Research of Stowing Material for Filling of Free Underground Spaces of Old Mine Works

Martin KLEMPA[1], Jiří MALIŠ[2], Jindřich ŠANCER[3], Vladimír SLIVKA[4]

[1] VSB – Technical University of Ostrava, Faculty of Mining and Geology, Institute of Clean Technologies for Mining and Utilization of Raw Materials for Energy Use, 17. listopadu 15, 708 00 Ostrava Poruba, Czech Republic; email: martin.klempa@vsb.cz
[2] VSB – Technical University of Ostrava, Faculty of Mining and Geology, Institute of Clean Technologies for Mining and Utilization of Raw Materials for Energy Use, 17. listopadu 15, 708 00 Ostrava Poruba, Czech Republic; email: jiri.malis@vsb.cz
[3] VSB – Technical University of Ostrava, Faculty of Mining and Geology, Institute of Clean Technologies for Mining and Utilization of Raw Materials for Energy Use, 17. listopadu 15, 708 00 Ostrava Poruba, Czech Republic; email: jindrich.sancer@vsb.cz
[4] VSB – Technical University of Ostrava, Faculty of Mining and Geology, Institute of Clean Technologies for Mining and Utilization of Raw Materials for Energy Use, 17. listopadu 15, 708 00 Ostrava Poruba, Czech Republic; email: vladimir.slivka@vsb.cz

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Abstract

In the areas with long-lasting coal mining (many centuries ago) a number of old mining works have emerged as a communication channel for uncontrolled methane outputs. Disposal of these underground areas represents not only a technical but also an economically challenging task, which requires a combination of technical knowledge from the use of materials and the creation of free spaces with an emphasis on high environmental protection. Semi-fluid mixtures based on fly ash and cement binder and waste sand bits appear to be the ideal solution for filling these open spaces in terms of their behavior and production economics. These building filler compounds are able to prevent the transport of mining gases at individual discontinuous sites of the mining environment. Their final strengths will ensure the stability of the sanitized site and at the same time will prevent the further creation of communication spaces of the surrounding rock environment.

Keywords: filling material, stowing material, free underground space

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Introduction

Old mining works have an impact on the various components of the environment and represent, in the long run, a significant problem associated with a number of changes not only in the rock environment. Primarily in the coalfields, these works are potentially risky in view of possible uncontrolled leakage of methane. If these old mining works are located in built-up areas, the risk associated with the possible accumulation of methane in caverns, cellar spaces and utility networks and its transport, e.g. through old boreholes, engineering networks and other communication channels, is relatively high.

Given that the completion of the mined areas with the base mixtures is a lasting solution and the rectification of the inappropriate foundation is almost unrealistic or a complicated and costly problem, the quality and ecological acceptability of these mixtures should be given extraordinary attention. The requirements for the quality of the flooded base mixtures result in particular from:

- geological, geomechanical, hydrogeological and geochemical assessment of the site of the mine or mining works, openings, preparation and mining in the affected part of the deposit;
- the state of mines, including abandoned and possibly old works in the area concerned;
- the possibility of the transport location of a hydraulic mixtures, location of a facility for receiving and temporary storage of large-scale waste, location of a mixtures production technology.

The main characteristics of the research of building and filling mixtures are in particular the determination of the criteria for selection of suitable mining by-products of the mines and energy used for these mixtures, the development of methodology for complex testing of selected by-products and their testing. An integral part of the research is also the design of mixtures of mixtures suitable for disposal of free underground spaces or boreholes, sampling of used mixtures, testing of used mixtures in laboratory and in-situ and evaluation of long-term behavior of mixtures after their application in old mining works.

Principles for the selection of suitable materials for the production of filler mixtures

The main constraints concern the physical and chemical properties of both feedstocks (mining and / or mining by-products) and the final product (filling mixtures). These criteria are also added to the legislative criteria. The basic criteria for the selection and evaluation of suitable mining and energy by-products in the final product can be defined as follows (Daněk et al., 2012; Wang et al., 2017):

Tab. 1. Recipes of prepared mixtures
Tab. 1. Skład badanych mieszanin

Mixtures	Binder/brightener	Binder ratio (%)	Brightener ratio (%)	Cement (%)	Water factor
A	LP1/PIS -ARC	50	30	20	0,8
B	UP2/PIS - ARC	50	30	20	0,8
C	LP3/PIS - ARC	50	30	20	0,8
D	UP4/PIS - ARC	50	30	20	0,8

