Mine Water Environ (2018) 37:366–375
DOI 10.1007/s10230-017-0466-0

TECHNICAL ARTICLE

Roadway Backfill Coal Mining to Preserve Surface Water in Western China

Qiang Sun[1,2] · Jixiong Zhang[1,2] · Nan Zhou[1,2] · Wenyue Qi[1,2]

Received: 4 November 2016 / Accepted: 31 May 2017 / Published online: 8 June 2017
© Springer-Verlag GmbH Germany 2017

Abstract In China's western eco-environmental area, water resources are very valuable. Longwall mining can cause these shallow water resources to leak, so most mines in this area use room-and pillar mining to prevent water inrush and protect water resources. However, over time, coal pillars can become unstable and collapse. To protect water resources and improve coal recovery, roadway backfill coal mining was proposed for the Ershike Coal Mine. The mechanical properties of backfill materials with different ratios of aeolian sand, fly ash, and Portland cement were studied in the laboratory to obtain an optimal ratio. Also, a 2-D physical simulation model was established to explore the development of mining-induced fractures and to conduct a stability analysis of aquiclude strata. The results can be used to guide coal mining in the study area and to protect local water resources.

Keywords Aquiclude · Backfilling materials · Physical modeling · Water inrush

Introduction

Approximately 285 of China's 600 key collieries have reported water inrush occurrences, which have caused considerable economic loss and fatalities (Zhang and Shen 2004). In addition, about 4.2 billion m^3 of mine water is discharged every year to prevent water disasters near coal mines in China, but only 26.2% of this water is used (He et al. 2008). In China's western eco-environmental frangible area, there are enormous coal resources buried at shallow depths (0–200 m); these account for more than 85% of China's total coal deposits (Verma 2014; Wang et al. 2012; Xie et al. 2012). Due to phreatic pore water in the Quaternary system and confined water in the Jurassic Zhiluo formation, water inrush often occurs in local coal mines (Liu et al. 2010). The mine water discharges total as much as 1.4 billion m^3, with only 40% disposed of and less than 15% utilized (Liu and Ren 2009). Water resource shortages have serious impacts on the ecological environment as well as local residents. Furthermore, with human activity intensifying in western China as a result of the Western Development Program and Silk Road Economic Belt project (Li et al. 2015), groundwater quality in western China is increasingly important (Li 2016). A solution is urgently needed to ensure harmonious social and economic development of the western coal mining areas; therefore, it is imperative to find a more suitable mining method.

In recent years, backfill coal mining technology has been widely used in China (Bian et al. 2012; Miao et al. 2010; Zhang et al. 2014). This technology has obvious economical and environmental benefits for exploiting coal resources under buildings, bodies of water, and railways, and controlling strata movement (Huang et al. 2011a, b; Jiang et al. 2016; Sun et al. 2015; Zhang et al. 2015). However, because of the differences in backfill materials and filling costs, it is important to choose the correct method (such as solid backfill, cemented paste backfill, or high-water backfill). Researchers have not yet found a rapid backfilling method that can be widely used locally. Therefore, there

✉ Jixiong Zhang
zjxiong@163.com

1 China University of Mining and Technology, Xuzhou 221116, China

2 Key Laboratory of Deep Coal Resource Mining, School of Mines, Ministry of Education of China, China University of Mining and Technology, Xuzhou 221116, China

is an urgent need to address this issue for productivity and environmental reasons.

Three key principles for backfilling China's western coal mines have previously been proposed (An et al. 2016; Deng et al. 2016; Verma et al. 2013; Zhang et al. 2016). The first principle involves the selection of reasonable backfill materials, based on locally available sources and geological conditions. The second involves selection of appropriate backfill mining method, process, and equipment for the particular coal mine. The third is controlling the height of the water-conducting fractured zone to maintain the stability of the aquiclude strata and thus ensure that the backfill body remains stable.

The goals of this paper were:

1. To review the geological and hydrogeological conditions of a typical district and the main controlling factors with respect to mining the coal while preserving surface water bodies;
2. To present and discuss the mechanical properties of aeolian sand-based cemented backfilling materials;
3. To discuss the impact of backfill coal mining method on the stability of the key aquiclude strata;
4. To develop a complete method of backfill mining for coal mining in China's western eco-environmental frangible area.

Study Area

Overview of the Ershike Coal Mine

The Ershike Coal Mine is located in the town of Poluo, about 33 km southwest of Yulin city in the Shaanxi Province of western China. The Ershike Coal Mine is about 1.9 km long, 1.6 km wide, covers an area of 3.04 km^2, and has an annual coal production of 600,000 t. The mine is located in the north of the late-Mesozoic Ordos basin; the strata has a monoclonal structure and a southwest dip of about 1°, which is near-horizontal. The occurrence is gentle and has no large fissure or folding structure. The Wuding River, which is a perennial river with adequate water, overlies the southern part of the coal mine. The average annual precipitation is 402.7 mm, and the annual evaporation is 978.7–1753.8 mm. From top to bottom, the stratigraphic succession consists of Quaternary, Neogene, and Jurassic strata. The coal seams are located in the Jurassic Yan'an formation, with absolute elevations ranging from 947 to 959 m. The buried depth of the coal seam ranges from 90 to 125 m. Room-and-pillar mining has been adopted to prevent water inrush and protect the fragile local ecological environment. Field observations show that the coal recovery ratio is less than 30% and that some of the remaining pillars have collapsed. At present, about 5 million tons of coal resources remain, which are mostly situated under aquifers and villages. Consequently, a solution is urgently needed to ensure congruous development of the Ershike Coal Mine. The geological map of the Ershike mining areas is shown in Fig. 1.

Geological Conditions

There are eight coal seams in the Ershike Coal Mine, with the No. 3 of the Jurassic Yan'an formation being the main coal seam. The thickness of this seam ranges from 2.2 to 2.4 m, with an average of 2.3 m. The main roof, which belongs to the Middle Jurassic Zhiluo Formation, is siltstone with an average thickness of 15.5 m; the immediate roof is mudstone with a thickness of 0.2–3.0 m. The coal seam floor is composed of mudstone and medium sandstone with a thickness of 3.1–9.7 m. Moreover, data from nearby coal mines show that after the No. 3 coal seam was mined out using longwall mining, surface subsidence was about 1.0–1.6 m, with an average subsidence of 1.3 m. The subsidence factor was 0.86 and the horizontal movement factor was 0.14.

