Fighting water hazard by grouting–practical applications

Roman Kuś[1]; Yurij Polozov[2]

[1]*The Geological & Drilling Company; 9 Teatralna Street, 41-200 Sosnowiec; Poland; e-mail prgw@prgw.com.pl*
[2]*SpecTampnażGeologia S.A.; 7a Pietrowskiego Street, 94613 Antracyt; Ukraine*

Abstract: Abstract presents the basic features required from grouting solutions used for generation of sealing curtains applied to prevent endangerment to mining and hydrotechnical objects. Advantages of sealing solutions on the basic of polimineral clays are discussed. The examples of applications of sealing solutions on the basis of polimineral clays in a grout constructing in the open-cast diamond mine (the MIR diamond, Yakutia), the rock salt mine (Stebniki, Ukraine), the underground workings (Wałbrzych, Poland) are presented.

1 THE BASIC REQUIREMENTS FOR DESIGNING OF SEALING GROUT CURTAINS AND SELECTION OF MATERIALS FOR THEIR PREPARATION

Water-bearing rock mass layers and their increased filtrating properties cause problems during construction and exploitation of hydrotechnical objects, and create endangerment in mining engineering. Aquiferous horizons may occur at different depths. As a rule, their occurrence is related to the presence of not-lithified coarse-grained sands and gravels, and sandstone or limestone beds. The separate source of endangerment are faults, fissures and karstic cavities.

Experiences gained until now, concerning the progress of mining construction (cross-headings, shafts) indicate that under conditions of water flow from 80-100 m^3/h the medium building progress does not exceed 7-8 m/month and its cost is 4-5 times higher comparing to building carried out under conditions of low water flow (Maximow, Yewtuszenko, 1978). The optimal and rational way to limit water endangerment during shaft and cross-cut driving in the range of highly water-bearing layers, is to form of sealing grout covers.

The rule of hydrotechnical object building, particularly these found in strongly cracked formations or built on sands and gravels, is to create sealing grout curtains in their rock basements. The basic assumptions can be expressed as follows:

- sealing grout curtains should be characterised by high isolating properties, preventing water to penetrate to the protected structures during the whole period of their building or exploitation;

- a sealing grout curtain should be characterised by a suitable mechanical strength providing the appropriate resistance to hydrostatic pressure produced by groundwater;
- a material used for creating sealing grout curtain should be highly resistant to corrosion caused by groundwater of various mineralisation type;
- sealing grout curtains should have a very large contact surface to impermeable layers (both in a bottom and a roof of the formation);
- materials applied to creation of a sealing grout curtain should be easily accessible, inexpensive and without negative impact to the environment.

Construction of sealing grout curtains is usually preceded by detailed recognition of geological and hydrogeolgical structure, an important part of which is to carry out chemical analysis of groundwater, essential to proper selection of suitable grouting solutions.

All grouting solutions practically applied so far can be divided into three groups, according to the cement type and their components:

1. Solutions on the basis of inorganic polymers
2. Solutions on the basis of organic polymers
3. Solutions on the basis of synthetic and natural mineral substances

All solutions made on the basis of water-glass can be comprised by the first group, solutions on the basis of bitumens, latex and synthetic resins – by the second group, and these cement-based, cement-sandy, cement-siliceous, argillaceous, argillo-siliceous together with solutions on the basis of clays belong to the third group.

Experience gained so far indicates that only low percentage of grouting solutions is applied at commercial scale of production (Adamowicz, 1980; Kipko, Polozow, et al 1984; Maximow, Yewtuszenko, 1978; Rogatin, Sienatozow, 1979). It is caused by the fact that a large number of solutions is inadequate to the desired requirements.

The basic requirements, obligatory for grouting solutions, can be expressed as follows:

1/ they should infiltrate easily in pores or fissures at a required depth;
2/ should have thixotropic properties enabling them to be propagated into beds at large distances;
3/ should fill precisely a sealed space;
4/ should be stable;
5/ should have a high rate of stabilisation, able to be regulated depending on a chosen propagation technology;
6/ should have good isolating properties within the formed structure;
7/ should be long-lasting and corrosion resistant;
8/ should not have a negative impact on the natural environment;
9/ should be made of easily accessible components (in the industrial-scale amounts);
10/ should be easy to prepare and propagate into sealed layers;
11/ should be made of inexpensive components.

