

Coupled Effect of Cement-to-Tailings Ratio and Solid Content on the Early Age Strength of Cemented Coarse Tailings Backfill

Hao Wang · Lan Qiao

Received: 1 July 2018 / Accepted: 22 November 2018 / Published online: 26 November 2018
© Springer Nature Switzerland AG 2018

Abstract Determining a reasonable backfilling slurry parameters is a big challenge for mining industry. The solid content (SC) and cement-to-tailings ratio (c/t) are two main factors on mechanical properties of cemented coarse tailings backfill (CCTB). In this paper, an experimental study is conducted to investigate the effect of c/t and SC on the uniaxial compressive strength (UCS) of CCTB. Four kinds of curve fitting (linear, logarithmic, exponential and power) are utilized to find the quantitative relationship between the UCS of CCTB and c/t and SC. Four types of c/t values (1/4, 1/6, 1/8 and 1/10) and five kinds of SC values (63 wt%, 65 wt%, 68 wt%, 70 wt% and 72 wt%) were prepared. The relationships among c/t , SC and the UCS are discussed. As the c/t increased, the UCS of CCTB increased; while the UCS increased with the SC increased. It is shown that the UCS and corresponding c/t of CCTB is in a logarithmic function with each other. However, the relationship between the UCS and SC meets exponential distribution. The results of this study can provide significant reference for the backfill design of underground mining.

Keywords Uniaxial compressive strength (UCS) · Cemented coarse tailings backfill (CCTB) · Curve fitting · Solid content (SC) · Cement-to-tailings ratio (c/t)

1 Introduction

Underground mining plays an important role in the mineral resource recovery, a large number of untreated voids have been left by underground mining, which have become one of the major hazard sources in mine (Zhou et al. 2013). There are lots of accidents caused by the collapse of voids all around the world. While the disposal and treatment of mining waste (mainly, tailings and waste rocks) produced from mine and mills have become a serious problem in many countries (Yilmaz et al. 2014a). In recent years, research has been focus on the tailings treatment technology to minimize the harmful effect to the underground environment. Backfilling technology is a simple and effective method, which can not only protect the land subsidence, but also decrease surface tailings storage requirements (Cao et al. 2018a, b). As a relatively new mine waste management technology, CCTB is widely applied in underground mine operations around the world because of its technical and economic advantages (Ke et al. 2015). Lots of cementitious materials are used as replacement of clinker to reduce cost, such as gangue (Wu et al. 2015;

H. Wang (✉) · L. Qiao
School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China
e-mail: 82339607@qq.com

H. Wang
China Aerospace Academy of Architectural Design & Research Co., Ltd, Beijing 100071, China

Franks et al. 2015; Cruz et al. 2015), fly ash (Hamzaoui et al. 2016; Chien-Hsing et al. 2015; Nawaz et al. 2016; Chousidis et al. 2015), water quenched slag (Jiang et al. 2015; Li et al. 2013; Feng et al. 2012). Cement is the most widely used construction materials for its high mechanical strength. Uniaxial compressive strength (UCS) is the most important property of CTB and concrete, other mechanical parameters such as compressive strength, tensile strength, elasticity modulus and passion rate all are related to the compressive tests closely. Plentiful experimental tests have been finished about compressive strength development of concrete and other building materials (Liu et al. 2015; Wang and Park 2015). Many researchers have studied the mechanical and physicochemical properties of cemented paste backfill (CPB). Kesimal et al. (2002) found that the chemical and mineralogical changes with time that affect the mechanical strength of the fill. Yilmaz et al. (2003, 2012, 2014b, 2018) also found that the factors affecting the strength and stability of paste backfill are the characteristics of binder, solids, and water and their mix rates in the filling mass. Ghirian and Fall (2014) and Cui and Fall (2015) had been studied the evolution of coupled thermal-hydraulic-mechanical-chemical (THMC) properties of underground CPB. Yin et al. (2012) investigated the effect of solid components on the rheological and mechanical properties of CPB. Yilmaz et al. (2014) also investigated the effect of binder type/dosage, water to cement ratio (w/c) and fines content (< 20 μm) of the tailings on ultrasonic pulse velocity (UPV) of cemented paste backfill (CPB) samples. At the same time, other scholars had done lots of researches on backfill (Morteza Sheshpari 2015; Guo Lijie et al. 2015; Li et al. 2016a, b).

However, reports about the quantitative relationship between c/t , SC and the UCS values are scarce. In this paper, an original laboratory investigation was undertaken to characterize the SC and c/t effect on the mechanical properties of CCTB. The major objective of this paper is to highlight the influence of the factors of c/t and SC on the tailings backfill strength acquisition. The main objectives of this study are as follows:

- To obtain the effect of the c/t and SC on the strength of CCTB.

- To investigate the relationship between c/t and the UCS of CCTB.
- To obtain the relationship between SC and the UCS of CCTB.

The results of the study can provide significant reference for the backfill design of underground mining.

2 Experimental Program

2.1 Materials

2.1.1 Tailings

The coarse tailings used in this study are provided by a gold mine in southeast of China. The particle size distributions of the coarse tailings are measured using a Winner2000 particle size analyzer in accordance with ASTM D421 and D4222 procedures. The particle size distribution (PSD) is shown in Fig. 1. The chemical compositions of coarse tailings used are given in Table 1.

From Fig. 1, it can be easily found that tailings contain sand-sized and silt-sized particles of 6.82 and 93.18%, respectively. We can also find that the most abundant mineral with in coarse tailings was SiO_2 (63%), Al_2O_3 (16.4%), CaO (1.89%) and MgO (0.48%).

