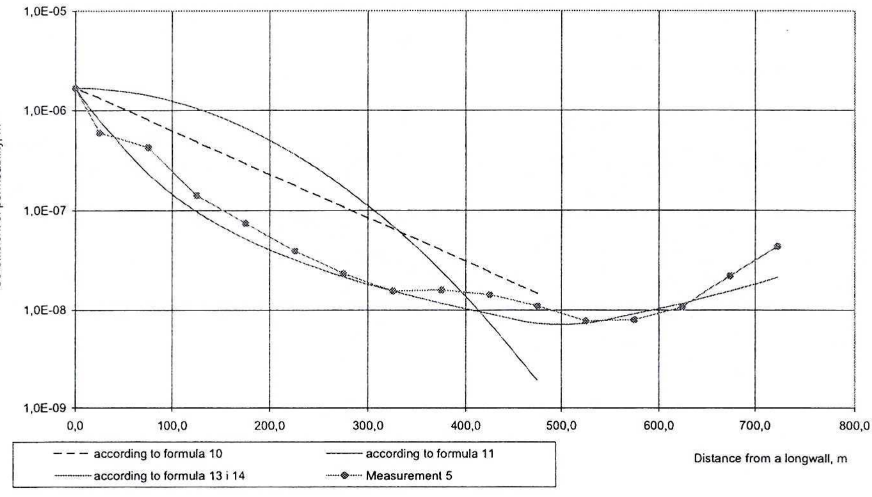

Fig 12. Change in co-efficient of permeability of caving zone for the last series together with approximation for longwall 220

Rys. 12. Zmiana współczynnika przepuszczalności strefy zawału dla ostatniej serii pomiarowej z aproksymacją tych zmian dla ściany 220

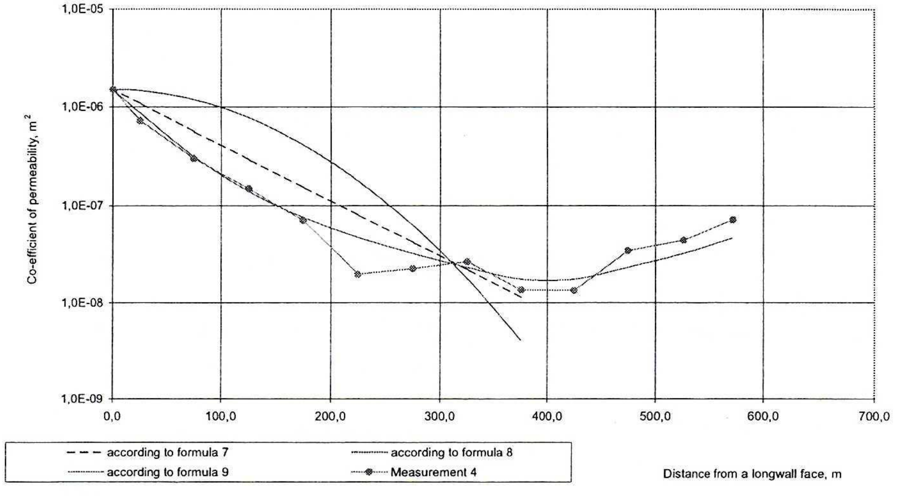

Fig 13. Change in co-efficient of permeability of caving zone for the last series together with approximation for longwall 765

Rys 13. Zmiana współczynnika przepuszczalności strefy zawału dla ostatniej serii pomiarowej z aproksymacją tych zmian dla ściany 765

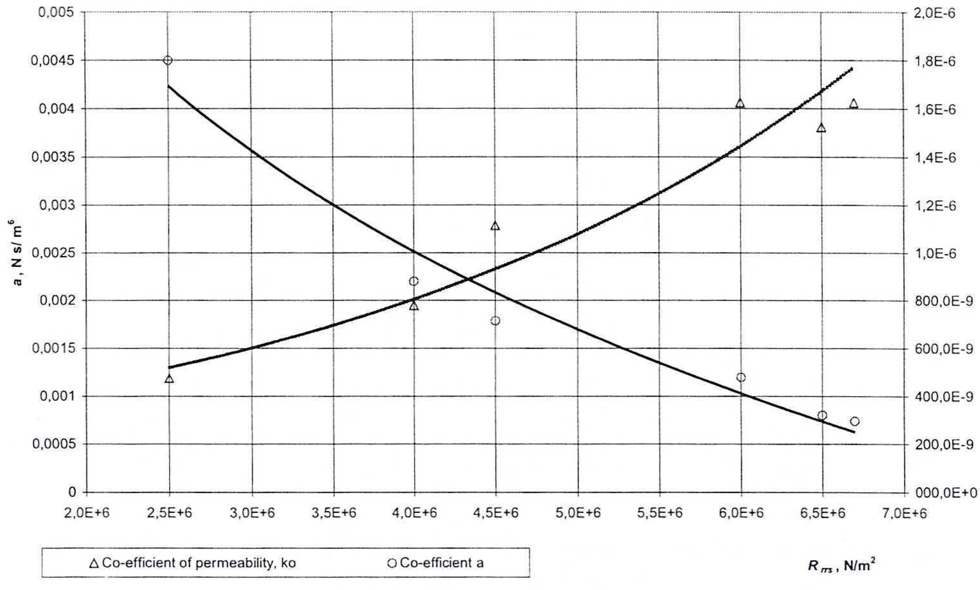

Fig. 14. Dependence of changing of co-efficient of permeability k_o and co-efficient a on bed seperation resistance of roof rock mass

