

Research of Cemented Paste Backfill in Offshore Environments

Kun Wang¹, Peng Yang^{1,2,*}, Wensheng Lyu¹ and Zhixiang Lin³

¹School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing, China

²Beijing Key Laboratory of Information Service Engineering, Beijing, China

³263 Brigade of Jiangxi Nuclear Industry Geological Bureau, Nanchang, China

*Corresponding author e-mail: yangpeng@buu.edu.cn

Abstract. To promote comprehensive utilization of mine waste tailings and control ground pressure, filling mine stopes with cement paste backfill (CPB) is becoming the most widely used and applicable method in contemporary underground mining. However, many urgent new problems have arisen during the exploitation in offshore mines owing to the complex geohydrology conditions. A series of rheological, settling and mechanical tests were carried out to study the influences of bittern ions on CPB properties in offshore mining. The results showed that: (1) the bittern ion compositions and concentrations of backfill water sampled in mine filling station were similar to seawater. Backfill water mixed CPB slurry with its higher viscosity coefficient was adverse to pipeline gravity transporting; (2) Bleeding rate of backfill water mixed slurry was lower than that prepared with tap water at each cement-tailings ratio; (3) The UCS values of backfill water mixed samples were higher at early curing ages (3d, 7d) and then became lower after longer curing time at 14d and 28d. Therefore, for mine production practice, the offshore environments can have adverse effects on the pipeline gravity transporting and have positive effects on stope dewatering process and early-age strength growth.

1. Introduction

Mine wastes tailings are unwanted, currently uneconomic, solid and liquid materials found at or near mine sites. Volumetrically they are one of the world's largest waste streams, and they often contain high concentrations of elements and compounds that can have severe effects on ecosystem and human [1] [2]. To date, there are totally 14.6 billion tons of mine waste tailings in storage in China, with its annual emission more than 1.5 billion tons since 2011 [3]. As one of the most effective and environmental ways to promote comprehensive utilization of these tailings, filling mine stopes with cement paste backfill (CPB) has been applied not only to control ground pressure and prevent the rock burst phenomenon in deep mining, but also to enhance the safety treatment of surface subsidence caused by mined-out underground spaces (stopes) [4]. CPB is a mixture of dewatered mill tailings and binding agent, with added water to achieve the required consistency for transporting the CPB to the mine stopes [5]. The rheological and settling properties of CPB slurry are the critical success factors in backfill mining pipeline gravity transporting and stopes dewatering process. Another important quality



criteria for the hardened CPB is mechanical stability. Indeed, the paste backfill must remain stable during the extraction of adjacent stopes to ensure the security of the mine workers.

Furthermore, most high-grade and easy exploitation ores in land have already been exploited. Contemporary mining therefore tends to focus on the extraction of ores in offshore, plateau and other special regions. However, along with the important practical significance and strategic value, many urgent new problems have arisen during the exploitation in these special regions mines owing to their complex topographic and geohydrology conditions. Located in Laizhou Bay area, Shandong Province, abundant in resource reserve, Sanshandao Gold Mine has become the first large-scale hard rock mine to exploit undersea using downward slicing drift mining with CPB. The orebody is located in the bottom of the Bohai Sea and the mining area is surrounded with coasts on three sides. There were once shallow islands in the ancient times in this area. And then with the geological and hydrologic state variations, the islands had been gradually connected with the land and become a peninsula. Additionally, the rock-mass joint fissures were well developed, leading to large amount of underground gushing water which consists of bedrock fissure brine, seawater and quaternary pore water [6]. Considered the economic and environmental factors, the CPB mixing water was mainly from the simply precipitated and filtered pit water. The adverse impacts on backfill slurry conveying, stopes dewatering and CPB strength had been caused by the bittern ions existed in the water. Thus the production schedule and safety mining were influenced.

Analyzing the influence rule of bittern ions on CPB various properties were essential for formulating effective measures to improve backfill quality in offshore environments. Therefore, the main objectives of the study were: (1) To investigate the rheological and settling properties of CPB slurries prepared by different mixing water through an extensive experimental work. (2) To assess the CPB mechanical stability by conducting uniaxial compressive strength (UCS) tests on laboratory samples. (3) To study the effect rules of different mixing water on each property.

2. Materials and Methods

2.1. Materials

The materials used for the CPB preparation include cement, tailings and water.