Grouting solutions on the basis of clays correspond these requirements to the highest degree and thanks to it have been widely utilised in sealing works (Kipko E. Polozow J. et al. 1984; Kuś R. Litowczenko W. 1997; Popow A. 1984).

2 COMPOSITION AND PROPERTIES OF GROUTING SOLUTIONS ON THE BASIS OF CLAYS

Properties of grouting solutions on the basis of clays depend on composition and content of their particular components. They are produced as a combination of clay mixtures and cements. Selection of suitable cements depends on the chemical composition of groundwater. After their hardening, grouting solutions on the basis of clays change their consistency to the viscoplastic one (the Bingham-Szwedow body). Formation of the structure during the hardening process is connected with lowering of distances between the elemental molecules of the solution and simultaneous strengthening of molecular bonds (van der Waals forces). Such properties as plasticity, stability, rigidity, resistance to corrosion and low value of the coefficient of permeability are related to specific properties of argillaceous rocks. Not all argillaceous minerals have appropriate dispersion and hydration to the same extent so they should be considered according to the suitable types. At present, from the point of view of features required to grouting solutions on the basis of clays, three groups of argillaceous minerals are distinguished:

a) the kaolinite group
b) the montmorillonite group
c) the hydromica group

High variability of illite causes that some minerals of this group become similar to the minerals of the montmorillonite group and the other (more stable) minerals become similar to the minerals of the kaolinite group. Large degree of dispersion and electric potential, and presence of exchangeable cations lead to the generation of specific spatial structures, responsible for their thixotropic features.

The intensive experimental research carried out on samples coming from about 60 mines of argillaceous minerals, has led to conclusion that the best material for grouting aims are polimineral clays composed of illite and kaolinite. Strength of the structures (rheologic properties) and the rate of hardening of grouting solutions on the basis of clays depend mainly on chemical, mineral and granulometric composition of clays and, in the large part, on a type and amount of exchangeable cations. The physical and chemical features of clays mentioned above have been evaluated with chemical, mechanical and X-ray structural methods. The statistic analysis of results of physico-chemical properties of investigated clays has enabled to classify them into four groups (Table 1).

Table 1

Composition and properties of clays	Utilisation degree			
	Very good	Good	Medium	Inadequate
	Qualitative and quantitative characterisation of clays			
Granulometric composition and plasticity index	Heavy clays, with <5µm grain content >60%,>50µm grain content <5%, I_p = 15-25	Heavy sandy clays, with <5µm grain content 40-60%, >50µm grain content 5-9%, I_p = 6-18	Sandy clays, with <5µm grain content 30-40%,>50µm grain content <15%, I_p = 6-18	a) common clays, with <1µm grain content >55%, I_p > 70 b) sandy clays, silty sands, <5µm grain content <20%
Mineral composition	Basic minerals from the kaolinite group with admixtures of hydromica, quartz in low quantities	Basic minerals from the kaolinite and hydromica groups, enriched in kaolinite-illite and illite-montmorillonite laminae, quartz, calcite feldspar in low quantities	Basic minerals from the illite and montmorillonite (+vermiculite) groups, enriched in montmorillonite-illite laminae, quartz, calcite, feldspar in low quantities	a) minerals of the montmorillonite group + quartz b) minerals of the illite group, enriched in kaolinite laminae; quartz, feldspar, calcite and gypsum in high quantities
Chemical composition	Al_2O_3 - 20 - 28% SiO_2 - 50 - 60%	Al_2O_3 - 18 - 24% SiO_2 - 55 - 65%	Al_2O_3 > 12 - 20% SiO_2 > 60%	a) Al_2O_3 < 20% SiO_2 > 65% b) Al_2O_3< 12% SiO_2> 65%
Ion exchangeability and participation of basic ions	15 - 30 mval per 100g of dry clay Ca^{2+}>Na^+>K^+>Mg^{2+}	25 - 40 mval per 100g of dry clay Ca^{2+}>Na^+>K^+>Mg^{2+}	40 - 50 mval per 100g of dry clay Ca^{2+}>Na^+>K^+>Mg^{2+}	a) > 60 mval per 100g of dry clay Ca^{2+}>Na^+>K^+>Mg^{2+} b) <10mval per 100g of dry clay Ca^{2+}>Na^+>K^+>Mg^{2+}
Recomended density of a mixture	1,18 - 1,23 g/cm^3	1,20 - 1,35 g/cm^3	1,25 - 1,45 g/cm^3	a) - b) -
Reagents adding to improve rheologic properties	not required	not required	required	a) - b) no possibility to improve rheologic properties