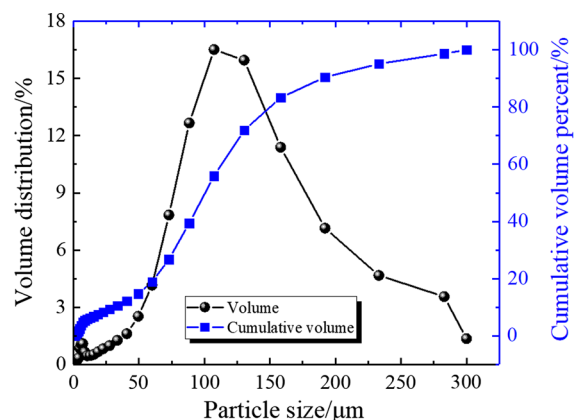


Fig. 1 Particle size distributions of coarse tailings

Table 1 Chemical compositions of the coarse tailings in the tests

Chemical component	SiO ₂	Al ₂ O ₃	CaO	c	P	Fe	S	Au
Coarse tailings (wt%)	63.6	16.4	1.89	0.48	0.08	3.01	0.17	≤0.01

2.1.2 Binder and Water

Water, binders and coarse tailings with different mix proportions are used to prepare the CCTB slurry specimens. Ordinary Portland cement (OPC) 32.5 R with granulated blast-furnace slag (GBFS), fly ash and silica fume was used to as ingredient. Tap water was used to mix cement and coarse tailings. The pH of the tap water is 7.01, which is basically neutral.

2.2 Mixture Preparation

Tap water was used to mix the binder and coarse tailings. Five types of SC values with 63 wt%, 65 wt% wt%, 68 wt%, 70 wt%, 72 wt% and four types of c/t values with 1/4, 1/6, 1/8 and 1/10 were prepared. The required amounts of coarse tailings and cement were weighed and mixed in a metal container. The calculating volume of tap water was weighed by a measuring cup, and the mixture was working until a homogeneous slurries was obtained. The CTB sample used for UCS testing is a cube with a side length of 7.07 cm in accordance with the ASTM C109/ C109 M-16a standard procedure (C109/C109 M-16a 2016). The CCTB slurries were added into 70.7 mm × 70.7 mm × 70.7 mm metal cubes. Setting the curing environment was 20 ± 1°C with a relative humidity of

92 ± 5%. The curing periods was 3 days. Figure 2 shows the maintenance process of CCTS samples, while Fig. 2a shows the curing box, Fig. 2b is the metal cubes and Fig. 2c is the produced samples.

2.3 Uniaxial Compressive Testing and Procedure

Uniaxial compressive strength (UCS) can directly be used to measure the compressive value of different kinds of materials. To determine the strength of CCTB gained based on the GB/T1767-1999 Chinese standard procedure, the SANS electronic universal testing equipment (having a maximum pressure of 300 kN) was used at a loading rate of 0.5 mm/min (Xue et al. 2018). The compressive device (as shown in Fig. 3) was used to investigate the relationship between compressive strength and axial displacement. This device was mainly composed by a loading plate, a pressure head, a base head.

The uniaxial compressive strength is defined by the ratio of the axial peak force F (N) and the cross section area A (m²).

$$UCS = F/A \quad (1)$$

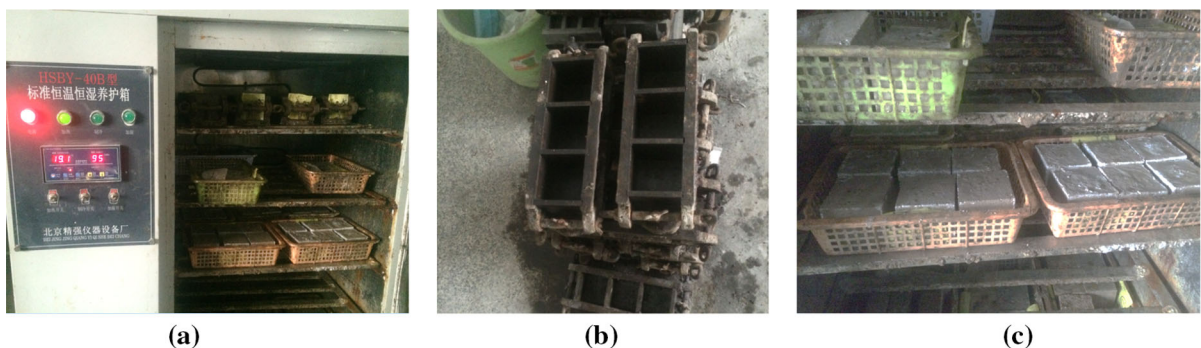


Fig. 2 Maintenance process of CCTS samples, **a** curing box, **b** metal cubes, **c** produced samples

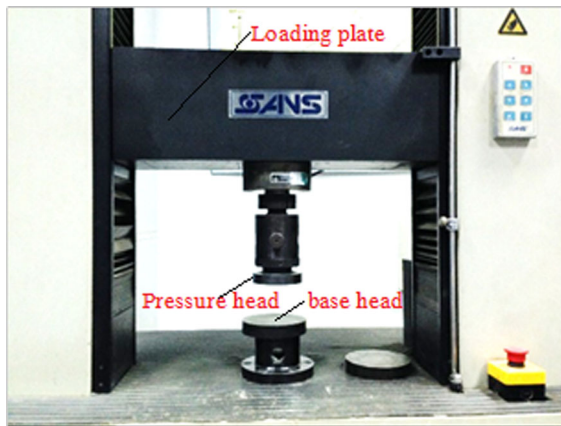


Fig. 3 Unconfined compressive device

2.4 Scanning Electron Microscope Testing

In this test, the S-360 scanning electron microscopy (SEM) system was used to analysis the microstructure and texture of CTB samples. The SEM method provides some advantages, such as high resolution, large magnification time, and 3D image views (Cao et al. 2018).