2.1.1. Tailings. Two types of tailings have been sampled from the Sanshandao Gold mine filling station which include unclassified tailings (UTs) and classified tailings (CTs). Table 1 lists the grain size compositions and specific surface areas (SSAs) of UTs and CTs particles. Furthermore, Fig. 1 shows the particle size distribution curves of them.

Table 1. Grain size compositions and specific surface areas of the tailings

	$d_{10}(\mu m)$	$d_{50}(\mu m)$	$d_{90}(\mu m)$	$d_{ave}(\mu m)$	$SSAs(m^2 cm^{-3})$
Classified Tailings	12.119	84.590	173.408	83.441	0.246
Unclassified Tailings	3.423	39.744	121.254	47.955	0.658

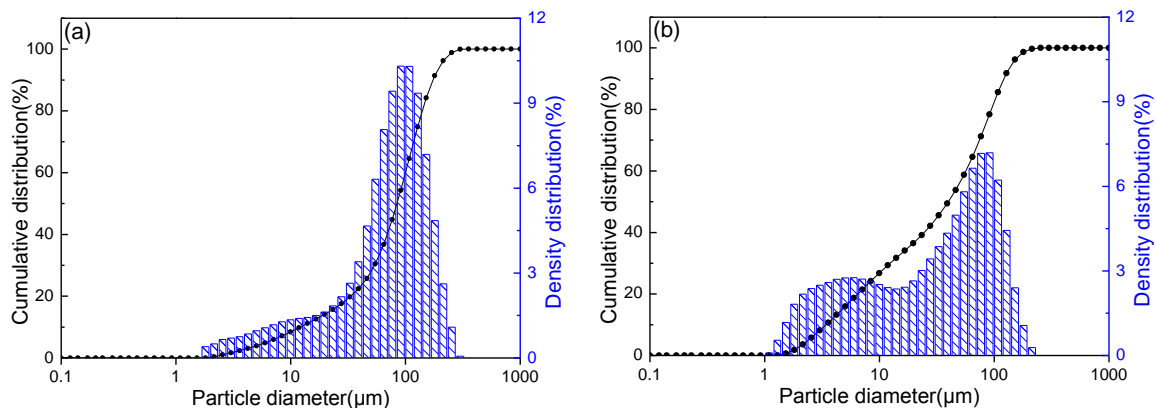


Figure 1. Particle size distribution curves of the classified (a) and unclassified (b) tailings

It can be noted from Table 1 and Fig.1 that UTs particles are denser than CTs, with its SSAs 1.67 times larger than CTs. 50% of the UTs particles are smaller than 39.744 μm (d_{50}) and only 10% are larger than 121.254 μm (d_{90}). The denser particles result in higher water content in the CPB slurry, which is not conducive to stopes dewater. Additionally, a low slurry conveying density (65%~72%) is requested in the slurry gravity transporting system, which increases the CPB dewater amount in the backfilled stopes. Therefore, as the common tailings used in the mine filling station, the CTs are used in this study for preparing the fresh CPB.

2.1.2. Cement and Water. The cement used in this study is C-fines, a kind of specialized cement self-produced and developed by the mine for CPB preparation. It can be noted from Table 2 that C-fines particles are denser than ordinary Portland cement, with its average grain diameter 46% smaller to 5.295 μm and its SSAs 41% larger to 2.382. It can be inferred that the hydration reaction would be carried out more easily and the CPB strength would also be formed earlier. Hence C-fines is more conducive. Backfill water sampled from the mine filling station is used to mix the cement and tailings. Table 3 presents the bittern ion concentrations of Bohai seawater and the backfill water. The ion compositions and concentrations of backfill water are similar to seawater, in which Cl^- concentration is as high as 20910 $\text{mg}\cdot\text{L}^{-1}$ and SO_4^{2-} concentration is up to 2436 $\text{mg}\cdot\text{L}^{-1}$. Tap water is also used in other control groups.

