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A Constitutive Model for Cemented Tailings Backfill Under Uniaxial Compression

Bingbing Tu [1,2], Lang Liu [3,4], Kangli Cheng [3], Bo Zhang [3], Yujiao Zhao [3], Qixing Yang [3] and Kiil Song [5]*

[1] College of Science, Xi'an University of Science and Technology, Xi'an, China, [2] State Key Laboratory of Green Building in Western China, Xi'an University of Architecture and Technology, Xi'an, China, [3] Energy School, Xi'an University of Science and Technology, Xi'an, China, [4] Key Laboratory of Western Mines and Hazards Prevention, Ministry of Education of China, Xi'an, China, [5] Department of Civil Engineering, Inha University, Incheon, South Korea

Constitutive model is the foundation describing the mechanical properties of materials. Cemented tailings backfill (CTB) plays an important role in goaf filling. However, a universally applicable constitutive model for CTB has not been proposed yet. In this paper, a two-stage constitutive model of CTB under uniaxial compression was established, based on the Weibull distribution density function, the strain equivalence principle and the damage mechanics theory. Eight groups of CTB samples with a diameter of 50 mm and a height of 100 mm prepared with different solid contents (70–78 wt%) and cement-sand ratios (1/4–1/10) were subjected to uniaxial compression tests to verify the validity of the theoretical model. The compared results showed that the predictions of the proposed constitutive model agreed well with the experimental results. The following conclusions were also obtained: (i) Solid content and cement-sand ratio had a significant effect on the basic mechanical parameters of the CTB samples, especially at the peak stress; (ii) The constitutive model of CTB was similar to that of the ordinary cement mortar M5, but with obvious residual stress; (iii) The failure mode of the CTB specimens under uniaxial compression was mainly tensile failure. The results presented in this paper contribute to a better understanding of the uniaxial compression characteristics of CTB and lay an important foundation for future research.

Keywords: cemented tailings backfill, constitutive model, strain equivalence principle, Weibull distribution, uniaxial compression strength

Edited by:
Longjun Dong,
Central South University, China

Reviewed by:
Jordan Yankov Hristov,
University of Chemical Technology and Metallurgy, Bulgaria
Laurent Olivier Louis,
New England Research, United States

****Correspondence:***
Lang Liu
liulang@xust.edu.cn

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HIGHLIGHTS

- A constitutive model for CTB under uniaxial compression was established.
- Influences of solid content and cement-sand ratio were analyzed.
- The failure mode of CTB specimens under uniaxial compression was mainly tensile failure.

INTRODUCTION

As one of the most commonly used filling aggregates for goaf filling, cemented tailings backfill (CTB) plays an important role in the safe, green, and efficient mining of metals [1]. CTB can effectively solve the problems related to deep rock pressure control and surface subsidence above the goaf, and can also avoid the environmental pollution caused by the accumulation of tailings

[2–4]. Typically, CTB consists of dewatered tailings, a hydraulic binder and mixing water [5, 6]. Since its first use for the Bad Ground Mine (Germany) in the late 1970s, CTB has been widely used in many metal mines worldwide [7–12].

Many factors affect the mechanical properties of CTB samples, such as the filling parameters (filling times, filling interval times, and filling surface angles) [13–15], curing conditions [16–19], binding materials, admixtures (superplasticizers, organosilanes, and limestone powders) [20–23], solid contents, and cement-sand ratios [24–26], which have been considered in previous studies. Meanwhile, the strength properties of CTB under a frozen state and with different fiber reinforcements [27–31] have been analyzed. Moreover, numerous experimental studies have been carried out, especially uniaxial compression tests, which provide the most important parameters for underground mine backfill design [32–35].

The abovementioned research mainly focused on the strength properties of CTB. However, the constitutive model of CTB, which is very important for assessing and predicting its mechanical properties, has not been adequately addressed.

Only a few studies have been performed to investigate the constitutive relation of CTB in the literature. For example, several multiphysics models have been presented to describe and predict the temperature-time behavior [36] and the thermo-hydro-mechanical-chemical behavior of CTB [37, 38]. Evolutive elasto-plastic models based on the D–P yield criterion [39] have been developed to capture the mechanical behavior of CTB. Moreover, intelligent constitutive models have been proposed, based on boosted regression trees (BRT), particle swarm optimization (PSO), random forest (RF), firefly algorithm (FA), machine learning (ML) algorithm, genetic algorithm (GA), and genetic programming (GP), to predict the uniaxial compressive strength of CTB [40–42].