3 Results Analysis

Different SC values (63 wt%, 65 wt%, 68 wt%, 70 wt% and 72 wt%) and c/t values (1/4, 1/6, 1/8 and 1/10) of the CCTB specimens were used in this experiment to analyze the relation among UCS, SC and c/t . Table 2 presents the result of UCS under different c/t , SC and curing period values.

3.1 The Effect of the c/t on the Development of UCS

The effect of the c/t on the compressive strength of CCTBs is shown in Fig. 4. The c/t is an additional

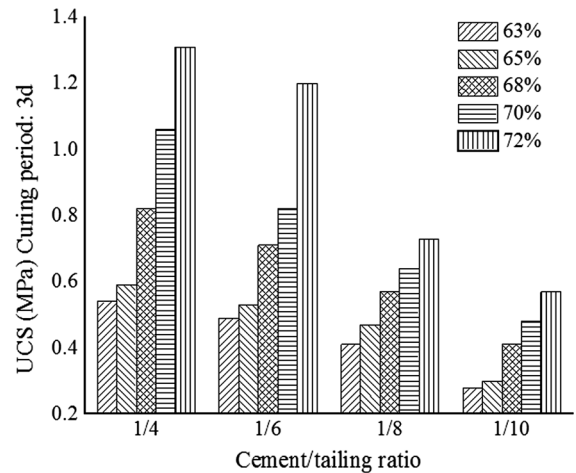


Fig. 4 Relationship between UCS and c/t

factor that should be considered to be a contributor to the strength of CCTB, which plays an important role in the development of the mechanical performance. The UCS values of the CCTB changed from 0.28 to 0.54 MPa, from 0.30 to 0.59 MPa, 0.41 to 0.82 MPa, 0.48 to 1.06 MPa and 0.57 to 1.31 MPa for 3 days curing period, with SC of 63–72 wt%. The results show that the compressive strength of CCTB increased with increasing of c/t . We also found that the cement content plays an important role in increasing UCS of CTB specimens. The influence of cement content on UCS was easy to understand, since increasing cement can speed up the binder hydration. The calcium hydroxide (CH), calcium silicate hydrate (C–S–H) increase with the cement content, which result in a corresponding increment in the CTB strength (Xu et al. 2018).

To study the relationship between UCS and c/t , different kinds of curve fitting (linear, logarithmic, exponential and power) are calculated (as illustrated in Table 3). In order to improve the accuracy of the calculation results, there are 5 groups of CCTB samples at 3 days curing period employed in this

Table 2 Result of UCS under different c/t , SC and curing period values

c/t	Curing period	UCS (MPa)				
		63 wt%	65 wt%	68 wt%	70 wt%	72 wt%
1/4	3	0.54	0.59	0.82	1.06	1.31
1/6	3	0.49	0.53	0.71	0.82	1.20
1/8	3	0.41	0.47	0.57	0.64	0.73
1/10	3	0.28	0.30	0.41	0.48	0.57

Table 3 Results of the curve fitting

Types of curve fitting	Average multiple correlation coefficient (R^2)
Linear	0.8489
Logarithmic	0.9186
Exponential	0.7899
Power	0.8760

Fig. 5 Correlation of UCS and c/t for CCTB samples under different c/t values: **a** linear fitting, **b** logarithmic fitting, **c** exponential fitting, **d** power fitting