Table 2. Grain size compositions of cement

	$d_{10}(\mu\text{m})$	$d_{50}(\mu\text{m})$	$d_{90}(\mu\text{m})$	$d_{ave}(\mu\text{m})$	SSAs(m^2cm^{-3})
Ordinary Portland Cement	1.739	8.558	37.353	7.754	1.689
C-fines	1.248	5.794	22.849	5.295	2.382

Table 3. Ion concentrations of backfill water and Bohai seawater (mg L^{-1})

	K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	CO_3^{2-}	HCO_3^-
Backfill water	248	10374	1273	1335	20910	2436	-	179
Bohai seawater	340	11117	372	1172	18381	2313	-	171

2.2. Specimen Preparation and Mix Proportions

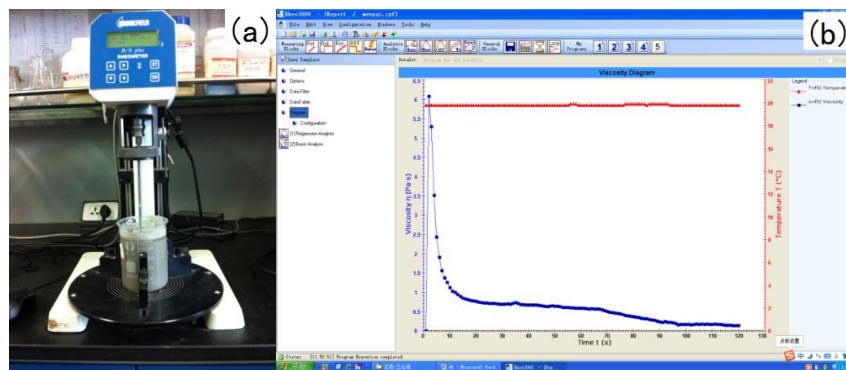
Table 4 lists the mixing proportions of these 3 kinds of materials, which are consistent with those the gold mine applies in practice. These materials are mixed and homogenized in a mixer for 4 min until a homogeneous CPB being obtained.

Table 4. Mixing proportions of the CPB samples

Cement-tailings ratio	Cement (wt%)	Tailings (wt%)	Water (wt%)
1/6	10	60	30
1/10	6.4	63.6	30
1/16	4.1	65.9	30

2.3. Experimental Test Program

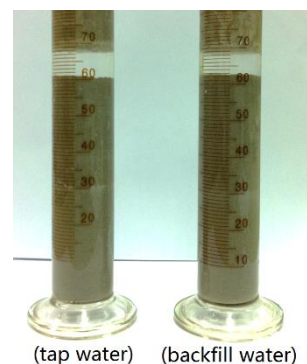
2.3.1. Rheological Tests. The rheological tests were carried out by V40_20_3to1 measuring system (Brookfield R/S plus Rheometer, USA) at $20 \pm 1^\circ\text{C}$. The rheological tests consisted of the following steps: (1) a linear increasing of shear rate from 0(1/s) to the maximum shear rate of 120(1/s) for 2 min; (2) the parameters including shear rate and shear stress were recorded and analyzed; (3) a report was generated and exported for further analysis.

**Figure 2.** Brookfield R/S plus Rheometer(a) and test curves(b)

2.3.2. Settling Tests. The homogeneous CPB slurry was transferred into a 100mL graduate cylinder for settling and bleeding rate tests (Fig. 3). The interface level heights between separated water and CPB slurry were recorded during the settling process until a stable interface was obtained. The bleeding rate (%) can be obtained by the formula:

$$B = \frac{V_w}{(W/G)G_w} \times 100\% \quad (1)$$

Where, V_w is the mass of bleeding water; W is the mass of mixing water; G is the mass of total CPB slurry; G_w is the mass of CPB slurry sample transferred in the cylinder.

**Figure 3.** Settling and bleeding rate tests

2.3.3. Mechanical Tests. The homogeneous CPB mixtures were also poured into 70.7*70.7*70.7 (mm) cube shape curing moulds for mechanical tests. The specimens were then sealed and cured in a humidity chamber maintained at approximately 80% humidity and $23 \pm 2^\circ\text{C}$ for different curing times: 7, 14 and 28 days. Uniaxial compression tests according to China's industry standard JGJ/T70-2009 were carried out to evaluate the mechanical properties of the prepared CPB samples. Furthermore, X-Ray diffraction of hydration products in cement paste was also carried out.

3. Results and Discussion

3.1. Rheological test results and Discussion

The liquid and suspended mixture of solid particles and water can be called as two-phase suspension fluid. Moreover, the formula relationship between shear rate and shear stress such as *Bingham*, *Ostwald*, *Herschel-Bulkley* model etc., which is defined as the flow pattern (FP), can be used to describe the two-phase suspension fluid rheological property [7]. Fluid of shear stress linear with shear rate is called as Newtonian Fluid. Otherwise, fluid with nonlinear relationship between shear stress and shear rate is called as non-Newtonian Fluid. According the rheological curves of CPB slurries (as shown in Fig. 4 and Table 3), the linear *Bingham* model (Eq. 2) with the highest fitting degree had been chosen to describe the flow pattern of CPB slurry in this study.

$$\tau = \eta\dot{\gamma} + \tau_0 \quad (2)$$

Where, τ is the shear stress (Pa); τ_0 is the yield stress (Pa); η is the viscosity coefficient (Pa s); $\dot{\gamma}$ is the shear rate(1/s).