However, the existing studies on constitutive models have mainly focused on experimental data and give stress-strain relationships for a specific situation, but no universally applicable constitutive model has been proposed.

When the tailing cement filling method is used to mine underground mineral resources, before the end of ore mining at the middle level, CTB often acts as a pillar to support the surrounding rocks. At this point, the CTB pillar is under uniaxial compression and its stability plays an important role in stope safety [43, 44]. Therefore, the study on the mechanical properties of CTB under uniaxial compression has a great significance to ensure construction safety of ore mining used the tailing cement filling method.

In this paper, we propose a universally applicable constitutive model to accurately describe and predict the mechanical behavior of CTB under uniaxial loading conditions. Meanwhile, the influences of solid content and cement-sand ratio are analyzed.

DAMAGE VARIABLE

It is assumed that the correlated variables of the CTB element follow the Weibull distribution [45, 46], and the probability density function can be expressed as [47]:

$$P(F) = \frac{m}{F_0}(\frac{F}{F_0})^{m-1} \exp[-(\frac{F}{F_0})^m], \tag{1}$$

where F is a random variable, and $m>0$ and $F_0>0$ are the shape parameter and the scaling parameter, respectively.

The damage variable D under a certain load is defined as follows [48]:

$$D = \frac{N_t}{N}, \tag{2}$$

where N_t is the number of broken elements, and N is the total number of elements.

In an interval of $[F, F+dF]$, the number of broken elements is $NP(F)dF$. When the external force is equal to F, the number of broken elements can be described as:

$$N_t(F) = \int_0^F NP(F)dF = N\left\{1 - \exp[-(\frac{F}{F_0})^m]\right\}. \tag{3}$$

Substituting Equation (3) into Equation (2) gives:

$$D = \frac{N_t}{N} = 1 - \exp[-(\frac{F}{F_0})^m]. \tag{4}$$

Equation (4) is established using the general theory of continuous damage and statistics. The random variable F can be replaced by other physical quantities to establish different damage models. The axial linear strain ε is defined as the random variable in this paper. Then, Equation (4) can be rewritten as:

$$D = 1 - \exp[-(\frac{\varepsilon}{F_0})^m]. \tag{5}$$

CONSTITUTIVE MODEL

According to the strain equivalence principle proposed by Lemaitre [49], the constitutive relation of damaged materials can be derived from undamaged materials, but the nominal stress is replaced by the effective stress of the damaged materials under uniaxial stress. Then, the constitutive relation can be defined [50]:

$$\sigma = E\varepsilon(1 - D). \tag{6}$$

Substituting Equation (5) into Equation (6) gives:

$$\sigma = E\varepsilon \exp[-(\frac{\varepsilon}{F_0})^m]. \tag{7}$$

Considering the effect of the residual stress, Equation (7) is redefined as a two-stage function:

$$\sigma = \begin{cases} E\varepsilon \exp[-(\frac{\varepsilon}{F_0})^m], \varepsilon < \varepsilon_m \\ E\varepsilon_m \exp[-(\frac{\varepsilon_m}{F_0})^m], \varepsilon \geq \varepsilon_m \end{cases}. \tag{8}$$

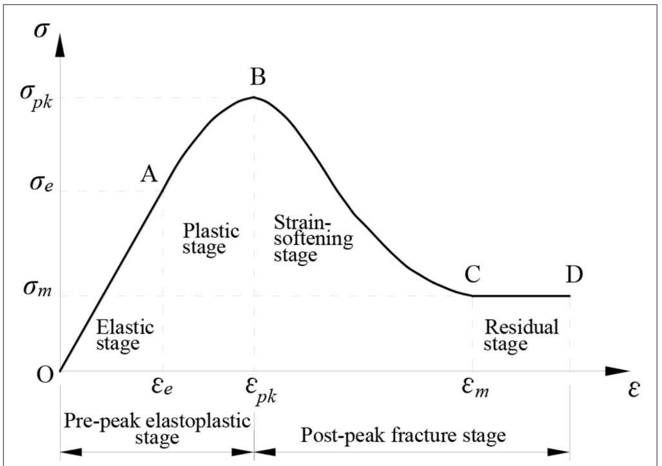

FIGURE 1 | Two-stage constitute model for CTB.

