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ORIGINAL PAPER

Groundwater control in open-pit mine with grout curtain using modified lake mud: a case study in East China

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Abstract

Curtain grouting is an effective measure to cut off groundwater flow and reduce mine drainage and the risk of water inrush in open-pit mines. In this paper, an innovative technique is presented in which groundwater flow of the Chengmenshan copper open-pit mine in Jiangxi Province, China, is cut off by using a grout curtain made up of an environmentally friendly material from modified lake mud. An automated grouting control system is used to improve the efficiency of grouting while ensuring grout quality and mine safety. In order to investigate the characteristics of the modified lake mud slurry, a set of orthogonal experiments with three parameters and three levels $L_9(3^3)$ are carried out. The results show that the specific gravity of the basic lake mud slurry is the most significant factor in the effectiveness of grouting. Moreover, the curtain grouting effect of the Chengmenshan copper mine is proved to be excellent through the relationship curve of unit grouting quantity of ZD-I and ZD-II, dispersion coefficient, and water injection tests. It is found that the karstic fractures and tectonic fracture zone are effectively intercepted by a continuous and tight grout curtain located at the east of the mine pit. Our study helps to explore and develop an automated grouting control system and an environmentally friendly material for grout curtains in open-pit mines.

Keywords Mine curtain grouting · Automated grouting control system · Modified lake mud · Time-varying behavior of viscosity · Karstic fractures

Introduction

In recent years, mine discharge and risk of water inrush are rapidly increasing with mining intensity and depth increasing in open and underground mines, especially in karstic formations or geologically active areas (Bakalowicz 2005; Vutukuri and Singh 1995; Wu et al. 2017; Yang et al. 2017). In order to reduce groundwater level and control the risk of water inrush in open-pit mines, drilling drainage and curtain grouting are the two most commonly used and effective methods (Sui et al. 2015; Yuan et al. 2018; Zhou et al. 2017). However, long-term mine drainage will make a lot of the original balance of groundwater destroyed, leading to serious geological, ecological, and environmental problems, such as groundwater level rapid reduction, regional groundwater funnel rapid expansion, uneven ground subsidence, rivers or springs running dry, soil erosion, and land desertification (Huang 1984; Qiao et al. 2020; Sui et al. 2010; G. Zhang et al. 2020b). Since the 1960s, curtain grouting sealing water method has been widely used in China's metal and coal mines with large water inflow for the prevention and control of water hazards, such as the Zhongguan iron mine in Hebei Province, China (Li et al. 2011), the Gaoyang iron mine in Shanxi Province, China (He et al. 2012), the Maoping lead-zinc mine in Yunnan Province, China (Han 2018; Yuan and Han 2020), the Zhuzhuang coal mine in Henan Province,

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China (Mou et al. 2020), the Zhanihe open-pit coal mine in Inner Mongolia Autonomous Region, China (Zhang et al. 2020a, 2020b), and the Zhangmatun iron mine in Shandong Province, China (Zhou et al. 2017). Figure 1 shows the relationship of grouting curtain with ore body-groundwater-formation interaction, according to a geological prototype of the Zhongguan iron mine, located in the strong groundwater runoff zone of the Handan-Xingtai Hundred Springs, China. Curtain grouting sealing water method has three advantages compared with other schemes proposed in the past for the geological environment protection and regional sustainable development of mines:

1. Ensure the safety of deep mining. Mine curtain grouting, as an integral water prevention and control project, has great significance to ensure the safety of deep mining and reduce the risk of water inrush. It is an artificial structure serving the whole life cycle of a mine.
2. Protect regional groundwater resources. Compared with the traditional drainage scheme, curtain grouting can greatly reduce the mine drainage, thereby reducing the damage to regional groundwater resources due to mine long-term drainage.
3. Reduce power consumption for drainage. A lot of power resources are consumed every year due to mine drainage in some mines where inflow of water is large. Although the short-term investment of curtain grouting is large, the long-term environmental and ecological benefits are huge.

In practical mine curtain grouting engineering, the selection of the grout materials is related to the geological conditions of the formations, such as the stability, fluidity, viscosity, water content, and gelling time of the grout, which are some of the most important factors that determine the effectiveness of grouting. Presently, typical grout materials are cement or fly ash single-liquid slurry, cement and sodium silicate double-liquid slurry, modified clay slurry, and organic polymer slurry (modified urea-formaldehyde resin, chrome lignin, epoxy resin, acrylate, etc.; Ge 2006; Sui et al. 2015; Vik et al. 2000; Wu et al. 2011). Moreover, the physical and chemical properties of the slurry can be altered by adding various modifiers for different geological conditions. In loose Quaternary deposits with large pore and high permeability, high-pressure rotary jet grouting or high-pressure permeation grouting with a single-liquid cement slurry or chemical slurry can be used (Liang et al. 2019; Zhang et al. 2020a, 2020b). For complex rock mass fractures, permeation grouting with cement and sodium silicate double-liquid slurry can be used. Chemical slurry can be used for micro-fractures, and modified clay slurry can be used for ground pre-grouting with static water conditions (Yuan et al. 2018). In karstic formations, the velocity of underground flow of water is generally high; therefore, high-pressure permeation grouting after aggregate filling with a single-liquid cement slurry can be used (Mou et al. 2020). In a water conducting medium, such as a fault or collapsed geological column, directional drilling can be used to position the grout hole in the correct location. Cement and sodium silicate double-liquid slurry can be injected to seal the medium for

