

MARCIN KRZYSZTOF POPCZYK*[#], RAFAŁ JENDRUŚ***IMPACT OF ASH AND WATER MIXTURE DENSITY ON THE PROCESS OF GOB GROUTING
IN VIEW OF LABORATORY TESTS****WPLYW GĘSTOŚCI MIESZANIN POPIOŁOWO-WODNYCH NA PROCES DOSZCZELNIANIA
ZROBÓW ZAWAŁOWYCH W ŚWIETLE BADAŃ LABORATORYJNYCH**

Increasing environmental pressure against waste disposal, particularly fine waste surface storage and concern about mining damages have resulted in an increase in the popularity of a fly ash, tailing and binding agent mixture used as compaction grout of roof fall rocks in a gob area of longwalls. Backfilling of voids forming as a result of exploitation with the fall of roof with mixtures containing fine-grained industrial wastes is a common practice in coal mines. It is aimed at achieving numerous technological and ecological advantages as well as at controlling mining hazards. Research on hydraulic transport of fine-grained slurry conducted to date focused mainly on issues related to the analysis of the conditions related to pipeline transportation. The processes concerning the propagation of mixtures within the gob, on the other hand, remain largely unknown. The process of flow of fine-grained slurry through the caving is subject to a series of factors related, among other things, with the properties of the applied wastes and mixtures, the characteristics of the gob as well as the variability of these properties during the flow through the gob and in time. Due to the lack of sufficient knowledge pertaining to the changes taking place in the gob and in the slurry while it penetrates the gobs, no methods allowing for the design and optimization of the gob grouting process have been established so far. The paper presents the selected results of laboratory tests regarding the flow of ash and water mixtures in a model of a gob, pertaining to two selected types of fly ash produced in hard coal combustion, particularly concerning the impact of the type of the ash and the density of the slurry on the effectiveness of the gob grouting process.

Keywords: backfill, fly ash – water mixtures, gob grouting

Wypełnianie pustek powstających w wyniku prowadzenia eksploatacji z zawałem stropu za pomocą hydromieszanin z udziałem drobnofrakcyjnych odpadów przemysłowych jest praktyką powszechnie stosowaną przez polskie kopalnie węgla kamiennego w celu uzyskania szeregu korzyści technologicznych i ekologicznych a w szczególności pozwala zminimalizować zagrożenie pożarowe powstające w zrobach poeksploatacyjnych. Dotychczasowe badania w zakresie hydrotransportu mieszanin drobnofrakcyjnych skupiały się głównie na zagadnieniach związanych z analizą warunków ich transportu rurociągowego. Słabiej rozpoznane są natomiast procesy towarzyszące rozplywowi hydromieszanin drobnofrakcyjnych

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w gruzowisku zawałowym. O przebiegu procesu przepływu hydromieszanin drobnofrakcyjnych przez gruzowisko zawałowe decyduje szereg czynników związanych między innymi: z własnościami stosowanych odpadów i mieszanin, charakterystyką gruzowiska zawałowego, a także zmiennością tych własności w czasie oraz na drodze przepływu przez zroby. Z uwagi na brak dostatecznej znajomości zmian zachodzących w gruzowisku i w samej mieszaninie w czasie jej penetracji przez zroby, dotychczas nie powstały metody umożliwiające kompleksowe projektowanie i optymalizację procesu doszczelniania zrobów. W artykule przedstawiono wybrane wyniki badań laboratoryjnych przepływu mieszanin popioło-wodnych w modelu gruzowiska zawałowego. Badania wykonano dla hydromieszanin na bazie dwóch wybranych rodzajów popiołów lotnych a analizie poddano wpływ rodzaju popiołu i gęstości mieszaniny na efektywność procesu doszczelniania zrobów.