In this paper, the elastic modulus E of the CTB is defined as follows, considering the influence of solid content and cement-sand ratio.

$$E = E(x_1, x_2), \tag{9}$$

where x_1 is the solid content, and x_2 is the cement-sand ratio.

Then, Equation (8) can be rewritten as:

$$\sigma = \begin{cases} E(x_1, x_2)\varepsilon \exp[-(\frac{\varepsilon}{F_0})^m], \varepsilon < \varepsilon_m \\ E(x_1, x_2)\varepsilon_m \exp[-(\frac{\varepsilon_m}{F_0})^m], \varepsilon \geq \varepsilon_m \end{cases}. \tag{10}$$

The corresponding constitutive model is shown in **Figure 1**, where σ_e, σ_{pk}, and σ_m represent the elastic stress, the peak stress, and the residual stress, and the corresponding strains ε_e, ε_{pk}, and ε_m are the elastic strain, the peak strain, and the starting strain of the residual stage, respectively.

DETERMINATION OF MODEL PARAMETERS

To determine the unknown parameters m and F_0 in the first formula of Equation (10), the following boundary conditions are given:

(i) $\sigma = \sigma_{pk}$, $\varepsilon = \varepsilon_{pk}$, (ii) $\varepsilon = \varepsilon_{pk}$, $d\sigma/d\varepsilon = 0$.

Based on the given boundary conditions (i), the following equation can be obtained:

$$E(x_1, x_2)\varepsilon_{pk} \exp[-(\frac{\varepsilon_{pk}}{F_0})^m]=\sigma_{pk}. \tag{11}$$

Then, according to the boundary conditions (ii), the following equation can be obtained:

$$\frac{d\sigma}{d\varepsilon}=E(x_1, x_2)[1 - m(\frac{\varepsilon}{F_0})^m] \exp[-(\frac{\varepsilon}{F_0})^m], \tag{12}$$

$$E(x_1, x_2)[1 - m(\frac{\varepsilon_{pk}}{F_0})^m] \exp[-(\frac{\varepsilon_{pk}}{F_0})^m]=0, \tag{13}$$

where $E(x_1, x_2)$ and $\exp[-(\frac{\varepsilon_{pk}}{F_0})^m]$ cannot be equal to zero, then Equation (13) can be simplified as:

$$1 - m(\frac{\varepsilon_{pk}}{F_0})^m=0. \tag{14}$$

Equation (11) and Equation (14) are solved simultaneously, and then the unknown parameters m and F_0 can be obtained:

$$m = -\frac{1}{\ln\left\{\sigma_{pk}/\left[E(x_1,x_2)\varepsilon_{pk}\right]\right\}}, \tag{15}$$

$$F_0 = \frac{\varepsilon_{pk}}{\sqrt[m]{1/m}}. \tag{16}$$

Substituting Equation (15) and Equation (16) into Equation (10) gives:

$$\sigma = \begin{cases} E(x_1, x_2)\varepsilon \exp[-(\frac{\varepsilon \sqrt[m]{1/m}}{\varepsilon_{pk}})^m], \varepsilon < \varepsilon_m \\ E(x_1, x_2)\varepsilon_m \exp[-(\frac{\varepsilon_m \sqrt[m]{1/m}}{\varepsilon_{pk}})^m], \varepsilon \geq \varepsilon_m \end{cases} \tag{17}$$

UNIAXIAL COMPRESSION TESTS

Characteristics of the Tailings

The tailings used in this paper are from a copper mine located in northwest China, and the particle size distribution is shown in **Figure 2**. The average particle size d_{50} is 80.41 µm, the uniformity coefficient C_u is 8.57, and the curvature coefficient C_c is 1.71. As shown in **Figure 2**, the particle grading curve is smooth and continuous, and Fits grade is mild. Therefore, the tailings selected here have good gradation, compaction, and mechanical properties.