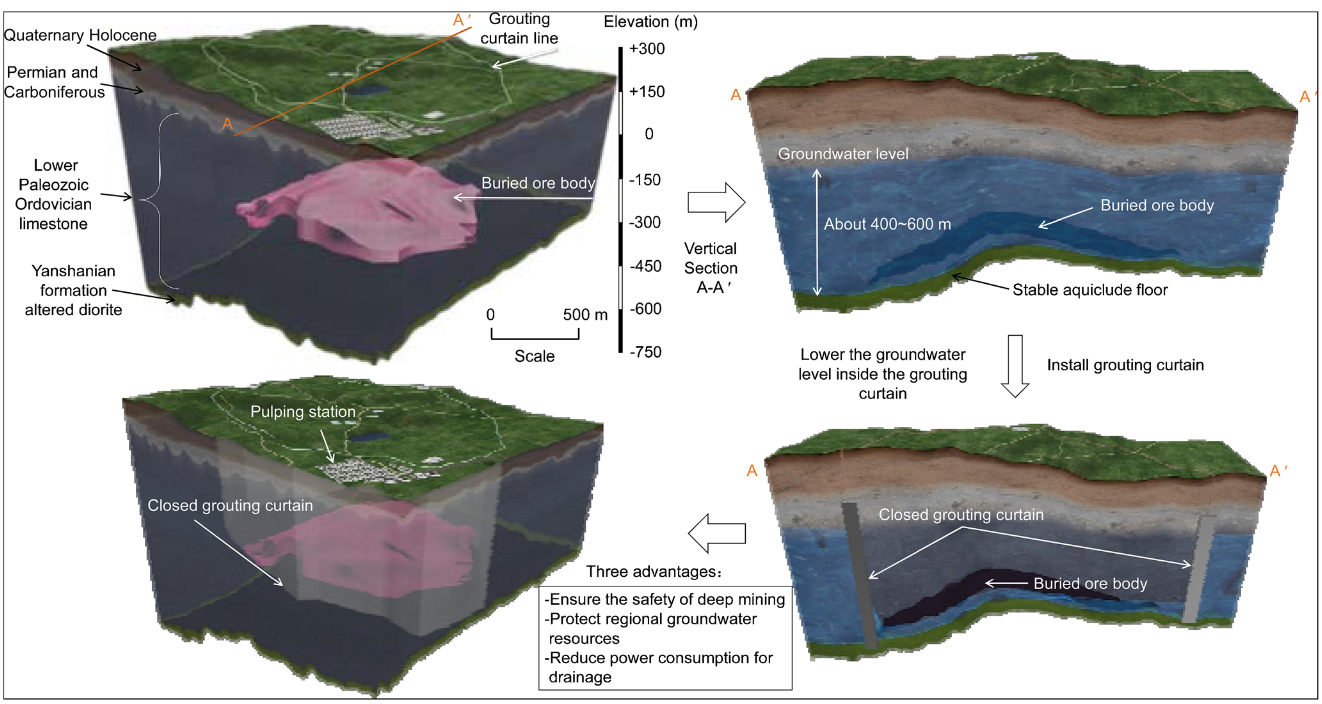

Fig. 1 Schematic relationship of grouting curtain with ore body-groundwater-formation interaction

strong water flow conditions (Qian et al. 2018). However, the injection of a large amount of chemical or cement grouts will have a negative effect on the underground geological and hydrological environments. For instance, chemical composition in the grout can increase the alkalinity and mineralization of groundwater which lead to serious contamination of the regional groundwater (Wang et al. 2008; Han 2017).

To minimize the impact on the environment due to the release of chemicals from the grout material in the surrounding environment, natural lake mud has been considered as an alternative to traditional chemical and cement grouts in Chengmenshan copper mine's curtain grouting engineering. In the Chengmenshan copper mine in Jiujiang city of the Jiangxi Province of China, natural lake mud layer with a thickness of several meters to more than 10 m is widely distributed around the mining pit, and large amounts of lake mud are stripped from the surface of the mine. In this paper, an investigative study has been carried out to explore the use of the modified lake mud as a grouting material in a cut-off grout curtain on groundwater control in the Chengmenshan copper mine. The grouting system used in the Chengmenshan copper mine and the basic properties of the grout material will be discussed in detail.

Geological description of the studied area

Location of the Chengmenshan copper mine

The Chengmenshan copper mine is located in the southeastern part of Jiujiang City-Ruichang City, otherwise known as JiuRui, which is a copper-polymetallic mineralization concentration field, located on the southwest of Jiujiang City in the Jiangxi Province of China (Fig. 2). The center of the mine pit is only 6.5 km from the south bank of the Yangtze River. It is a typical stratabound massive sulfide copper deposit. The reserves are about 1.65 Mt copper, 69 t gold, and 35.66 Mt sulfur (Mohammed et al. 2015). The mine pit was designed with a width of 1250 m, length of 1400 m, and depth of 430 m. The height of the bench is 24 m and the overall slope angle is about 50°. The design mine capacity of the Chengmenshan copper mine is 0.2 Mt of ore (mining volume) and 1.25 Mt of waste (stripping volume) per year. There are many natural lakes of various sizes around the mine, of which the largest one is the Sai Lake (seasonal lake) with a water surface area of 61.32 km^2 and a catchment of 960.95 km^2 (Zhang et al. 2016). The mine site has a subtropical damp climate with a mean annual temperature of 17°C, and an average annual rainfall of 1400 mm of which more than 43.2% of the rainfall occurs between the months of April and June.

Regional tectonic framework

The subsurface stratigraphy of the mined area has been affected by multiple periods of tectonic movement, folding, and faulting. Therefore, a series of anticline and syncline structures with an NEE-SWW trend have been developed in the region and are closely arranged, from south to north, as follows: the Changshan-Chengmenhu anticline, Wushijie-Saihu syncline, Dachong-Dingjiashan anticline, Henglishan-Huangqiao syncline, Jieshou-Daqiao anticline, and Dengjiashan-Tongjiangling syncline. Secondary synclines are developed in the axis of the anticlines, and secondary anticlines are developed in the axis of the synclines, which form a W-shaped syncline group and M-shaped anticline group. A complex array of dominantly NEE-striking faults are developed in the region. These folds and faults are characterized by complicated mechanical properties and groundwater seepage conditions.

