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Filling underground voids to prevent water hazards in active and decommissioned hard coal mines

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SUMMARY: In hard coal mines in Poland, the use of filling of caving is widespread. Mixtures of water and fly ash from coal combustion in power plants are used for this purpose. In addition to many other benefits, attention has been paid to this technology's usefulness in reducing water hazards. For this purpose, laboratory tests have been undertaken on fly ash-water mixtures samples conductivity using a falling-head permeameter. The results showed that the mixtures achieve permeability values range from $8x10^{-7}$ m/s to $1{,}2x10^{-9}$ m/s. Additionally, caved zone structure and flow of fill mixtures in longwall cavings have been discussed.

Keywords: water hazard, mining with caving, filling of cavings, permeability of fill materials, insulation of gob area

1 INTRODUCTION

Underground mining is associated with numerous impacts on both surface and subsurface environments. When operating with a roof collapse, the most considerable impact is rock masses' movement, resulting in deformations of the rock mass and the ground surface. These deformations have the nature of continuous displacements - without disturbing the structure of the rock and discontinuities, which includes, among other things, the formation of underground voids and fractures, the expansion and development of existing fissures, which accompanied the transformation of continuous rock layers into separate rock blocks and blocks.

For groundwater flow and water hazard considerations, it is convenient to adopt the model of the rock mass fracturing process proposed by Palchik (2003). It assumes the creation of zones of increased vertical and horizontal interconnections between rock strata in the roof of a coal seam extracted using longwall with caving, Figure 1. This model is still in use, also in currently appearing works (Guo et al. 2019; Ning et al. 2019).

Above the gob area (caved zone), a fracture zone occurs, divided into three sub-zones, as illustrated in Figure 1. The lower subzone consists of separated blocks separated by vertical and horizontal fractures, and the vertical displacement of the rock blocks may occur. However, in the middle zone, flat and interconnected vertical fractures exist of smaller dimensions and without individual rock blocks. Finally, there are only interlayer bed separations in the upper area. Above this structure, a continuous subsidence trough extends up to the carboniferous formation roof and further upward to the ground surface (Guo et al. 2019; Ning et al. 2019; Palchik 2003).

Similarly, the process of creating a fracture zone proceeds in the case of longwall mining with backfill. However, in this case, the fracture zone's extent is reduced, and the dimension of the fractures is smaller (Figure 2). Separate rock blocks are larger and their convergence smaller than in the case of mining with caving.

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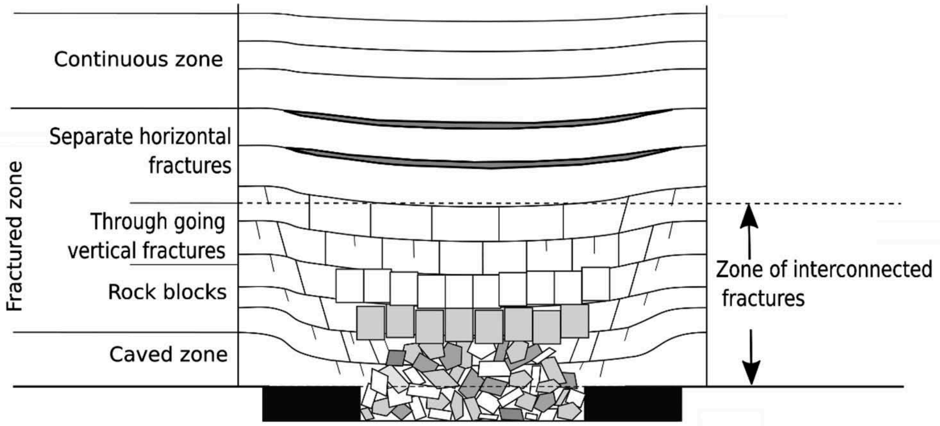

Figure 1. Zones of fractures in the roof rock strata resulted from the longwall mining with caving.
Source: own elaboration after Palchik, 2003.

