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ENGINEERING SCIENCES

Experiments and Application of Reclamation of High-Mineralized Mine Wastewater for Confecting Grouting Slurry

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Abstract: Owing to the high mineralization and high treatment cost, Ordovician limestone water is often regarded as a mine wastewater. In order to make rational use of mine water with high mineralization and turn waste into treasure. In this work, the natural water quality of Ordovician mine water in the Weibei coalfield had been tested, and the suspended matter and trace elements of Ordovician mine water in the selected deep detained area had been further tested. As a contrast, the water quality of Ordovician mine water after heating and concentration had been tested. The mechanical and hydraulic parameters of concentrated mine water-loess and concentrated mine water-cement slurry had been tested and compared with conventional slurry. The results showed characteristics of deep detained Ordovician limestone mine water is high salinity, certain suspended matters, limited special material and high permanent hardness. However, compressive strength of loess samples increased, while the permeability reduced. The initial setting-time of the modified material was short, while it showed an increased compressive strength. In practical terms, the quantity of grouting produced in engineering applications can be reduced by 16%, whereas the discharge of high-mineralized mine water can be decreased by about 40,000 m^3/a.

Key words: mine water, mineralized, coal mining, water-proof material, grouting.

INTRODUCTION

Coal resource in China is mainly distributed in six regions, including North China, South China, Northeast China, Northwest China, Tibet and Taiwan, while the Coal mining in North China is seriously threatened by water damage from coal floor (Li & Chen 2015, Shi & Singh 2001, Wu et al. 2011). The main source of water inrush from coal floor is the Ordovician limestone confined aquifer (Figure 1). Due to the huge aquifer thickness, water volume and water pressure, the aquifer is difficult to manage.

Water inrush from coal floor has been studied for more than 80 years, and the most widely used method is water inrush coefficient method. The water inrush coefficient (*Ts*), defined as the water pressure that can be sustained by the unit aquiclude thickness of the coal seam floor, was first put forward at the Jiaozuo Mine Water Control Conference in 1964 (Liu 2009). Subsequently, this method has been perfected many times. At present, it is considered that the water inrush from the floor mainly depends on two factors, the effective thickness of the intermediate strata (between the coal seam and the Ordovician limestone confined aquifer) (Qiao et al. 2009, Yao et al. 2012) and the pressure of the Ordovician aquifer on the intermediate strata.