The preparation regime of grouting solutions on the basis of clay has been divided into two stages. During the first stage the basic clay mixture of defined parameters is prepared. At the second stage cement is added to it together with additional components influencing the rate and the way of the grout structure formation.

The basic physico-chemical parameters of clay mixtures are:

- density γ [kg/m^3]

- conventional viscosity	T	[s]
- steady shear stress	Θ	[Pa]
- sand content	P	[%]
- twenty-four hour precipitation		[%]

The mentioned parameters of clay mixtures are measured by standard research methods (in laboratories):

- density	by an areometer	γ	[kg/m^3]
- conventional viscosity	by a field viscometer	T	[s]
- steady shear stress	by a SNS2 device	Θ	[Pa]
- sand content	by a OM2 device	P	[%]
- twenty-four hour precipitation	by a measuring cylinder		[%]

The addition of a suitable cement is determined by particular conditions occurring in the given location, from which the most important are temperature and chemical composition of groundwater.

Rheologic properties of grouting solutions on the basis of clays can be changed by reagents forming their structures. An admixed reagent influences the intensity of structure formation at the first stage and increases the resistance to washing by groundwater suffosion.

The strength of grouting solutions on the basis of clays at the all stages of their consolidation (hardening) is evaluated by their flow stress. This parameter is the basic rheologic criterion on the basis of which sealing covers are designed. The flow stress value is measured by laboratory methods, starting from the moment when the solution shows thin consistency to the moment of its total stabilisation.

At the first stage of hardening, the solution fluidity is measured by the AzNII conical device, next the steady shear stress by the SNS2 apparatus, and a structure viscosity together with dynamic shear stress estimated by rotating viscometers. At the following stages of hardening (the second and third stage of the structure formation) flow stress value is measured.

Rheologic properties of grouting solutions on the basis of clays, such as structural viscosity and dynamic shear stress, are essential for calculation of a propagation radius (spreading distance) of the solution in the sealed beds, as well as calculation of pressure and yield parameters necessary for production of tight sealing curtains. Measurements of rheologic parameters are carried out by rotating viscometers of various construction. The basis for shear stress calculation is the Bingham-Szwedow formula:

$$\tau = \tau_0 + \eta * du/dt \quad , \qquad [1]$$

τ	- shear stress	[Pa]
τ_0	- dynamic shear stress	[Pa]
η	- structural viscosity	[Pa*s]
du/dt	- rate gradient	

To measure the flow stress value the conical penetrator method is applied, with a cone plunging into a hardening grouting solution. This method enables to evaluate the most objectively change in time physico-mechanical properties of the material, properties characteristic for viscoplastic bodies (so-called the

Bingham-Szwedow body) the representative of which are grouting solutions on the basis of clays.

Flow stress is calculated according to the formula:

$$P_m = K_\alpha * F / h^2 \quad , \qquad [2]$$

where:

	P_m	- flow stress (yield stress), [Pa]
	K_α	- coefficient depending on an apex angle of a cone
	F	- indenter weight
	h	- penetration depth of a cone into a sample
	α	- an apex angle of a cone

The K coefficient is calculated according to the formula:

$$K = 1/\rightarrow \ * \cos^2(\alpha/2) \ * ctg(\alpha/2)$$

It is possible to measure the flow stress value of the consolidating grouting solution at all its alteration stages by changing the indenter weight .