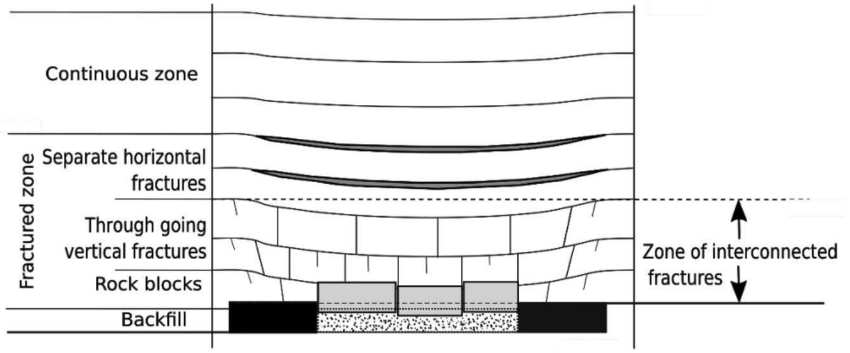

Figure 2. Zones of fractures in the roof rock strata resulted from the longwall mining with backfill.
Source: own elaboration after Palchik, 2003.

The number of fractures and their length per specific volume of roof rocks is much smaller than in the case of caving. It depends primarily on backfill material compressibility, roof convergence at the distance of the open space of the longwall, and quality of backfill operations. Also, the eventual presence of the "backfill zero" (space below the roof that cannot be filled up, e.g., due to the disadvantageous geometry of the coal seam) is an essential factor. Of course, the use of backfill reduces the values of deformation parameters of subsidence troughs, which is the primary purpose of using backfill.

However, any mining operations cause water relations changes in the rock mass (Rogoż 2004; Sztelak 1998; Trembecki 1972). Minimal increase in water hazards and ground waters migration can be achieved using backfill. Still, due to the low profitability of hard coal mining in Upper Silesia Coal Basin conditions, the total output comes from mining with caving. Therefore, the paper attempts to discuss the impact of filling of cavings on the reduction of water risk and groundwater migration conditions in the rock mass, which arises as a result of mining with caving.

The purpose of this paper is to present the process of the filling of cavings in the aspect of limiting water hazard and creating opportunities to improve hydrogeological conditions in the active and decommissioned mines through the planned creation of insulating layers in the gob area of extracted coal seams.

2 GROUNDWATER THREAT MITIGATION IN HARD COAL MINES

In the conditions of the existing water hazard in mines, especially when mining with caving is the only or dominating mining system, an increase in water threat by creating new fracture zones and gob areas in extracted coals seams may occur. This increase in risk is intensified in multi-seam mining operations when the extraction of lower and lower coal seams promotes an increasingly higher zone of hydraulically interconnected fractures and voids (Ning et al. 2019; Sztelak 1998).

In the mine liquidation phase, previously drained rock mass areas become zones of accumulation and flow of groundwater (Mzyk 2016; Trembecki 1072). When a decommissioned mine lies adjacent to an active mine, it may be advantageous to limit groundwater migration from a flooded to an active mining area. That target can be achieved, e.g., by isolating specific parts of the rock mass and creating convenient groundwater runoff routes to other parts of it. In practice, this goal may be achieved by planned closure activities (e.g., by tight isolating or damming of working) or by maintaining selected main workings as water collectors (Mzyk 2016). In this way, it is possible to divert groundwater to drainage pumps of the active mines' protection system.

The caved zone formed by the gob area and the separated rock blocks creates space for retention of large volumes of groundwater, and the large fractures allow its unrestricted flow (Figure 3). The vertical flow becomes more limited in the higher layers, while the horizontal movement of water and their retention are still high. Only in the zone of separated horizontal layers, the horizontal flow becomes moderately more extensive than in initial conditions. Finally, in the area of continuous deformations, groundwater flow and retention dominate, governed by natural hydrogeological conditions of the rock mass (Figure 3).

In mining with backfill, the fracture system is weakly developed, which means that the increase in groundwater flow dynamics and the disturbed rock mass strata's retention capacity are much smaller (Figure 4).