Based on the theory of water inrush coefficient, Chinese engineers put forward 3

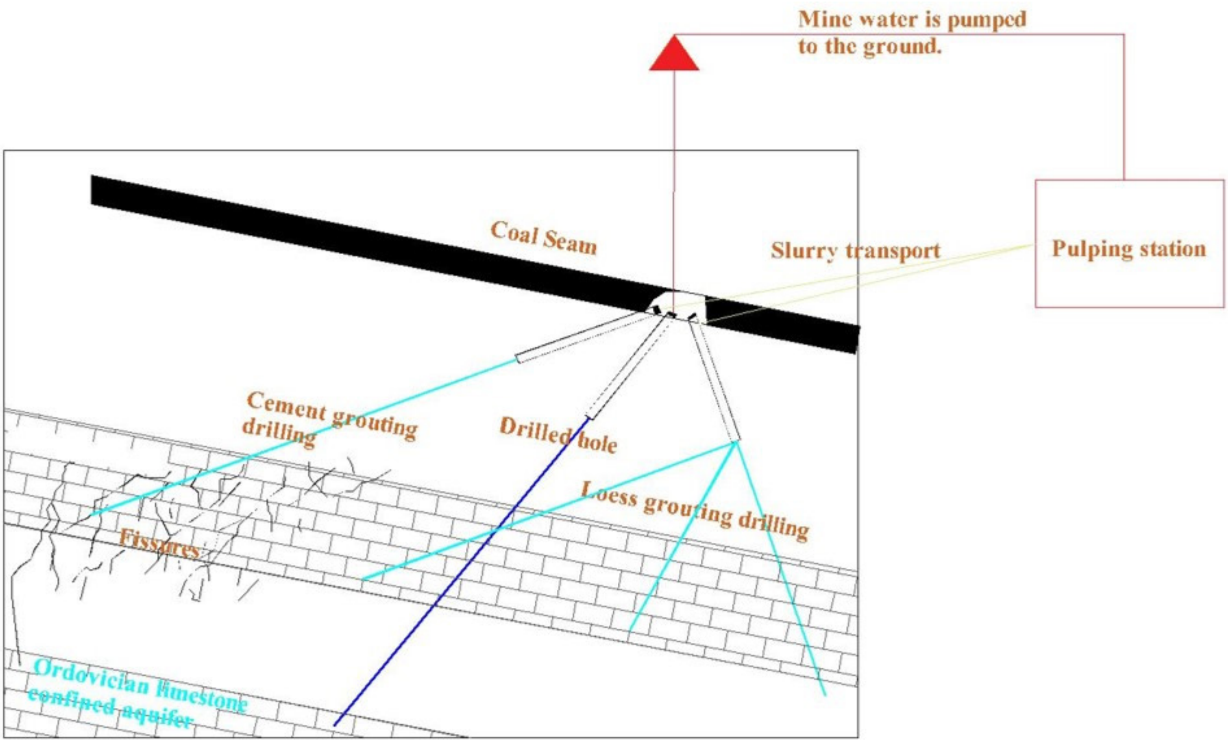

Figure 1. Spatial relationship between mining coal seam and Ordovician limestone aquifer in North China.

solutions for water damage of coal floor. The first plan is to drain the Ordovician aquifer. The first method is to drain the Ordovician aquifer, through which the water pressure on the middle stratum (between the coal seam and the Ordovician limestone confined aquifer) can be greatly reduced, thereby reducing the occurrence of water damage of coal floor. But the disadvantage of the first method is that it produces a large amount of clean mine water, which has very little suspended matter (not directly discharged into the mining space) but is highly mineralized. This kind of mine water is generally treated by ion exchange, membrane separation, reverse osmosis and other methods (Tuttle et al. 1969, Garcia et al. 2001, Feng et al. 2000, Christensen et al. 1996, Valenzuela et al. 2005, Lange et al. 2010, Wolkersdorfer & Boewll 2004, Chen et al. 2019, Liu et al. 2018, Li 2018, Lu et al. 2018), while the treatment cost too much. The second method is to reinforce the middle stratum by grouting (Li et al. 2015, Liang et al. 2015, Han et al. 2009). For the poor water resisting stratum, the injected slurry is mainly clayey soil. For the naturally fractured area with low strength, cement is the main injection. The effect of the second method is to greatly increase the effective water barrier thickness of the middle stratum, thereby reducing the occurrence of water damage of coal floor. The defect of the second method is that the cost of grouting project is very huge, the grout injected into a coal mining face is more than 50,000 m^3, in addition, grouting project also consumes a large amount of water resources, resulting in the waste of water resources. The third method is a combination of the first two. The third method balances technical security with economic efficiency, but its drawbacks inherit the first two. It is an important scientific research and production topic how to exploit the coal resources in this area by synthetically considering the factors of safety, economy and environmental protection.

Coal mining in North China extends deep at a rate of about 12m/a, generally reaching a mining depth of 1000 meters. Because the clean mine water in Ordovician limestone aquifer of deep mine drainage is generally rich in various minerals and its salinity is generally greater than 1 g/L, the difficulty and cost of treatment in deep mine water is much higher than that of shallow mine water. However, deep mine water has the potential characteristics of modified floor grouting material, so relevant research can be attempted.to broaden the utilization direction of this kind of clean mine water and reduce the drainage of mine water.

In this paper, by comparing the water quality before and after heating of deep Ordovician mine water and the performance of slurry prepared by concentrated mine water, the potential characteristics of mine concentrated water used in coal mine waterproof slurry had been analyzed. Through practical engineering test, it is feasible to use concentrated mine water for mine water hazard prevention and control (Figure 1). This provides a new way for mine water recycling.

MATERIALS AND METHODS

Preparation of Mine Water for Grouting Materials

In this work, a total of 10 Ordovician limestone groundwater samples were collected from Weibei Coalfield, Shaanxi Province, China. The sampling area covered the mining areas of Chenghe, Hancheng, Pubai, and Tongchuan. The study area and sampling locations are shown in Figure 2. Table I presents various characteristics of the collected samples.

As shown in Figure 1, there are two Ordovician limestone hydrogeological units in Weibei Coalfield. One is the Hancheng unit, which includes the Hancheng mining area, while the other is Heyao unit and includes the mining areas of Chenghe, Pubai, and Tongchuan. Sample H1 to H6 (Table I) were collected in deep detained Ordovician limestone mine water of Hancheng hydrogeological unit, and the depth of sampling is below 1000 m from ground