Hydrogeological Conditions

According to drilling records and hydrogeological data, the main aquifers from bottom to top, are the phreatic aquifer in a loose bed of the Quaternary Salawusu formation and the confined aquifer of the Jurassic Zhiluo formation, which are 0–18.5 and 0–20.3 m thick, respectively. The upper aquifer, mainly composed of sandstone, sediment, and diluvial loess, is an important ecological water source on the surface. The lower aquifer is composed of 2 or 3 layers of rock, which is mainly grey-green sandy mudstone, gray-blue medium sandstone, and siltstone. These strata contain large quantities of water. The upper aquicludes are mainly sandy clay (brown/yellow/purple) of the Neogene Jingle and the Quaternary Lishi formations, and are 0–30.0 m thick. The lower aquicludes are mainly mudstone and siltstone of the Jurassic Zhiluo formation, and are about 18.0 m thick. Based on a hydrological drill hole in the underground Ershike coal mine, the unit water inflow is 80 m^3/h and slightly alkaline. The geologic sequence of the ZK2855 borehole in the east working face is shown in Fig. 2.

Materials

Materials Used and Sample Preparation

The actual geological conditions of the local area were used to assess material source adequacy and cost of materials. In this paper, aeolian sand, which is widespread on the surface in the local area, was selected as the main backfill material. In addition, level III fly ash (FA) collected from a local power plant in Yulin of Shaanxi province, and ordinary Portland cement 42.5R (P.C. 42.5), collected from the village of Mao in Xuzhou of Jiangsu province were used as binders in all the samples. Nine experimental schemes and proportions were designed by varying the aeolian sand, FA, and P.C. 42.5 contents, water/cement (W/C) ratio, and curing times (1, 3, 7, 14, and 28 days), are shown in Table 1.

In this experiment, the amounts of aeolian sand, FA, and P.C. 42.5R used to achieve the desired composition and W/C ratio were combined using a mixer (NJ160) for 2–3 min, until a homogeneous paste was obtained (Fig. 3a). The samples were formed using a 70.7 mm cube specimen (Fig. 3b). After 12–14 h, the samples were removed from the molds and cured in an environmental chamber (SHBY-40B) at room temperature (25 ± 2 °C) (Fig. 3c). After the respective curing times, the samples were subjected to mechanical properties testing (Fig. 3d).

Material Properties Analysis

The uniaxial compressive strength (UCS) is especially important for evaluating the mechanical stability of cemented paste backfill (CPB) structures and increasing mining productivity (Ghirian and Fall 2014; Nasir and Fall 2010). In this experiment, a WAW-1000D electro-hydraulic servo-motor test system (Changchun Xinte Instruments Company, Changchun, China) was used as the loading equipment. The maximum load was 50 kN, which was implemented at a relatively slow rate (0.15–0.20 kN/s). The UCS testing of the CPB samples (135 total) can be seen in Fig. 4e, f; the detailed results are listed in Table 2.

Methods

In this paper, roadway backfill coal mining (RBCM) was adopted to study the deformation characteristics and stability of the overlying strata, with the focus on aquicludes. RBCM is an underground coal mining method

