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ASSESSEMENT OF CAVINGS FILL EFFICIENCY AS A FUNCTION OF RHEOLOGICAL PARAMETERS OF FINE-GRAINED SLURRY

Summary. Abandoned mining areas where extraction of minerals took place without backfilling (longwall with caving, room & pillar, etc.) represent, from one side, areas of intensified surface subsidence risk, and from the other side, a large volume of underground space, which can be filled up with waste or other redundant substances. Also a significant problem in numerous coal mines is utilization of saline waters from their drainage systems. The paper presents results of laboratory experiments on flow and distribution in cavings of slurries containing saline waters and selected types of coal combustion by-products. Authors wanted to expose the role of type of fly ash and concentration of solids on flow properties of grouts in transport pipelines and migration properties after discharge in cavings area. 16 compositions of slurries made with four types of fly ash have been taken under consideration in hydraulic transport analyze. Additionally a flow of selected slurries in a single rectangular cavity of given aperture has been analyzed using an equation of flow of Bingham fluids between two parallel plates.

OCENA SKUTECZNOŚCI WYPEŁNIENIA GRUZOWISKA ZAWAŁOWEGO W FUNKCJI PARAMETRÓW REOLOGICZNYCH MIESZANINY DROBNOFRAKCYJNEJ

Streszczenie. Obszary zrobów poeksploatacyjnych pozostawione bez wypełnienia podsadzką (np. systemy ścianowe zawałowe, filarowo-komorowe itp.) stanowią z jednej strony strefy zagrożone intensywnymi deformacjami powierzchni, a z drugiej obszary występowania pustek podziemnych o znacznej objętości, które mogą zostać wypełnione odpadami lub innymi zbędnymi substancjami. Do takich należą między innymi zasolone wody z odwadniania kopalń. W artykule przedstawiono wyniki badań laboratoryjnych parametrów przepływu w rurociągach i rozpływu w gruzowisku zawałowym mieszanin sporządzonych z wybranych ubocznych produktów spalania węgla kamiennego i słonych wód kopalnianych. Celem autorów było między innymi przedstawienie wpływu rodzaju zastosowanego popiołu lotnego i koncentracji części stałych na parametry przepływu mieszanin do doszczelniania zrobów w rurociągach i rozpływu w gruzowisku zawałowym. Przeanalizowano 16 rodzajów mieszanin sporządzonych z 4 rodzajów popiołów lotnych. W drugiej części pracy przedstawiono próbę analizy przepływu mieszanin drobnofrakcyjnych

przez pojedynczą szczelinę o prostokątnym przekroju w oparciu o równania ruchu cieczy Binghama między płytami równoległymi.

1. Introduction

All methods of underground mining operations require control of the roof, it means a way how to deal with unsupported overburden strata being exposed after extraction of coal from the seam. Generally, there are two dominating methods of roof control in underground coal mining:

- Leaving the roof open and letting the roof rocks to break and collapse, what generates movements in all overburden strata up to ground surface considered as mine subsidence – this activity refers to mining with caving,
- Replacement of extracted coal with other suitable material to avoid roof collapse by its support – this is a basic idea of backfilling.

Consequences of mining with caving are mainly damages to structures on the surface, impacts on mining structures in the overburden strata, and increased gas and water permeability of fractured rock strata.

From the other hand, application of backfill significantly increases costs of mining, complicates cycle of work, and reduces efficiency of production by increased work- and time consumption of mining operations. Moreover, backfilling often does not solve completely all problems related to mine subsidence, but only reduce them to certain level, and from the point of the view of costs of mining operations, makes it often unacceptable for mine operator.

On that background, a third option has been developed, which binds caving method of mining with filling of voids resulted from roof collapse and evolution of subsidence, with use of relatively low-cost and technically effective method of grouting. Grouting of fractured rock strata does not harm the efficiency of mining operations, however is able to significantly reduce or fully eliminate many negative effects of caving.