Tab. 2. Average values of simple pressure strength (laboratory tests)
Tab. 2. Średnie wartości wytrzymałości na ściskanie mieszanin (testy laboratoryjne)

Mixtures	Pressure strength after 28 days (MPa)	Pressure strength after 60 days (MPa)	Pressure strength after 90 days (MPa)
A	8,3	8,8	8,8
B	6,1	6,6	6,9
C	6,3	7,6	7,5
D	0,8	1,09	1,2

Tab. 3. Average values of simple pressure strength and gas permeability (in-situ tests)
Tab. 3. Średnie wartości wytrzymałości na ściskanie i przepuszczalności gazu (badania in-situ)

Mixtures	Pressure strength after 28 days (MPa)	Permeability after 28 days (mD)	Pressure strength after 60 days (MPa)	Permeability after 60 days (mD)	Pressure strength after 90 days (MPa)	Permeability after 90 days (mD)
A	9,1	463,5	9,6	449,3	9,6	432,4
B	7,3	549,4	8,6	513,7	8,8	514,3
C	6,8	651,9	8,1	601,1	8,2	606,3
D	1,1	751,8	1,4	734,2	1,3	729,9

Tab. 4. Average values of thermal conductivity
Tab. 4. Średnie wartości przewodności cieplnej

Mixtures	Thermal conductivity (W/m·K)
A	0,110
B	0,115
C	0,613
D	0,974

- the suitability of by-products;
- the criterion of compliance with the product's limit properties;
- the environmental acceptability criterion of the product.

The basic requirements for these structural filling compositions are in particular mechanical resistance and stability, fire safety, health and environmental protection and safety. Underground space disposal must be designed in such a way that the loads that will cause it do not result in the destruction of the underground spaces, the greater degree of surface deformation due to the significant drops, the sudden and significant drops of the area, the drop of the surface due to the loss of stability of the surrounding rocks of the abandoned underground works. (Slivka et al., 2007; Xu et al., 2018) Liquidation should be designed and implemented in such a way as to avoid the occurrence of a mine fire, to prevent the spread of fire on adjacent parts of the deposit and mines. Disposal must also be done in a way that does not endanger human health, primarily due to the release of toxic gases, uncontrolled leakage of mine gases from the underground to the surface, contamination of mine waters and uncontrolled outbursts of highly mineralized mine waters. (Slivka et al., 2007; Ahmaruzzaman, Gupta, 2012)

Description and characteristics of input materials

Hydraulic base mixtures applied in both active and submerged mines are basically based on the use of two, three basic types of waste: flotation tailings from coal and fly ash and slag from power plants and heat plants. The foundry sand is used as a filler in flooded foundations. If required to achieve higher final strengths in the simple pressure of the solidified mixtures, Portland cement is added as a binder. The presented research deals with mixtures for the hydraulic ash-cement base. These mixtures exhibit the ability of, in particular, physical stabilization (i.e., solidification) induced by the feather properties of dry ash. From this perspective, the hydraulic mixture is a specific type of concrete mixture, wherein:

- ash represents the classical material in the mixture;
- mineral phases of dry ash exhibiting pulcanic properties are a hydraulic binder in the mixture (also cement);
- water is then a factor that allows the desired concentration and associated physical or mechanical properties of the mixture to be achieved. The amount of water relative to the remaining components of the mixture (classifiable material + hydraulic binder) is most often expressed using the so-called water coefficient (water / dry mix).

Foundry sands

Foundry sands are mostly composed of quartz sands containing clay binder. They are used as a material in molding mold casting molds. The grain size ranges from 0.1 to 0.5 mm. Part of the used sand is returned to the production process (10 to 15%). The surplus quantity is also unusable for production and is exported to the rolling stock. This sand is polluted by water glass, clay, graphite, ferro-chromium slag, talc and organic curing agents in varying amounts.

The analysis of aqueous extracts shows that the risk parameters of leachability are represented in particular by pH, chlorides and phenols, of metals in some cases Sb and Mo.

Fly ash

Ashes represent a small fraction of solid residues after combustion of solid fuels, which is carried by gaseous flue gas from the boiler or furnace hearth. Of the total volume of waste from the burning of fossil fuels, it is about 75–85%. Always contain remnants of the original or different grade of the converted fuel outside the mineral remains. Ash is a heterogeneous material composed of particles of different physical, mineralogical, morphological and chemical properties. Ashes are usually produced in a finely ground condition when firing solid fuels. The properties of ash affect mainly the chemical composition of coal, the combustion structure and the control of the combustion process.