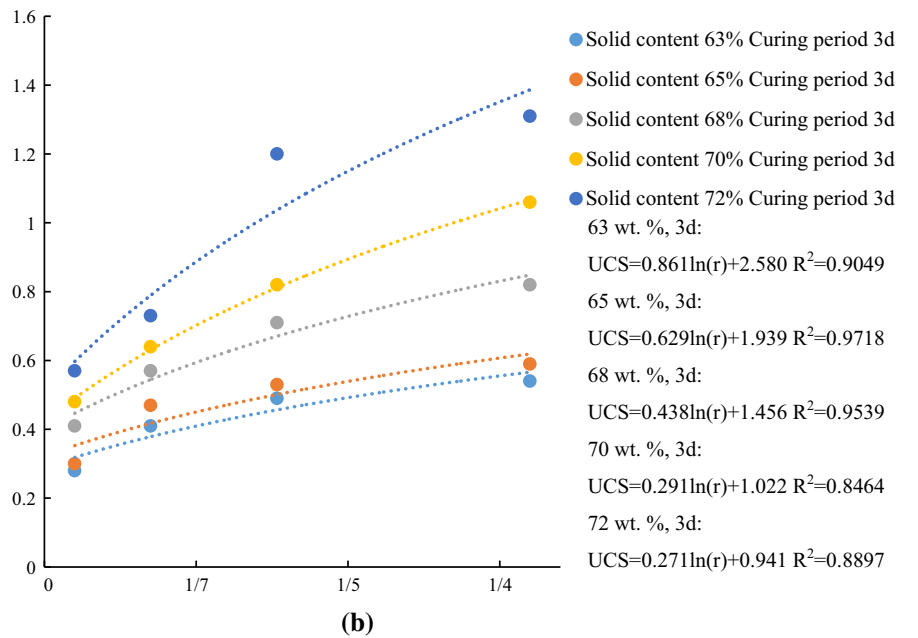
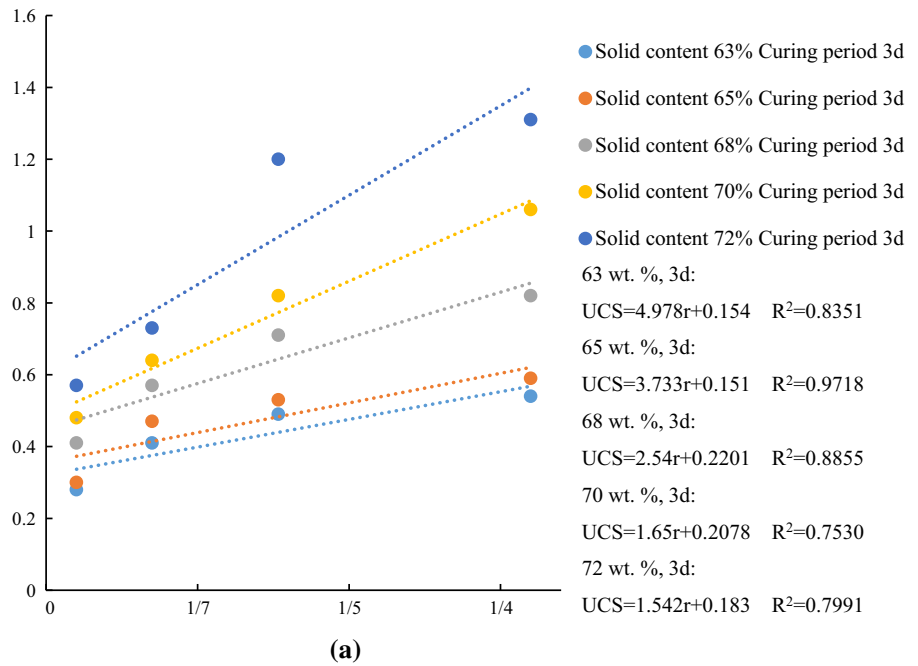
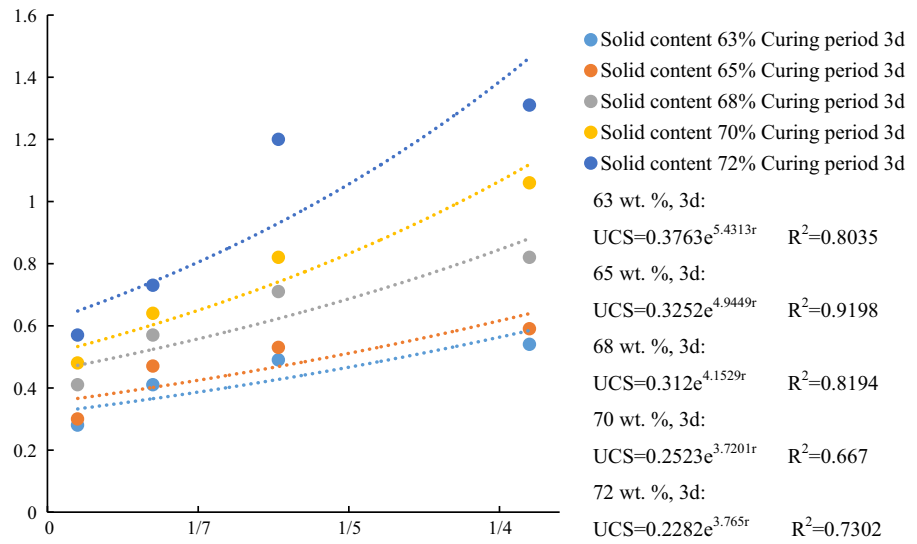
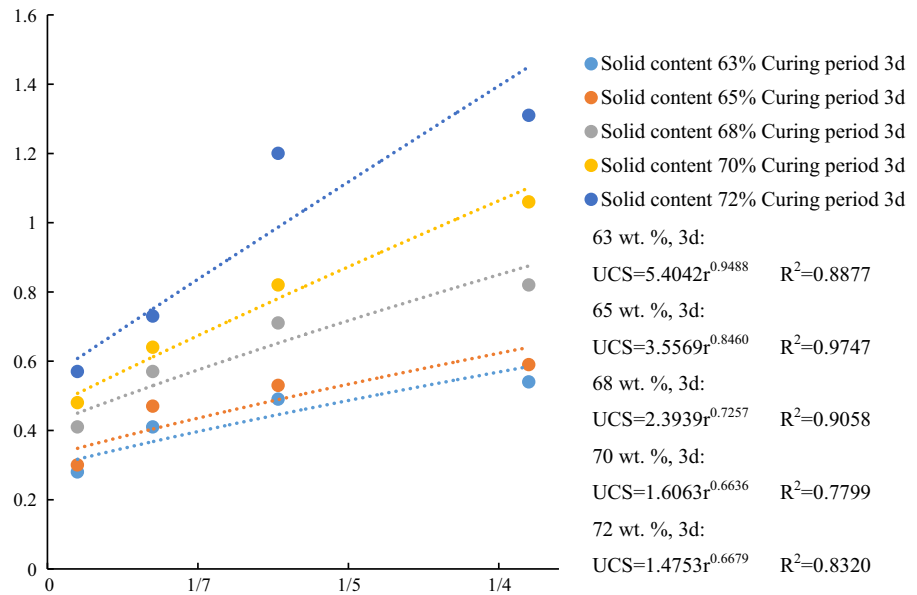


Fig. 5 continued



(c)



(d)

calculation. As demonstrated in Table 3, multiple correlation coefficients (R^2) of four kinds of fitting methods are 0.8489, 0.9186, 0.7899 and 0.8760, respectively. It is found that the logarithmic fitting has the highest correlation coefficient. Thus, the relationship between UCS and c/t of the CCTB samples prepared at different SC values are in a logarithmic relationship. Figure 5 shows the fitting

result between UCS and c/t for CCTB, as exhibited by the following equation:

$$UCS = a_1 \ln(r) + b_1 \tag{2}$$

where UCS is the uniaxial compressive strength, and r is c/t value. Also a_1 and b_1 are parameters related to c/t and UCS values.