Grouting of cavities being left by roof collapse results in a 90 - 95% reduction of spontaneous coal combustion, improvement of ventilation, reduction of heat load and improves face conditions - particularly the stability of gates (Palarski, 2004). The best effects can be obtained with use of selected types of coal combustion by-products as main component of properly composed fill slurries. Tight filling together with good mechanical properties of cured grout can result in significant reduction of mine subsidence (up to 50%), elimination of contaminants leaching (like heavy metals or barium), and re-consolidation of fractured zone. The paper is devoted to hydraulic transportation in pipelines and fractures of slurries applied by filling of cavities.

2. Laboratory procedures for fill slurries evaluation

Four types of coal combustion by-products (CCP) have been chosen for examination: fly ash from ordinary combustion vessels (without flue-gas desulphurisation by-products) from power plants "S" and "J" – marked as **OS** and **OJ**, and fly ash from fluidization bed vessels from the same plants – marked as **FS** and **FJ**. In first stage of research, these by-products have been mixed with water in wide range of solids to water ratio, with respect to their table spread test result (D_s). The latter is modified viscosity cup test, adopted for purpose of easy composition of mixtures that possess similar flow properties. Result of the test is diameter of a circle created by a volume of 120 cm^3 of liquid spread on a flat smooth surface from a height of 30 cm, using a truncated cone with 4 cm diameter bottom outlet.

Fig.1. presents relation between solids to water ratio and spread D_s for slurries made with four types of CCPs. The S/W ratio on the graph is expressed as mass of solids in proportion to elementary mass of water. Salt mine of water of density ρ_w = 1020 kg/m^3 has been used, while coal mines utilise salt waters from their drainage systems for purposes of grouting or backfilling in that way.

Four values of spreads D_s have been selected for further analysis of slurries: 160, 200, 240, and 280 mm. This selection range is remarkable for slurries of physical properties required by application as grout in most conditions offered by Polish coal mines. For selected slurries yield shear stress τ_0 and dynamic viscosity η_B have been determined using rotational viscometer, under assumption that these slurries, similarly to fresh concrete and mortars can be described by Bingham model.

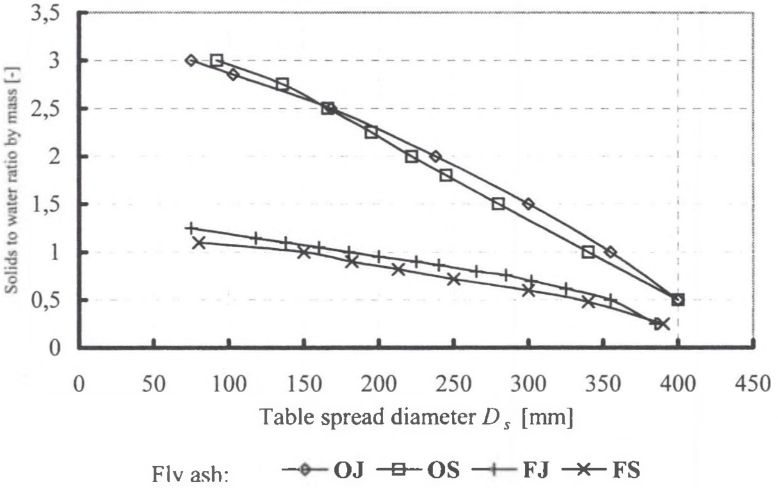

Fig. 1. Composition of slurries expressed as solids to water ratio by mass, in relation to spread diameter for selected types of coal combustion by-products

Rys. 1. Skład mieszanin popiołowo-wodnych wyrażony jako stosunek masowy części stałych do wody, w relacji do rozlewności dla wybranych rodzajów popiołów lotnych