3 APPLICATION OF GROUTING SOLUTIONS ON THE BASIS OF POLIMINERAL CLAYS UNDER CONDITIONS OF BRINE WATER OCCURRENCE. CONSTRUCTING OF SEALING CURTAINS IN ROCK SALT FORMATIONS

The presented below example have occurred in workings No 115/I the Stebniki mine No 2 (Ukraine). Inrush of water has occurred in the roof zone of the bed No 10. The maximal water flow reached 2000m^3/twenty-four hours at first and next stabilised at the level of 200-220 m^3/twenty-four hours.

The saliferous formations composed of halite, sylvine and longlinite 100 - 150 m thick included three aquiferous horizons within the overlaying rock formations:

- the Quaternary aquiferous horizon;
- the aquiferous horizon within the gypsum formation (gypsum cap dome);
- the aquiferous horizon situated above the saliferous formation.

The mineralisation of groundwater within the upper and middle aquiferous horizons has increased with depth and has reached the level of 130 - 150 g/m^3. The mineralisation of groundwater within the horizon overlying the saliferous formation has been much higher and reached the values of 300-320 g/dm^3.

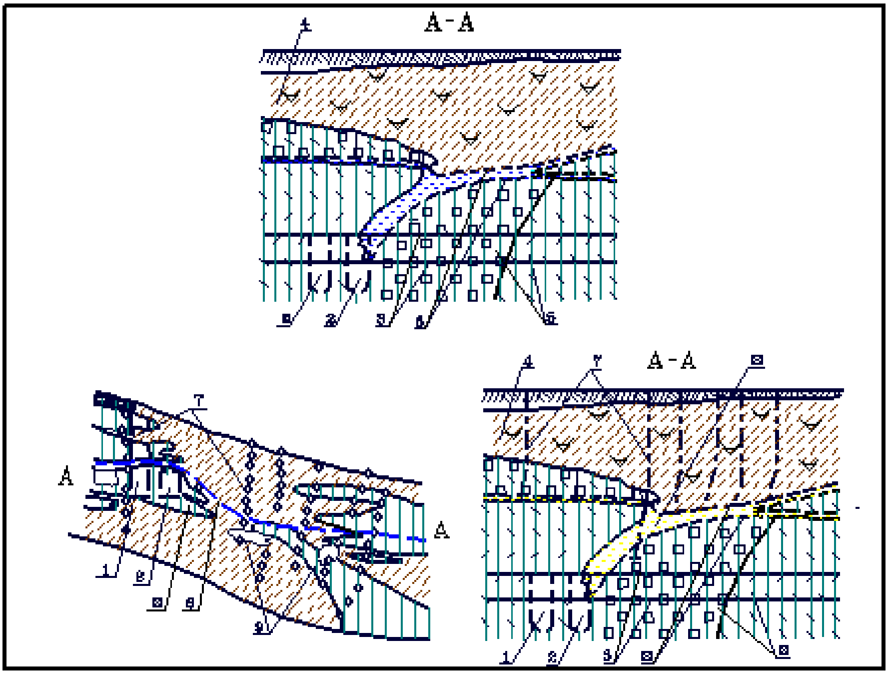

Figure 1 The scheme showing karstic cavities sealing in the Stebniki rock salt mine (Ukraine)
1. working chamber No 115; 2. working chamber No 116; 3. mine workings; 4. gypsum-silt cap (gypsum-silt dome); 5. rock salt deposits; 6. margin of the karst occurrence; 7.injection borehole; 8. grouting solution; 9. karstic funnels

Abnormally high water flows to the workings together with low filtrating properties of the covering beds have caused karstic cavities and cavern formation in the roof parts of the saliferous formation. Surface subsidence has confirmed the development of karstic phenomena. As a result of erosional activity of groundwater safety pillars left between mine workings were broken and the catastrophic inrush of water to the low exploitation levels occurred. Due to high concentration of magnesium salts (30-120 g/dm^3) application of grouting solutions of the basis of polimineral clays with an admixture of special reagents have been required.