The shear stress (τ) and shear rate ($\dot{\gamma}$) could be obtained from the rheological tests. Thus the rheological parameters including yield stress (τ_0) and viscosity coefficient (η) were calculated (as shown in Table 5).

From Fig. 4 and Table 5, it could be observed that: (1) the shear stress of slurry prepared with tap water was higher at low shear rate. And then with the increasing of shear rate, the shear stress of backfill water mixed slurry became higher; (2) with the decreasing of cement-tailings ratio (from 1/6 to 1/16), the shear stress at different shear rate increased, and the slope of linear fit curve which is defined as viscosity coefficient (η) in *Bingham* rheological model also increased; (3) the viscosity coefficient (η) of slurry prepared with backfill water was much higher than it prepared with tap water at different cement-tailings ratio.

The viscosity coefficient (η) is an index used to reflect the viscous resistance of fluid flow. A low viscosity coefficient is conducive to pipeline transportation. So it can be concluded that, backfill water mixed CPB slurry with its higher viscosity coefficient is adverse to pipeline gravity transporting and more likely to lead to pipeline plugging. And the result is also in accordance with the mine backfill field practice.

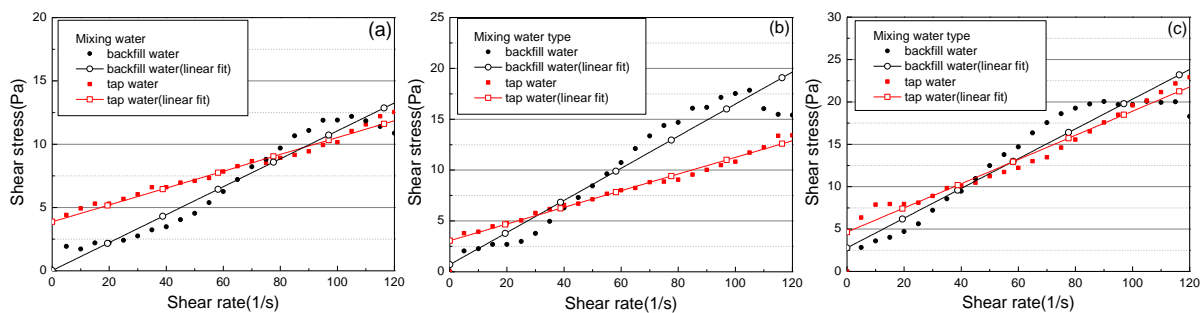


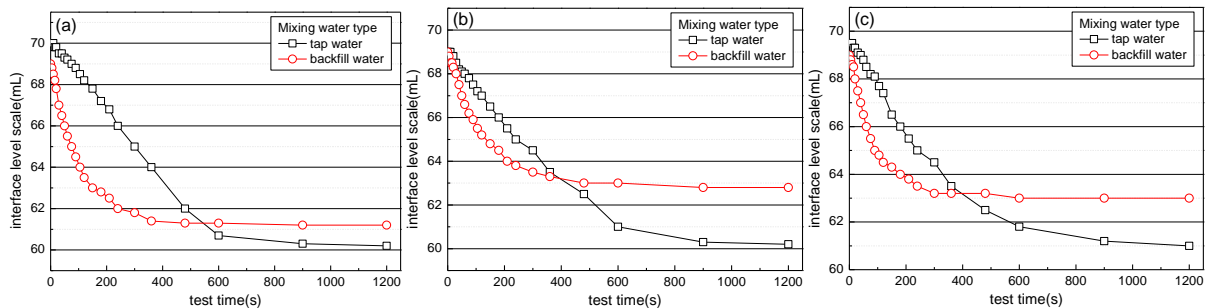
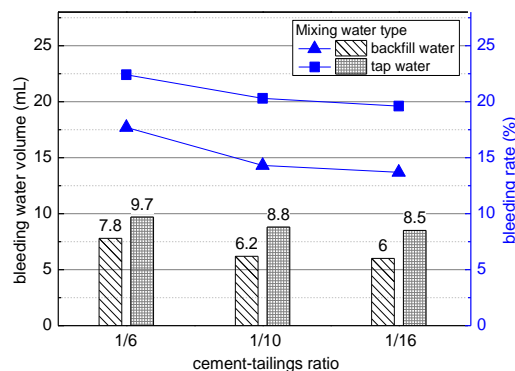
Figure 4. Rheological curves of CPB slurries (Cement-tailings ratio is (a)1/6; (b)1/10; (c)1/16)