Słowa kluczowe: doszczelnianie zrobów, mieszaniny popiołowo – wodne

1. Introduction

Backfilling of voids in the rock mass forming as a result of exploitation conducted with the fall of roof using properly selected mixtures of water and power-production wastes – fine-grained materials, namely fly ash – is a technology that is commonly applied in mining in many countries. The method is practiced in many variations and to achieve various results. In Polish hard coal mining, most of the coal mines conduct works consisting in gob grouting using mixtures of fly ash produced in combustion of hard coal and water. Flotation wastes produced in coal processing or other wastes and binding materials are less common. These mixtures are characterised by a relatively low density, which – on one hand – ensures the free propagation within the goaf, but decreases the effectiveness of the process (the effectiveness should be understood in the context of the amount of solids placed in the cavities in relation to the total amount of the introduced slurry) and promotes the increase of the water hazard in the mine, on the other. Sealing of goafs conducted in such a manner is mostly aimed at limiting the risk of spontaneous combustion of the remaining carbon and the migration of gases through the goafs and is currently conducted in most Polish hard coal mines (Ciania & Czaja, 1978; Czaja, 1986; Plewa & Mysłek, 2001).

The mixtures prepared with a dominant content of fly ash are increasingly often used for filling shallow goafs, to eliminate the occurrence of mining damage at the surface (Dodd, 2000) and to limit the emissions of acidic mine water to the watercourses on the surface (Rudisell et al., 2001). Technologies of pumping fine-grained slurry into the Weber cavities (voids occurring for a short period in the overburden of the exploited seam in the early phase of formation of a subsiding trough in the rock mass) or directly into the newly formed goafs to limit the deformations of the rock-mass and the subsidence of the area subject to exploitation are being introduced.

The difficulty in describing the flow of fine-grained slurry through the cavings results from the complexity of the mechanisms involved and the changing factors which have an impact on the process. The variability and the irregular shapes of the cavities constituting channels for the flow of the mixture within the gob (their dimensions vary from a few millimetres to dozens of centimetres (Plewa et al., 2006), results in the high variability of the local flow rates and the flow regimes (laminar/turbulent). Thus, the sedimentation conditions for the solids and the conditions for the formation of a solid sediment are highly different in different locations within the goaf.

Moreover, the dimensions of the cavities which allow for the flow of the slurry in the gob grouting process change in time and thus, also the flow conditions and the paths of the slurry flow from the outlet to deeper goaf parts tend to vary. This is caused by the process of formation of the gob and the pressure of the rock mass.

The latter aspect was considered in detail in the paper (Szlązak & Szlązak, 2005), in view of the permeability of the goafs with ventilation in mind. Based on measurements conducted in longwalls with fall of roof, the researchers have found that the permeability of goafs, which is the highest near the top part of the longwall, decreases with the increase of the distance from it, reaching a minimum at 2/3 of the length and increases again towards to bottom part of the longwall.

Designing pipeline transportation systems for fine-grained slurry, both gravitational and with pumps, allows for a precise determination of flow parameters for selected conditions – mostly pertaining to the physical properties of the slurry and the geometric arrangement of the path of transportation (pipeline configuration).

In the process of gob grouting, however, the stage starting at the point at which the slurry flows out of the pipeline and begins to migrate freely through the cavings, which is accompanied by the gradual backfilling of voids – is equally important.

The cavities in the gob are gradually backfilled by the solids subject to sedimentations, while rendering further flow of the slurry impossible. At the same point, the concentration of the solid parts drops and changes in the rheological properties of the slurry occur. The movement of the slurry within the goaf, accompanied by the precipitation of solids, may be classified as a flow with mass exchange. With respect to highly fragmented cavings, one may speak of mechanical clogging (Trzaska, 2000). In the remaining cases, however, the dimensions of the fallen roof rocks and the dimensions of the voids between them exclude the use of such analogy. The analysis of the sedimentation process, even considered outside the problem of the movement of the slurry stream, also requires experiments on the analysed configuration, as the existing calculation methods are unreliable (Koch & Noworyta, 1995).

The effectiveness of backfilling of cavities and the propagation of the slurry is assessed every time based on trials performed with pilot or industrial systems. Based on the results of observations of the process, modifications of the system operation parameters are introduced. The modifications are often intuitive or arbitrary and do not reflect the actual process, the results of which are often difficult to assess directly to the lack of access to the area of the gob.

At such a large number of factors that are difficult to assess and which affect the parameters of the slurry propagation in the goafs, an attempt was made to determine the changes of characteristic properties of fine-grained mixtures due to the flow through the gob area by laboratory tests using a model of a gob. The properties included: the density of the mixture, the spill radius and the rheological parameters. The test was aimed at the determination of how the properties of the slurry and the goaf parameters would impact the flow of the slurry through the goafs and the determination of the efficiency of backfilling.