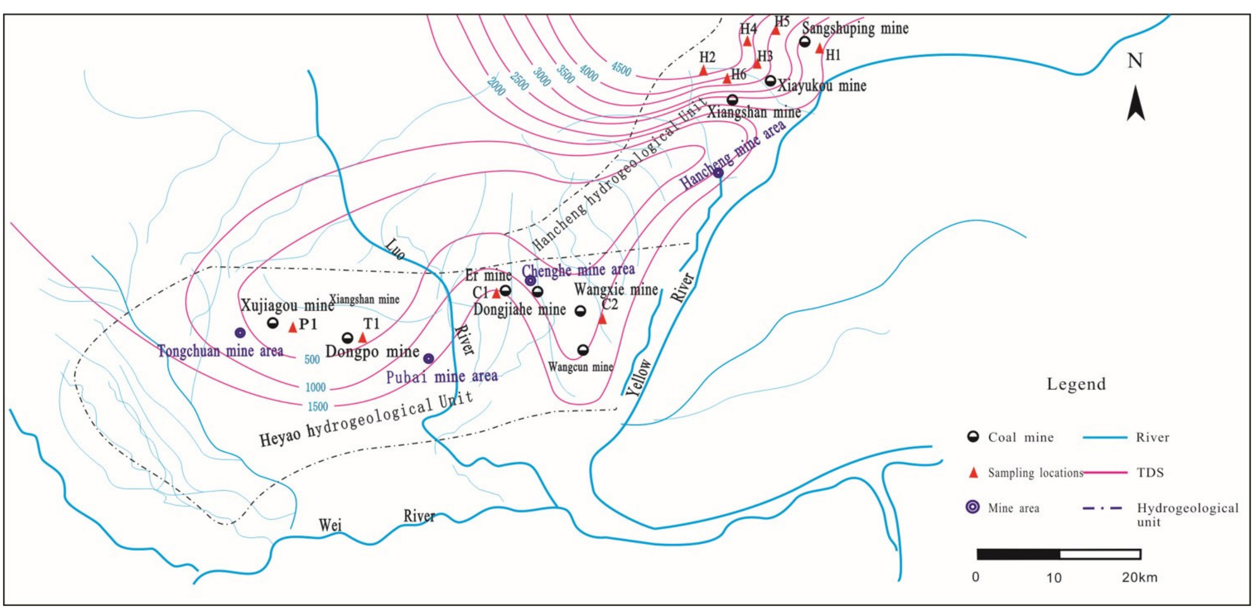

Figure 2. Locations of the study area and sampling.

surface. The total dissolved solids (TDS) in H1 to H6 samples were higher than in others (Table I), and varied within the range of 2379.0 - 4614.2 mg/L. This indicated a longer residence time for the groundwater (and water-rock interaction), which resulted in more dissolution of minerals. The dominant cations in H1 to H6 samples were determined to be Ca^{2+}, and Na^{+}, which were followed by Mg^{2+}, whereas the dominant anions were Cl^{-}, SO_4^{2-} and HCO_3^{-}.

The Ordovician limestone layer is exposed to surface in Tongchuan and Pubai mining areas, due to which, the Ordovician limestone water circulates in shallow depths. The water samples, T1 and P1 (Table I) were collected from Tongchuan and Pubai mining areas. Both the T1 and P1 were alkalescent in nature. Chenghe mining area is an Ordovician limestone water run-off area. The water samples C1 and C2 (Table I) were collected from this mining area (Chenghe). The total dissolved solids (TDS) in C1 and C2 were found to lie between the values for samples collected from Hancheng and Tongchuan-Pubai mining areas.

Based upon these results, the Hancheng is the most suitable reservoir among all to modify and test the loess and cement grouting materials for Ordovician limestone mine water. All mine water samples were taken from the deep detained reservoir of Hancheng mining area.

The deep detained Ordovician limestone mine water samples were tested for suspended matter. The results showed that the suspended matter was present in the concentration of 121 mg/L. The particle sizes of the samples were also analyzed using the laser particle size analyzer. The <5 μm particle size fraction constituted 68% of the total particles, whereas <10 μm size fraction constituted 98% of the total particles in the tested samples.

Furthermore, in conventional cement, the <80 μm size fraction constitutes about 5% of the total particles, whereas in super-fine cement, <5 μm size fraction constitutes about 60% of the particles. Compared with the above cement grouting material, the cement grouting material modified using Hancheng mine water produces finer diffusivity and intensity. This is due to the reason that the particle size of suspended matter is small, while the specific surface area is large, due to which, the hydration reaction is fast. It has been reported that suspended matter can improve the strength of cement.

Based on the water quality analysis, trace elements in the three mine water samples were determined. There were 45 different elements present in the water samples, and included Sc, Be, Ti, Mn, Cr, Cu, Zn, Ga, Rb, Y, Nb, Mo, Cd, Sb, Ni,

Table I. Results of Ordovician limestone water quality analysis.