The chemical compositions of the tailings used in this paper are shown in **Figure 3**, which indicates that the main chemical compositions of the tailings are Fe_2O_3 and S_iO_2, accounting for 79% of the total solid weight. The content of CaO is less than 10%, which shows that the used tailings are low-calcium tailings.

Specimen Preparation and Experimental Equipment

CTB is composed of gelling agents, aggregates and water. The gelling agent used in this experiment is ordinary Portland cement P.O42.5, the aggregates are the tailings mentioned above and the water is ordinary city tap water from Xi'an in China's Shaanxi Province. Eight groups of CTB cylinder specimens with dimensions of 50 and 100 mm in diameter and height, respectively, were made to perform uniaxial compression tests. Three specimens were in each group, and a total of 24 specimens, contained five groups with a constant cement-sand ratio of 1/4 and solid contents of 70, 72, 74, 76, and 78 wt% and three groups with a constant solid content of 76 wt% and cement-sand ratios of 1/6, 1/8, and 1/10. The curing environment was set at a constant temperature of 20°C with a relative humidity of 95%, and the curing period was 28 days. Then, the average value of each group was taken as the final result for the relevant quantities.

The experimental equipment is LRT-300 electric-fluid servo triaxial compression machine (see **Figure 4**) and the sample is loaded as **Figure 5**. The loading process was controlled by displacement at the rate of 1×10^{-5} m/s.

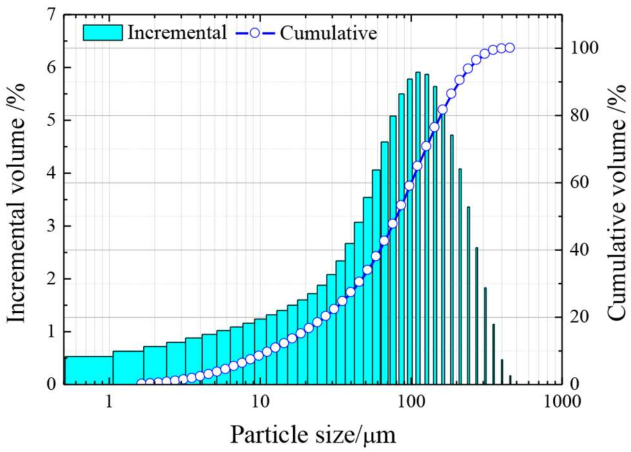

FIGURE 2 | Particle size distribution of the used tailings.

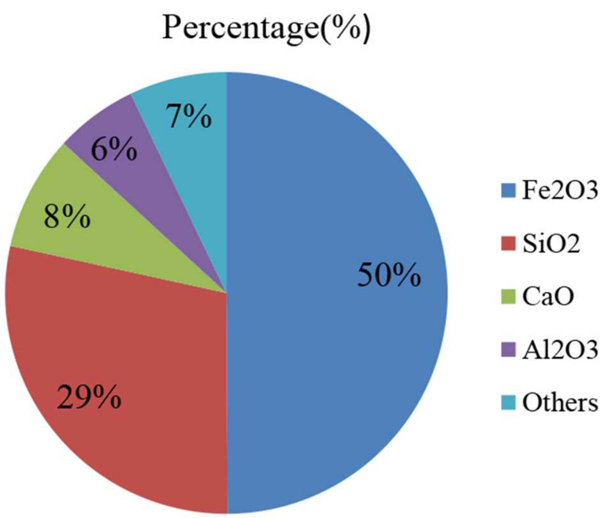

FIGURE 3 | Chemical components of the used tailings.

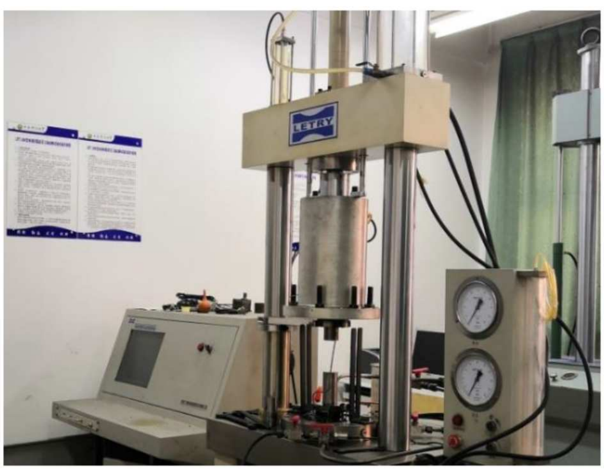

FIGURE 4 | LRT-300 electric-fluid servo triaxial compr-ession machine.