The purpose of the tests of the flow of ash and water slurry through the model of the gob, conducted by the authors, was to identify and describe the mechanisms accompanying the flow of fine-grained mixtures through a gob area in order to allow for the improvement of methods of designing and optimising the selection of operational parameters of gob grouting systems.

According to the PN-G / 11011: 1998 standard, the term “pourability” is defined, which defines the state of consistency. Depending on the type of dry water-soluble raw material component (solids) used, in constant proportions of dry matter to water, a different spill radiuses value is obtained. For comparison purposes, it is necessary to maintain a constant parameter defining the consistency in this case of constant spill radius.

2. Sampling and methods

The aim of the research was to determine the mechanism of the sedimentation process (solid deposition) and its influence on the change of the of fine-grained mixtures flow through the model gob of area.

While considering the method for the laboratory tests of the flow of fine-grained mixtures through the cavings, it was assumed that such a flow may be treated similarly to a filtration flow through a porous medium. For the purposes of the study it was assumed that in case of a medium such as a goaf, porosity may be defined as a ratio of the volumes of voids between the rocks of the goaf and the total volume of a selected area of the goaf.

A schematic drawing of the test stand for the measurement of the flow parameters of fine-grained mixtures through cavings has been presented in Figs 1 and 2.

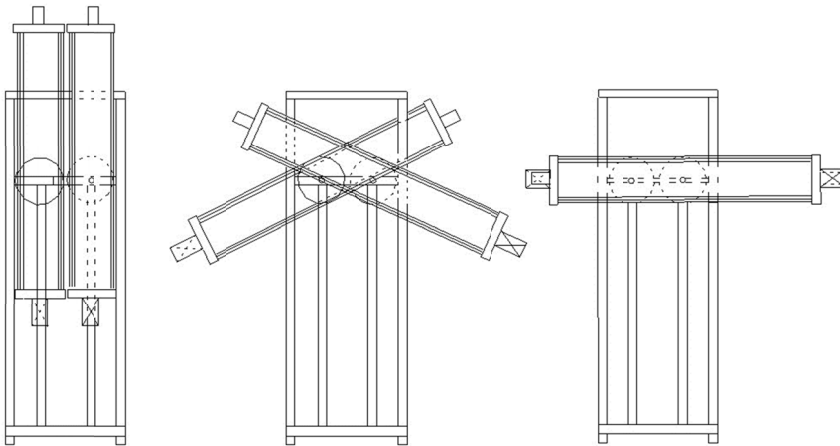


Fig. 1. A schematic drawing of the test stand for the measurement of flow parameters of fine-grained mixtures through cavings

The main element of the stand was constituted by a 1500 mm long pipe with an internal diameter of 172 mm, filled with roof rocks with a grain size from 50 to 120 mm, in such a manner so as to achieve the porosity of $n = 50\%$. The placement on a rotary base allowed to achieve any inclination angle of the model. The measurements were made at an inclination of 5, 10, 15 and 30 degrees. It is mentioned that, the adoption of such a research procedure was caused by the fact that the seams in Polish geological conditions do not have a steady inclination and change in the range from 0 to over 45 degrees.

Both ends contained valves and connectors used for feeding the slurry into the gob model and to collect the discharged mixture. The flow always took place in accordance with the angle of inclination of the gob area model, i.e. a point with a higher level to a point with a lower height level compared to the imitated model of the floor of the gob area.

The slurry was fed to the model at a constant pressure of 200 mm of the slurry head for 1 minute. The concept of constant pressure refers to that adopted for the purposes of laboratory tests called. “hydrostatic pressure”, referring to a constant feed height of 20 cm.