Table 1

Selected physical parameters of fly ash – water slurries used in tests

Fly ash code	Fly ash density ρ_s [kg/m^3]	Spread diameter D_s [mm]	Mixture density ρ_m [kg/m^3]	Concentration by volume C_V [-]	Solids/water ratio by mass S : W	Yield shear stress τ_0 [Pa]	Dynamic viscosity η_B [Pa·s]
OJ	2063	160	1597	0,553	2,50 : 1	116,03	0,3506
		200	1569	0,527	2,25 : 1	81,35	0,2076
		240	1539	0,497	2,00 : 1	52,77	0,1475
		280	1481	0,442	1,60 : 1	33,41	0,1207
OS	2017	160	1577	0,558	2,50 : 1	111,50	0,6903
		200	1551	0,532	2,25 : 1	86,85	0,2560
		240	1495	0,477	1,80 : 1	47,90	0,1702
		280	1450	0,431	1,50 : 1	35,71	0,1050
FJ	2614	160	1483	0,291	1,05 : 1	131,60	0,3860
		200	1451	0,270	0,95 : 1	99,04	0,2494
		240	1424	0,253	0,87 : 1	72,78	0,1603
		280	1385	0,229	0,76 : 1	49,70	0,1204
FS	2689	160	1445	0,255	0,90 : 1	106,10	0,6519
		200	1416	0,237	0,82 : 1	77,38	0,2479
		240	1378	0,215	0,72 : 1	57,35	0,1342
		280	1329	0,185	0,60 : 1	32,18	0,1107

3. Calculation of flow parameters in transport pipeline

Most of grouting systems in Polish coal mines operate with gravitational transport in pipelines as a result of adaptation of classical hydraulic backfill infrastructures for new purposes. In case of gravitational flow in pipeline, velocity and other flow parameters depend on balance between hydraulic head and pressure drop, governed by Darcy-Weisbach equation. Value of drag coefficient can be easily obtained from general equations for laminar and turbulent flow of Bingham fluid dependently on Reynolds number *Re*. This is possible under assumption of homogeneity of considered slurries, which is justified, at least in case of roughly engineering estimations, for fly ashes.

Taking into account a pipeline of constant diameter *D*, length *L*, and elevation difference ΔH, as well as slurry described by parameters collected in Table 1, well known formulations (presented in all handbooks of fluid mechanics) allow to calculate flow velocity v_m, from which related parameters can be easily derived: flow rates of: slurry Q_m, solids Q_s, and water Q_w.

Below two examples of pipelines for transportation of grouts will be discussed. Both are located in the same coal mine. Pipelines connect fill preparation plant placed directly nearly shaft "West" with longwalls marked as 503 and 557 located at different depths and distances from the shaft. Cavings of these longwalls are subject of grouting operations. Diameter of pipelines is constant at all length. Influence of curves on the head loss at the route of the pipeline has been omitted as negligible.

Case I: Pipeline from shaft "West" to longwall 503

Simplified geometry of pipeline: $D = 0{,}15$ m; $\Delta H = 720$ m, $L = 2527$ m.

Flow rates expected to occur in this pipeline during a flow of slurries described in Table 1 and calculated with use of Bingham model equations have been collected in Table 2.

As it can be seen from Table 2, flow velocities that can be achieved in pipeline to 503 longwall ranging from zero up to 4,17 m/s. The most dense slurries considered in tests, of spread diameter D_s equal to 160 mm, are practically out of range of potential use in this pipeline. The highest velocities achieve slurries of lowest concentration (spread D_s = 280 mm), however, taking under consideration flow rate of solids as an efficiency criterion, the pipeline will work most efficiently with slurries of spread diameter D_s = 240 mm. Relevant flow rates values for slurries of D_s = 240 mm are higher than for slurries of D_s =

280 mm (see Fig. 2), however the differences for specific types of fly are not significant. The effect becomes more significant when lower water consumption is also considered, Fig. 3. The latter results in shorter cure time and better mechanical properties of the fill. Similar flow rates of solids as for slurries of D_s = 280 mm achieve slurries of spread diameter D_s = 200 mm, with significantly lower consumption of water, thus they seem to be optimal for such a conditions where relatively low volume of water introduced underground with slurry could be beneficial, i.e. presence of water in voids to be filled, high mechanical performance of a fill after cure, etc.