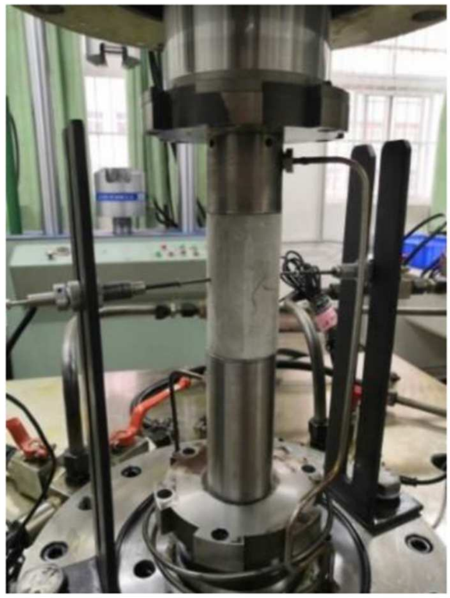

FIGURE 5 | Experimental process.

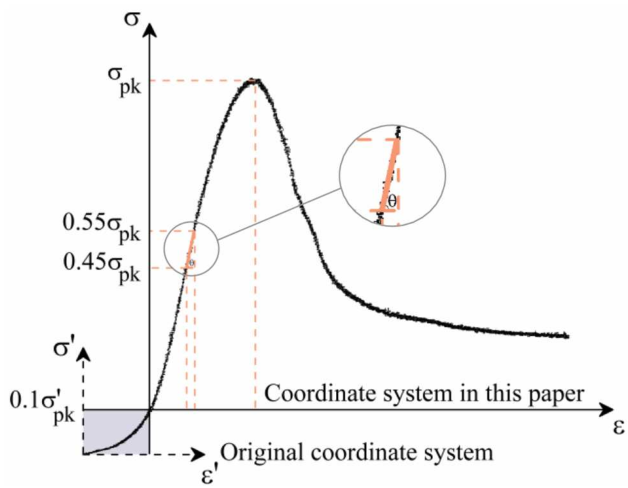

FIGURE 6 | Initial compaction stage and value of elastic modulus defined in this paper.

Model Parameters

Through experimental investigation, it is found that at the initial stage of loading, when the stress is less than 10% of the peak value, the CTB has a compaction phase, especially for the low strength specimens [51]. At this stage, the stress-strain curve is concave, and the initial cracks are closed under axial pressure. For convenience in application, the constitutive model is simplified into two stages in the theoretical part of this paper, without considering the initial compaction stage. Therefore, the initial compaction stage of the material is ignored in this paper, assuming that the material starts directly from the elastic stage after loading, as shown in **Figure 6**. σ'-ε' and σ'_{pk} represent the original coordinate system and the true peak stress, and σ-ε and

TABLE 1 | Model parameters and constitutive models.

Group number	Solid content /wt%	Cement-sand ratio	E /GPa	σ_{pk} /MPa	ε_{pk} /%	m	ε_m /%	Constitutive model ($\varepsilon < \varepsilon_m$)
1	70	1:4	0.74	3.80	0.74	2.74	1.60	$740\varepsilon \exp[-(93.54\varepsilon)^{2.74}]$
2	72	1:4	1.32	5.59	0.61	2.74	1.39	$1320\varepsilon \exp[-(113.48\varepsilon)^{2.74}]$
3	74	1:4	1.53	6.59	0.6	3.02	1.15	$1530\varepsilon \exp[-(115.58\varepsilon)^{3.02}]$
4	76	1:4	1.98	7.2	0.49	3.35	0.89	$1980\varepsilon \exp[-(142.26\varepsilon)^{3.35}]$
5	78	1:4	2.26	7.51	0.47	2.88	0.95	$2260\varepsilon \exp[-(147.37\varepsilon)^{2.88}]$
6	76	1:6	1.11	3.88	0.5	2.79	0.93	$1110\varepsilon \exp[-(138.46\varepsilon)^{2.79}]$
7	76	1:8	0.49	2.04	0.64	2.33	1.57	$490\varepsilon \exp[-(108.70\varepsilon)^{2.33}]$
8	76	1:10	0.21	1.37	0.78	5.60	1.33	$210\varepsilon \exp[-(94.25\varepsilon)^{5.60}]$

The parameters of each group in the table are the average values.