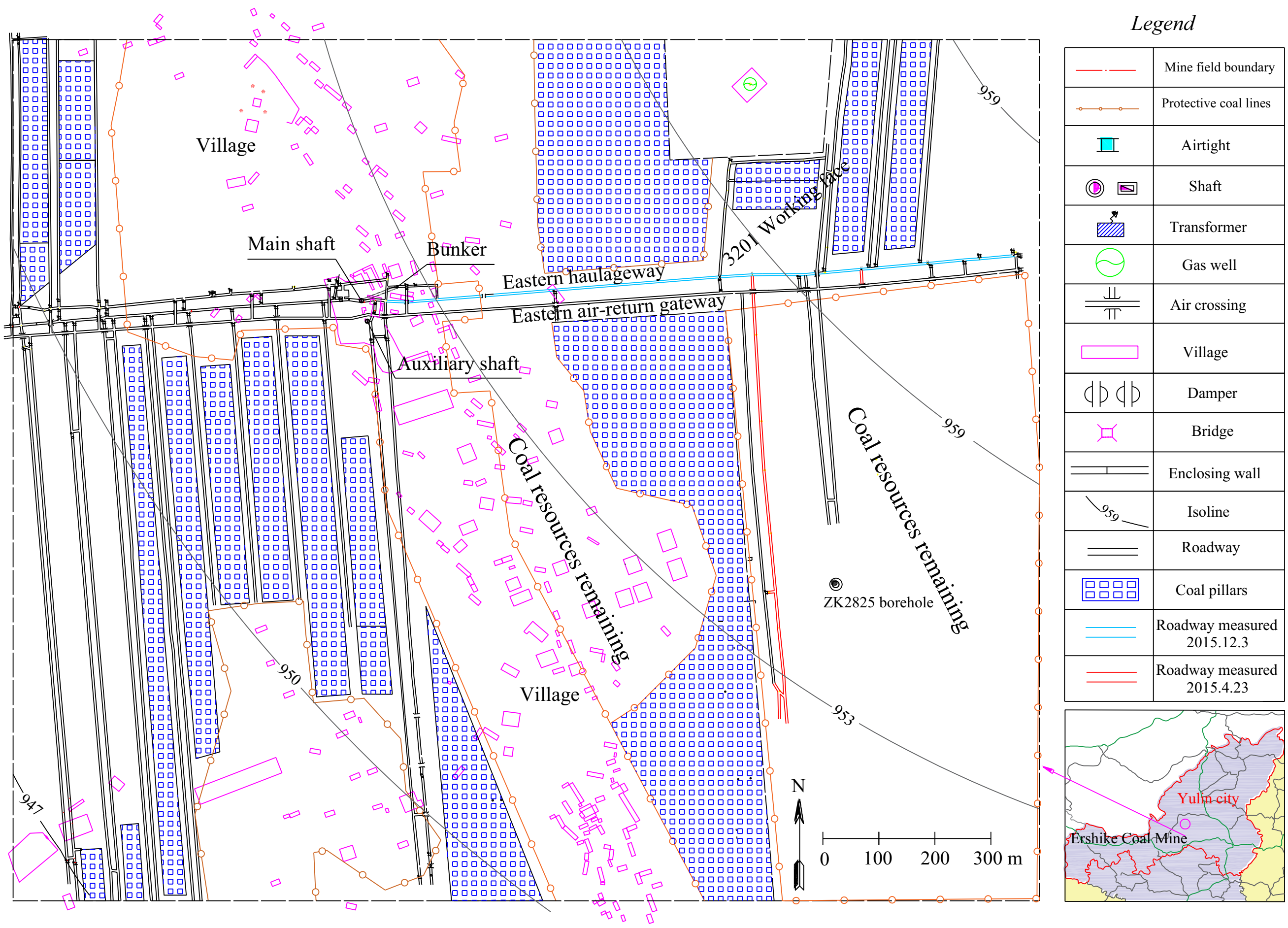

Fig. 1 Geological map of the Ershike mining areas

that involves a cross-cutting excavation between two entries of the working face using a fully-mechanized coal mining roadheader. The backfill materials to be filled into the roadway are then mined out using pumping or other backfilling equipment. The technical principle and process have been described in detail in previous studies (Deng et al. 2014; Sun et al. 2017; Zhang et al. 2016). A 2-D physical simulation was established to explore the development of mining-induced fractures and to conduct a stability analysis of the aquicludes with the goal of preventing water in-rush disasters. The model assumed a length of 1400 mm in the dip direction, a width of 100 mm in the strike direction, and a height of 1200 mm; the geometric similarity of the simulation model was 1:100 (Fig. 4). The physical and mechanical parameters of the rock are shown in Table 3.

The RBCM mining scheme in this study was designed with 5 m wide roadway coal pillars formed by mining 5 m of roadway, followed by backfilling of those roadways. After the first stage, the 5 m coal pillars formed during the first RBCM stage were mined out and backfilled again. The distance between the coal mining face and backfill face was maintained at 25 m to avoid mining-induced stress influence (e.g. when the fourth roadway was mined, the first roadway was backfilled). During RBCM, the strata movement and fracture development of the aquicludes were observed. Combining the geologic conditions with production practices and the mechanical properties test results of the CPB materials, the fifth experimental scheme (Table 3) and proportions of CPB (70.0% aeolian sand, 25.7% FA, and 4.3% P.C. 42.5) were selected. The backfill materials in the physical simulation were composed of different sponges

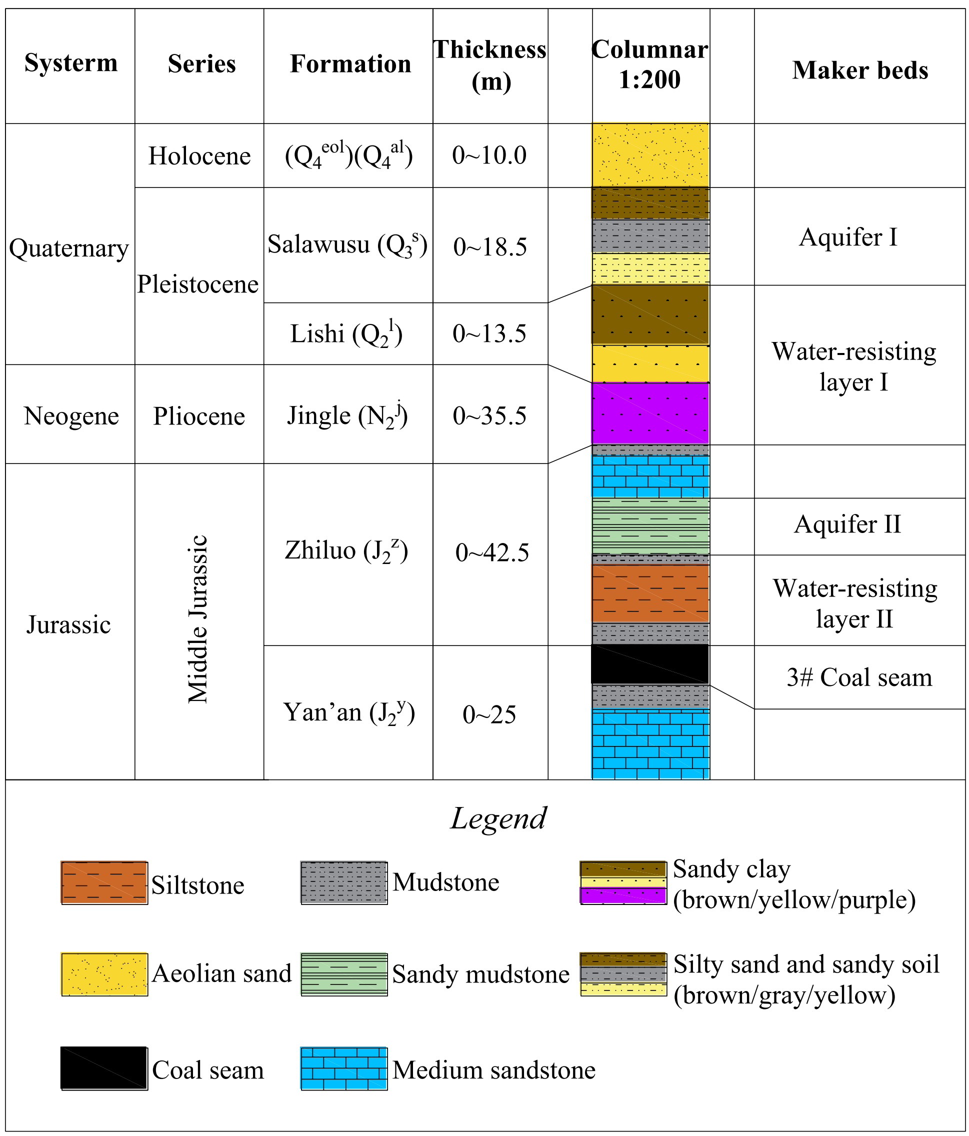

Fig. 2 Stratigraphic column of the ZK2855 borehole in the east working face

and papers; optimally similar materials were selected according to the analogous theory (Huang et al. 2011a, b; Newman et al. 2010).