Geological conditions of the site

The subsurface stratigraphy of the mine consists of the Upper Silurian Formation of Shamao (S_3s), Middle Silurian Formation of Luoreping (S_2l), Upper Devonian Formation of Wutong (D_3w), Middle Carboniferous Formation of Huanglong (C_2h), Lower Permian Formation of Liangshan (P_1l), Qixia Formation (P_1q), Maokou Formation (P_1m), Middle Permian Formation of Longtan (P_2l), Changxing (P_2c), Lower Triassic Formation of Daye (T_1d), Middle Triassic Formation of Jialingjiang (T_2j), and Holocene alluvial deposits (Q_4^{al}) and diluvium (Q_4^{dl}). Table 1 lists the general geologic stratigraphy of the Chengmenshan copper mine. The sedimentary strata in the mining area are inclined to the NW with a dip angle of 45–60°. The lithology of the Silurian Formation is purplish red quartz sandstone with a thickness of more than 200 m, thus forming a conformable contact with the underlying formation. The main ore controlling strata in the mining area is the Chengmenshan compound rock mass with multiple ultra-shallow invasions of intermediate-acid magmatic rocks of the Yanshanian period (about 180–90 Ma). The main lithology of the area is granodiorite porphyry ($\gamma\sigma\pi$) and quartz porphyry ($Q\pi$).

Hydrogeological conditions of the site

The Chengmenshan copper mine is located in the southern margin of the Wushijie-Saihu syncline, which is a large water storage structure. It is a complex hydrogeological mine surrounded by lakes on three sides. Most ore bodies of the Chengmenshan copper mine are buried at the bottom of the lake. The quartz sandstones with shale located south of the mining area of Devonian and Silurian are mostly a relatively weak aquifer. The limestones are Triassic, Permian, and

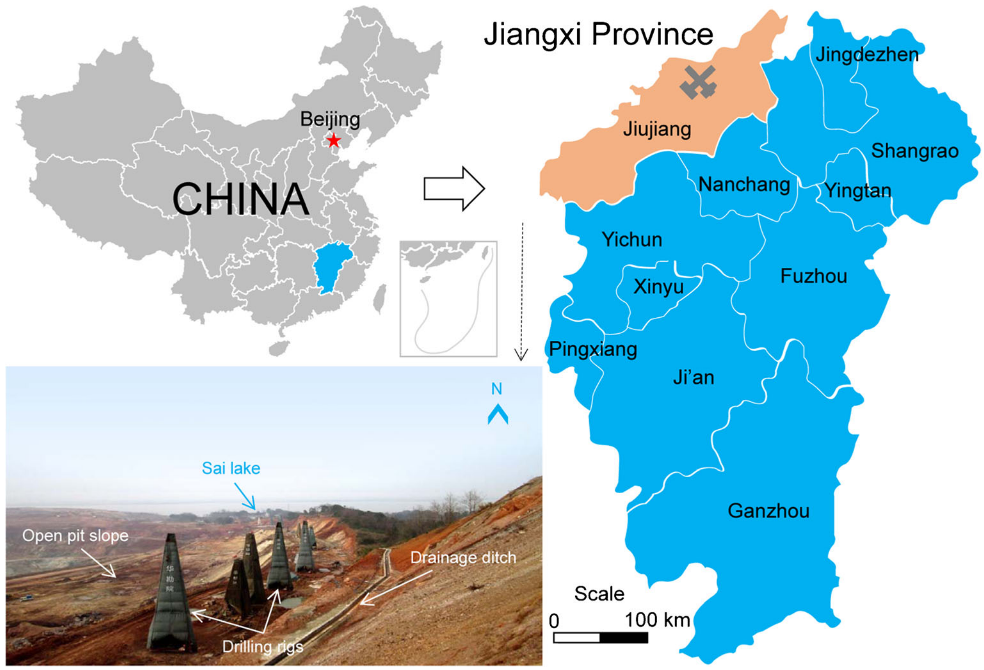

Fig. 2 Location of the Chengmenshan copper mine in China

Carboniferous in the east, west, and north of the mining area, respectively, with a strong karst aquifer that is covered by 15–25-m-thick uniformly distributed lake mud. The water yield of mine pit can reach 50,000–70,000 m^3/day, because the karst fracture network is strongly developed above −100m level. Presently, the groundwater control scheme adopted by the Chengmenshan copper mine is a combined method of drilling drainage and vertical cut-off by using grout curtain. Therefore, a 620-m-long grout curtain is installed east of the mine pit to seal the karstic fissure channels and hidden tectonic fracture zone, as shown in Fig. 3.

Grouting system and material

Grouting scheme

According to the hydrogeological conditions of the mine site and groundwater control scheme, underground drainage with deep well pumping is adopted at the north and southwest of the mine site and curtain grouting scheme is used east of the mine site for seepage control. The grout curtain starts from the F1 fractured zone in the Upper Devonian Formation of Wutong (D_3w) and the Upper Silurian Formation of Shamao (S_3s), and terminates at the Lower Triassic Formation of Daye (T_1d) (Han 2017). The total designed length of the grout curtain is 620 m with 47 drilled holes (Fig. 3).

Figure 4 shows the cross section of the grout curtain in the Chengmenshan copper mine. The top of the grout curtain is 5 m above the stable groundwater level, and the rock at the bottom of the grout curtain has a coefficient of permeability less than 5 Lu measured by using a water injection test. The first series of drilled holes, denoted as group ZD-I, were installed with a horizontal spacing of about 10–20 m. The second series of drilled holes, denoted as group ZD-II, were installed in the middle between two drilled holes in group ZD-I. The bottom diameter of the drilled hole is larger than 91 mm with a maximum vertical deflection of less than 1% of the depth of the drilled hole. The length of each grouted section is about 10–20 m with a grout pressure of 1.5–2.0 times the hydrostatic water pressure. The grout material is modified lake mud, which is an environmentally friendly material, and widely found on the surface of the mine pit. If the flow rate of the grout was less than 10 L/min for more than 20 min, grouting was considered to have been completed.