The solution has consisted of:

- polimineral clays	- 21 - 24 %
- reagents	- 7,2 - 10.5 %
- natural solution (with groundwater)	- complement to 100 %

In the course of the grouting works more than 91 000 m^3 of the grouting solution on the basis of polimineral clays has been propagated through the injection boreholes. The results of the undertaken action has been groundwater flow extinguishing to the workings and stopping the surface subsidence due to i the karstic cavities filling by the grouting solution. The examination of the grout state in the mine workings and karstic cavities has confirmed high resistance of the produced sealing curtain to the brine presence and high stability of grout consolidated in the newly formed structure.

Evaluation carried out after the completing of the works associated with the mine endangerment prevention has enabled to verify that application of other sealing materials under the conditions described above would be ineffective, and due to a high volume of propagated material and high required costs the whole enterprise would be impossible to accomplish.

In this place, the prevention the water endangerment to the Wieliczka mine is brought to mind in the obvious way. Means and materials applied in this mine enabled to confirm " about inadequacy [for rock salt mines] the grouting methods for rocks and workings, applied in the another mining branches" (Wilk, 1988). Preserving works carried out from 4th May 1993 to the end of 1996 left the endangerment to the mine at the same level as it was in the moment of inrush of water to the "Mina" shaft. The conclusion has led to assumption that "...under the present conditions the hydrodynamic equilibrium could be lost in any moment and, consequently, the most precious art monuments of the Wieliczka mine, situated nearby, are menaced by appearance of groundwater inflows. " (Gonet,.*et al.,*1997). Amount of the grout propagated into beds (566,35 m^3) according to Gonet, *et al.,* (1997) is not in any proportion to the

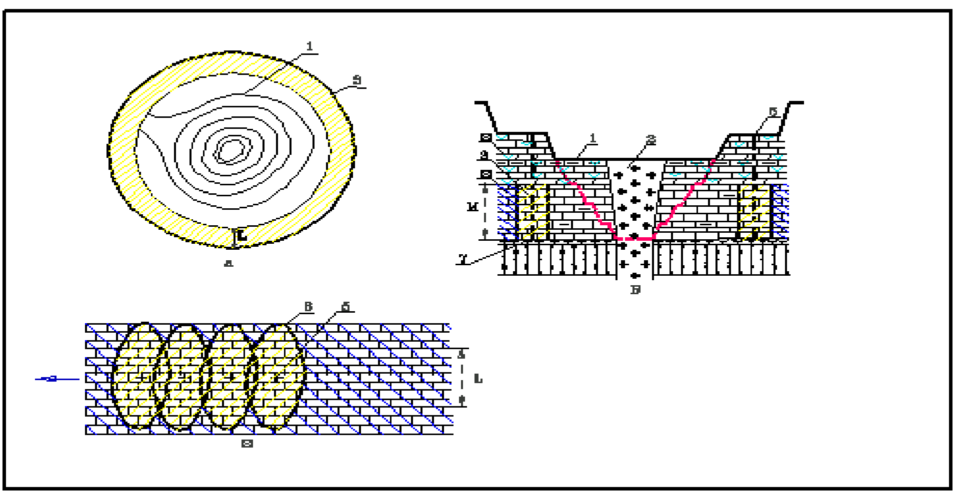

Figure 2 The scheme of sealing curtain made in the MIR diamond pit (Siberia)
1. the mine area; 2. kimberlite plug (pipe); 3. sealing curtain; 4. aquiferous horizon; 5. injection borehole; 6. contour of grouting solution spreading out from one borehole; 7. impermeable layer, 8. permafrost layer; m - thickness of the impermeable cover; l - thickness of the sealing curtain

rock mass removed from the mine workings in the period from April 1992 to August 1995 (64 000 tones) and the dimension of the subsidence basin -

48900 m^3 (Garlicki, *et al.,* 1996). The example of successful preventing of water endangerment in the Stebniki mine negates the opinion (Wilk, 1988) that there are no methods enabling to protect rock salt mines against the water endangerment. For the "Wieliczka" mine the authors of the presented paper have proposed to protect it by recreation of its natural clay curtains separating the mine beds from the water-bearing Chodyniec layers occurring in their surroundings. Therefore the composition of grouting solution on the basis of clays from the "Wieliczka" brickyard has been designed with this aim. The proposal of preventing the water endangerment caused by the Mina shaft by utilisation of the natural sealing cover which are argillaceous minerals of the Wieliczka mine has been recommended to the mine commission as well as was presented as a short communication at 4th Conference of Scientific and Technical Progress in Coal Mining Geology in Szczyrk (Poland) in 1992. In a view of the last reference communication (Garlicki, *et al.,*1996, Gonet, *et al.,*1997) the proposition to protect the mine by methodology successfully used in the Stebniki mine and applied in Poland since several years is still valid (Kuś, Litowczenko, 1997).