Results

Mining-Induced Fracture Development

As shown in Fig. 5a–c, the overburden slowly sank during the first RBCM stage as the roadway was mined out and backfilled. When the excavation was 70 m long (seven roadways mined out), no fracture development was observed in aquiclude layer II. When the mined face advanced to 120 m (12 roadways mined out), there was still no fracture development observable with the naked eye. When the excavation was about 130 m, initiation of micro-fractures was seen; the mining-induced fractures were about 1.2 m long. After the first RBCM stage, some horizontal micro-fractures of aquiclude layer II measured 2.5 m in length. At this stage of advancement, the 5 m coal pillars were the main load-bearing body and the backfill materials had no obvious load-bearing effects.

As shown in Fig. 5d–f, mining-induced fractures developed as the roadway was mined out and backfilled during the second RBCM stage. When the excavation was 120 m long, 12 coal pillars remained after mining, and some horizontal fractures appeared in the immediate roof. After the second RBCM stage, the results showed a separation between the main roof and immediate roof. Additionally, there were some vertical mining-induced fractures in the immediate roof and horizontal micro-fractures in the main

Table 1 Experiment scheme and proportions of CPB

Experiment scheme	Aeolian sand content (%)	FA content (%)	P.C. 42.5 content (%)	Mixing water	W/C ratio	Curing time (days)
1	65.0	30.0	5.0	Tap	5.3	1, 3, 7, 14, 28
2	65.0	30.0	5.0	Tap	4.7	1, 3, 7, 14, 28
3	65.0	30.0	5.0	Tap	4.1	1, 3, 7, 14, 28
4	66.7	30.8	2.5	Tap	4.7	1, 3, 7, 14, 28
5	70.0	25.7	4.3	Tap	4.7	1, 3, 7, 14, 28
6	60.4	35.0	4.6	Tap	4.7	1, 3, 7, 14, 28
7	62.6	28.9	8.5	Tap	4.7	1, 3, 7, 14, 28
8	60.0	34.3	5.7	Tap	4.7	1, 3, 7, 14, 28
9	69.6	25.0	5.4	Tap	4.7	1, 3, 7, 14, 28

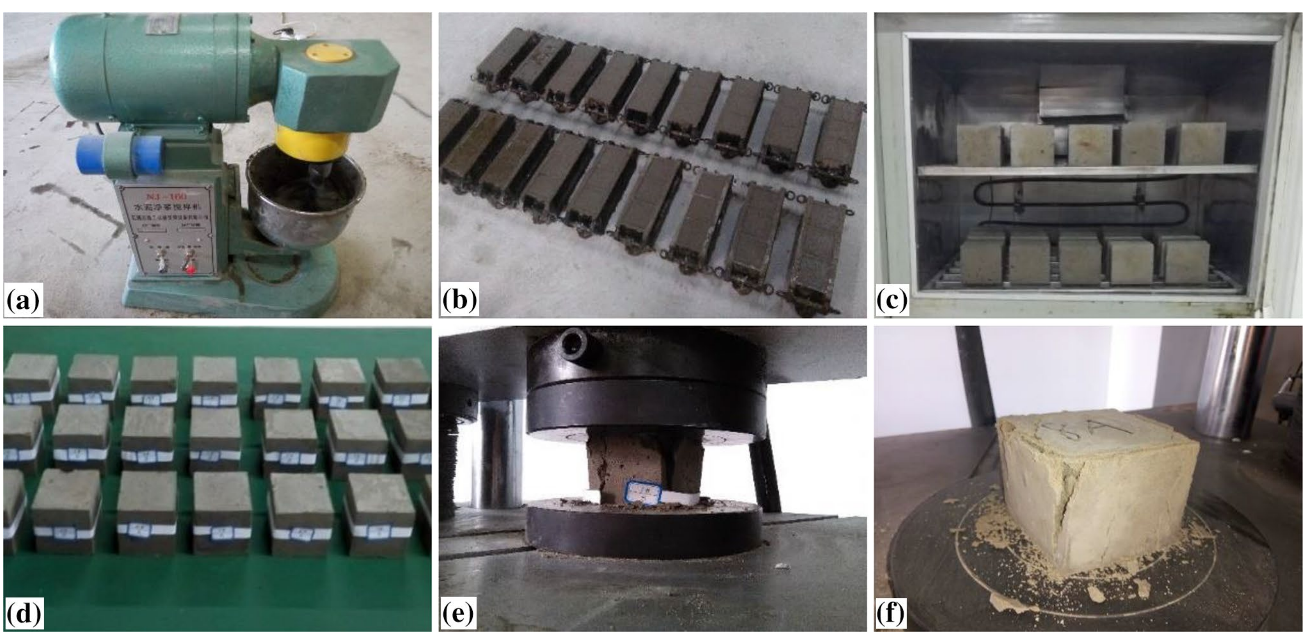

Fig. 3 Process of samples testing: **a** mixing, **b** production, **c** curing, **d** forming, **e** testing, **f** results

roof. The maximum height of mining-induced fractures was about 4.5 m. At this stage, mining-induced stress was gradually transferred to the backfill materials and the support function was gradually enhanced. There were no obvious vertical fractures as mining advanced, and aquiclude layer II was not broken, which showed that the backfill was able to support the overlying load, and a water inrush channel was not formed. The characteristics of overburden fracture development with RBCM are shown in Fig. 5 and the curve of the mining-induced fracture height vs. advancing distance is shown in Fig. 6.

The mining-induced fractures developed mainly in the late stage (120–140 m) of the first phase of RBCM (Fig. 6). During the second phase of RBCM, mining-induced fractures developed mainly in the middle stage (80–120 m), followed by a gradual decrease. Fractures did not develop in the confined aquifer of the Jurassic Zhiluo formation, which indicated that development of mining-induced fractures was well-controlled.