Automated grouting control system

An automated grouting control system was used in the curtain grouting project of the Chengmenshan copper mine. The computerized system controls the silo for raw material storage; water tank; high-speed variable frequency stirrer; low-speed stirrer; weight, pressure and flow sensors; high-pressure grouting pump (XPB-90EX pump with a maximum grout pressure of 25 MPa); sensing and control system; slurry delivery system; borehole deflection measurement and correction device; etc. The schematic diagram of the automatic grouting control system is shown in Fig. 5.

In preparation for the grout material, sedimentary lake mud was excavated and air-dried, crushed, and stirred to remove sand and gravel. The computer system can adjust the proper solid to liquid ratio to meet design requirements by using three

Table 1 General geologic stratigraphy of the studied area

Stratigraphic Unit			Thickness (m)	Lithology	Remarks
System	Formation	Unit			
Quaternary	/	Q	2–126	Gravelly clay, silt, silty sand, silty fine sand	Brown red, yellow brown, mainly distributed in the edge of rivers and lakes
Trias	Jialingjiang	T_2j	>500	Limestone, dolomitic limestone	Gray, grayish white, thick or huge thick layer, conformable contact relationship with Permian system
	Daye	T_1d	>200	Limestone with calcareous shale	Light gray, medium thick, containing a large number of calcite veins
Permian	Changxing	P_2c	41	Chert limestone, carbonaceous shale	Gray, dark gray, unconformable contact relationship with Carboniferous system
	Longtan	P_2l	0.1–11	Carbonaceous shale	Dark gray, black, intercalated with lenticular limestone
	Maokou	P_1m	450–500	Limestone	Grayish white, dark gray, thick, or huge thick layer
	Xixia	P_1q	130–150	Limestone	Dark gray, black, medium thick to thick layer
	Liangshan	P_1l	0–5	Carbonaceous shale and clay shale	Dark gray, thin layer
Carboniferous	Huanglong	C_2h	18–75	Limestone, dolomitic limestone, dolomite	Gray, flesh red, dense, and thick layer
Devonian	Wutong	D_3w	10–53	Sandy shale, quartz sandstone, gravelly quartz sandstone	Grayish white, unconformable contact relationship with Silurian system
Silurian	Shamao	S_3s	>200	Quartz sandstone, siltstone	Purplish red, intercalated with grayish-green shale, unconformable contact relationship with underlying strata

weight sensors installed at the bottom of the water tank and two storage silos for the dried mud. Dried mud and water can be fully and evenly mixed by using a frequency stirrer at varying high speeds. After thorough mixing, the slurry was pumped into a low-speed stirrer for grouting. Pressure and flow sensors were installed and connected in a series between the grouting pump and the pipe to monitor the progress of grouting and at the same time, collect data for analysis. The flow chart of the automated grouting system is shown in Fig. 6. This is a patented system invented by the North China Engineering Investigation Institute Company Limited (NCEIICL), which can greatly enhance grouting efficiency while ensuring quality and safety.

Grouting material

The material used for the grout curtain in the Chengmenshan copper mine was environmentally friendly and made from modified lake mud by mixing it with Portland cement and sodium silicate. The natural lake mud was excavated from the basin of the Sai Lake during the dry season when the mud was dried. Table 2 shows the basic physical and index properties of the natural lake mud, which show that the natural lake mud is classified as a silty clay with low plasticity based on the Standard for Engineering Classification of Soil (GB/T 50145-2007) (Standardization Administration of China 2007). Table 3 shows the results of the chemical composition of the lake mud. In the formation of the lake mud, its particle size distribution, geotechnical properties, and chemical composition are slightly different in different locations due to the differences in the rate of shrinkage and regional hydrodynamic conditions.

The Portland cement and sodium silicate used for the grout curtain were obtained from Jiujiang city, Jiangxi Province of China. Ordinary Portland cement with strength grade 42.5 (P.O 42.5) and sodium silicate of 40° Baume were used to improve the properties of the basic lake mud slurry. The addition of the Portland cement and sodium silicate can change the properties of the lake mud slurry, such as its flow pattern, time-dependent rheological properties, plastic strength, grout spreading range, permeability, water separating proportion, and groutability. In order to investigate the characteristics of the grout, a set of orthogonal experiments with three factors and three levels $L_9(3^3)$ were carried out. The parameters are the specific gravity of the basic lake mud slurry (A), amount of Portland cement (B), and amount of sodium silicate (percentage of the cement weight) (C). Table 4 shows the $L_9(3^3)$ experimental program. The three values for parameter A are 1.15 g/cm^3, 1.12 g/cm^3, and 1.10 g/cm^3; parameter B are 100 kg/m^3, 150 kg/m^3, and 200 kg/m^3; and parameter C are 2.5%, 5%, and 10%.

Experimental results and analysis

Rheological property of modified lake mud slurry

The rheological property of grouting material determines its pumpability and injectability. The flow diameter of modified lake mud slurry with different cement contents with 2.5%