Table 5. Bingham model fitting results

Cement-tailings ratio	Mixing Water	Flow pattern equation	Stability index
1/6	Backfill water	$\tau = 0.1103 \gamma + 0.0227$	$R^2 = 0.9464$
	Tap water	$\tau = 0.0665 \gamma + 3.8706$	$R^2 = 0.9506$
1/10	Backfill water	$\tau = 0.1578 \gamma + 0.7074$	$R^2 = 0.9281$
	Tap water	$\tau = 0.0819 \gamma + 3.0612$	$R^2 = 0.9757$
1/16	Backfill water	$\tau = 0.1754 \gamma + 2.7788$	$R^2 = 0.9191$
	Tap water	$\tau = 0.1427 \gamma + 4.6392$	$R^2 = 0.9709$

3.2. Settling test results and Discussion

The CPB slurry is often in a saturated state in the initial mixing stage. And then natural compaction happens due to the capillary pressure and solid particle gravity, leading to volume reduction and water bleeding, which is called the slurry natural settling process [8]. According to the settling curves shown in Fig.5, the maximum settlement appeared after 1000 sec, and the settling rate of tap water mixed CPB slurry is much lower. This is because the anions and cations (as shown in Table 3) have played a role of inorganic flocculants which can promote the formation of complexes and settling process. The resistance of CPB slurry in pipeline transportation is proportional to its settling rate. Hence, the backfill water mixed CPB slurry with a high settling rate is not conducive for pipeline transportation. Moreover, the bleeding water volume and bleeding rate calculated by Eq. (1) are shown in Fig. 6. The result shows: (1) with the cement-tailings ratio decreases from 1/6 to 1/16, the bleeding rate decreases from 22.4% to 19.6% (tap water) and 17.7% to 13.7% (backfill water). This is due to the higher content of cement with denser particles (as shown in Table 2); (2) Bleeding rate of backfill water mixed slurry is lower than that prepared with tap water at each cement-tailings ratio. In mine production practice, lower bleeding rate is beneficial for the stope dewatering process, which can improve the production efficiency.

**Figure 5.** Settling curves of CPB slurries (Cement-tailings ratio is (a)1/6; (b)1/10; (c)1/16)**Figure 6.** Bleeding water volume and bleeding rate of CPB slurries

3.3. Mechanical test results and Discussion

The UCS test results showed that the UCS values for all of the samples increased with curing time and cement-tailings ratio (Fig. 7). And the UCS values of backfill water mixed samples were higher at early curing ages (3d, 7d) and then became lower after longer curing time at 14d and 28d. The three main hydration products including C-S-H, Ca(OH)_2 and ettringite (AFt, $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O}$) in cement samples at 28d were tested and analyzed by X-ray diffraction (Fig. 8).