Stability Analysis of the Aquicludes

Deformation characteristics of the aquicludes are shown in Fig. 7a. During the first mining phase, the overburden slowly sank as the roadway was mined out and backfilled. The average subsidence of aquicludes I and II were 6.7 and 8.6 mm, respectively; their thicknesses were 30 and 18 m, respectively. Comparisons of the subsidence and thickness of the aquiclude strata showed that the deformation was small, which indicated that RBCM had only a mild impact on stability.

The maximum subsidence of aquiclude I and II were 74 and 132 mm, respectively, after the second phase of RBCM (Fig. 7b). The maximum subsidence of the lower aquiclude of the Jurassic Zhiluo formation was 160.7 mm; the rate of deformation was 0.89% (18 m thick). After RBCM, the backfill was able to support the overlying load effectively and the aquicludes were stable, thus achieving the goals of water preservation and environmental protection.

Discussion

Compared with other backfill mining technologies, RBCM is a simple system with low production costs and had relatively little impact on fractures of the overlying strata. After the CPB materials were backfilled by pumping into the mined-out area, they provided sufficient strength to ensure the support and stability of the key aquiclude strata during mining operations. Therefore, the technology has important advantages for improving production and coal recovery,

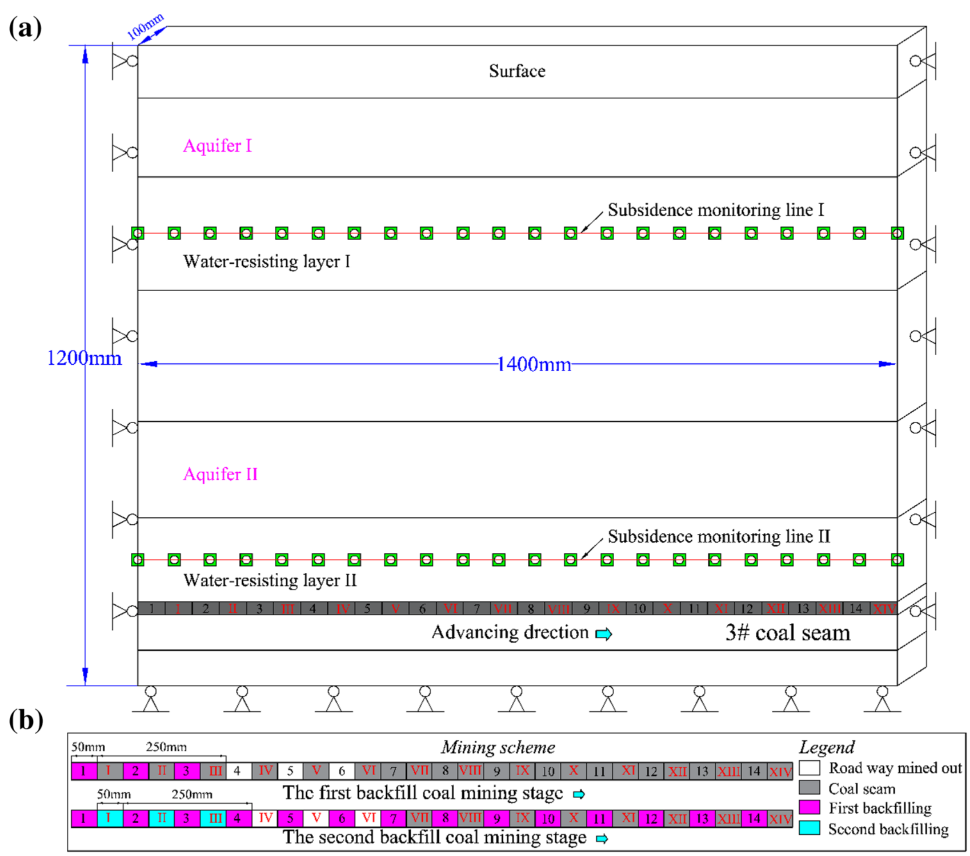

Fig. 4 Experimental scheme design of RBCM

Table 2 Uniaxial compressive strength of CPB

No.	1 day		3 days		7 days		14 days		28 days	
	σ(MPa)	$\bar{\sigma}$(MPa)	σ(MPa)	$\bar{\sigma}$(MPa)	σ(MPa)	$\bar{\sigma}$(MPa)	σ(MPa)	$\bar{\sigma}$(MPa)	σ(MPa)	$\bar{\sigma}$(MPa)
1	0.176	0.182	0.534	0.524	0.866	0.914	1.122	1.120	1.428	1.394
	0.218		0.550		0.892		1.080		1.252	
	0.252		0.488		0.984		1.158		1.502	
2	0.194	0.204	0.644	0.697	1.001	0.977	1.242	1.258	1.402	1.559
	0.218		0.720		1.054		1.172		1.548	
	0.200		0.727		0.876		1.360		1.727	
3	0.252	0.261	0.630	0.641	1.375	1.223	1.538	1.542	1.884	1.944
	0.256		0.616		1.268		1.574		1.892	
	0.275		0.628		1.026		1.514		2.056	
4	0.144	0.154	0.412	0.407	0.426	0.410	0.416	0.424	0.572	0.539
	0.151		0.355		0.408		0.364		0.544	
	0.167		0.454		0.396		0.492		0.501	
5	0.188	0.184	0.556	0.612	0.903	0.921	1.420	1.488	1.760	1.696
	0.178		0.612		0.896		1.530		1.646	
	0.186		0.668		0.964		1.514		1.682	
6	0.293	0.284	0.929	0.907	1.064	1.230	1.424	1.272	1.364	1.392
	0.256		0.878		1.292		1.660		1.348	
	0.303		0.914		1.334		1.732		1.464	
7	0.478	0.441	0.740	0.804	1.712	1.688	2.198	2.360	2.792	2.838
	0.412		0.884		1.668		2.434		2.878	
	0.433		0.788		1.664		2.448		2.844	
8	0.271	0.241	0.614	0.644	1.012	0.870	1.286	1.326	2.364	2.382
	0.218		0.644		0.816		1.330		2.172	
	0.234		0.674		0.782		1.362		2.610	
9	0.238	0.261	0.674	0.604	1.062	1.058	1.266	1.510	1.962	1.712
	0.278		0.540		1.074		1.958		1.548	
	0.264		0.598		1.038		1.306		1.626	

