Experimental study on stress-strain-strength behavior of cemented tailings backfill with different curing age

Yongyan Wang* and Lizhuang Cui
School of mechanical and electrical engineering, Qingdao University of Science and Technology, Qingdao 266061, China

*Corresponding author email: cvlizon@mails.qust.edu.cn

Abstract. In order to understand the changes in the properties of the cemented tailings backfill (CTB) during the curing process. In this paper, the CTB samples with a cement-sand ratio of 1:6 were prepared and cured for 3, 5, 7, 14, 21, 28, 60, 140 and 200 days respectively, and then a series of uniaxial compression tests were carried out. Then the stress-strain relationship, compressive properties, elastic modulus, etc. of the CTB with different curing age were analyzed. Results indicate that when the samples are cured at a short curing age that is shorter than 7 days, CTB mainly shows plasticity, while as the age increases, the samples’ deformation mainly experienced four stages. And as the age increases, the unconfined compressive strength (UCS) and the modulus of elasticity keep increasing, but the growth rate gradually slows down.

Keywords: Cemented tailings backfill, curing age, stress-strain-strength, unconfined compressive strength.

1. Introduction
CTB is a composite mixing prepared by water, tailings and cement in a certain proportion, which is gradually condensed through hydration reaction of the cement clinker, and finally consolidated and hardened to form a stone-like body with a certain strength[1]. In the backfilling mining, the backfilling material is used to fill up the gob in order to control strata movement and deformation. However, CTB exhibits different properties due to curing age differences in the consolidation and hardening process.

At present, there have been a lot of research on the influence of curing age on cementing materials. However previous studies on the effect of curing age on the properties of cementitious materials are mainly carried out on concrete[2,3]. And for backfilling material, Erol et al.[4] found that consolidation characteristics of cemented paste backfill (CPB) are greatly affected by the content and type of binder as a function of curing time, and the one-dimensional consolidation properties of early age CPB were investigated. Xu et al.[5] analysed the electricity resistivity characteristic and the relevance between the electricity resistivity and the UCS of CPB during the whole consolidation process, and the quantity equation was established, besides, they summarized the entire consolidation process into five stages. Hou et al.[6] studied the influence of curing age on the damage characteristics and energy dissipation of CTB, and they found that the prolongation of curing age can effectively hinder the initiation and expansion of cracks. Fu et al.[7] analyzed the intensity sensitivity of CTB and found that CTB intensity
follows an exponential function with increasing curing age, and the sensitivity of the backfills’ strength to curing age is the highest.

However, litter research has been conducted to understand the effects of curing age on the stress-strain-strength behavior of CTB. Therefore, the aim of this study is to investigate the effects of the curing age on stress-strain behavior, compressive strength and elastic modulus, etc. A series of uniaxial compression tests on the CTB samples of different curing ages (3, 5, 7, 14, 21, 28, 60, 140 and 200 days) were conducted in this study.

2. Materials and Methods

2.1. Materials
The materials used for the CTB preparation in this study included tailings, binder and water.

2.1.1. Tailings. The tailings used are full tailings fillers, sourced from a gold mine in Shandong, China. The chemical composition of tailings used for the CTB preparation was obtained from an X-ray Fluorescence (XRF) analysis, and listed in Table 1.

| Chemical parameter | SiO$_2$ | Al$_2$O$_3$ | K$_2$O | Fe$_2$O$_3$ | CaO | SO$_3$ | MgO | Others |
|--------------------|--------|------------|-------|------------|-----|-------|-----|--------|
| Values (%)         | 64.644 | 16.785     | 5.406 | 4.838      | 2.722 | 1.721 | 1.142 | 2.742  |

2.1.2. Binder. The binder used in the experiment is ordinary Portland cement (OPC, namely, PO42.5, used as a reference).

2.1.3. Mixing water. In this study, pure water was used to mix cement and tailings, and the water temperature was controlled within the range of 18°C-23°C.

2.2. Samples preparation
A cement-tailing ratio (c/t = 1:6) is used for CTB and a water to cement ratio (w/c) equal to 2.33. The tailings material, cement and water were mixed and homogenized in a food mixer for about 7 min[8]. Pour the mixed slurry into an acrylic cylindrical mold with a diameter of 50 mm and a height of 110 mm. After being cured for 24 hours, the mold will be released. Place the newly prepared CTB sample in a constant temperature and humidity curing box and cure for 3, 5, 7, 14, 21, 28, 60, 140, 200 days. The curing humidity is set to 95%, and the curing temperature is 20°C.
2.3. UCS Tests
UCS is measured by TAW-200 material testing machine (Figure 2). The terminal faces of samples are smoothed with a grinder and applied with petroleum to reduce the influence of stress concentration and friction between the sample and the indenter on the experimental results and failure modes. The compression tests are carried out at a constant deformation rate of 0.2 mm/min.

3. Analysis of experimental results

3.1. Stress-strain curve analysis
Figure 3 presents the stress-strain curves of CTB samples at different curing ages obtained by a series of uniaxial compression tests. It can be found that the stress-strain curves of CTB samples under the different curing age can be roughly divided into four stages, namely the compaction stage (OA), elastic stage (AB), yield stage (BC) and failure stage (CD), which has been presented in the Figure 3. But the difference in curing age leads to great differences in the four stages. At the curing age of 3 days and 5 days, the failure stage is not obvious, but the yield failure occurs and becomes main form continuously, and there is no rapid post-peak fall. The stress of the CTB sample begins to have an obvious peak when the curing age is greater than 21 days. Therefore, when the samples are cured at a short curing age that is shorter than 7 days, CTB mainly shows plasticity, as a result, there is a long yield stage obviously on the stress-strain curves. As the age increases, an obvious post-peak drop appears on the stress-strain curve, that is, the failure stage is more obvious, showing the typical stress-strain behavior of rocks, which shows that CTB is consolidated and hardened into a strong rock-like material under the long age cured.