σ_{pk} represent the coordinate system selected in this paper and the corresponding peak stress, respectively.

The elastic modulus E is defined as the tangent of the secants corresponding to 45–55% of the peak stress [52]. The average stress-strain curve of the specimens with a cement-sand ratio of 1/4 and a solid content of 76 wt% was taken as an example to show the value of the elastic modulus E defined in this paper (see **Figure 6**).

Table 1 lists the values of σ_{pk} and the model parameters involved in the constitutive model of Equation (17). Meanwhile, the first stages of the corresponding constitutive models are given. The average stress-strain curve of the three CTB cylinder specimens for each group was obtained. Then, the variables of E, σ_{pk}, ε_{pk}, and ε_m in **Table 1** were gained from the average stress-strain curves. The value of E was defined as **Figure 6**, σ_{pk} and ε_{pk} are the peak stress and strain of the average curves, ε_m is the starting strain of the residual stage, and m was calculated according to Equation (15).

RESULTS AND DISCUSSION

Effects of Solid Content and Cement-Sand Ratio

Different solid contents (70, 72, 74, 76, and 78 wt%) and cement-sand ratios (1/4, 1/6, 1/8, and 1/10) were considered in the tests to analyze the effects of solid content and cement-sand ratio on the mechanical properties of CTB. The change in the mean stress-strain curves and the basic mechanical variables with solid contents and cement-sand ratios are shown in **Figures 7**, **8**. The values of all the relevant variables in each group are the mean values of the three specimens.

It can be seen from **Figure 7** that the solid content gradually increases from 70 to 78 wt% or the cement-sand ratio gradually increases from 1/10 to 1/4, the peak points of the stress-strain curves rise and shift to the left relative to the axis, which indicates that the strength (σ_{pk} and σ_m), the elastic modulus E and the energy dissipation capacity of the CTB specimens increases, while ε_{pk} decreases. Meanwhile, with the increase of the solid content or the cement-sand ratio, the descending part of the curves gradually steepens, which indicates that the ductility decreases and the friability increases.

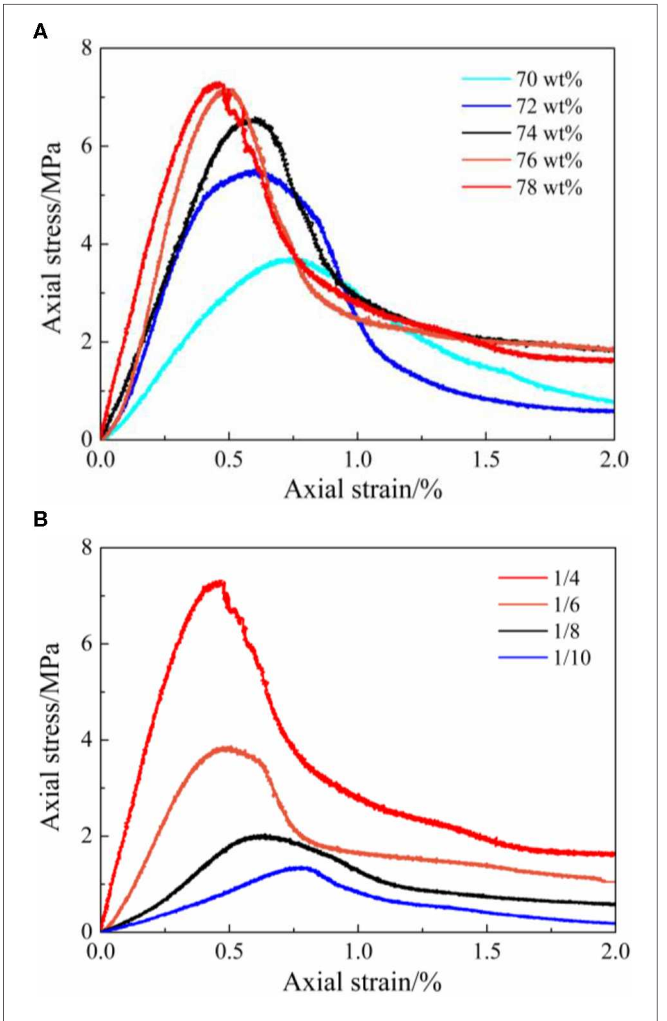

FIGURE 7 | Stress-strain curves for different solid contents and cement-sand ratios: **(A)** solid contents, **(B)** cement-sand ratios.