In both cases, further vertical run-off of groundwater depends on the rock material's insulating properties lying on the extracted coal seam floor. In the case of mining with backfill,

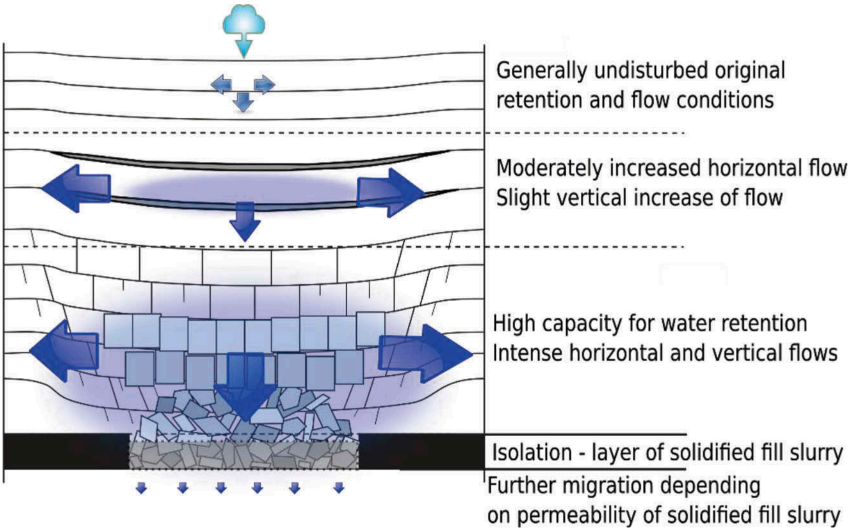

Figure 3. Schematic diagram of the changes in groundwater dynamics and retention in the rock mass caused by longwall mining with caving.

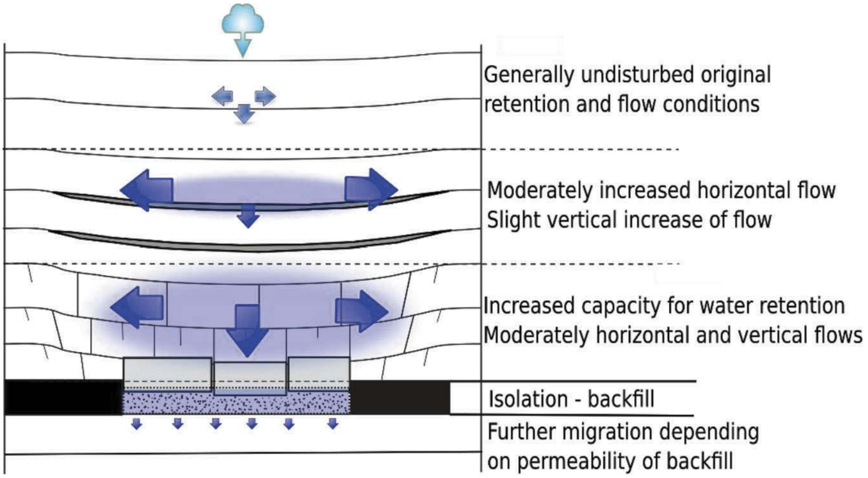

Figure 4. Schematic diagram of the changes in groundwater dynamics and retention in the rock mass caused by longwall mining with backfill.

the insulation level depends primarily on the water permeability of the backfill material. On average, the permeability of the hydraulic backfill made from sand is 2x10^{-4} m/s, which is a small value considering that the permeability of coal in an undisturbed seam equals about 5x10^{-6} m/s (Sztelak 1998; Trembecki 1972). Therefore, the main effect of restricting the free flow of groundwater in the rock mass through the backfill occurs by limiting the size of the fracture system in layers above the coal seam.

As already mentioned, the conditions of free groundwater movement and extensive retention possibilities can significantly increase the level of a water hazard in mining with caving. Filling cavings on the entire surface of the extracted coal seam with solidifying mixtures may substantially reduce this water hazard. (Figure 3).