Ashes are composed of particles of different size and shape. The size of the fly ash is about 0.001 to 0.2 mm. Particles of ashes from conventional pulverized coal combustion are most commonly spherical in shape (microspheres) and are either hollow, foamed or solid. Ash ash from fluid combustion has to preserve the original morphology of the coal grain. Ashes are mainly formed by the amorphous phase and the crystalline component is represented by approximately 10–15%. Mineralogically, mullite, quartz or cristobalite, pericyla, calcite are represented in the crystalline component, and various Fe minerals (magnetite, hematite, maghemit, or metallic Fe) are quite common. Fluid ash has a significantly higher proportion of calcium, and thus there are many minerals present in the presence of Ca in the structure. These are mainly gypsum, portlandite, anhydrite, calcite, ettringite and others. At the surface of the ash grains, the carbon coating is often formed, or a portion of the unburnt carbon is contained in the ash in the form of a coke. There is also an oxygenated ash present. The color of ash is from light gray to black. (Slivka et al., 2007)

The chemical composition of fly ash is very diverse due to different conditions in different parts of the combustion process. To a large extent, however, it reflects the chemical composition of the original coal.

It is reported that most trace elements can be bound to both the coal and the inorganic phase (ash). It is true, however, that such elements as Ge, Be, B and Ga are bound mainly to the organic constituents of coal, whereas Hg, Zr, Zn, Cd, As, Mo and Mn are preferably bound to the inorganic phase.

The analyzes of the water extracts of power plants and heat treatment ashes show that limiting parameters of leachability are in general: pH, metallic elements mainly As, Cr, Cd, for some ash, Tl, Hg, Ni, and practically all fly ash they are fluorides (F-).

Laboratory and in-situ testing of filling mixtures samples

For the purpose of the present research, 4 types of base mixtures with A, B, C, D were tested. Two bedding fly ash samples (LP1, LP3) and two flight fly ash samples (UP2, UP4) were tested. The aim of the tests was to obtain and test mixtures in real conditions of the in-situ environment and to compare the results obtained with laboratory results - the main comparative parameter is the simple pressure strength. The other parameters monitored were gas permeability and thermal conductivity. Laboratory samples and in-situ samples were always tested at 28, 60 and 90 days.

Preparation of the mixture and production of test specimens was carried out as follows. Samples of the mixtures were mixed at 20°C and 50% relative humidity in the ratios given in Table 1.

For laboratory testing, the blends were filled into plastic molds suitable as 100 x 100 x 100 mm cubeshaped test specimens. Each test mixture had three cubes for the determination of shear strength for a given time interval. After filling into molds, the surface was aligned and the mixture was compacted. After compaction, the test cube was sealed in plastic wrapping to maintain a high relative humidity environment and did not dry out during maturation. Three boreholes (for 28, 60 and 90 testing days) to a final depth of 4 m were drilled for in-situ testing of the mixtures. The boreholes were equipped with PE pipes, which were always perforated and wrapped in geotextile in the last meter. The reason was the induction of real conditions prevailing in the rock environment (especially humidity, etc.). Then, all boreholes were filled with the test mixtures to a height of about 1.3 m. The head of the boreholes was always closed during the tests. At each time interval, one of the boreholes of the given type of mixture was excavated and a sample of the test compound was carefully withdrawn from it. Subsequently, three rolls samples of 37.5 mm in diameter and a length of 40–50 mm for the determination of shear strength and one similar roller for permeability determination were prepared.

Strength characteristics were evaluated after maturing days on the MTS 816 Rock Test System. Samples were loaded with a constant force of 5000 N/s. Determination of shear strength under standard pressure was followed by ČSN EN 12390 (731302) Testing of hardened concrete. Permeability was determined on the Instrument Permeameter of the French company Vinci Technologies. The KD2 Pro Mobile Appliance was used to determine the thermal conductivity.

Results of laboratory and in-situ testing of filling mixtures samples

For the laboratory testing, the resulting simple pressure strength parameters were determined at given time intervals – Table 2. The results of the in-situ testing (simple pressure strength and gas permeability) are given in Table 3. Determinations of the average thermal conductivity on laboratory samples are given in Table 4.

Conclusions

Environmental protection is an integral part of the development of the standard of living of the population. Industrial agglomerations generally belong to those areas that are affected by landscape devastation due to disproportionate black coal production, steel production and energy, and the resulting large quantities of waste materials. The handling of these wastes in the form of landfilling on landfills is becoming more and more complicated as the storage space is rapidly dwindling. The abovementioned waste is the amount that can be successfully used in mining or building construction.