![Figure 3](image)

Figure 3. (a) The typical stress-strain curve; (b) The stress-strain curves of CTB samples at different curing ages.

3.2. Analysis of UCS
The evolution of UCS and peak strain acquired from the stress–strain curves with different curing age was investigated for all of the samples and the results are shown in Figure 4. It is seen that as the curing age increases, the UCS keeps increasing, but the growth rate gradually slows down. When the CTB samples are cured from 3 days to 7 days, the UCS increased by 148.81%, and increased by 91.81% when the samples cured from 7 days to 28 days, while compared to the samples cured 28 days, it increased by 83.58% when cured 200 days. In terms of the general mine goaf, to meet the requirements of backfilling mining, the strength of the backfilling body need to attain about 2 Mpa to 3 Mpa, which means the CTB in this study can meet the requirements of backing filling mining after 21 days of curing.

According to the hydration reaction mechanism of cement, when the CTB slurry is evenly mixed, the hydration reaction happened with cement clinker minerals quickly to precipitate hydration Hydration products such as Ca(OH)$_2$ crystal, hydrate calcium silicate (C-S-H bonds) and ettringite (AFT). The increase in UCS is mainly attributed to the internal hydration products of CTB accumulate with curing.
The voids between the tailings cement particles are filled with hydration products to cement and adhere, and the tissue structure becomes denser.

In the same way, because the voids between particles such as tailings and cement are filled with products such as C-S-H bonds generated by the hydration reaction, the peak strain decreases continuously until the age increases to 28 days, and then the decreasing trend is no longer obvious. It can also be seen in combination with Figure 4 that when the age is greater than 21 days, the peak strain of CTB is basically stable and fluctuates at $13 \times 10^{-3}$.

3.3. Analysis of elastic modulus

The elastic modulus can reflect the deformation and mechanical properties of CTB. From a macro perspective, the elastic modulus is a measure of the ability of CTB to resist elastic deformation during compression. From a microscopic point of view, the elastic modulus can reflect the sparseness of the internal structure of CTB and the strength of cementation between particles. Calculate the elastic modulus of CTB at different ages, as shown in Figure 5. The elastic modulus value at the age of 140 days is an outlier. But it can be seen from Figure 5 that the sharp increase in the elastic modulus of CTB samples mainly occurred before 28 days, which means the greater the stress required for a certain elastic deformation of the CTB, and the stiffness of CTB samples become greater. As a result, the smaller the elastic deformation will happen when the CTB is under certain stress, which is beneficial to control strata movement and deformation.

When the curing age exceeds 28 days, the properties include UCS, peak strain and elasticity indicators of CTB samples tend to be flat with increasing curing age. Therefore, in backfilling mining, the properties of CTB basically measured with the samples cured after 28 days.
4. Conclusions
In this study, a series of uniaxial compression tests were carried out on the CTB samples cured for 3, 5, 7, 14, 21, 28, 60, 140 and 200 days. The main conclusions are as follows:

(1) At the curing age of 3 days and 5 days, the failure stage of the stress-strain curve is not obvious, but the yield failure occurs and becomes main form continuously, and there is no rapid post-peak fall. However, there will be four stages of the stress-strain curves and an obvious peak when the curing age is greater than 21 days.

(2) The UCS of the CTB increases with the increase of the curing age. However, the growth rate gradually slows down. While the peak strain decreases continuously until the age increases to 28 days, and then the decreasing trend is no longer obvious.

(3) The sharp increase in the elastic modulus of CTB samples mainly occurred before 28 days. When the curing age exceeds 28 days, the properties include UCS, peak strain and elasticity indicators of CTB samples tend to be flat with increasing curing age.

References
[1] Ke Xing. Study on structure and properties of the consolidation mass of cemented tailings backfill. [D]: Wuhan University; 2016.
[2] Chen Xiaopeng. Study on Shrinkage Characteristic of Concrete at Early Age. [D]: Changjiang River Scientific Research Institute; 2016.
[3] Jin Xianyu, Tian Ye, Jin Nanguo. Early age properties and cracking control of concrete. Journal of Building Structures; 2010(31) 6 204-212.
[4] Yilmaz E, Belem T, Bussière B, Mbonimpa M, Benzaazoua M. Curing time effect on consolidation behaviour of cemented paste backfill containing different cement types and contents. CONSTR BUILD MATER. 2015;75:99-111.
[5] Xu Wenbin, Tian Xichun, Qiu Yu, Dang Peng, Yin Tianjun. Experiment of the resistivity characteristic of cemented backfill mass during the whole consolidation process. Journal of China University of Mining & Technology. 2017;46:265-72.
[6] Hou Yongqiang, Yin Shenghua, Cao Yong, Dai Chaoqun. Analysis of damage characteristics and energy dissipation of cemented tailings backfill with different curing ages under uniaxial compression. Journal of Central South University (Science and Technology). 2020;51:1955-65.
[7] Fu Jianxin, Du Cuifeng, Song Weidong. Strength sensitivity and failure mechanism of full tailings cemented backfills. Journal of University of Science and Technology Beijing. 2014;36(9): 1149-1157.
[8] Ghirian A, Fall M. Coupled Behavior of Cemented Paste Backfill at Early Ages. Geotechnical and Geological Engineering. 2015;33:1141-66.