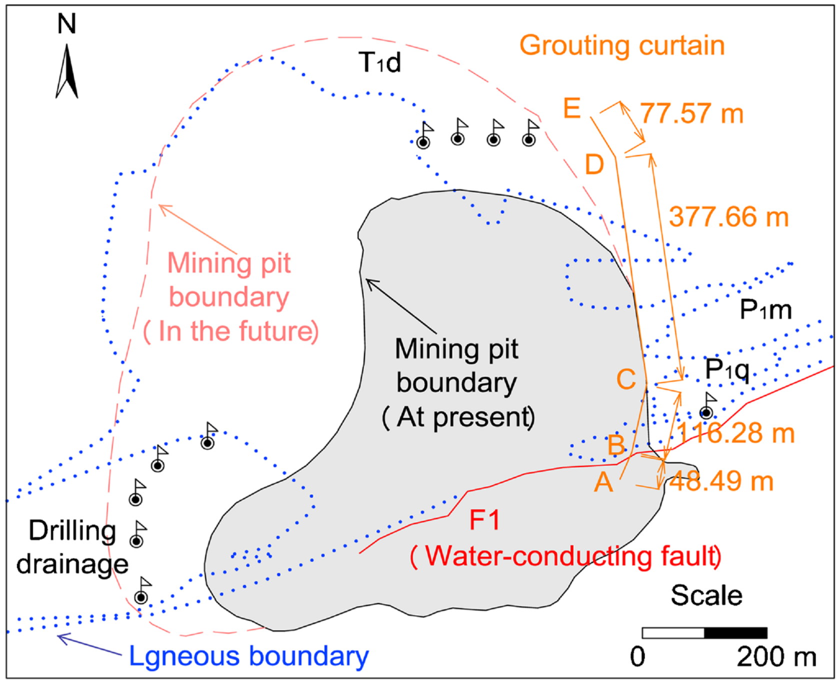

Fig. 3 Plan view of mine pit and water control schemes

sodium silicate is shown in Fig. 7. The test method of fluidity is based on the specification of "mine curtain grouting" (DZ/T 0285-2015) mainly compiled by NCEIICL (The Industry Standard Editorial Committee of the People's Republic of China 2015). As can be seen, the fluidity diameter of modified lake mud slurry decreases gradually with the increase of the added amount of cement and the specific gravity of the basic lake mud slurry. This is because, for one thing, sodium silicate has a coagulation promoting effect on cement particles, and it shortens the hydration process, which results in a small flow diameter, and, for another, the lake mud particles are finer, and the particles are mostly elliptical and spherical, which can accelerate the reaction time of cement and sodium silicate within a certain range.

Viscosity time-dependent behavior of modified lake mud slurry

The rheological response of the modified lake mud slurry can be approximated by using a typical Bingham fluid model with time-dependent viscosity. The time dependency of the viscosity is an important factor to account for the grout ability and extent of the effective diffusion of the grout due to the uneven spatial distribution of the grout with different viscosities in the

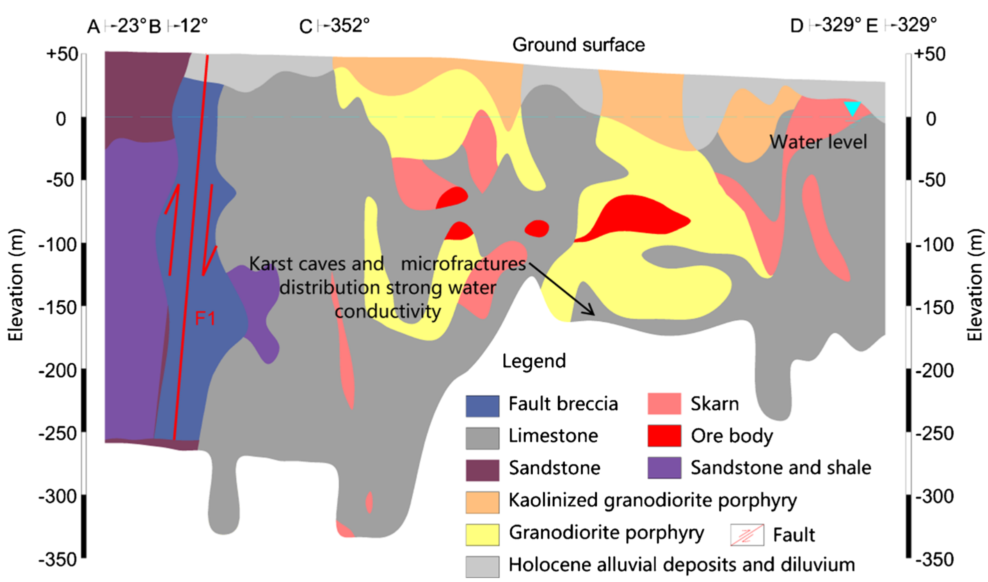

Fig. 4 Cross section of grout curtain in the Chengmenshan copper mine

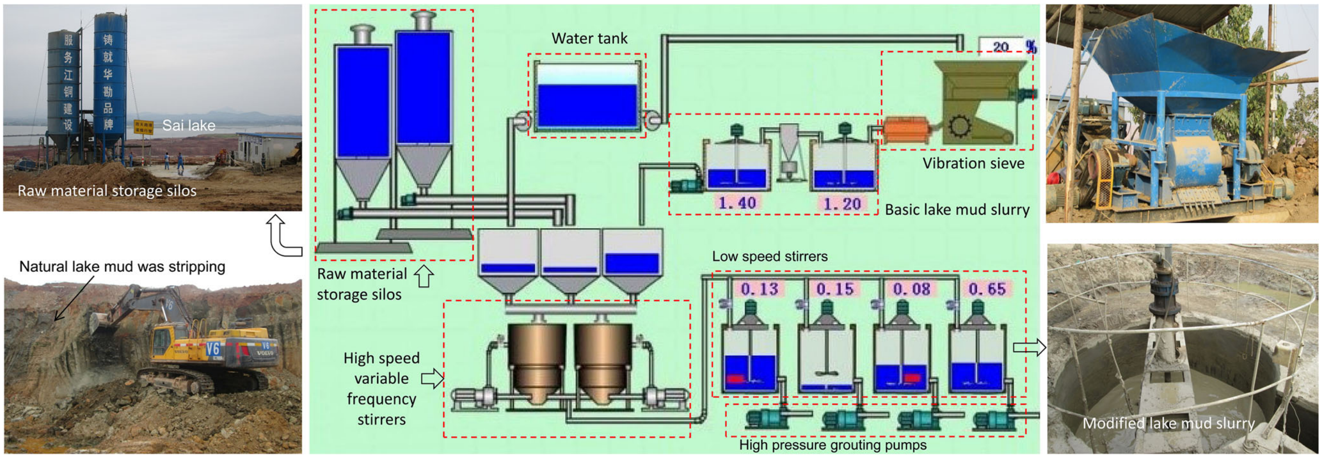

Fig. 5 Schematic diagram of the automatic grouting control system

diffusion regions (Zhang et al. 2015; Li et al. 2013). Considering the time taken from the completion of the preparation of the grout to the time of injection, the plastic viscosity is defined as the viscosity after 5 min that the grout preparation is completed, which can be measured by using a ZNN-D6 rotary viscometer. Using the Bingham model, the constitutive equation of the modified lake mud grout can be expressed as:

$$\tau = \tau_0 + \mu(t)\gamma \quad (1)$$

where τ is the shear stress of the modified lake mud slurry; τ_0 is the yield shear stress of the modified lake mud slurry; μ(t) is the time-dependent viscosity, and γ is the shear rate.