4 CONSTRUCTION OF SEALING COVERS IN THE DIAMOND OPEN PIT IN YAKUTIA (SIBERIA)

The complicated conditions of mine workings in the open-cast pit in the MIR diamond mine have been related to the permafrost layer existing within the Cambrian formation where the occurring aquiferous horizons are infilled by highly saline confined groundwater. The necessity to carry on mine workings has been related to the need of pumping out more than 100 m^3/h of brines and draining them to the surface waters. Dumping of such amount of brines to the Wilia river basin was unacceptable due to ecological reasons. Since it has been decided to create at the depth of 400 m a cylindrical grout 30 m in width, 3,5 km in circumference and 200 m thick. To propagate the grout the injection boreholes have been drilled out up to 500m deep. Preparation of a proper grouting solution under permafrost condition was one of the main problems needed to be solved in this case.

The aquiferous complex, situated in the middle part of the permafrost layer, within which the margins of outcrop mine MIR occur, is characterised by increased filtration in the N-S fault zone. It carries highly mineralised sodium-chlorine groundwater (90-130 g/dm^3, temperature - 2^oC), with the lowered freezing point. Hydrogen sulphide H_2S ~150 mg/dm3, methane (CH_4), heavier hydrocarbons, nitrogen and carbon dioxide dominate in its gas composition. The concentration of sulfate ions SO_4^{2+} reaches 6000 mg/dm^3. Grouting solutions stabilising in temperatures below 0^oC and resistant to aggressive features of groundwater have been prepared on the basis of local materials (clays).

Since 1998 more than 460 000m^3 of grout has been propagated enabling the progress of mining without hazard to the environment caused by highly mineralised, aggressive ground water. Creation of the sealing curtain with any other technology application under the Yakutia conditions would beimpossible, both from the economic and technical point of view.

5 SEALING OF THE PEŁCZNICA RIVER BED IN THE REGION OF DRAINING SHAFT IN WAŁBRZYCH

Due to closing of the coal mines in Wałbrzych there was a need to build a draining shaft connecting the "Chwalibóg" shaft with the "Fridrich-Wilhelm" working. At the projecting stage of work it was found that the designed working would be drifted several meters below the channel of the Pełcznica river. Preliminary recognition works indicated that the rocks occurring in the river basement were fractured and the river channel was leaking. There was a requirement to preserve the designed working against groundwater endangerment as well as the river against planned mine workings. It has been decided to seal and consolidate the basement applying to this aim grouting solutions on the basis of polimineral clays. The basic material constituted silts from the Jaroszowiec outcrop.