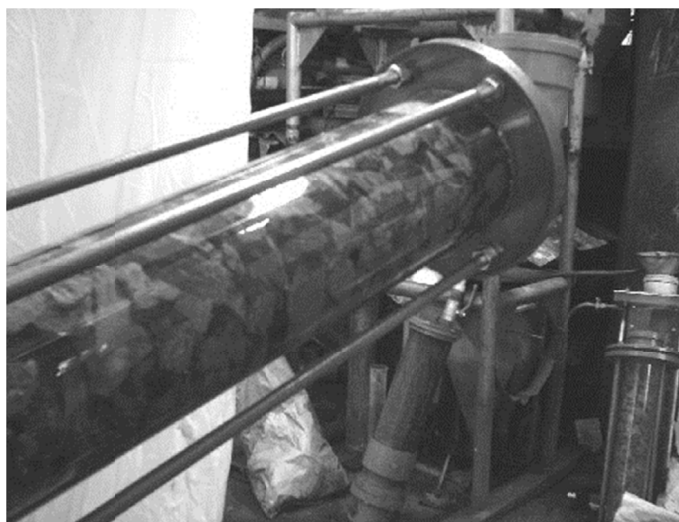


Fig. 2. A general view of the original test stand for the measurement of the flow parameters of fine-grained mixtures through the gob

In that time, the volume of the slurry received at the outlet of the model was measured, allowing for the determination of the volumetric flow rate of the slurry through the gob model. The following values were determined for each of the mixtures: density, spill radius (Ford viscosity cup method), the amount of supernatant water and the rheological parameters (using the FANN 35 SA viscometer). The density and the rheological parameters were measured before and after the flow through the cavings in order to determine the possible changes in the properties of the slurry due to the flow through the cavings.

Moreover, measurements of the density and amount of the supernatant water of the sediment samples acquired from inside the model, after the flow, were conducted. All tests were conducted according to the guidelines of the PN-G-110111:1998 standard.

For selected samples, a grain composition analysis was conducted with the Fritsch Analysette 22 laser particle sizer using the wet method.

For the purposes of the analyses, it was assumed that the water and ash mixtures in the range of solid particle concentrations in concern may be considered as pseudo-homogeneous liquids fulfilling the criteria of the Bingham model, that is, as being characterized by a dynamic viscosity coefficient (η_B) and yield point (τ_0).

3. Results and analysis

In the tests referred to in this study, fly ash produced in combustion of hard coal without the products of flue gas desulphurization (“B” symbol) as well as containing the products of semi-dry desulphurization method (“P” symbol) were used. The fly ash was produced by one selected power-plant. The water and ash mixtures with different proportions were prepared to achieve fixed spill radiuses for each of the types of fly ashes, amounting to 180, 210 and 250 mm. The

applied criterion of fixed spill radius allows to achieve mixtures comprised of different solid components while maintaining similar flow properties.

The basic properties of the water and ash mixtures used for the test of flow through a model of a gob have been presented in table 1.

During the flow of the water and ash slurry through the gob, the voids are filled by the immobilized sediments, which results in the decreasing content of solids in the mixture. Depending on a series of factors, the discharge rate of the slurry from the model changes and the density of the slurry decreases (along with the concentration). Also selected rheological parameters of the slurry change, which has been presented in the charts in Figs 3 and 4.

TABLE 1

Basic physical parameters of water and ash mixtures used in the test of flow through a model of a gob

Waste type	Density ρ_s [kg/m ³]	Spill radius R [mm]	Slurry density ρ_m [kg/m ³]	Volumetric concentration C_V [-]	Mass ratio P : W	flow threshold τ_0 [Pa]	Viscosity coefficient η_B [Pa×s]
B	2100	180	1490	0.445	1.68 : 1	4.1	0.0488
		210	1430	0.391	1.35 : 1	3.6	0.0288
		250	1380	0.333	1.08 : 1	2.0	0.0145
P	2160	180	1520	0.418	1.68 : 1	5.7	0.0600
		210	1460	0.396	1.42 : 1	4.2	0.0315
		250	1430	0.371	1.27 : 1	2.6	0.0266

As exhibited in the charts above (Fig. 3), the highest decreases in the density of the ash and water slurry occur for the mixtures with the spill radius of $R = 180$ mm, that is, the mixtures with the highest concentrations of solids. Increasing the spill radius of the mixtures up to 210 mm is related with the decrease in the concentration of solids and a decrease of one of the rheological parameters