Table 3 Mechanical parameters of coal (rock) strata in simulation

Aquifer/water-resisting layer	Lithology	Thickness (m)	Density (kg/cm^3)	Tensile strength (MPa)	Cohesion (MPa)	Internal friction angle (°)	Bulk modulus (GPa)	Shear modulus (GPa)
	Aeolian sand	10.0	1870	0	0.1	16	0.05	0.03
Aquifer I	Silty sand and sandy soil	18.5	1670	0.01	0.2	16	0.08	0.05
Water-resisting layer I	Sandy clay	30.0	1800	0.05	0.5	18	0.12	0.08
	Mudstone	6.4	1600	0.8	0.6	28	0.63	0.5
	Medium sandstone	11.5	2400	1.2	1.6	27	1.35	1.32
Aquifer II	Sandy mudstone	20.3	2200	0.6	1.0	28	0.63	0.5
Water-resisting layer II	Mudstone	2.5	1600	0.8	0.6	28	0.63	0.5
	Siltstone	12.5	2250	1.0	0.8	30	0.87	0.73
	Mudstone	3.0	1600	0.8	0.6	28	0.63	0.5
	Coal seam	2.42	1400	1.86	0.3	25	0.8	0.41
	Sandy mudstone	3.0	2200	0.6	1.0	28	0.63	0.5
	Siltstone	7.8	2250	1.0	0.8	30	0.87	0.73

and is especially suitable for middle- or small-scale coal mines.

Physical simulation is an effective way to study mining-induced fractures and deformation characteristics of overlying strata in mining engineering. In this experiment, a 2-D physical simulation model was established to explore mining-induced fracture development and to conduct a stability analysis of the aquiclude strata. The results showed that the maximum height of mining-induced fractures was about 4.5 m, which was not enough to affect the stability of the key aquiclude. However, the dynamic mechanism of instability and the seepage properties of the aquiclude strata play an important role in material selection and mining operations. Thus, it will be useful to investigate the seepage-stability of the aquiclude strata with this method in the future.

Backfill materials that use or reuse waste materials are in compliance with the environmental protection policy of China's Western Development Program. Using aeolian sand-based CPB materials for RBCM can reduce the potential danger of a dust storm. Additionally, fly ash produces dust and pollutes the atmosphere if it is not dealt with properly. As an admixture of cemented materials, fly ash can replace a large amount of binder contents, decrease water consumption, and reduce costs. Furthermore, it can enhance the liquidity and impermeability of the cemented materials, which effectively restrains aggregate deposits and improves the conveying property of the slurry pipe. In this study, mining-induced fractures were well-controlled and there was no interaction between the backfill materials and groundwater, which suggests that these materials will not contaminate groundwater, though adverse effects are still possible (Verma and Singh 2013). This issue is complicated and needs further investigation.

Conclusions

In this study, roadway backfill coal mining was proposed as a water-preserving mining option for the Ershike Mine. After theoretical analysis, experimental testing, and physical simulation, the primary conclusions were:

1. The main control factors of water-preserving coal mining in China's western area were analyzed according to the geological and hydrogeological conditions of a typical district. This analysis led to the development of the