The effects of the influencing factors on the plastic viscosity can be determined by using variance analysis. The factors are the specific gravity of the basic lake mud, parameter A; the cement content, parameter B; and the percentage by weight of the silicate, parameter C. The mean values and the variances of these three parameters are shown in Table 5. The water separating proportion and degree of consolidation are also analyzed in the orthogonal experiments, and the results are also shown in Table 5. The specific gravity of the basic lake mud slurry (parameter A) has the most effect on the viscosity; namely, the mean and variance of parameter A are greater than those of parameter B, which are greater than those of parameter C. Therefore, in order to ensure the effectiveness of grouting, the specific gravity of the basic lake mud slurry should be strictly controlled.

Distribution of grout along the grouting curtain

Figure 8 shows the grout volume per unit length of the drilled holes of groups ZD-I and ZD-II, which is shown in black and blue lines, respectively. It can be observed that the grout volume per unit length of ZD-I is greater than that of ZD-II. The average grouting volume per unit length of ZD-I is 19 m^3/m, while that of ZD-II is 5 m^3/m, or 26.5% of the volume of ZD-I. The reduction in the grouting volume of ZD-II is due to the blocking of the main water flow channels from the ZD-I grouting program, thus reducing the connectivity of the fracture network in the aquifer. The reduction in the grouting volume of ZD-II also indicates that the ZD-II grouting is connected to the ZD-I grouted medium. Moreover, the grouted

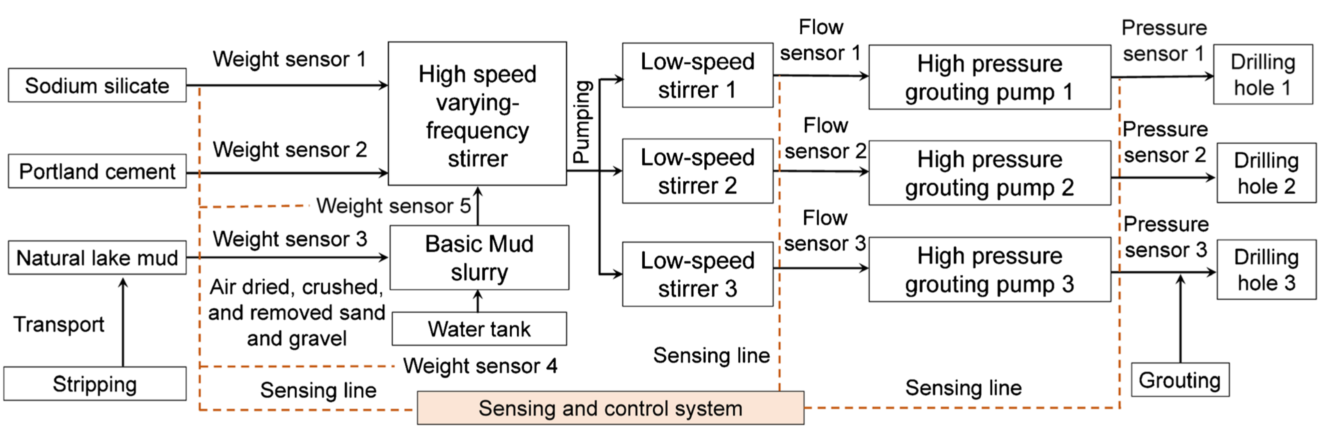

Fig. 6 Flow chart of the automatic grouting system

Table 2 Physical and index properties of natural lake mud

Specific gravity of solids	Maximum dry density (g/cm^3)	Void ratio	Permeability coefficient (cm/s)	Liquid limit	Plastic limit	Plasticity index	Liquidity index	Granulometric composition (%)			
								2–0.5 (mm)	0.5–0.25 (mm)	0.25–0.075 (mm)	<0.075 (mm)
2.71	1.67	0.622	1.2×10^{-5}	28.0	17.8	10.2	0.25	4	10.1	13.3	72.6

medium of ZD-I is further reinforced by the grout from the ZD-II blocking the residual fractures and forming a continuous and water tight grout curtain.

Grouting effectiveness analysis

The discrete coefficient is a measure to evaluate the effectiveness of grouting. The discrete coefficient can be calculated from:

$$\delta = \frac{\sigma}{\mu} = \frac{\frac{\sum_{i=1}^{n}\mu_i}{n}}{\sqrt{\frac{\sum_{i=1}^{n}\mu_i^2 - n\mu^2}{n-1}}} \quad (2)$$

where δ is the discrete coefficient, σ is the standard deviation of the grouting volume per unit length, n is the number of drilling holes, and μ is the average grouting volume per unit length. The average discrete coefficient of ZD-I is 0.513, and ZD-II is 0.426, which indicates that the main water flow channels have been blocked, and the grouting program is effective.

Water injection tests were carried out to evaluate the effectiveness of the curtain grouting program in six inspection holes. As shown in Table 6, the maximum permeability per unit length and the permeability of the hole are 3.13 Lu and 1.13 Lu, respectively, which indicate that the grouting program is effective and meets the design requirements (<5 Lu).