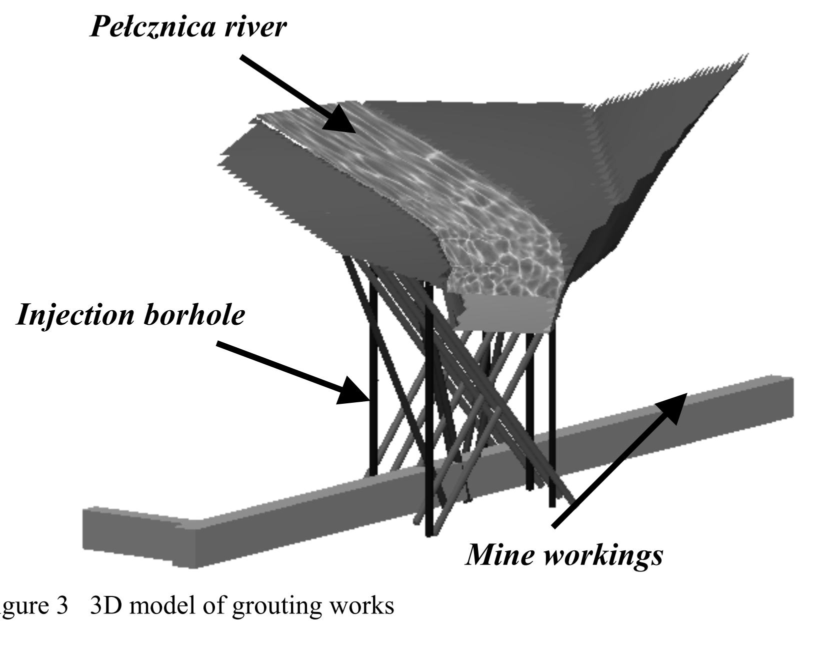

Figure 3 3D model of grouting works

The whole grouting works were performed in the period from 12th of November to 1st of December 1999. To create the grout curtain 20 injection boreholes were drilled from 16,0 to 24,0 m long; their total length - 371,5 m. Most of them were directed at the angle of 72-45^{o}. Propagation of the grouting solution was performed under pressure of 4 atm. In order to create the sealing cover the volume of 373,5m^3 of the grouting solution was used. Observation of the grout propagation confirmed the previous expectation concerning the basement quality and the state of the Pełcznica embankment. The injection workings were stopped many times because of achieving the hydraulic connections between the injected section and the ground surface, the river channel or even the mine forehead located several meters from the injected section. The ground loosening wasconfirmed by cavity zones found during drilling and loss of the drilling fluid related to them.

Quality of injection works was controlled by geophysical methods and finally, quality of accomplished works were confirmed during the drift making where there was found water flow from the Pełcznica river.

REFERENCES

Adamowicz A. ,1980. Zakreplienie gruntow i protiwfiltracjonnyje zawiesy. *Energia*, Moskwa (in Russia)

Garlicki A., Paulina M., Różkowski J.,1996. Influence of karstic phenomena on water endangerment in The Wieliczka salt mine. *Przegląd Geologiczny nr10,* Warszawa

Gonet A. Brudnik K. Stryczek S.,1997. Protection The Wielczka salt mine from water endangerment in the area of Mina shaft. *Bezpieczeństwo Pracy i Ochrona Środowiska w Górnictwie nr 12.* Katowice.

Kipko E. Polozow J.et all, 1984. Komplieksny mietod tomponaża pri stroitielstwie szacht. *Niediera.* Moskwa, (in Russia)

Kuś R. Litowczenko W.,1997. Usage of polimineral clay-based sealing for creating hydroisolating walls. *Gospodarka wodna nr 6 i 7*. Wydawnictwo SIGMA-NOT, Warszawa

Maksimow A. Yewtuszenko W.,1978. Tamponaż gornych parod, - *Niediera*. Moskwa, (in Russia)

Popow A.,1984. Razrabotka tamponażnych roztworow dla wodoizloacji kapitalnych gornych wyrabotok w sloznych gorno-geologiczielskich uslowijach. *Dysertacje doktorska, Szachty*, (in Russia)

Rogatin N. Sienatozow N.,1979. Protiwfiltracjonnyje zawiesy na karejerach. *Niediera* Moskwa, (in Russia)

Wilk Zb.,1998. Water inrushes and breakdowns in Polish salt mines and their effect on the surface level. *Hydrogeology of urbanised and industrialised areas.* Wydawnictwo Uniwersytetu Śląskiego. Katowice

Cechy wymagane od roztworów cementujących – zastosowanie praktyczne

Roman Kuś, Yurij Polozov

Streszczenie: Zaprezentowano główne cechy wymagane od roztworów cementujących stosowanych w produkcji osłon uszczelniających, używanych dla ochrony przed zagrożeniami ze strony górnictwa i obiektów hydrotechnicznych. Omówiono: zalety roztworów uszczelniających bazujących na glinach

polimineralnych, podano przykłady zastosowania roztworów cementujących bazujących na glinach polimineralnych w tworzeniu torkretu w odkrywkowej kopalni diamentów (MIR „słup" diamentowy, Jakucja), kopalni soli kamiennej (Stebniki, Ukraina) oraz w wyrobiskach podziemnych kopalń węgla (Wałbrzych, Polska).