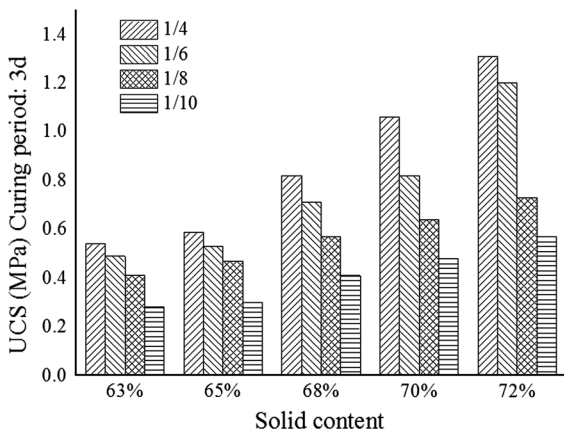


Fig. 6 Relationship between UCS and SC

Table 4 Results of the curve fitting

Types of curve fitting	Average multiple correlation coefficient (R ²)
Linear	0.9513
Logarithmic	0.9445
Exponential	0.9801
Power	0.9766

3.2 The Effect of the SC on the Development of UCS

Figure 6 demonstrates the effect of SC (63 wt%, 65 wt%, 68 wt%, 70 wt% and 72 wt%) on the evolution of UCS development versus curing period at the same *c/t*. It is evident that the UCS value of CCTB samples increase with the rise of SC. In addition, Fig. 6 illustrates that the UCS of CCTB samples increase with the *c/t* values increase. From the microscopic point, the hydration products (C–S–H gel and ettringite) wrap up the tailings particles and link them together. These products fill the pore space and improve the connecting stress between particles of tailings. Consequently, this can lead to an increase in the mechanical performance. The reason for this higher strength of CTB with higher SC is because higher SC increases the compactness of tailings, and the hydration products are more closely bonded (Fall and Pokharel 2011; Claude et al. 2009).

To find the relationship between the UCS of CCTB and SC, different kinds of curve fitting (linear,

logarithmic, exponential and power) are calculated (as illustrated in Table 4). In order to improve the accuracy of the calculation results, there are 5 groups of CCTB samples at 3 days curing period employed in this calculation. As demonstrated in Table 4, multiple correlation coefficients (R²) of four kinds of fitting methods are 0.9513, 0.9445, 0.9801 and 0.9766, respectively. It is conducted that, the relationship between UCS and SC of CCTB samples prepared at different *c/t* values are in an exponential relationship with the highest multiple correlation coefficient (R²). Figure 7 shows the fitting result between UCS and SC for CCTB, as exhibited by the following equation:

$$UCS = a_2 \cdot e^{b_2 \cdot w} \tag{3}$$

where *UCS* is the uniaxial compressive strength, and *w* is SC value. Also *a*₂ and *b*₂ are parameters related to SC and UCS values.

According to this fitting result, the UCS values of the CCTB samples can possibly be obtained.

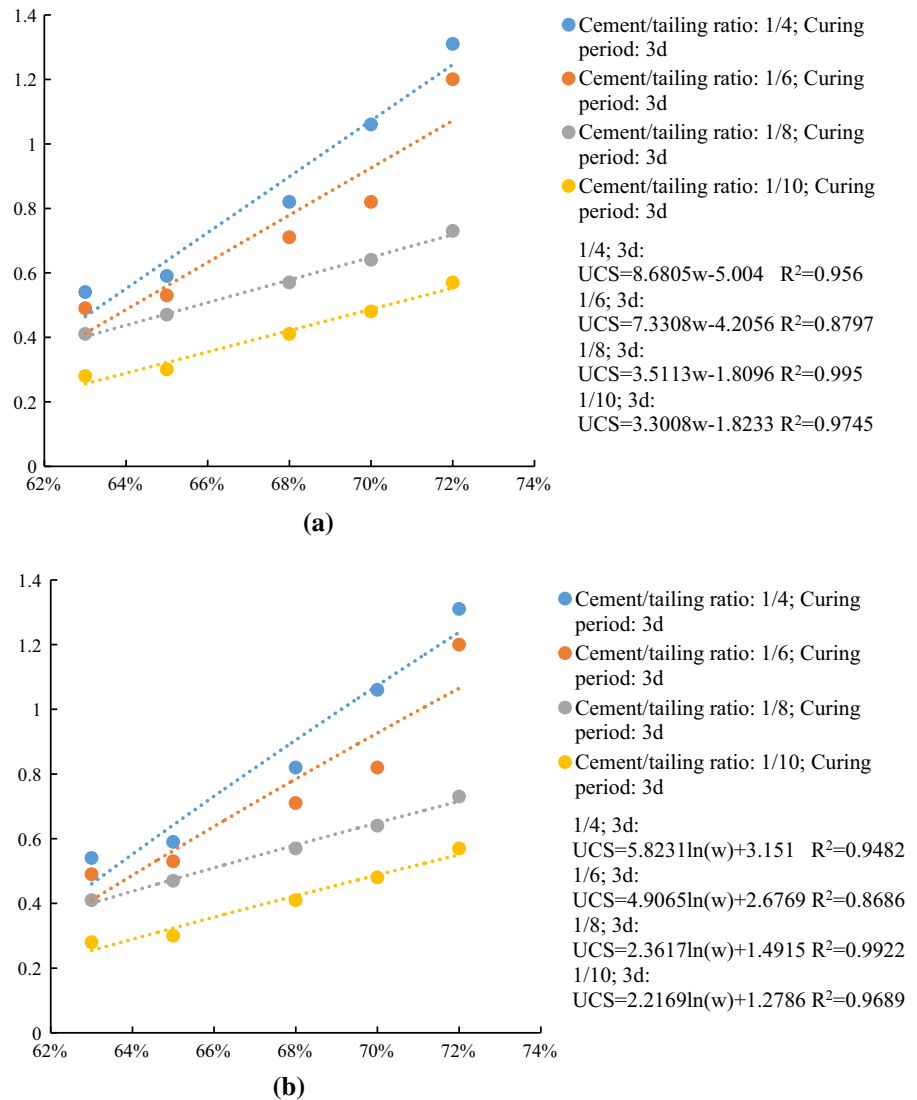
Although the highest multiple correlation coefficients (R²) were found for the obtained equations, it does not mean the goodness-of-fit of these equations. Therefore, *t* and *F* tests were used to verify the validity of these equations. The *t* test compares the computed values with tabulated values using null hypothesis. A 95% level (*p* < 0.05) of confidence was selected in the *t* and *F* tests. If the computed *t* and *F* are greater than the tabulated ones, the null hypothesis is rejected. The results of *t* and *F* tests are shown in Table 5. As shown in Table 5, the computed *t* and *F* values are both greater than the tabulated ones, indicating the validity of those equations.