Table 2

Flow parameters of slurries characterised in Table 1 in the pipeline discussed in Case I

Type of fly ash	Flow velocity v_m and flow rates value of slurry (Q_m), solids (Q_s) and water (Q_w) for slurry of given spread D_s				Flow velocity v_m and flow rates value of slurry (Q_m), solids (Q_s) and water (Q_w) for slurry of given spread D_s			
	D_s = 160 [mm]				D_s = 200 [mm]			
	v_m [m/s]	Q_m [m^3/h]	Q_s [m^3/h]	Q_w [m^3/h]	v_m [m/s]	Q_m [m^3/h]	Q_s [m^3/h]	Q_w [m^3/h]
OJ	0,00	0,0	0,0	0,0	3,46	219,9	115,9	104,0
OS	0,45	28,7	16,0	12,7	3,42	217,9	115,9	102,0
FJ	0,00	0,0	0,0	0,0	1,51	95,8	25,9	69,9
FS	0,29	18,3	4,7	13,6	3,42	217,7	51,6	166,1
	D_s = 240 [mm]				D_s = 280 [mm]			
OJ	3,86	245,6	122,1	123,5	4,17	265,6	117,4	148,2
OS	3,85	244,6	116,7	127,9	4,17	265,6	114,5	151,1
FJ	3,52	224,0	56,7	167,3	3,87	245,9	56,3	189,6
FS	3,72	236,8	50,9	185,9	4,13	262,6	48,6	214,0

As it can be seen from Table 2, flow velocities that can be achieved in pipeline to 503 longwall ranging from zero up to 4,17 m/s. The most dense slurries considered in tests, of spread diameter D_s equal to 160 mm, are practically out of range of potential use in this pipeline. The highest velocities achieve slurries of lowest concentration (spread D_s = 280 mm), however, taking under consideration flow rate of solids as an efficiency criterion, the pipeline will work most efficiently with slurries of spread diameter D_s = 240 mm. Relevant flow rates values for slurries of D_s = 240 mm are higher than for slurries of D_s = 280 mm (see Fig. 2), however the differences for specific types of fly are not significant. The effect becomes more significant when lower water consumption is also considered, Fig. 3. The latter results in shorter cure time and better mechanical properties of the fill. Similar flow rates of solids as for slurries of D_s = 280 mm achieve slurries of spread diameter D_s = 200 mm, with significantly lower consumption of water, thus they seem to be optimal for such a conditions where relatively low volume of water introduced underground with slurry could be beneficial, i.e. presence of water in voids to be filled, high mechanical performance of a fill after cure, etc.

Influence of fly ash type on flow parameters in gravitational pipeline transport should also be noticed. For both groups of slurries, of spread diameters D_s = 240 mm and D_s = 280 mm, fly ashes of type "O" achieve round two times higher flow rates of solids than of type "F", and require smaller addition of water – by 22% ÷ 31%. This observation is to be expected due to differences in chemical and physical of both types of fly ash, however differences can be also seen for slurries made with use of the same type of fly ash, but taken from other source ("J" and "S"). In the case presented here these differences are equal to few cubic meters per hour, however even these could be important in more precise analyses. Moreover, by deliveries from numerous sources at a time, differences of flow parameters resulting from the use of the same type of fly ash from different power plants might be much more significant.

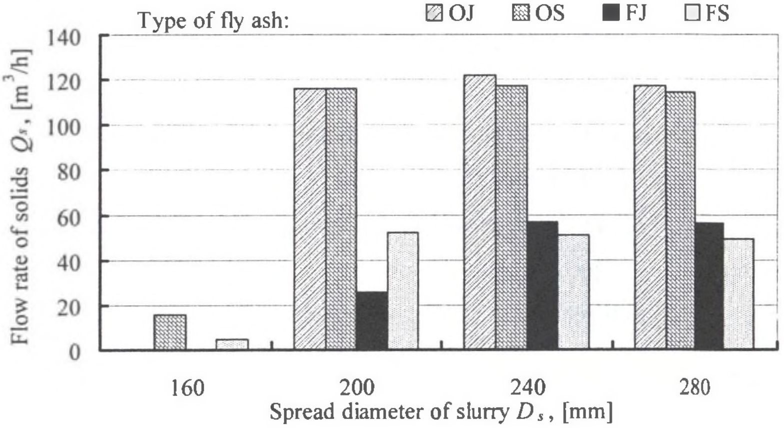

Fig. 2. Flow rate of solids in pipeline from Case I, in relation to spread diameter and type of fly ash in the slurry