No.	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	SO_4^{2-}	HCO_3^{-}	Cl^{-}	pH	TDS
H1	202.30	9.70	405.10	63.90	1001.40	421.50	270.60	6.48	2379.00
H2	408.10	19.40	835.90	151.10	2237.00	307.50	641.40	7.42	4614.20
H3	359.30	26.20	684.10	91.40	1744.40	583.10	325.60	7.26	3826.30
H4	390.20	14.90	533.50	184.60	2102.10	222.40	716.30	7.09	4375.30
H5	488.90	10.60	435.40	147.50	1522.30	248.00	595.30	7.18	3497.80
H6	545.20	13.90	513.10	171.40	1762.50	229.10	649.40	7.01	3879.00
C1	102.10	10.00	215.30	87.80	602.40	319.20	200.70	7.60	1545.80
C2	109.10	13.40	146.20	50.70	625.60	297.90	115.10	7.50	1364.60
T1	3.50	-	88.10	29.20	168.10	274.60	12.40	8.00	575.90
P1	5.70	-	66.10	24.90	22.10	295.90	10.60	8.00	425.50

Unit: mg/L except pH.

Cs, Co, Ba, La, Ce, Lu, Pr, Nd, Sm, Tl, Eu, W, Gd, Bi, Tb, Pb, V, U, Dy, Sr, Th, Hf, Ho, Yb, Er, Tm, and F. The results for the presence of trace elements in mine water samples are listed in Table II.

The results show that the trace elements were present within the normal ranges except for Sr (which varied between the concentration range of 2415 - 12797 μg/L) and F (which varied between the concentration range of 8235 - 3548 μg/L). Sr element is alkaline earth metals, so it can promote hydration reaction of cement. F element is also can promote hydration reaction of cement.

The results also showed that Cu etc. heavy metal elements are limited in this mine water sample, heavy metal ions such as Cu will replace low-priced ions adsorbed by clay, resulting in changes in clay structure and deterioration of clay slurry performance. So, it is avoided negative impacting on strength and permeability of clay grouting material modified by this mine water (Bu 2012). Similarly, the contents of radioactive elements, such as Th and U were low in the samples, and did not pose any threat to human health. Sr is an alkaline earth metal, and can promote the hydration reaction of cement. Additionally, F can also promote the hydration reaction of the cement.

The deep detained Ordovician limestone mine water samples were concentrated to 30% and 50% of the original volume at 60 °C and atmospheric pressure with experimental heater (Figure 3). The water quality analysis results for the concentrated samples are compared with the untreated water sample, and the results are presented in Table III. Based upon the results, following observations can be made.

Observation 1: The ionic concentrations in water samples increased after heating and concentrating, except for the HCO_3^- ions, which was due to its thermal decomposition at 60 °C However, the concentration of HCO_3^- was very

Table II. Results of Ordovician limestone water trace element determination.

No.	Li	Be	Sc	Ti	V	Mn	Cr	Co
1	106	0.033	14.1	2.73	54.6	149	78	2.08
2	73.4	0.161	10.5	1.14	6	8.23	70	0.438
3	198	<0.002	11.3	2.91	26.4	7.53	32.8	3.71
No.	**Ni**	**Cu**	**Zn**	**Ga**	**Rb**	**Y**	**Nb**	**Mo**
1	28.9	8.15	35.3	0.125	17.4	0.062	0.027	1.63
2	6.15	3.78	17.9	0.025	23.4	2.22	0.002	0.959
3	48.6	10.1	25.4	0.069	17.1	0.154	0.018	0.949
No.	**Cd**	**Sb**	**Cs**	**Ba**	**La**	**Ce**	**Pr**	**Nd**
1	0.006	0.302	0.625	20.5	<0.002	<0.002	<0.002	<0.002
2	0.002	0.414	1.3	46.6	0.069	0.282	0.086	0.615
3	0.005	0.292	0.866	10.9	<0.002	<0.002	<0.002	<0.002
No.	**Sm**	**Eu**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**
1	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
2	0.247	0.065	0.286	0.05	0.31	0.067	0.206	0.024
3	<0.002	<0.002	<0.002	0.002	<0.002	0.003	<0.002	<0.002
No.	**Yb**	**Lu**	**W**	**Tl**	**Pb**	**Bi**	**Th**	**U**
1	<0.002	<0.002	0.145	0.007	<0.002	<0.002	<0.002	1.64
2	0.138	0.018	<0.002	<0.002	<0.002	<0.002	0.017	0.069
3	<0.002	<0.002	0.028	<0.002	0.003	<0.002	0.015	0.07
No.	**Sr**	**In**	**Zr**	**Hf**	**F**			
1	4011	0.005	0.009	<0.002	823			
2	2415	<0.002	0.017	<0.002	1532			
3	12797	<0.002	0.012	<0.002	3548			