3 USE OF FINE-GRAINED FILL MIXTURES IN LONGWALL MINING WITH CAVING

The primary purpose of filling cavings in mines is to improve ventilation and protect against spontaneous ignition of coal residues in the gob areas. As a material for filling voids, fly ash from the combustion of hard coal mixed with water is used, mainly due to these mixtures' ability to solidify and convenient rheological properties that allow their easy hydraulic transport in pipelines and placement into the cavings (Palarski et. al. 2014). Various aspects of the technology of filling of cavings have been discussed in numerous works devoted to this issue, so there is no need to discuss them in this paper.

From the point of view of this paper's subject, important is the ability of the fly ash – water mixture to efficiently penetrate the fractures and voids in the gob area. Large fractures make the filling process more effective, so the filling procedure is performed at a short distance behind the front of the longwall. The most successful filling of cavings may be achieved for (Palarski et. al. 2006):

- Seams with inclination 5° ÷ 10° and thickness 2,0 m ÷ 2,5 m,
- Roof strata with advantageous fragmentation and regular fracturing,
- Longwalls 200 m ÷ 220 m wide, advancing up the dip with filling from the pipeline with multiple outlets in the longwall face or
- Shorter longwalls in more inclined seams, advancing along with the dip with filling from a single pipeline outlet located in the headgate (Figure 5).

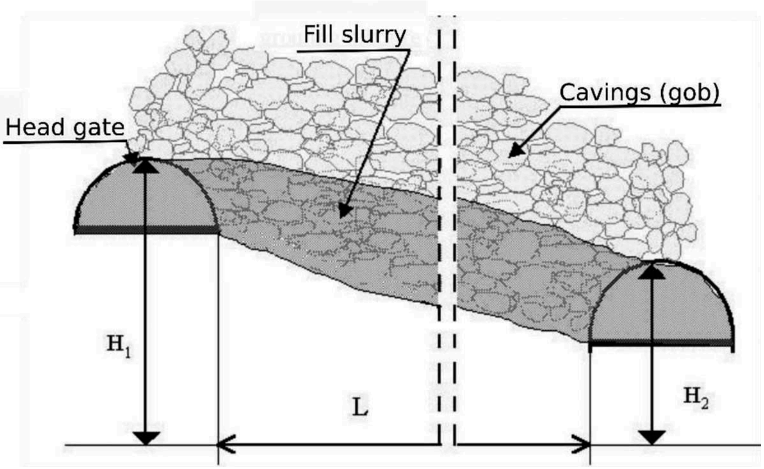

Figure 5. Flow of fill mixture through the longwall cavings.
Source: own elaboration after Palarski et.al. 2006.

4 FLOW CONDITIONS OF FLY ASH – WATER MIXTURES THROUGH CAVINGS

In most known bibliography, mixtures of water and fly ash are considered the same as real liquids. The flow in pipelines is relatively easy to describe using well-known equations for laminar and turbulent flow with reference to their rheological properties (most often, these mixtures meet the criteria of the Bingham plastic fluid). Much less attention is paid to the conditions of the mixture spreading freely in the caving zone.

The equation of mixture flow in the caving zone can be derived by combining the Darcy equation's three-dimensional form with the continuity equation. The flow takes place as the inclination of the seam floor (hydraulic gradient *I*) is larger than (Palarski et. al. 2006):

$$I = \frac{H_1 - H_2}{L} > \frac{3f\tau_0(1-n)}{\rho g n d} \tag{1}$$

Where:
H_1 – the height of the pipeline outlet in the headgate,
H_2 – the height of the fill at the wall of the tailgate,
L – length of the longwall,
f – factor of the Surface roughness in the gob area,
τ_0 – the yield stress of the filling mixture,
n – the porosity of the cavings,
g – acceleration of gravity,
d – average diameter of rock blocks,

The formula for a volumetric flow rate through the cavings downwards the slope of the gob area is:

$$Q = \frac{n^3}{1-n^3}\frac{d^2}{f^2 N}\frac{\rho g}{\eta}\left(1 + 4\delta^3 - 3\delta\right) Ins \frac{H_1 - H_2}{2} \tag{2}$$