3.3 Hydration Products and Microstructure Analysis

In this test, the authors used S-360 to scan the fracture of CCTB to figure out the microstructure features of CCTB after a long period of curing time. The samples were prepared according to the size of 10 mm × 10 mm × 10 mm and are subjected to a carbon spray treatment for two or more times for each sample. Then, every sample is analyzed under different magnification factors and thus the SEM and EDS results are obtained, which are shown in Fig. 8.

It was found that the hydration products are calcite (aft) and C–S–H gel, and the elements of hydration

Fig. 7 Correlation of UCS and c/t for CCTB samples under different SC values. **a** Linear fitting, **b** logarithmic fitting, **c** exponential fitting, **d** power fitting



products mainly include C, O, Mg, Al, Si, K and Ca. There are several voids on the surface of the samples, it can be explained that the hydration is not enough because of the short time hydration.

4 Conclusions

Backfill slurry solid content (SC) and cement-to-tailings ratio (c/t) are critical to the quality of the cemented tailings backfill. Accurate control of slurry's SC and c/t is a big problem for mining industry all around the world. In this study, the effect of c/t and SC on the early age strength of CCTB are investigated.

CCTB samples made at different c/t values (1/4, 1/6, 1/8 and 1/10) and SC values (63, 65, 68, 70, 72 wt%) are subjected to UCS measurements at 3 days of curing period. The UCS values of CCTB samples increase with the increase of c/t and SC. It is shown that the UCS and corresponding c/t values of CCTB are in a logarithmic function with each other. Also the relationship between the UCS and SC meets an exponential distribution.

The laboratory results obtained in this paper is based on a gold mine in southeast of China. However, the parameters such as tailings type, mineralogy, and cement are different for each mine. Thus, this study

Fig. 7 continued

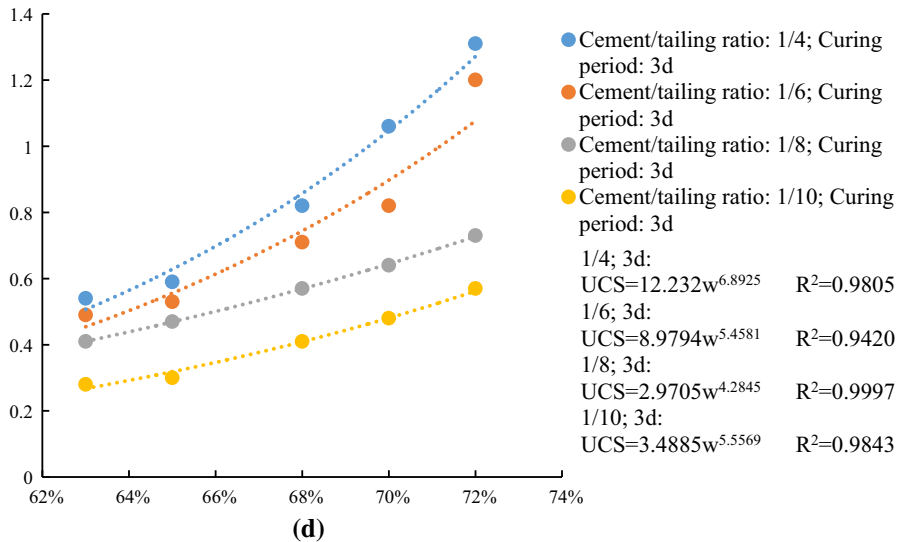
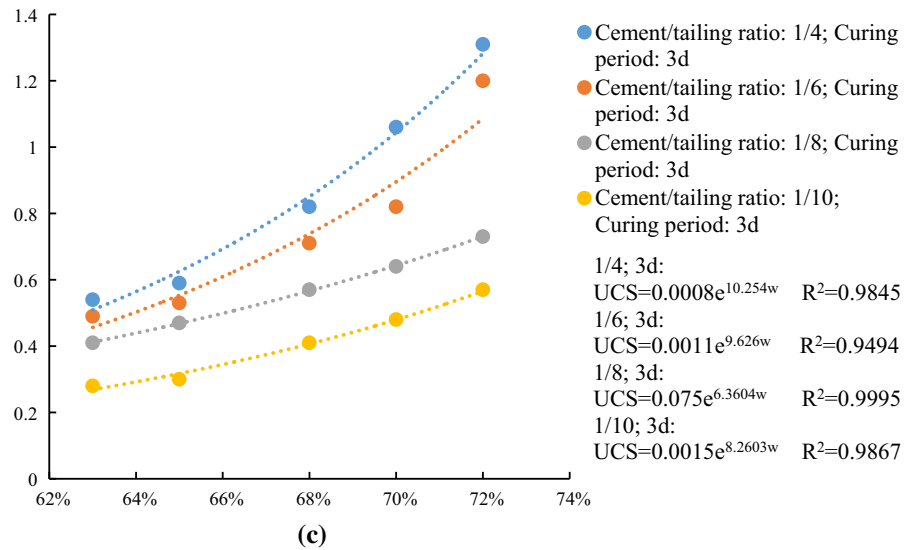