Rys. 2. Natężenie przepływu części stałych podczas przepływu w rurociągu w wariancie I, w relacji do rozlewności mieszaniny i rodzaju popiołu

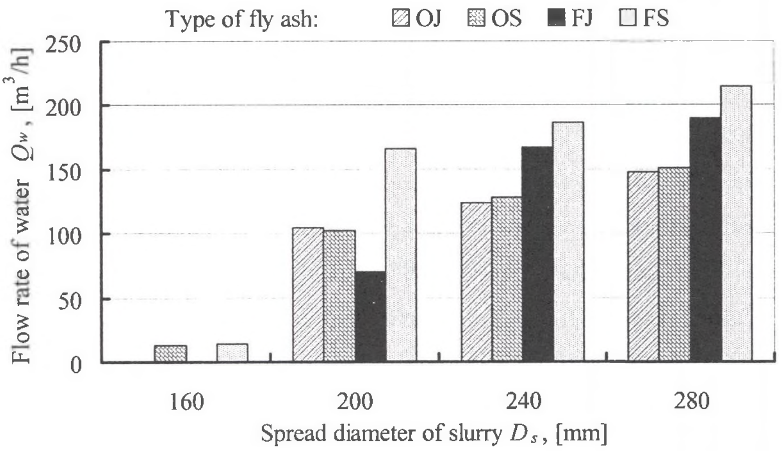

Fig. 3. Flow rate of water in pipeline from Case I, in relation to spread diameter and type of fly ash in the slurry
Rys. 3. Natężenie przepływu wody podczas przepływu w rurociągu w wariancie I, w relacji do rozlewności mieszaniny i rodzaju popiołu

Case II: Pipeline from shaft "West" to longwall 558

Simplified geometry of pipeline: $D = 0{,}15$ m; □$H = 720$ m, $L = 4190$ m.

Flow rates expected to occur in this pipeline during a flow of slurries described in Table 1 calculated with use of Bingham model equations have been collected in Table 3.

Pipeline in case II is much longer as it is in Case I. In gravitational transport of slurries it results in significantly lower velocities of flow than in Case I, see Table 2 and 3. In presented case, slurries of spread diameter D_s = 160 mm cannot be used at all, by spread diameter D_s = 200 mm only use of fly ah type "FS" makes possible hydraulic transport of slurry, by spread diameter D_s = 240 mm slurry made with fly ash type "FJ" will not flow in the pipeline, Fig. 4. Flow parameters of slurries with spread diameter D_s = 240 mm in Case II show in more drastically way a risk of transport failure by change of fly ash type in slurry preparation plant. From the other side, in comparable combinations of type of fly ash and spread diameter D_s in both pipeline cases, flow parameters seem to be relatively invulnerable for changes in pipeline geometry, see Fig. 5, what happens often in mining practice, where a number of locations are to be fed from one slurry plant at a time.

Table 3

Flow parameters of slurries characterised in Table 1 in the pipeline discussed in Case 2