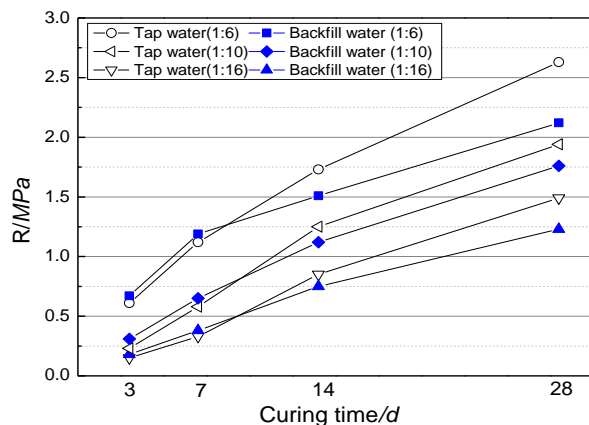


Figure 7. UCS test results of CPB samples with different curing time

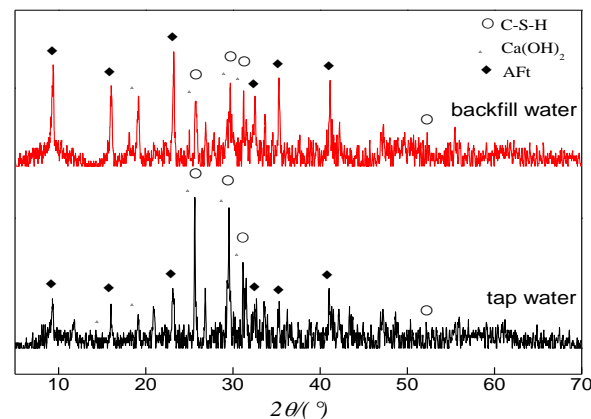


Figure 8. X-ray diffraction of hydration products in cemented samples at 28d

The characteristic peaks of C-S-H and Ca(OH)_2 in backfill water mixed samples were weaker. This is because the Ca(OH)_2 products can be consumed by the SO_4^{2-} ions in backfill water. The Ca(OH)_2 product cannot directly affect the strength. However, the C-S-H production which has positive effects on the strength is influenced by the Ca(OH)_2 [9]. Furthermore, the characteristic peaks of AFt were much heighten. This is because the SO_4^{2-} ions in backfill water are beneficial to the formation of AFt [10]. AFt has positive effects on the early strength growth, which explains the UCS test results at early ages.

4. Conclusion

The CPB in offshore environments were examined experimentally in this paper. Valuable results were gained regarding the rheological, settling and mechanical properties of CPB in offshore environments, as well as those properties of CPB prepared with normal tap water.

The results showed that: (1) with the decreasing of cement-tailings ratio (from 1/6 to 1/16), the shear stress at different shear rate increased. And backfill water mixed CPB slurry with its higher viscosity coefficient was adverse to pipeline gravity transporting. (2) Bleeding rate of backfill water mixed slurry was lower than that prepared with tap water at each cement-tailings ratio. (3) The UCS values of backfill water mixed samples were higher at early curing ages (3d, 7d) and then became lower after longer curing time at 14d and 28d. According to the X-ray diffraction test result at 28d, the characteristic peaks of C-S-H and Ca(OH)_2 in backfill water mixed samples were weaker, and the characteristic peaks of AFt were much heighten, which explained the UCS test results. Therefore, for mine production practice, the offshore environments can have adverse effects on the pipeline gravity transporting and have positive effects on stope dewatering process and strength growth at early ages.

Acknowledgments

This work was financially supported by National Natural Science Foundation of China (51641401) and 12th “Five-year” National Science and Technology Pillar Project (2012BAB08B01).

References

- [1] Hudson-Edwards KA, Jamieson HE, Lottermoser BG. Mine wastes: past, present, future. *Elem.* 2011, 7(6): 375-380
- [2] Yang P, Cai SJ. Advanced hard rock mining. Metallurgical Industry Press, Beijing. 2010
- [3] Xue YZ, Tang JX, Fan JT. Report of mineral resources saving & comprehensive utilization in China. Geological Publishing House, Beijing. 2015
- [4] Ghirian A, Fall M. Coupled behavior of cemented paste backfill at early ages. *Geotech and Geol Eng.* 2015, 33(5): 1141-1166
- [5] Fall M, Benzaazoua M, Ouellet S. Experimental characterization of the influence of tailings fineness and density on the quality of cemented paste backfill. *Miner Eng.* 2005, 18(1): 41-44
- [6] Wang K, Yang P, Lv WS, Liu J, Zhang H. Effects of superplasticizer on transport properties of backfill slurry contained bittern. *Met Min.* 2016, 10: 45-49
- [7] Kim JY, Song JY, Lee EJ, Park SK. Rheological properties and microstructures of Carbopol gel network system. *Colloid Polym Sci.* 2003, 281(7): 614-623
- [8] Deng DQ, Gao YT, Yao ZL, Yang YL. Study on settling property of cement-classified tailings filling slurry. *Chin J Underground Space Eng.* 2009, 04: 803-807
- [9] Han PJ, Liu X, Bai XH. Effect of sodium sulfate on strength and micropores of cemented soil. *Rock Soil Mech.* 2014, 09: 2555-2561
- [10] Li Y, Ni W, Chen DP, Wang ZJ, Zhang B. Experimental investigation on concrete made from iron and steel slags for building high-strength artificial reefs. *J Unive Sci Technol Beijing.* 2012, 11: 1308-1313