Table 5 Results of *t* and *F* tests for Eqs. (2) and (3)

Equation number	Computed <i>t</i>	Tabulated <i>t</i>	Computed <i>F</i>	Tabulated <i>F</i>
(2)	6.384	± 2.02	58.684	4.46
(3)	5.436	± 2.02	74.368	4.46

can only provide a basis for the backfilling design of the studied gold mine.

In future research works, the authors will consider applying the results obtained in this test to a metal

mine backfilling. We also demonstrate the results of the laboratory research based on the technical problems that may arise during the backfilling process.

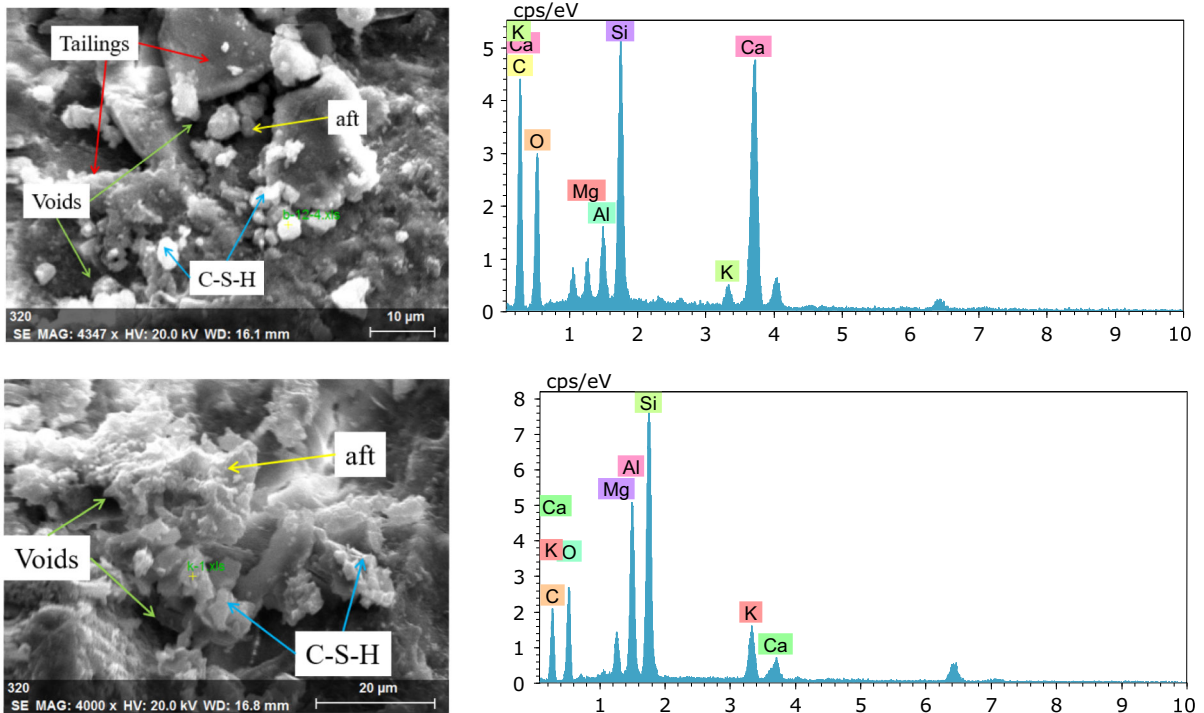


Fig. 8 SEM images and EDS spectra of CCTB

References

- ASTM Standard C109/C109 M-16a (2016) Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or (50-mm) cube specimens. Annual book of ASTM (American Society of Testing Material) standards, 04.08. ASTM International, West Conshohocken. https://doi.org/10.1520/C0109_C0109M-16A
- Cao S, Yilmaz E, Song WD (2018a) Dynamic response of cement-tailings matrix composites under SHPB compression load. *Constr Build Mater* 186:892–903
- Cao S, Yilmaz E, Song WD (2018b) Evaluation of viscosity, strength and microstructural properties of cemented tailings backfill. *Minerals* 8(352):1–19
- Chien-Hsing L, Chen J-C, Chuang K-H, Wey M-Y (2015) The different properties of lightweight aggregates with the fly ashes of fluidized-bed and mechanical incinerators. *Constr Build Mater* 101:380–388
- Chousidis N, Rakanta E, Ioannou I, Batis G (2015) Mechanical properties and durability performance of reinforced concrete containing fly ash. *Constr Build Mater* 101:810–817
- Claude J, Célestin H, Fall M (2009) Thermal conductivity of cemented paste backfill material and factors affecting it. *Int J Min Reclam Environ* 23:274–290
- Cruz N, Peng Y, Wightman E (2015) Interactions of clay minerals in copper-gold flotation: part 2-Influence of some calcium bearing gangue minerals on the rheological behaviour. *Int J Miner Process* 141:51–60
- Cui L, Fall M (2015) A coupled thermo–hydro-mechanical–chemical model for underground cemented tailings backfill. *Tunn Undergr Space Technol* 50:396–414
- Fall M, Pokharel M (2011) Strength development and sorptivity of tailings shotcrete under various thermal and chemical loads. *Can J Civ Eng* 38:772–784
- Feng Y, Yanzhen Y, Qiu L, Wan X, chen L (2012) Performance of water quenched slag particles (WQSP) for municipal wastewater treatment in a biological aerated filter (BAF). *Biomass Bioenerg* 45:280–287
- Franks GV, Forbes E, Oshitani J, Batterham RJ (2015) Economic, water and energy evaluation of early rejection of gangue from copper ores using a dry sand fluidized bed separator. *Int J Miner Process* 137:43–51
- 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* 170:11–23
- Hamzaoui R, Bouchenafa O, Guessasma S, Leklou N, Bouaziz A (2016) The sequel of modified fly ashes using high energy ball milling on mechanical performance of substituted past cement. *Mater Des* 90:29–37
- Jiang Y, Ideta Keiko, Kim J, Miyawaki J, Jung D-H, Yoon S-H, Mochida I (2015) The crystalline and microstructural transformations of two coal ashes and their quenched slags with similar chemical compositions during heat treatment. *J Ind Eng Chem* 22:110–119

- Ke X, Hou HB, Zhou M, Wang Y, Zhou X (2015) Effect of particle gradation on properties of fresh and hardened cemented paste backfill. *Constr Build Mater* 96:378–382