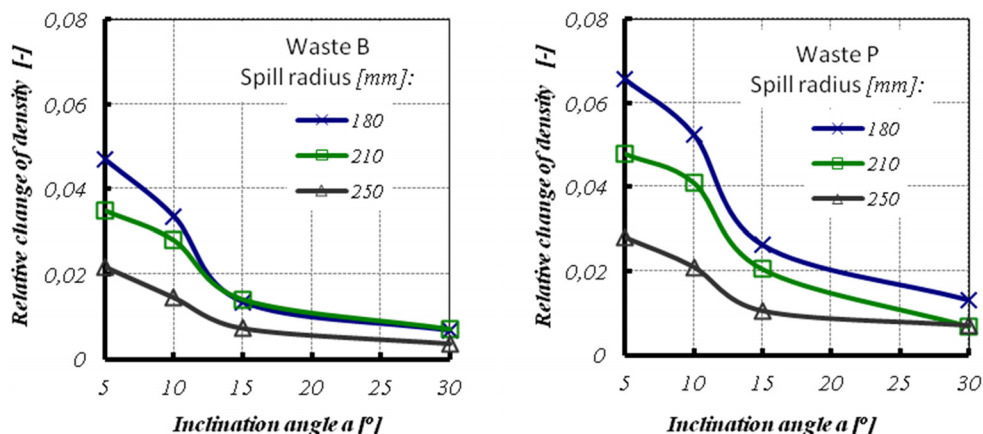


Fig. 3. Relative change of the density of the water and ash slurry caused by the flow of the slurry through the gob model, depending on the inclination angle of the model and the spill radius of the mixtures prepared from different types of fly ashes produced by a selected "X" power-plant. P – with FGD by-products, B – without FGD by-products

of the slurry – the flow threshold (Fig. 4), which leads to the increase in the flow rate through the gob model and the decrease in the density of the slurry caused by the flow through the gob.

Further limitation of the concentration of solids in the mixtures, expressed by the spill radius decreased to $R = 250$ mm, leads to a further decrease of the slurry density caused by the flow through the gob.

The difference in the properties of each of the fly ash types is becoming evident in the analysis of the decrease of concentration of solids proceeding between the inlet and the outlet from the gob model, Fig. 4. The higher the initial concentration of the slurry (lower spill rate) and the lower the flow rate through the model (lower inclination angle), the higher the drop in the concentration of the grouting slurry.

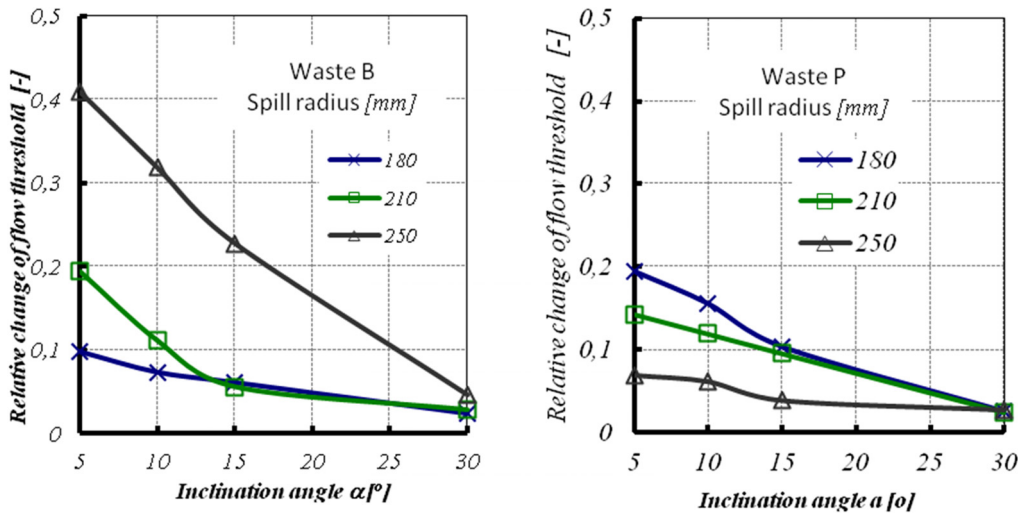


Fig. 4. Relative change of the flow threshold of the water and ash slurry caused by the flow of the slurry through the gob model, depending on the inclination angle of the model and the spill radius of the mixtures prepared from different types of fly ashes produced by a selected “X” power-plant. P – with FGD by-products, B – without FGD by-products