Where:
η – dynamic viscosity of fill mixture,
N – coefficient ($N = 250 \div 300$),

s – the width of flowing stream of a mixture,
In equation (2), δ is equal to:

$$\delta = \frac{3\tau_0 f}{2\rho g I n d} \tag{3}$$

5 ASSESSMENT OF INSULATING PROPERTIES OF SOLIDIFIED FLY ASH – WATER MIXTURES

The basic condition that must be met by the material constituting the insulation barrier is the satisfactory value of tightness. The tightness is characterized by the filtration coefficient K. Under natural conditions, rocks achieve a filtration coefficient down to about $10^{-10} \div 10^{-12}$ m/s (Freeze and Cherry 1979). Such almost impervious behavior is represented by unweathered clays (among unconsolidated rocks) and unfractured metamorphic and igneous rocks and shales – perpendicular to the layering (among consolidated hard rocks). Natural materials for constructing impermeable barriers for waste depositories should exhibit a filtration coefficient no less than 1×10^{-9} m/s (Plewa et. al. 2006; Plewa et. al. 2009). Most of the rock formations in Carboniferous rock mass and its younger, Quaternary overburden represent significantly higher permeability and the ability for water retention (aquifers). Hydraulic conductivity of highly fractured rocks and gravels may range from over 1 m/s down to 10^{-3} m/s. Sandstones, mudstones, hard coal (unfractured), as well as fine sands and silts, may achieve conductivity in the range from 10^{-4} m/s to 10^{-7} m/s. Such rocks may be considered semi-permeable but not capable of containing reach aquifers (Rogoż 2004).

5.1 *Measurement method and equipment*

There are two laboratory methods for measuring hydraulic conductivity: the constant-head method and the falling-head method (Amoozegar and Wilson 1999). In the constant-head method, water moves through the specimen under a steady-state head condition, while the volume of water flowing through the soil specimen is measured over a period of time. By knowing the volume ΔV of water measured in a time while the volume of water flowing through the soil specimen is measured over a period of time over a specimen of length l and cross-sectional area A, as well as the head h, the hydraulic conductivity, K, can be derived simply rearranging Darcy's law (Amoozegar and Wilson 1999; Laksmahan 2011):

$$K = \frac{\Delta V}{\Delta t}\frac{l}{Ah} \tag{4}$$

In the falling-head method, the soil sample is first saturated under a specific head condition. The water is then allowed to flow through the soil without adding any water, so the pressure head declines as water passes through the sample. If the head drops from h_1 to h_2 in a time Δt, then the hydraulic conductivity is equal (Amoozegar and Wilson 1999); Laksmahan 2011):

$$K = \frac{l}{\Delta t} ln \frac{h_f}{h_i} \tag{5}$$

Both measurement methods are generally supposed to be used to measure soils as relatively highly permeably grained materials (Sandoval et. al. 2017). For rocks with low permeability, the most appropriate measurement method is the flow pump method. The water flow rate through the sample is kept constant; however, this method requires a special laboratory stand.

The falling-head method has been selected to measure solidified fill materials' conductivity obtained from fly ash – water mixtures. The method has been selected because of the simplicity of the measuring system and the ability to perform measurements in the range of very low conductivities (Plewa et al. 2006; Plewa et al. 2008; Wilson et al. 2000).

Measurements were carried out in a permeameter, the schematic diagram of which is shown in Figure 6. Permeameter has been adjusted to measure small conductivity values. It means small diameter and height of specimens, high water tube – and what is important during long time measurements – a control tube was placed to measure the effect of water evaporation on the downward rate of water in the cylinder.

Hydraulic conductivity is related to the permeability with relationship (Sztelak 1998):

$$T = Km\ [\mathrm{m}^2/\mathrm{s}] \tag{6}$$

Where:
T – Permeability index,
m – thickness of the water-bearing layer,

Water permeability index T describes the volume of water flowing in the unit of time through a water-bearing layer of thickness m and 1 m wide.

5.2 *Materials used in conductivity measurements*

Hard coal-powered power plants use different combustion vessel constructions, flue gas desulphurization technologies, etc. These produce different physical and chemical properties of fly ash, affecting their mixtures' properties with water.