Unit: μg/L.

small, and therefore, there was only a slight consumption of calcium and magnesium ions. Ions including Ca^{2+}, SO_4^{2-}, and Cl^- are beneficial to modifying the grouting, and their concentrations increased after the heating and concentrating process., unlike HCO_3^- which decreased after the heating and concentrating process. In general, 1 mol of Ca^{2+} or Mg^{2+} could be consumed by 2 mol of HCO_3^-. Due to the limited concentration of HCO_3^- in the mine water, only a few calcium and magnesium ions were consumed during the process of concentrating the samples. As a result, the ionic concentrations (except for the bicarbonate) increased after the process of heating and concentrating.

Observation 2: During the heating process, almost 10% of the total hardness (carbonate hardness) significantly decreased, and about 90% of the total hardness (non-carbonate hardness) remained. These results were obtained for the mine water sample, which was concentrated to 30% of the original volume. The results also showed that, higher the concentrations of ions, stronger the impact was on the modification of grouting.

Observation 3: The pH value of water samples increased a little after the heating and concentrating process. Based on the study of Ma et al. (2013), with the increase in pH value, the rate of hydration of cement was accelerated. Additionally, the unconfined compressive strength increased for the pH value of less than 12.

Therefore, the above heating and concentrating of mine water was found to be more suitable for modifying grouting materials.

Preparation of Loess Grouting Materials

The loess samples of Lishi group were collected from Hancheng mining area. For these samples, the X-ray diffraction and particle size determination were performed. The results are presented in Tables IV and V.

The loess is mainly composed of montmorillonite mineral, which is beneficial for the expansion and waterproofing (phyllosilicat smectite is representing montmorillonite in Table IV). Additionally, the loess consisted of silt (highest content), clay particles, and sand content (lowest content) (Table V).

A total of 4 kinds of sand removing loess samples were taken and separately mixed with super-ultrapure water, deep detained Ordovician limestone mine water, and 30% and 50% concentrated mine waters for 5 days. The variable head penetration and unconfined

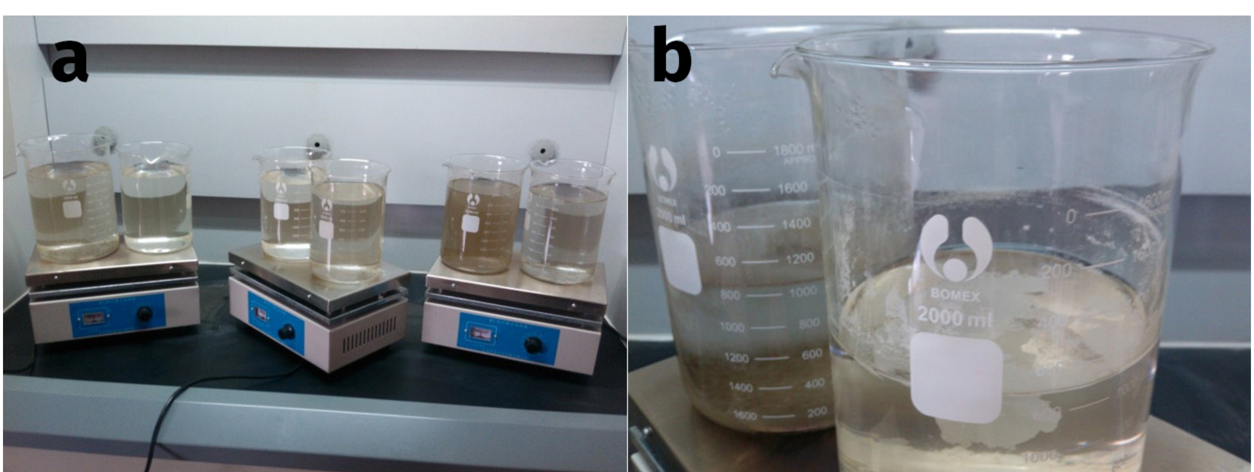

Figure 3. (a) Mine water heating and concentrating (b) After heating and concentrating.

compression tests of mixed loess samples with 18% of water content, and the results are presented in Table VI. In addition, after being dried, crushed and sieved, the viscosity tests of the soaked loess samples were carried out. The results were compared with the test results of the untreated loess samples at the similar temperature (15 °C), similar solid-liquid ratio (1:1), similar experimental time (in the first min after pulping), and similar solution (ultra-pure water). The results are presented in Table VII.