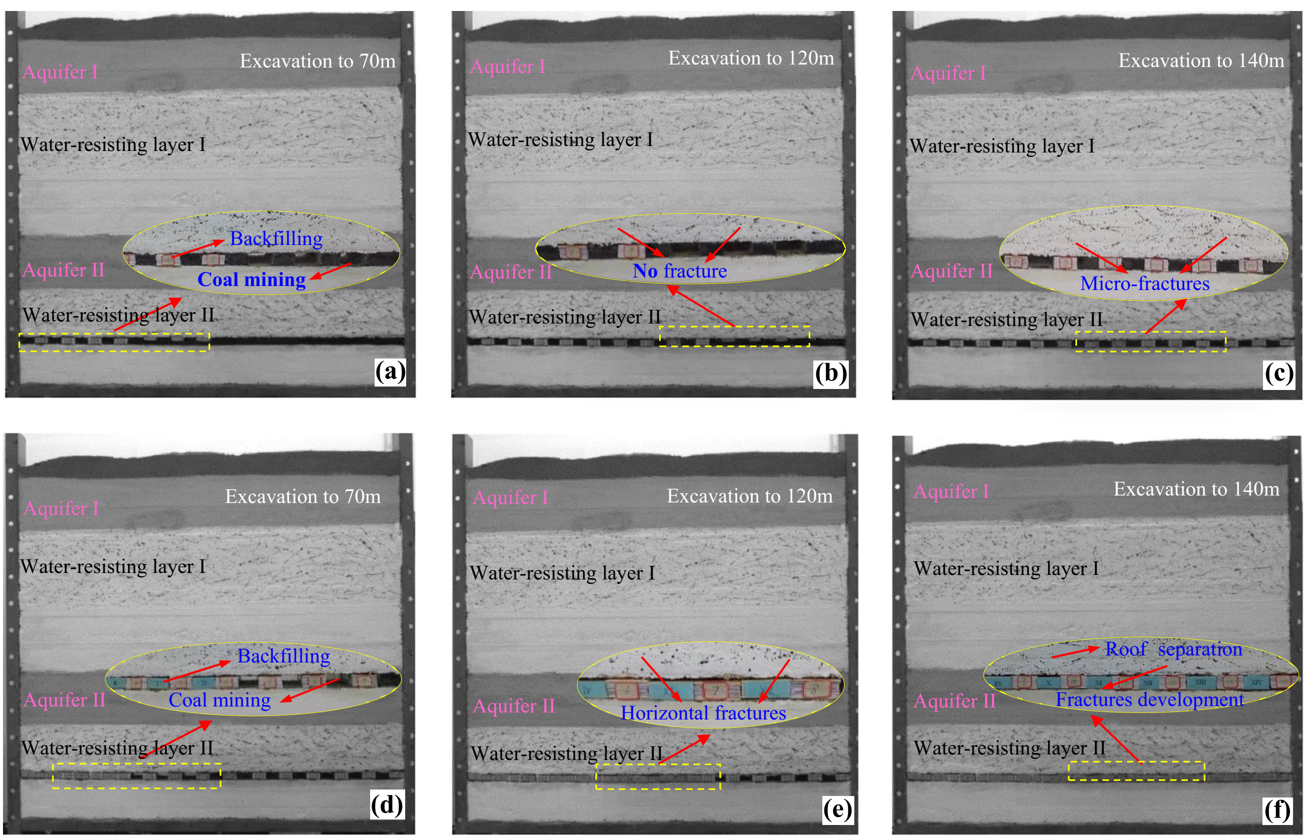

Fig. 5 Characteristics of overburden fracture development with RBCM

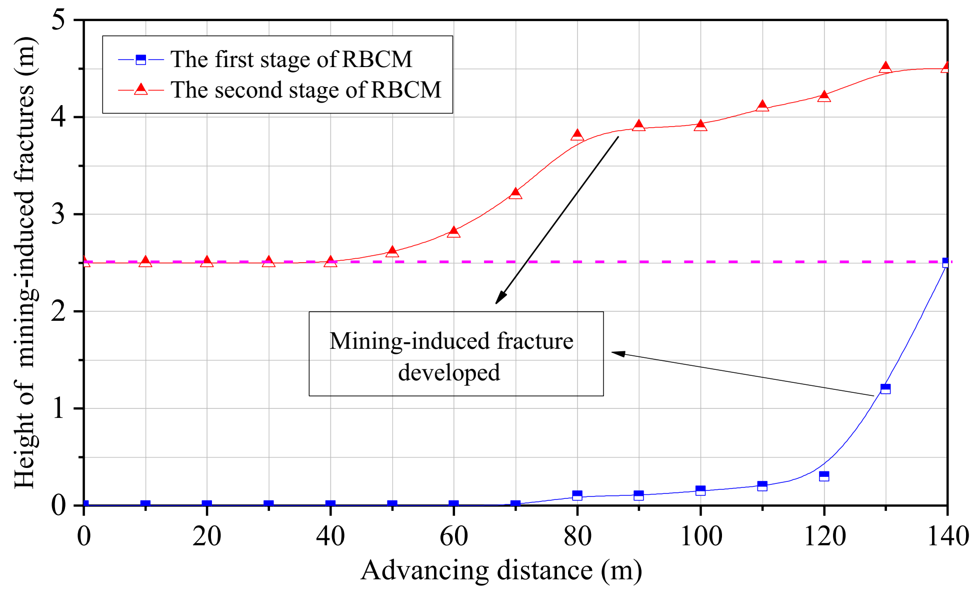

Fig. 6 Curve of mining-induced fracture height versus advancing distance

key principles of water-preserved backfill coal mining in China's western eco-environmental frangible area.

2. The mechanical properties of aeolian sand, fly ash, and Portland cement were studied at different ratios for a new backfill material in laboratory experiments, and an appropriate proportion for CPB (70.0% aeolian sand, 25.7% FA, and 4.3% P.C. 42.5) was selected for the Ershike Coal Mine.
3. A 2-D physical simulation model was established to explore mining-induced fracture development and to

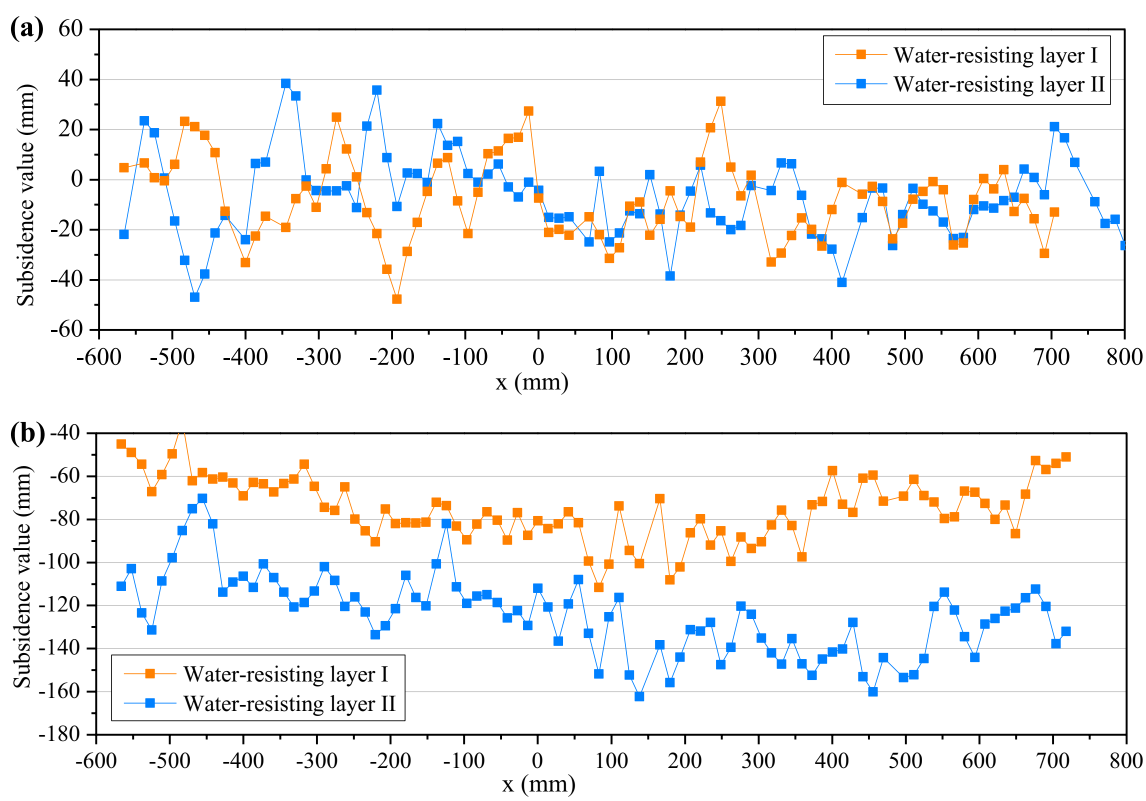

Fig. 7 Deformation characteristics of the water-resisting layers after RBCM: **a** first phase, and **b** second phase

conduct a stability analysis of aquiclude strata. The results showed that the maximum height of mining-induced fractures was about 4.5 m, the maximum subsidence of the lower aquiclude of the Jurassic Zhiluo formation was 160.7 mm, and the rate of deformation was 0.89%. It was also concluded that the backfill body could successfully support the overlying load and the aquicludes were stable.