Type of fly ash	Flow velocity v_m and flow rates value of slurry (Q_m), solids (Q_s) and water (Q_w) for slurry of given spread D_s				Flow velocity v_m and flow rates value of slurry (Q_m), solids (Q_s) and water (Q_w) for slurry of given spread D_s			
	D_s = 160 [mm]				D_s = 200 [mm]			
	v_m [m/s]	Q_m [m^3/h]	Q_s [m^3/h]	Q_w [m^3/h]	v_m [m/s]	Q_m [m^3/h]	Q_s [m^3/h]	Q_w [m^3/h]
OJ	0,00	0,0	0,0	0,0	0,00	0,0	0,0	0,0
OS	0,00	0,0	0,0	0,0	0,00	0,0	0,0	0,0
FJ	0,00	0,0	0,0	0,0	0,00	0,0	0,0	0,0
FS	0,00	0,0	0,0	0,0	2,12	134,9	32,0	102,9
	D_s = 240 [mm]				D_s = 280 [mm]			
OJ	3,42	217,7	108,2	109,5	2,93	186,3	82,3	104,0
OS	3,51	223,1	106,4	116,7	2,91	185,3	79,9	105,4
FJ	0,00	0,0	0,0	0,0	3,31	210,8	48,3	162,5
FS	3,40	216,0	46,4	169,6	3,79	241,1	44,6	196,5

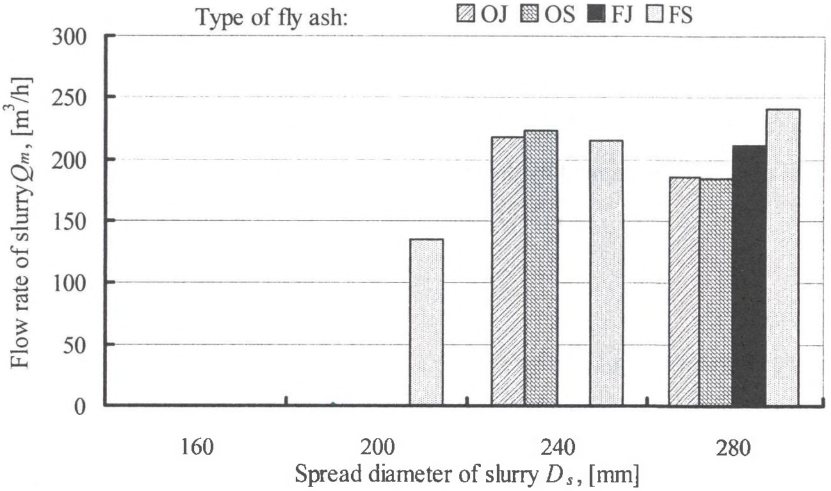

Fig. 4. Flow rate of slurry in pipeline from Case II, in relation to spread diameter and type of fly ash in the slurry
Rys. 4. Natężenie przepływu mieszaniny w rurociągu w wariancie II w zależności od rozlewności mieszaniny i rodzaju popiołu lotnego

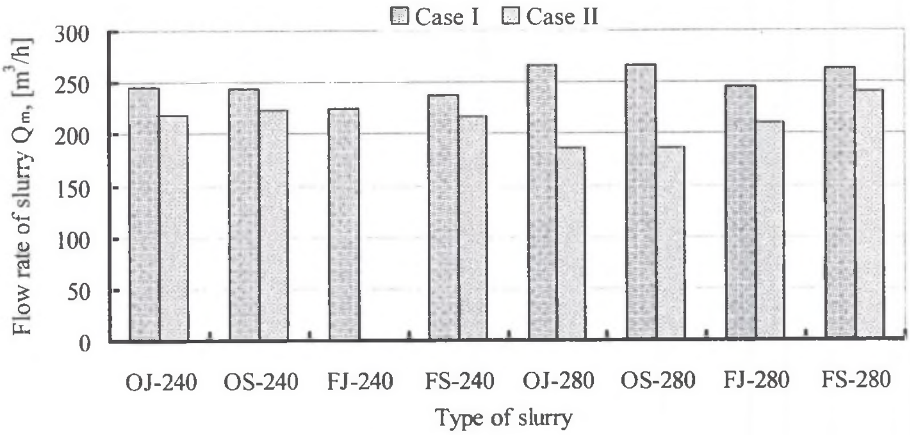

Fig. 5. Flow rates of slurries of spread diameter 240 and 280 mm in pipelines described in Case I and Case II
Rys. 5. Porównanie wielkości natężenia przepływu mieszanin popiołowo-wodnych o rozlewności 240 i 280 mm w rurociągach w wariantach I i II w zależności od rodzaju popiołu lotnego