Preparation of Cement Grouting Material

A total of 3 kinds of cement grouting materials were prepared using a water/solid ratio of 1:2. In the first type, deionized water was mixed with 325 Portland cement, whereas in the second, 50% concentrated mine water was mixed with 325 Portland cement. For the third type, 30% concentrated mine water was mixed with 325 Portland cement. Then, the unconfined compressive strengths with the conservation of water at 20 °C were conducted. In addition, the initial setting times of the cement samples were also determined. The initial setting times and the average unconfined compressive strengths after 1 day, 3 days, and 28 days for the 6 samples of each type were determined, and the results are presented in Table VIII.

In addition, based upon the water-to-cement ratio of 1:2, two kinds of cement slurries were prepared using 50% concentrated mine water and ultra-pure water. After the completion of slurry preparation, the viscosities were measured at 0 min, 20 min, 40 min and 60 min using Markov funnel. Considering the influence of temperature, the ambient temperature was kept constant at 15 °C during the tests. For each sample, the test was repeated thrice, and the average value was used for further analysis. The viscosity of two kinds of slurries under different times is shown in Figure 4.

RESULTS

Experiments on loess grouting materials modified by the Ordovician limestone water obtained from the deep detained reservoir

As presented in Table VI, the unconfined compressive strength of loess samples, modified by the concentrated deep detained Ordovician limestone mine water increased. Meanwhile, the permeability coefficients decreased. The mechanisms for both the processes can be described as follows.

(1) Carbonate and other substances in soil and solution will flocculate and precipitate under the influence of either physical or chemical reaction. The precipitates obtained from the reaction between Ca^{2+} of concentrated mine water and CO_3^{2-} of loess blocked a certain number of pores in the loess samples. Due to this reason, the permeability of the modified loess was reduced.

(2) The activity of high-valent ions was greater than that of the low-valent ions. The adsorption of high-valent ions on soil particles was higher than that of the low-valent ions in the single-ion solution. The increase in ionic concentration or the potential, which is caused

Table III. Results of concentrated mine water quality analysis.

Concentration degree	Ca^{2+}	Mg^{2+}	SO_4^{2-}	HCO_3^-	Cl^-	Na^+	TDS	pH
Non	816.81	131.34	2213.03	299.63	639.57	398.08	4518.34	6.96
50%	1160.86	206.32	3457.96	172.87	1367.46	775.63	7176.81	7.74
30%	1769.22	394.47	4967.34	58.34	1939.11	1245.33	10421.12	8.09

Unit: mg/L except pH.

by the replacement of monovalent ions by the di-valent ions, will result in the reduction of interlayer repulsion force, thereby causing the aggregation of soil particles. The double layer structures of clay particles flocculated, because Ca^{2+} in the concentrated mine water replaced Na^{+} in the loess (Table IX) in neutral and alkalescent solution. Due to this reason, the compressive strength of loess samples increased. In addition, as the pH of the concentrated mine water increased, its adsorption capacity for ions became stronger, which further strengthened the adsorption of Ca^{2+}.

(3) In a multi-ion system, high-valent ions are more competitive. The mine water was precisely a multi-ion system, which further enhanced the adsorption of high-valent ions. Based upon a previous work, in addition to Na^{+} ions, Ca^{2+} also enhanced the strength of soil. Additionally, the dominant cations of concentrated mine water were found to be Ca^{2+}, and Na^{+} (Table III).

(4) There were many types of cations in the concentrated mine water. Among them, Ca^{2+} was the most abundant, followed by Na^{+}. Additionally, the calcium ions are divalent ions and exhibit a stronger adsorption potential. Therefore, they were the most adsorbed and exchanged by loess after soaking in the concentrated mine water, followed by the Na^{+} ions. Furthermore, large addition of calcium ions made the structure of double electric layer of the soil thinner, due to which, the structure of the soil flocculated. The flocs reduced the viscosity of slurry and made it more fluidic and injectable.

Experiments on the cement grouting materials modified by the Ordovician limestone water obtained from the deep detained reservoir

Using the coal mine water, the initial setting times of samples were found to be short, while the strength of early and later stages also improved. In addition, the viscosity of cement paste, produced using the concentrated mine water, increased due to the presence of rapid-setting of early-strength ions.

The mechanisms for the process can be explained as follows.

(1) This is mainly related to the concentrations of Ca^{2+}, SO_4^{2-}, Cl^{-}, and other well-known early-strength ions in the mine water. It is worth noticing that the amount of SO_4^{2-} in the cement admixture was low (except for the coal seam floor grouting) because there was no rebar to be added.

(2) Compared to the single component early-strength ions, the multicomponent early-strength ions can promote early-strength more. The electronic microscope observation showed that the mine water modified samples were smoother and their cementing properties were far better.