4. Mining operations in China's western region are often associated with coal pillar instability, surface subsidence, water-inrush, and other environmental problems. The RBCM method can effectively improve coal recovery and achieve water-preserving coal mining, which is beneficial for economic and social development in the eco-environmental frangible area of western China.

Acknowledgements This research was financially supported by the Fundamental Research Funds for the Central Universities (2017XKZD13).

References

An BF, Miao XX, Zhang JX, Ju F, Zhou N (2016) Overlying strata movement of recovering standing pillars with solid backfilling by physical simulation. Int J Min Sci Technol 26(2):301–307

Bian ZF, Miao XX, Lei SG, Chen SE, Wang WF, Struthers S (2012) The challenges of reusing mining and mineral-processing wastes. Science 337:702–703

Deng XJ, Zhang JX, Zhou N, An TL, Guo S (2014) The research and application of longwall-roadway cemented backfilling mining technology in extra-thick coal seam. J Min Saf Eng 31(6):857–862

Deng XJ, Zhang JX, Kang T, Han XL (2016) Strata behavior in extra-thick coal seam mining with upward slicing backfilling technology. Int J Min Sci Technol 26(4):587–592

Ghirian A, Fall M (2014) Coupled thermo-hydro-mechanical–chemical behaviour of cemented paste backfill in column experiments: Part II: mechanical, chemical and microstructural processes and characteristics. Eng Geol 170(1):11–23

He XW, Yang J, Shao LN, Li FQ, Wang X (2008) Problem and countermeasure of mine water resource regeneration in China. J China Coal Soc 33(1):63–66

Huang YL, Zhang JX, Zhang Q, Nie SJ (2011a) Backfilling technology of substituting waste and fly ash for coal underground in China coal mining area. Environ Eng Manag J 10(6):769–775

Huang YL, Zhang JX, An BF, Zhang Q (2011b) Overlying strata movement law in fully mechanized coal mining and backfilling longwall face by similar physical simulation. J Min Sci 47(5):618–627

Jiang HQ, Miao XX, Zhang JX, Liu SW (2016) Gateside packwall design in solid backfill mining—a case study. Int J Min Sci Technol 26(2):261–265

Li PY (2016) Groundwater quality in western china: challenges and paths forward for groundwater quality research in western China. Expo Health (London) 8(3):305–310

Li PY, Qian H, Howard KWF, Wu JH (2015) Building a new and sustainable "silk road economic belt". Environ. Earth Sci 74(10):7267–7270

Liu TF, Ren ZS (2009) The mine water treatment and development analysis in west mining area. Shaanxi Coal 28(1):11–13 **(in Chinese)**

Liu TF, Jiang DL, Wang Y (2010) Discussion on integration technology of mine water treatment for medium and small mines in west part of China. Coal Eng 11:81–83

Miao XX, Zhang JX, Guo GL (2010) Study on waste-filling method and technology in fully-mechanized coal mining. J China Coal Soc 35(1):1–6

Nasir O, Fall M (2010) Coupling binder hydration, temperature and compressive strength development of underground cemented paste backfill at early ages. Tunn Undergr Space Technol 25(1):9–20

Newman AM, Rubio E, Caro R, Weintraub A, Eurek K (2010) A review of operations research in mine planning. Interfaces 40(3):222–245

Sun Q, Zhang JX, Ju F, Li LY, Zhao X (2015) Research and application of schemes for constructing concrete pillars in large section finishing cut in backfill coal mining. Int J Min Sci Technol 25(6):915–920

Sun Q, Zhang JX, Yin W, Zhou N, Liu Y (2017) The study of stability of surrounding rock and characters of overburden strata movement with longwall roadway backfill coal mining. J China Coal Soc 42(02):404–412

Verma AK (2014) A comparative study of various empirical methods to estimate the factor of safety of coal pillars. Am J Min Metall 2(1):17–22

Verma AK, Singh TN (2013) Prediction of water quality from simple field parameters. Environ Earth Sci 69(3):821–829

Verma AK, Saini MS, Singh TN, Avi D, Bajpai, RK (2013) Effect of excavation stages on stress and pore pressure changes for an underground nuclear repository. Arab J Geosci 6(3):635–645

Wang LG, Wang ZS, Huang JH (2012) Prediction on the height of water-flowing fractured zone for shallow Seam covered with thin bedrock and thick wind blown sands. J Min Saf Eng 29(5):607–612

Xie HP, Wang JH, Shen BH, Liu JZ, Jiang PF, Zhou HW, Liu H, Wu G (2012) New idea of coal mining: scientific mining and sustainable mining capacity. J China Coal Soc 37(7):1069–1079

Zhang JC, Shen BH (2004) Coal mining under aquifers in China: a case study. Int J Rock Mech Min Sci 41(4):629–639

Zhang JX, Huang YL, Zhang Q, Li M, Liu Z (2014) Test on mechanical properties of solid backfill materials. Mater Res Innov 18(S2):S2-960–S2-965

Zhang JX, Zhang Q, Sun Q, Gao R, Germain D, Abro S (2015) Surface subsidence control theory and application to backfill coal mining technology. Environ Earth Sci 74(2):1439–1448

Zhang JX, Sun Q, Zhou N, Jiang HQ, Germain D, Abro S (2016) Research and application of roadway backfill coal mining technology in western coal mining area. Arab J Geosci 9(10):1–10