4. Flow of slurries in cavities

The steady laminar velocity of a viscous incompressible fluid flow through a pair of parallel smooth plate walls separated by distance *h* satisfies the Darcy equation (Tsang, 1993):

$$v = k_f I \tag{1}$$

where:

I – hydraulic gradient,

k_f – coefficient of hydraulic conductivity

Value of coefficient k_f can be obtained from a formula:

$$k_f = \frac{h^2 g}{12\mu_k} \tag{2}$$

where:

g – acceleration of the earth,

μ_k – kinematical viscosity of the fluid.

Then flow rate of a fluid per elementary width of a fracture is equal to:

$$q = vh = \frac{h^3 g}{12\mu_k} I = -\frac{h^3}{12\mu_d} \frac{\Delta p}{L_f} \tag{3}$$

where:

Δp – pressure lost over the length of fracture L_f.

μ_d – dynamic viscosity of the fluid.

Thus, flow rate of a fluid in a fracture (rectangular cavity) of aperture *h*, width *b*, and length L_f can be expressed as:

$$Q_f = -\frac{bh^3\Delta p}{12\mu_d L_f} \tag{4}$$

In case of non-Newtonian (Bingham) fluid, equation (4) takes a form:

$$Q_f = \frac{b}{12\mu_B}\frac{1}{\left(\frac{dp}{dx}\right)^2}\left[h^3\left(\frac{dp}{dx}\right)^3 + 4\tau_0^3 - 3\tau_0 h^2\left(\frac{dp}{dx}\right)^2\right] \tag{5}$$

where we can assume that

$$\frac{dp}{dx} \cong \frac{\Delta p}{L_f}$$

The maximal distance at which a slurry can flow into a cavity defined as above is equal: (Palarski, 2007):

$$L_{\max} = \frac{p_{\max} h}{2\tau_0} \tag{6}$$

where:

p_{max} – maximum value of injection pressure or pressure resulted from elevation difference by gravitational filling.

Alternatively, equation (6) can be presented in a form:

$$p_{\min} = \frac{2\tau_0 L_f}{h} \tag{7}$$

where:

p_{min} – minimum pressure necessary to fill all fractures (cavities) of aperture higher then *h*.

Fig. 6 presents calculations result of filing process of a single rectangular cavity with slurries discussed in previous chapter using equation (5), with all assumptions about their homogenity and rheology. Aperture of the cavity is $h = 0{,}05$ m, width $b = 0{,}20$ m, hydraulic head of slurry at the inlet into the cavity is 1 m. Slurries analysed in the graph are made with fly ash type "OS" with spread from 160 up to 280 mm. Density and rheological parameters of these slurries have been shown in Table 1.

Taking under consideration a reasonable time span it can be seen that the slurry can reach certain maximal distance in a cavity. In the column on the right side of Fig. 6 maximal values of transport distance calculated with equation (6) have been shown.

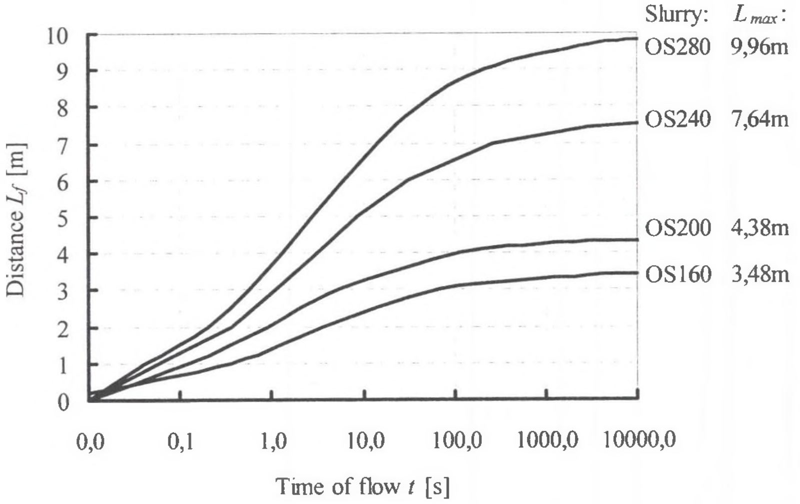

Fig. 6. Flow of selected slurries in a single rectangular fracture in relation to rheological properties of slurry. See the text for details