Based on the differences in the density of the mixtures introduced and discharged from the gob model, conclusions may be drawn related to the process of filling the voids. By measuring the density of the produced slurry (ρ_{m1}) as well as the slurry discharged from the model (ρ_{m2}) and knowing the density of the fly ash (ρ_s) and water (ρ_w), the volumetric concentration of the mixture may be determined

- before introducing the slurry to the gob (produced) C_{V1} :

$$C_{V1} = \frac{\rho_{m1} - \rho_w}{\rho_s - \rho_w} \quad (1)$$

- after flowing through the gob C_{V2} :

$$C_{V2} = \frac{\rho_{m2} - \rho_w}{\rho_s - \rho_w} \quad (2)$$

Knowing the value of the volumetric flow rate of the slurry through the gob Q_m , the volumetric flow rate of the solids in the mixture may be determined:

- in the stream introduced to the gob Q_{s1} :

$$Q_{s1} = C_{V1} Q_m \quad (3)$$

- in the stream discharged from the gob model Q_{s2} :

$$Q_{s2} = C_{V2} Q_m \quad (4)$$

The difference in the volumetric flow rate of solids between the streams of the mixtures introduced to and discharged from the model, represents the volume of the solids remaining in the gob (Q_{ps}) and participating in the process of filling the voids:

$$Q_{ps} = Q_{s1} - Q_{s2} = \frac{Q_m (\rho_{m1} - \rho_{m2})}{\rho_s - \rho_w} \quad (5)$$

The curve representing the dependence of the rate of the filling of the voids with solids from the model's inclination angle, the spill radius of the slurry and the ash type, has been presented in Fig. 5.

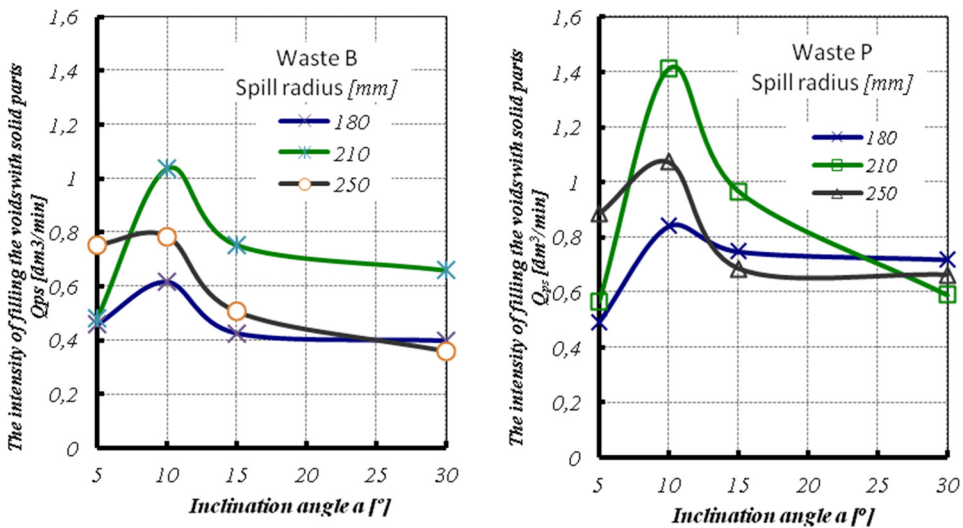


Fig. 5. Rate of filling the voids with solids caused by the flow of the slurry through the gob model, depending on the inclination angle of the model and the spill radius of the mixtures prepared from different types of fly ashes produced by a selected "X" power-plant. P – with FGD by products, B – without FGD by-products

In the conditions of the conducted laboratory tests regarding the flow of water and ash mixtures through a model of a gob, the maximal value of the void filling rate, amounting to 1.4 dm³/min, was achieved in case of the slurry exhibiting a spill rate of $R = 210$ mm, prepared with the "P" type fly-ash (Fig. 5b). Per six tested water and ash mixtures, in four cases the de-

pendence between the void filling rate with solids and the gob model inclination, the maximum values were achieved at an inclination angle of 10° .

The curves shown in Fig. 5 also exhibit that the optimal value in view of the void filling process efficiency is achieved in case of the slurry with the spill radius of $R = 210$ mm. It should also be mentioned that the mixtures exhibiting the remaining two spill radiuses, that is, $R = 180$ mm and $R = 250$ mm, ensure the highest void filling rates at an inclination not exceeding 10 - 15° . The above may suggest that gob grouting in in situ conditions would be optimal at such a range of inclinations of the workings. One should state that the mean inclination of headings in the conditions of Polish mines is usually within that range, which may suggest that the gob grouting process is a correct solution.