For the conductivity measurement, three types of fly ash have been used: ordinary fly ash from vessels without desulphurization by-products (OFA), fly ash from a vessel with semi-dry flue gas desulphurization process (SDD) and fly ash from fluidized bed vessel (FLB). Figure 7 shows the grain-size distribution of these kinds of fly ash.

Tap water has been used to prepare mixture samples, and the temperature was kept constant at 20°C throughout the measurements. Three samples of each mixture have been prepared, and average values from three measurements have been considered as results.

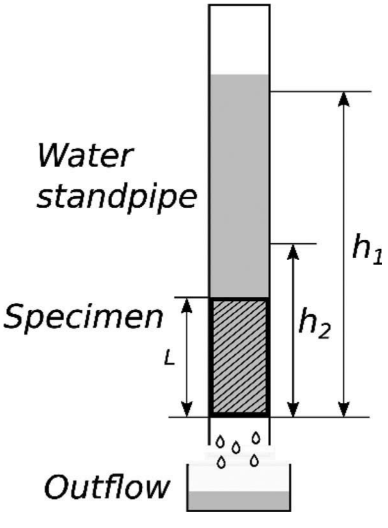

Figure 6. Falling-head permeameter used in measurements.

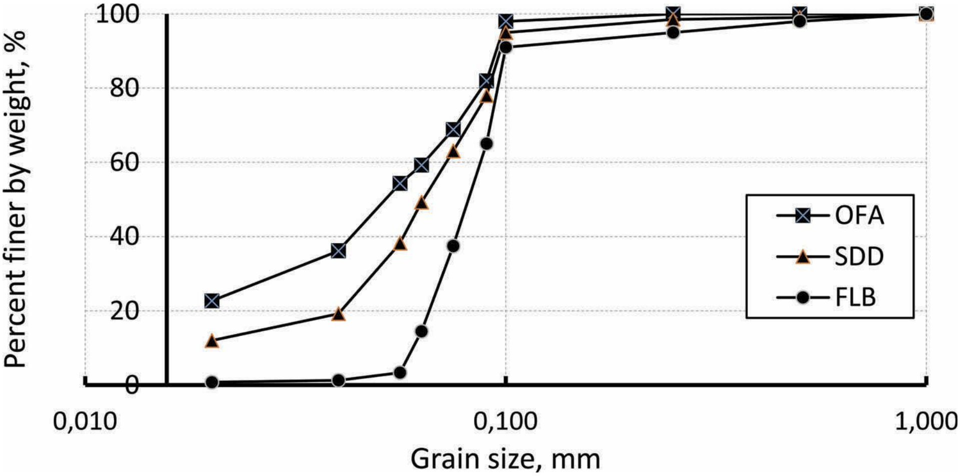

Figure 7. Grain-size distribution of fly ash samples used in measurements.
Source: own measurements.

The mixtures' composition has been selected so that mixtures from different types of fly ash exhibit similar rheological properties. The fly ash's general properties –water mixtures used in conductivity measurements have been shown in Table 1.

5.3 *Hydraulic conductivity measurement results and analysis*

The specimens of fly ash – water mixtures after preparation have been cured inside permeameter tubes constantly for a period of 98 days (14 weeks). The water levels in permeameter tubes have been measured daily for the first week of curing and then once a week. At the early stage of stabilization of the specimens, the hydraulic conductivity values decreased rapidly from about $(3 \div 7)x10^{-5}$ m/s down to $6x10^{-6}$ m/s for OFA fly ash, $1,2x10^{-6}$ m/s for SDD fly ash, and $8,5x10^{-8}$ m/s for FLB fly ash – Figure 8. In the next phase of sample curing, lasting up to about 11 weeks, a slight decrease in all samples' hydraulic conductivity was observed, followed by no further significant changes in hydraulic conductivity. Specimens of fly ash – water mixtures made from OFA, SDD, and FLB fly ash after 98 days cure time achieved final values of the hydraulic conductivity equal $8x10^{-7}$ m/s, $1x10^{-8}$ m/s, and $1,2x10^{-9}$ m/s respectively, Figure 8.