(3) Although the conventional quick-setting early-strength chemical additives will enhance the early strength of the cement slurry, they will have some damage in the later-stage strength. In comparison, mine water was rich in various fine, suspended particles, which were beneficial to improve the late-stage strength of the cement slurry.

Table IV. **Results of X-ray diffraction test.**

No.	S	I/S	I	K	Cl	O
1	25	15	22	26	10	2
2	24	15	25	23	11	2

Unit: %, S: Smectite, I/S: Illite-smectite, I: Illite, K: Kaolinite, Cl: Chlorite, O: Others.

Table V. Results of loess particle size analysis.

No.	>50μm(sand particle)	5~50μm(silt particle)	<5μm(clay particle)
1	12.7	72.4	14.9
2	10.4	58.9	30.7

Unit: %.

Table VI. Physical properties comparison of loess with mine water modification.

No.	Concentrated percentage of mine water (%)	Permeability coefficient (m/d)	Unconfined compressive strength (kPa)
1	Super ultrapure water	0.082	102
2	100	0.026	128
3	50	0.011	148
4	30	0.009	169

Table VII. Viscosity of modified loess by concentrated mine.

No.	1	2	3	4	5	6	7	8
Soaking solution	Ultra-pure water				Concentrated mine water			
Viscosity	30.5	30.0	31.0	30.5	29.5	29.5	29.0	28.5
Average viscosity	30.5				29.1			

Unit: second.

Table VIII. Physical properties comparison of cement with mine water modification.

Mixed with cement	Initial setting time (min)	average unconfined compressive strength (d)		
		1	3	28
Deionized water	205	6.5	19.6	49.3
50% Concentrated mine water	170	8.2	24.9	57.6
30% Concentrated mine water	150	9.8	27.3	66.4

Unit: MPa.

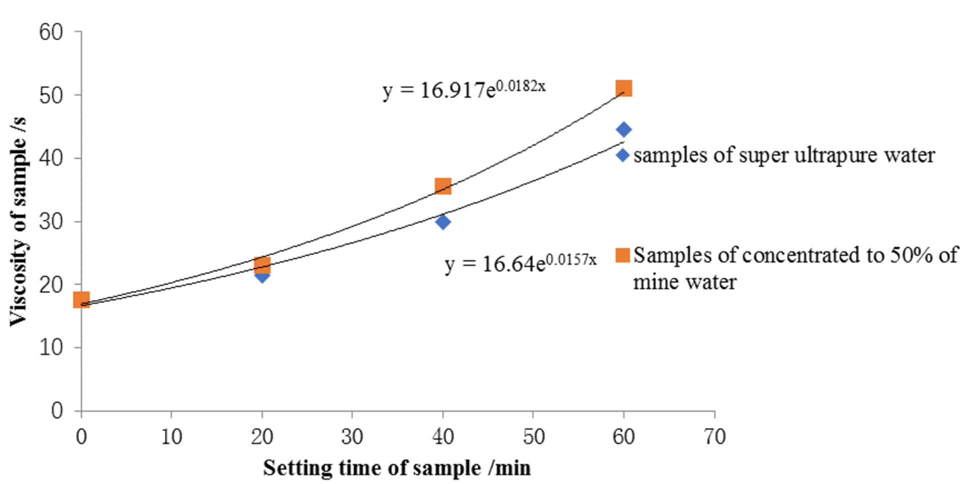

Figure 4. Influence of concentrated mine water on cement paste viscosity.

Table IX. Variations of element adsorbed by loess with mine water modification.

Major elements in soil	50% Concentrated mine water	30% Concentrated mine water	Original soil
Na	0.687	0.896	0.505
Mg	0.924	0.889	0.935
Al	7.905	7.865	8.261
Si	32.878	29.744	38.717
K	1.178	0.976	1.516
Ca	2.789	3.764	0.562
Fe	3.458	3.143	3.631
Cu	0.0018	0.0016	0.0029
Zn	0.005	0.006	0.009
CO_3^{2-}	4.235	2.755	8.659
P	0.0150	0.0151	-

Unit: %.

Figure 5. The ground grouting system (a) where mine water is concentrated and the ground grouting system (b).

ENGINEERING APPLICATION

Engineering introduction

The location for engineering application as selected to be Hancheng mining area of Weibei coal field, China. The target of grouting was the floor of coal seam. The main mining coal seam was No. 11 in Hancheng mining area. There was an aquifer under No. 11 coal seam, and the distance was 20 - 30 m. In order to prevent water from rushing into the goaf, the stratum between No. 11 coal seam and aquifer was reinforced using grouting before excavation. In this study, the loess modified by the concentrated mine water (degree of concentration was 50%), instead of the natural loess, was used as the grouting material. In the area of structural development, a small amount of cement slurry mixed with concentrated mine water will be added to replace the normal cement. The mine water is concentrated using solar energy, and the ground grouting system is automated.