Discussions

Relationship between grouting volume of groups ZD-I and ZD-II

Figure 9 shows three hypothetical relationships between grouting volume of groups ZD-I and ZD-II, which reflects the influence of ZD-I on ZD-II. During the installation of the grout curtain, if the grout volume follows the pattern in Fig. 9a, namely the grout volume of ZD-I is greater than that of ZD-II for all of the drilled holes, this indicates that the grouting results are excellent, and the main water flow channels have been blocked. On the contrary, if the grout volume of ZD-II is greater than that of ZD-I for all of the drilled holes, this means that the first ZD-I grouting program is not effective since more grout is needed for the subsequent ZD-II program. Therefore, a continuous and tight water barrier has not been formed due to possible weak connectivity of the karst fracture network. There is a third type of relationship between ZD-I and ZD-II. There are some locations where the grout volume of ZD-II is greater than that of ZD-I. This means that the ZD-I program is not effective in some locations and the spacing between the drilled holes should be reduced. In the curtain grouting project of the Chengmenshan copper mine, the relationship between the grout volume of ZD-I and ZD-II (Fig. 8) follows Fig. 9a which suggests that a continuous and tight water barrier has been formed.

Chemical reaction of the natural lake mud, Portland cement, and sodium silicate

In the preparation of the grout, the cement powder gradually dissolved in the water and hydration started after mixing with the water. A gelatinous colloidal substance was precipitated and calcium hydroxide was produced:

$$3CaO\cdot SiO_2 + nH_2O = 2CaO\cdot SiO_2(n-1)H_2O + Ca(OH)_2$$

When sodium silicate ($Na_2O\cdot nSiO_2$) was added to the mud slurry and cement, the reaction of the sodium silicate with the calcium hydroxide produced the calcium silicate hydrate gel with a certain strength:

$$Ca(OH)_2 + Na_2O\cdot nSiO_2 + mH_2O \rightarrow CaO\cdot nSiO_2\cdot mH_2O + 2NaOH$$

Table 3 Results of chemical composition measurements of natural lake mud (%)

Sample	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	Na_2O	Loss on ignition (LOI)
1	61.77	15.88	5.19	2.66	1.39	1.07	0.57	11.47
2	72.07	11.80	3.42	2.16	1.04	1.02	0.98	7.51
Average	66.92	13.84	4.305	2.41	1.215	1.045	0.775	9.49

Table 4 Orthogonal experimental array $L_9(3^3)$ for the mixed slurry

Test no.	Test array $L_9(3^3)$	Test factors and levels		
		Specific gravity of the basic lake mud slurry (A), g/cm^3	Added amount of Portland cement (B), kg/m^3	Added amount of sodium silicate (percentage of cement weight) (C), %
1	A1B1C1	1.15	100	2.5
2	A1B2C2	1.15	150	5.0
3	A1B3C3	1.15	200	10.0
4	A2B1C2	1.12	100	5.0
5	A2B2C3	1.12	150	10.0
6	A2B3C1	1.12	200	2.5
7	A3B1C3	1.10	100	10.0
8	A3B2C1	1.10	150	2.5
9	A3B3C2	1.10	200	5.0

The reaction between the sodium silicate and calcium hydroxide took place quickly. While the reaction was taking place, more and more colloids emerged which increased the strength of the cement slurry. Therefore, the strength of the cement slurry is mainly due to the reaction between the sodium silicate and calcium hydroxide at the initial stage, while the strength of the cement slurry at the later stage is due to the hydration of the cement itself.

The ion exchange reaction in the sodium silicate and lake mud is as follows:

$$Ca^{2+}-(Clay-OH)_2 + Na_2O \cdot nSiO_2 \rightarrow 2Na^{+}-(Clay-OH)_2 + CaSiO_2$$

That is, some of the calcium clay was converted into sodium clay. The sodium clay has double ions and its layered structure is increased in thickness. Also, the stability and suspension ability of the sodium clay are high, and also generated relatively stable large calcium micelles of the silicon-silicon molecules, such that the original slurry thickened quickly.

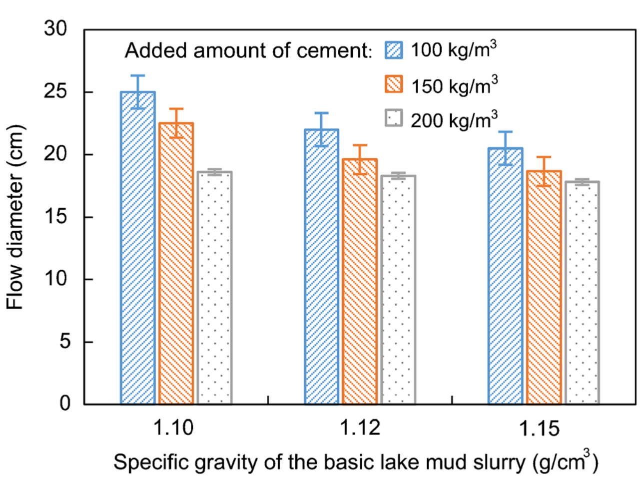

Fig. 7 Fluidity of modified lake mud slurry with 2.5% sodium silicate content

The reaction that took place between the free NaOH in the sodium silicate and lake mud is as follows:

$$Ca^{2+}-(Clay-OH)_2 + 2NaOH \rightarrow 2Na^{+}-(Clay-OH)_2 + Ca(OH)_2$$

Finally, some sodium clay and relatively stable calcium hydroxide micelles were formed.

Since the grout curtain is at the edge of the mine pit and within the reach of mine blasting, the grouting material used in the curtain grouting program of the Chengmenshan copper mine should be a ductile plastic material made of lake mud-cement-sodium silicate mixed material. The material has certain energy absorption, energy dissipation, and shockproof characteristics which provide a grout curtain with a certain level of earthquake resistance.