It can be concluded that the stabilized (solidified) fly ash – water mixtures about three months after placement in cavings achieve a relatively very high level of impermeability compared to typical rocks found in the Carboniferous layers. A similar range of hydraulic conductivity exhibits unfractured sandstones (Freeze and Sherry 1979). The highest value of

Table 1 . Physical properties of fly ash – water mixtures used in hydraulic conductivity tests.

	Type of fly ash		
Parameter	OFA	SDD	FLB
Density of fly ash [kg/m^3]	2060	2340	2620
Bulk density [kg/m^3]	1040	1120	1340
Solids/water ratio by mass S:W	2,78	1,88	0,95
Density of mixture [kg/m^3]	1555	1528	1380
Table spread [mm]	180	180	180

Source: own measurements.

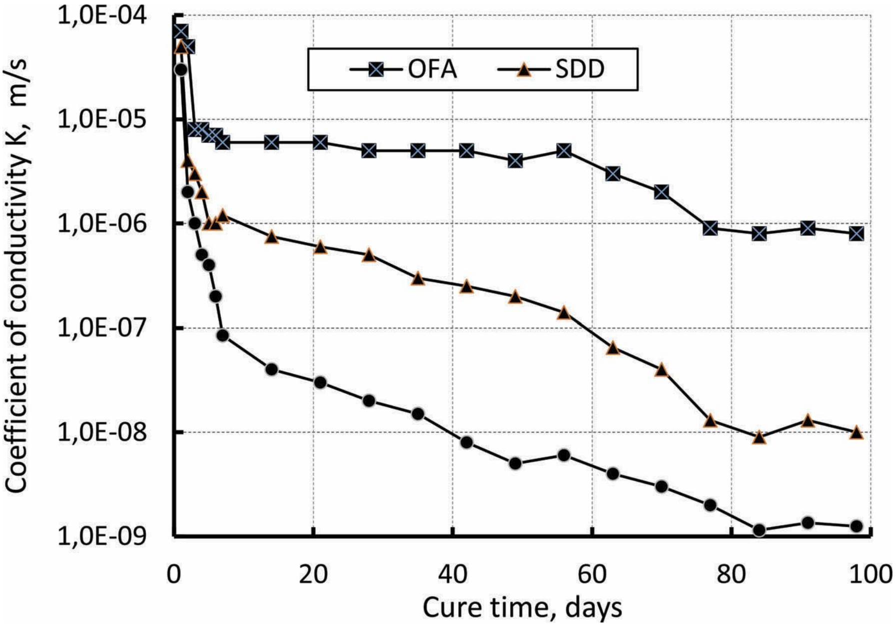

Figure 8. Hydraulic conductivity measurement results.

Source: own measurements.

hydraulic conductivity shows mixtures made from ordinary fly ash from combustion vessels without any desulphurization process (OFA); however, this type of combustion vessel becomes obsolete. The best result has been achieved for a mixture made from fly ash from a fluidized bed combustion vessel (FLB). This type of ash contains a significant amount of calcium oxide (CaO), which gives it strong binding properties, which are probably responsible for the low conductivity of its solidified mixture with water.

6 CONCLUSION

Filling cavings is a technology widely used in the mining industry, primarily aimed at improving ventilation conditions and protecting against the formation of endogenous fires in the remains of seams (gob areas) during longwall mining with caving.

Mining with caving is associated with significant damage to the roof rock structure, which in the conditions of presence of static or flowing groundwater in mines may cause an increase in the water hazard.

Laboratory tests of the permeability of ash – water mixtures used for filling cavings have shown that this procedure can promote the creation of an insulating protective layer limiting the flow of water to lower parts of the coal bed.

The hydraulic conductivity of tested fly ash – water mixtures ranges from 8 x 10^{-7} m/s to 1,2 x 10^{-9} m/s, which allows them to be classified as low- or impermeable materials.

The creation of impermeable screens can also protect adjacent active mines and regulate the direction of groundwater flow in decommissioned mines.

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