Rys. 6. Przebieg przepływu wybranych mieszanin w pojedynczej szczelinie o prostokątnym przekroju w zależności od własności reologicznych mieszaniny – szczegóły w tekście

Due to asymptotic course of presented time relation, reaching of maximal distance L_{max} occurs after unrealistic long time, however, presented relation shows clearly how the fill efficiency of a slurry is changing with its rheological properties and concentration of solids.

Next graph, Fig. 7, presents the same relation as Fig. 6, however for slurries of the same spread diameter (D_s = 280 mm) made from different types of fly ash (see Table 1).

As it can be seen from Fig. 7, slurries made with fly ash of types "OJ", "OS", and "FS" present relatively similar maximal fill distance (L_{max}) and fill ratio (inclination of the curve, especially within first 60 seconds of flow. Definitely lower fill properties express slurry made with fly ash of type "FJ".

During filling of underground cavings, slurry flows in the same time through a number of cavities and each of them has different dimensions. Thus, distribution of pressures and range of filling will be differentiated.

During injection of grout into cavings some part of water might be absorbed by surrounding rocks or chemically bound by active compounds of grout (hydration of cement or fly as.), which are able to significantly reduce the range of filling.

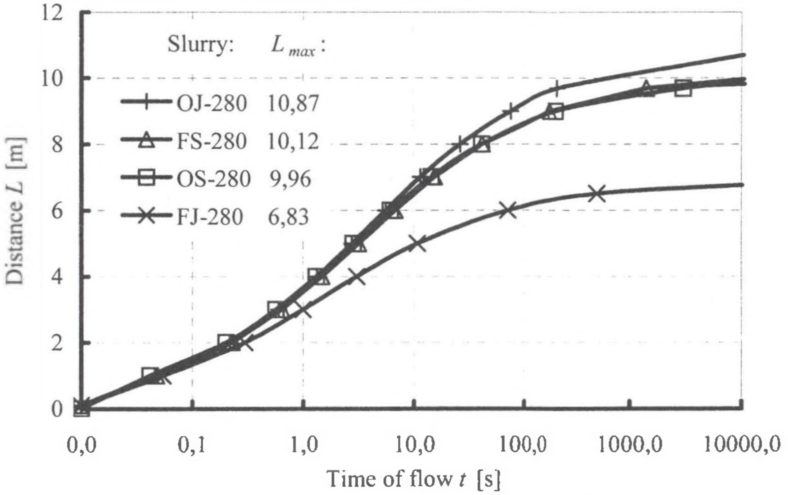

Fig. 7. Flow of slurries of the same spread diameter (D_s = 280 mm) in a single rectangular fracture. See the text for details

Rys. 7. Przebieg przepływu mieszanin o tej samej rozlewności (D_s = 280 mm)w pojedynczej szczelinie o prostokątnym przekroju w zależności od rodzaju popiołu – szczegóły w tekście

5. Conclusion

Presented in this paper research and analysis is only a selection of large scientific program related to all aspects of use of coal combustion by-products in underground mining technologies. Both hydraulic transportation in pipelines and filling of underground voids require thoroughly design of slurries composition. Similar types of coal combustion by-products differ from each other enough to result in significant differences in flow and migration parameters. Preçise control of slurries parameters offers possibility for optimization of its composition from the point of the view fill efficiency, utilization of saline waters, range of grouting from single pipe outlet etc.

Flow of slurry in a single fracture of simplified geometry alone is only an additional tool for comparison of different slurries. Combining of this method with numerical modeling of flow in grids of fractures of complex geometry can be an useful tool for advanced analyses of grouting, filling of voids, and other process related to flow through porous media.

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