- Kesimal A, Yilmaz E, Ercikdi B, Alp I, Yumlu M, Ozdemir B (2002) Laboratory testing of cemented paste backfill. *Madencilik* 41(4):25–32
- Li H, Li Y, Gong Z, Li X (2013) Performance study of vertical flow constructed wetlands for phosphorus removal with water quenched slag as a substrate. *Ecol Eng* 53:39–45
- Li Y, Jin L, Zhang L (2016a) Long-term strengthening effect of cemented tailings considering the loading rates. *Electron J Geotech Eng* 21(3):955–968
- Li Y, Jin L, Zhang L (2016b) Mechanical parameters of cemented paste backfilling and its failure modes under different loading rates. *Electron J Geotech Eng* 21(3):969–978
- Lijie G, Keping Z, Xiacong Y (2015) Model-experimental study on cemented rock-tailings backfilling process. *Electron J Geotech Eng* 20(5):1703–1715
- Liu Q, Huang S, Kang Y, Liu X (2015) A prediction model for uniaxial compressive strength of deteriorated rocks due to freeze-thaw. *Cold Reg Sci Technol* 120:96–107
- Nawaz A, Julnipitawong P, Krammart P, Tangtermsirikul S (2016) Effect and limitation of free lime content in cement-fly ash mixtures. *Constr Build Mater* 102:515–530
- Sheshpari M (2015) A review of underground mine backfilling methods with emphasis on cemented paste backfill. *Electron J Geotech Eng* 20(13):5183–5208
- Wang X-Y, Park K-B (2015) Analysis of compressive strength development of concrete containing high volume fly ash. *Constr Build Mater* 98:810–819
- Wu D, Yang BG, Liu YC (2015) Transportability and pressure drop of fresh cemented coal gangue-fly ash backfill (CGFB) slurry in pipe loop. *Power Technol* 284:218–224
- Xu W, Cao PW, Tian MM (2018) Strength development and microstructure evolution of cemented tailings backfill containing different binder types and contents. *Minerals* 8(167):1–15
- Xue GL, Yilmaz E, Song WD, Cao S (2018) Compressive strength characteristics of cemented tailings backfill with alkali-activated slag. *Appl Sci* 8:1537
- Yilmaz E (2018) Stope depth effect on field behaviour and performance of cemented paste backfills. *Int J Min Reclam Environ* 32(4):273–296
- Yilmaz E, Kesimal A, Ercikdi B (2003) The factors affecting strength and stability of paste backfill. *Turkish J An Earth Sci* 28:155–169
- Yilmaz E, Belem T, Benzaazoua M (2012) One-dimensional consolidation parameters of cemented paste backfills. *Miner Resour Manag* 28(4):29–45
- Yilmaz E, Belem T, Benzaazoua M (2014a) Effects of curing and stress conditions on hydromechanical, geotechnical and geochemical properties of cemented paste backfill. *Eng Geol* 168:23–37
- Yilmaz E, Benzaazoua M, Bussi ere B, Pouliot S (2014b) Influence of disposal configurations on hydrogeological behaviour of surface paste disposal: a field experimental study. *Int J Miner Process* 131:12–25
- Yilmaz T, Ercikdi B, Karaman K, K ulek ci G (2014c) Assessment of strength properties of cemented paste backfill by ultrasonic pulse velocity test. *Ultrasonics* 54:1386–1394
- Yin SH, Wu AX, Hu KJ, Wang Y, Zhang YK (2012) The effect of solid components on the rheological and mechanical properties of cemented paste backfill. *Miner Eng* 35:61–66
- Zhou J, Li XB, Mitri HS, Wang SM, Wei W (2013) Identification of large-scale goaf instability in underground mine using particle swarm optimization and support vector machine. *Int J Min Sci Technol* 23:701–707

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.