Conclusions

This paper presents a case study to examine the use of an environmentally friendly material made from modified lake mud in a grout curtain to control underground seepage in an open-pit mine in China. Based on an analysis of the regional tectonic framework and the geological and hydrogeological conditions of the Chengmenshan copper mine, a water control scheme has been adopted which is a combined method of drainage that uses drilled holes and seepage cut-off that uses a grout curtain. A 620-m-long grout curtain was installed east of the mine pit to intersect karstic fissures and channels and hidden tectonic fracture zones. An automated computerized grouting control system is used in the project. The system is a patent invention by NCEIICL, which can greatly enhance the efficiency of grouting and ensure the quality of the results and safety of personnel. The lake mud is modified by mixing it with Portland cement and sodium silicate for the installation of the grout curtain. The lake mud is an environmentally friendly and sustainable material which is widely found on the surface of the mine pit. The basic physical properties and chemical composition of the natural lake mud are then analyzed, and a set of orthogonal experiments with three factors and three levels $L_9(3^3)$ are carried out. The results show that the specific gravity of the basic lake mud slurry (parameter A) is the most important factor in the effectiveness of the grouting program which is indicated by the mean values of A >B >C. Therefore, in order to ensure the effectiveness of the grouting program, the specific gravity of the basic lake mud slurry must be strictly controlled. Moreover, the success of the grouting program

Table 5 Mean and variance of plastic viscosity, water separating proportion, and consolidation degree for parameters A, B, and C

Physical properties	Mean (K_{ij}) and variance (R)	Parameter A, g/cm^3	Parameter B, kg/m^3	Parameter C, %
Plastic viscosity, mPa/s	K_{i1}	13.07	14.10	13.83
	K_{i2}	16.03	15.33	15.90
	K_{i3}	18.73	18.40	18.10
	R	5.67	4.30	4.27
Water separating proportion, %	K_{i1}	1.18	0.82	0.70
	K_{i2}	0.60	0.67	0.63
	K_{i3}	0.17	0.46	0.62
	R	1.01	0.36	0.08
Consolidation degree, %	K_{i1}	96.00	96.68	97.37
	K_{i2}	97.45	97.80	97.48
	K_{i3}	99.17	98.13	97.77
	R	3.17	1.45	0.40

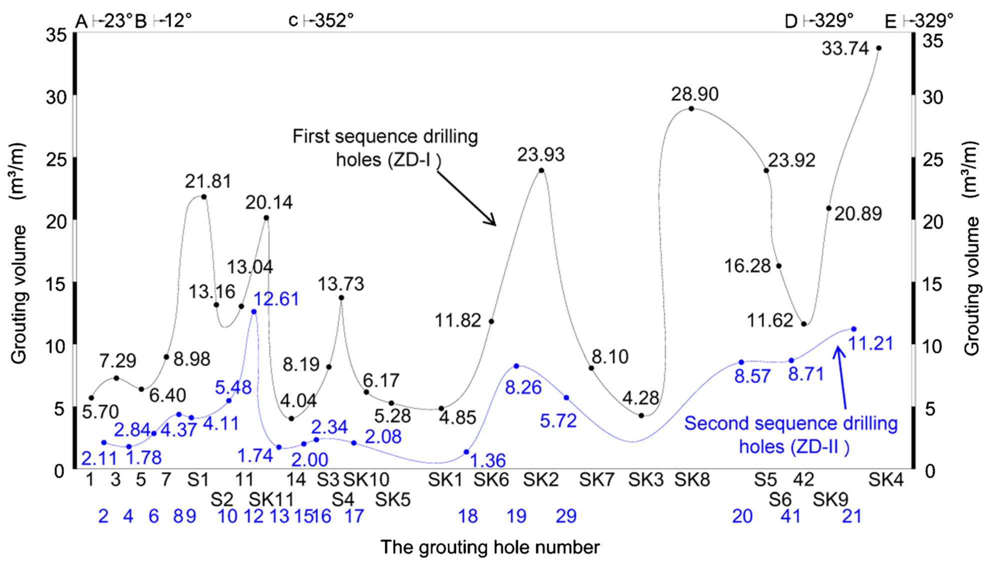

Fig. 8 Grout volume in each drill hole in groups ZD-I and ZD-II

is evaluated by examining the relationship between the grout volume used in ZD-I and ZD-II with a discrete coefficient based on water injection tests. Therefore, the karst fractures and tectonic fracture zone in the Chengmenshan copper mine are successfully blocked by forming a continuous and tight grout curtain east of the mine pit.

Table 6 Results of water injection test in six inspected drilled holes

Inspection hole	Permeability per unit length (Lu)			Permeability of the entire drilled hole (Lu)
	Maximum value	Minimum value	Average value	
J1	2.46	1.19	1.61	0.30
J2	1.58	0.90	1.17	0.29
J3	1.71	1.21	1.39	0.13
XJ1	1.61	1.10	1.41	0.51
XJ2	2.09	1.93	2.03	1.13
XJ3	3.13	1.98	2.72	1.03

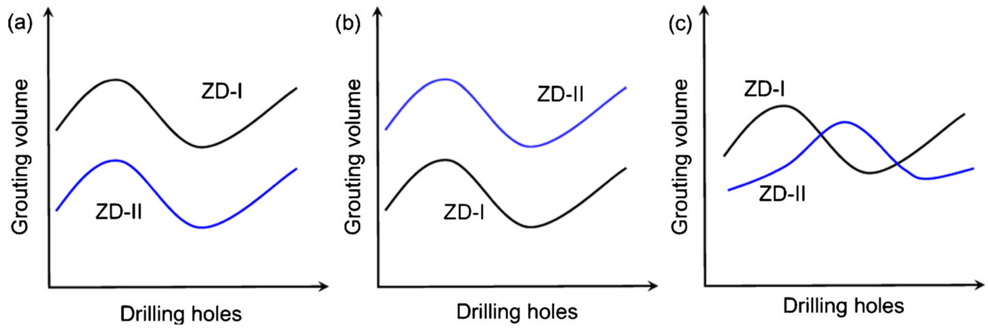

Fig. 9 **a**–**c** Various types of grout volume relationships between groups ZD-I and ZD-II

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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