The aim of this presented research was the creation of filling mixtures that would meet the requirements for the load-bearing capacity of mine works and also the requirements for the stabilization of the pollutants contained in the wastes to the extent that the resulting mass would meet the mining sanitation requirements. These mixtures were subsequently laboratory and in-situ tested. The results of the studied mixtures are based on a number of facts.

Based on the laboratory tests and the in-situ long-term behavioral tests of the given grouting mixtures, several conclusions can be drawn. The results of the measurements made clear that compound A (bedding fly ash) has the best strength properties (laboratory and in-situ). The strength values are very good and the other accompanying characteristics (relatively low permeability, low specific thermal conductivity) confirm the suitability of the mixture for the purpose of filling the free underground spaces generated by the mining activity. The input materials used for compound A are suitable for leachability, i.e. it can be assumed that they will not adversely affect the environment when used in remediation and replenishment mixtures.

Due to the characteristics of the binder properties of the ash tested, it is preferable to use flue gas mixtures in ash mixtures. The strength of the mixtures in which the ash from the grate boilers was used was not sufficient, the reason being the type of combustion technology. In general, however, it can be said that the collection of fly ashes for research is becoming more difficult, the materials do not appear to be stable and negotiations with suppliers are difficult. This may be one of the reasons why some fly ash does not have sufficient binding characteristics. Fly ash from the fluidized bed process exhibits better binder characteristics, and as a result, mixtures with these ashes are more solid. However, the clear conclusion that the fly ash is more suitable is not easy to pronounce. In terms of the strength and economy achieved, i.e. the cost of production of mixtures, it seems more appropriate to prepare mixtures based on fly ash from fluidized bed combustion. On the other hand, it is possible to increase the inadequate binder properties of the fly ash by adding more cement in combination with the coarser sharpening. The economic parameters in this case may not be too different.

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Literatura – References

1. Ahmaruzzaman, M.; Gupta, V., K.: Application of coal fly ash in air quality management. Industrial and Engineering Research, volume 51, issue 47, 2012. ISSN 08885885
2. Daněk, T.; Thomas, J.; Mališ, J.; Jelínek, J.: Strength properties of sludge solidified with fly coal ash and portland cement. Advanced Materials Research 378-379, 2012.
3. Slivka, V.; Dvořáček, J.; Cigánek, J.; Hudeček, V.; Žůrek, P.; Adamec, Z.; Podzemský, K.; Daněk, T.; Kukutsch, R.; Martinec, V.; Novotný, K.; Rakouš, I.: Likvidace hlubinného dolu zakládáním po ukončení báňské činnosti pro snížení bezpečnostních a ekologických rizik. Monografie, Vysoká škola báňská – Technická univerzita Ostrava, projekt VaV ČBÚ č. 42-05, 2007. ISBN 978-80-248-1680-7
4. Wang, P.; Wang, J.; Qin, Q.; Wang, H.: Life cycle assessment of magnetized fly-ash compound fertilizer production: A case study in China. Renewable and Sustainable Energy Reviews, volume 73, 2017. ISSN 13640321
5. Xu, G.; Shi, X.: Characteristics and applications of fly ash as a sustainable construction material: A state-of-the-art review. Resources, Conservation and Recycling, volume 136, 2018. ISSN 09213449

Badanie materiału do wypełniania pustek poeksploatacyjnych w zamkniętych kopalniach

Na obszarach o długotrwałym wydobyciu węgla (wiele wieków temu) powstało wiele starych prac górniczych jako kanał komunikacyjny dla niekontrolowanych produktów metanu. Utylizacja tych obszarów podziemnych jest nie tylko zadaniem technicznym, ale także trudnym ekonomicznie, wymagającym połączenia wiedzy technicznej z wykorzystania materiałów i tworzenia wolnych przestrzeni z naciskiem na wysoką ochronę środowiska. Mieszaniny półpłynne na bazie popiołu lotnego i spoiwa cementowego oraz odpadających piasków wydają się idealnym rozwiązaniem do wypełnienia tych otwartych przestrzeni pod względem ich zachowania i ekonomiki produkcji. Te wypełniacze budowlane są w stanie zapobiegać transportowi gazów wydobywczych w poszczególnych nieciągłych miejscach środowiska górniczego. Ich ostateczne moce zapewnią stabilność oczyszczonego miejsca, a jednocześnie zapobiegną dalszemu tworzeniu przestrzeni komunikacyjnych otaczającego środowiska skalnego.

Słowa kluczowe: podsadzka, składowanie, pustki poeksploatacyjne