Grouting thickness design

(1) Design basis for the grouting thickness

Duan Hongfei proposed that the water resistance per meter rock P_{zi} was related to the strength of rock's expansion limit (long term strength). The water resistance per meter rock can be calculated by Equation (1).

$$p_{zi} = \alpha_i \cdot \sigma_{ci} \quad (1)$$

where P_{zi} is the average water resistance of the bottom layer *i* (MPa/m), σ_{ci} is the strength of rock's expansion limit (MPa/m) which is tested by triaxial test considering confining pressure and α_i is the conversion coefficient of average water resistance of the bottom layer *i* (m^{-1}).

(2) Design of grouting thickness

The comparison test conducted using the low-pressure three-axis servo instrument showed that the value of σ_{ci} after the loess modification increased by 19.5%. Under the similar water pressure, the total water pressure resistance of the rock stratum, which did not occur during the water inrush, was quite evident. According to the principle of effective stress, the water pressure resistance after grouting was due to the water pressure resistance of the grouting material. Therefore, with any grouting material, the increase in water resistance was calculated using Equation (2).

$$h_1 \cdot \alpha_1 \cdot \sigma_{c1} = h_2 \cdot \alpha_2 \cdot \sigma_{c2} \quad (2)$$

where h_1 is the grouting thickness of natural loess (MPa/m), α_1 is the conversion coefficient of average water resistance of the bottom layers (m^{-1}), σ_{c1} is the strength of natural loess' expansion limit (MPa/m), h_2 is the grouting thickness of modified loess (MPa/m), α_2 is the conversion coefficient of average water resistance of the bottom layers (m^{-1}) and σ_{c2} is the strength of modified loess' expansion limit (MPa/m).

Therefore, when the conversion coefficient was constant, the modified loess grouting thickness was 0.84 times that of the natural loess grouting thickness.

Analysis of grouting effect

There were some high-mineralized mine water gushing points in the coal mine of Hancheng mining area, whereas the stable water inflow was around 70 m^3/h. Most of the mine water was raised to the ground in Yellow River branch of the water system, the surface water was seriously polluted. The application of the modified grouting material using concentrated mine water has the following characteristics.

(1) On average, if a coal-mine's face grouting requires around 50,000 m^3 of natural loess and cement grouting material, the use of modified grouting material prepared using concentrated mine water reduces the amount by 16%, and

therefore, only 42,000 m^3 of modified grouting material is needed for the similar mine.

(2) Due to the reduced injection (by 16%), the two coal mining faces were safely recovered and around 375,000 tons of coal resources were collected.

(3) About 80,000 m^3 high mineralized mine water was used in the two coal-mining face-grouting projects, which effectively reduced the sewage efflux, the use of chemical additives in the slurry, and the environmental pollution.

CONCLUSIONS

In this paper, hydrological and mechanical properties as well as the mechanisms of loess and cement grouting materials modified by concentrated Ordovician limestone mine water from deep detained reservoir were studied using suitable experiments. The approach was then applied to a mining area in China. Based upon results, following conclusions are drawn.

1) There is a kind of mine water, which is characterized by high mineralization, varying from 2379.0 to 4614.2 mg/L, certain amount of suspended matter of 121 mg/L, limited amounts of special materials and high permanent hardness. The cost of this kind of mine water for recycling and utilization is high. However, the increased Ca^{2+}, SO_4^{2-}, Cl^-, pH values and the reduced HCO_3^- in the concentrated mine water are beneficial for the modification of coal floor waterproofing materials.
2) Loess grouting material modified by concentrated Ordovician limestone mine water obtained from the deep detained reservoir undergoes flocculation of clay particles' double layer structures. Therefore, the modified loess grouting material exhibits better water resistance and strengthening effect for coal floor waterproofing.
3) Cement grouting material modified by concentrated deep retention reservoir Ordovician limestone mine water has multi-component early-strength ions. Therefore, the modified cement grouting material has quicker initial setting time and better strengthening effect for coal floor waterproofing.
4) The engineering application shows that the amount of grouting material is reduced by 16%, and the discharge of highly mineralized mine water is reduced by about 40,000 m^3/a.

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Tao Li & Ying Gao contributed to the conception of the study. Tao Li, Yu Liu & Ying Gao performed the experiment. Tao Li & Junwei Yang contributed significantly to analysis and manuscript preparation.