The volumetric fill rate of voids with solids, formulated above, should not, however, be mistaken with the efficiency of filling the voids. In the assumed method of determining the amount of solids immobilized within the gob, only the grain sizes of the solids is taken into consideration. In reality, grouting produces a sediment constituted by a loose structure of grains of solids and water filling the space between them.

As exhibited by the conducted analysis of the grain-size distribution of fly ash in the produced slurry and the slurry discharged from the gob model, the immobilized material mostly contains coarser grain fractions of the grouting slurry. The granulometric curves in Fig. 6, present an example of results of a grain-size distribution test for mixtures prepared using the “B” ash, before and after flowing through the gob model. Grains with diameters of $5\ \mu\text{m}$ - $50\ \mu\text{m}$ are dominant in the produced mixture, while after the flow through the gob model, the grains with diameters from 5 to $10\ \mu\text{m}$ are dominant.

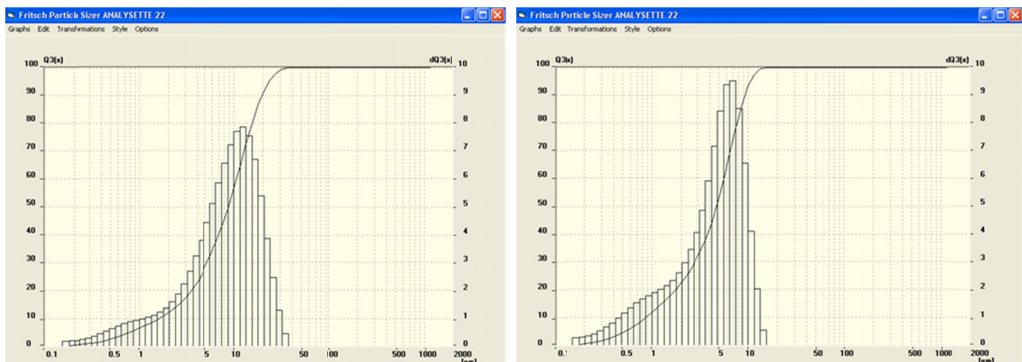


Fig. 6. Results of the grain size distribution test of the “B” fly ash (left – in the prepared slurry, right – after the flow through the model)

4. Summary and conclusions

A series of factors has an impact on the process of gob grouting using fine-grained mixtures. These factors include the physical properties of the slurry introduced to the gob (thickness, concentration of solids, rheological properties), the parameters of the gob such as porosity or the inclination of the gob floor as well as the variation of these properties during the process and

with the distance from the outlet of the pipeline. The conducted laboratory measurements of the flow of mixtures of selected fine-grained wastes through a gob model, indicate – among other things – that the basic physical parameters of these mixtures are subject to significant changes even at a small distance from the outlet of the pipeline feeding the slurry to the gob.

The high values of the relative decrease in the density of the mixture, with the 10-15° inclination of the gob, indicate the optimal ability of these mixtures to aggregate the carried solid fine-grained in voids. At higher slopes, under real conditions, this would mean that the mixture would flow freely without causing voids to fill around the outlet of the pipeline. The creation of a static sediment would occur only at a considerable distance from the outlet of the pipeline, where the speed of the mixture movement would be correspondingly lower.

The effectiveness of the grouting process is highly dependent on the density of the slurry, which should be optimized not only in terms of the transport capability of the pipeline feeding the slurry to the gob, but also in terms of the effectiveness of the process of filling the voids.

The complexity of the phenomena accompanying the process of immobilization of the transported material in the voids, the sedimentation and consolidation of the backfill, render the determination of the dependencies allowing for forecasting the grouting process based on the knowledge of basic parameters of the mixtures difficult.

The considerations presented above indicate the necessity to conduct further research regarding the issue. The research should encompass both laboratory and industrial scale studies and will require supporting the design and implementation works pertaining to gob grouting with adequate laboratory and model tests, giving consideration to the conditions in which the technology is being applied as well as to the fine-grained wastes that are available for use in the process.

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