Rys. 14. Zależność zmian współczynnika k_0 i współczynnika a od oporu rozwarstwienia skał stropowych

However the change in co-efficient a was approximated by dependence:

$$a = 6 \cdot 10^9 R_{rrs}^{1.74} \text{ [Nsm}^{-6}\text{]} \tag{16}$$

To sum up it can be concluded that the co-efficient of gob permeability is dependent on:

1) the physical and structural characteristics of the roof rock mass forming the caving,

2) the distance from the longwall face.

Ad 1. Rocks with lower resistance are more susceptible to caving and form caving characterised by a greater packing and simultaneously by a smaller co-efficient of permeability. However rocks less liable to caving form caving are characterised by much bigger co-efficients of permeability.

Ad 2. It has the greatest value behind a longwall face and gradually decreases as the distance from it increases. After reaching the minimum value, the co-efficient of permeability increases to the commencement of longwall. At the point where a longwall begins the value of the co-efficient decreases with time (as the distance from caving increases); however it is much bigger than at the point where the gob is most tightly packed.

6. Conclusions

1. One of the most important parameters characterising the airflow in a caving zone is the co-efficient of gob permeability. The value of this co-efficient is dependent on the kind of roof rock mass forming caving. Cavings formed by roofs with different bed separation resistance create different conditions for airflow. Analysing the results of measurements it can be concluded that as bed separation resistance increases, both the co-efficient of gob permeability and the volumetric stream of air in a caving zone increase.

2. On the basis of the analysis of measurements and calculations it can be concluded that the co-efficient of gob permeability decreases as the distance from a longwall face increases. The greatest value of the co-efficient of permeability is obtained close to a longwall and the smallest at a distance of approximately 2/3 of the line of longwall. After reaching the minimum, the co-efficient of permeability increases until a longwall begins. As the line of longwall increases, the co-efficient of permeability decreases at this point; however it is always much bigger than the minimum value for a particular longwall. As the line of longwall increases, the segment of gob with a small co-efficient of permeability increases too.

3. The biggest values of the co-efficients of permeability are characteristic of gob for which bed separation resistance is the lowest. As the bed separation resistance of the roof rock mass decreases, the co-efficient of gob permeability decreases. The measurements were taken for bed separation resistance of roof rock mass ranging from $2.5 \cdot 10^6$ to $7.0 \cdot 10^6$ N/m^{-2}.

REFERENCES

Chudek M., 1976: Mechanika gorotworu. Skrypty centralne studiow dla pracujących nr 598/20, Gliwice.

Gluzberg E.J., Graszczenkow N.F., Szalajew W.S., 1988: Kompleksnaja profilaktika gazowoj i pożarowoj opasnosti w ugolnych szachtach. Nedra, Moskwa.

Instrukcja klasyfikowania stropów wyrobisk ścianowych dla oceny warunków kierowania stropem i doboru obudowy (na podstawie pomiarów hydraulicznym penetrometrem otworowym), Katowice 1976.

Kidybiński A., 1982: Podstawy geotechniki kopalnianej, Wyd. Śląsk, Katowice.

Klebanow F.S., 1957: O dwiżeniju wozducha po gornym wyrabotkam pri naliczi wyrabotannych prostranstw. Gornyj Żurnal no 4.

Litwiniszyn J., 1949: Stationary flows in heterogenously unisotropic mediums. Annales de la Societe Polonaise de Mathematique t. XXII.

Mileticz A.F., 1962: Utieczki wozducha w szachtach. Moskwa.

Szlązak J., 1980: Wpływ uszczelniania chodników przyścianowych na przepływ powietrza przez zroby. Praca doktorska, AGH, Kraków.

Szlązak J., Szlązak N., 1987a: Determination of aerodynamic drag of goaf the breaking down longwalls. Archives of Mines vol. 32, i. 4 .

Szlązak J., Szlązak N., 1987b: The air escapes through the caving goaf of the longwalls during the ventilation by c-system in the direction of the strike. Archives of Mines vol. 32, i. 4.

Szlązak J., 2000: Airflow in the zone of caving in the light of theoretical and experimental research. Uczelniane Wydawnictwa Naukowo-Dydaktyczne, Dissertations Monographies nr 90, Kraków

Uszakow K.Z., 1956: Charakteristyka utieczek wozducha ceries wyrabotannoje prostranstwo na szachtach Doniecko-Makiewskowo rajana Donbassa. Nauczny je trudy po woprosam gornowo diela 16.

REVIEW BY: PROF. DR HAB. INŻ. WACŁAW TRUTWIN, KRAKÓW

Received: 20 June 2001