From **Figure 8A**, it can be observed that when the solid content ranges from 70 to 78 wt%, the corresponding value of E varies between 0.5 and 2.0 GPa, σ_{pk} varies between 4.0 and 7.5

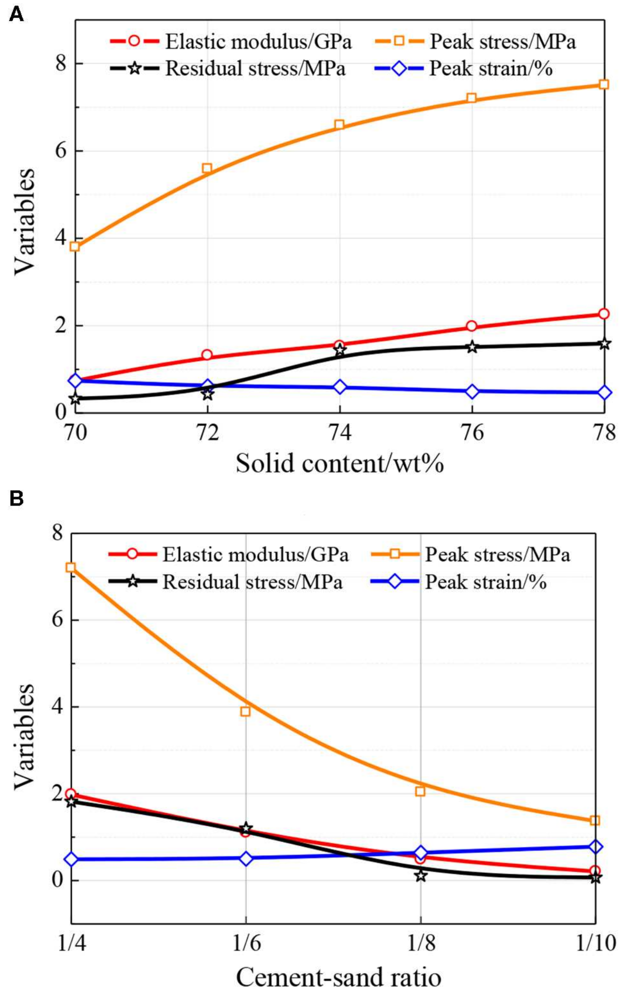

FIGURE 8 | Basic mechanical variables for different solid contents and cement-sand ratios: **(A)** solid contents, **(B)** cement-sand ratios.

MPa, ε_{pk} varies between 0.5 and 0.8% and σ_m varies between 0.5 and 1.5 MPa. Then, if the initial compaction stage is considered, the value range of σ_{pk} is from 4.5 to 8.5 MPa and the value range of σ_m is from 1.0 to 2.5 MPa.

From **Figure 8B**, it can be observed that when the cement-sand ratio ranges from 1/4 to 1/10, the corresponding value of E varies between 0.5 and 2.0 GPa, σ_{pk} varies between 1.5 and 7.5 MPa, ε_{pk} varies between 0.5 and 0.8% and σ_m varies between 1.0 and 2.0 MPa. Then, if the initial compaction stage is considered, the value range of σ_{pk} is from 2.0 to 8.5 MPa, and the value range of σ_m is form 0.3 to 3.0 MPa.

As shown in **Figure 8**, the influence of the solid content and cement-sand ratio on σ_{pk} is more obvious than that of the other quantities (E, ε_{pk} and σ_m), and the variation gradients of E and σ_m increase with the increase of solid content and cement-sand ratio are approximately equal. From **Figures 7**, **8**, it can be seen that the increasing gradient of σ_{pk} gradually decreases with the increase of solid content but increases with the increase of cement-sand ratio.

Verification and Comparison of the Constitutive Model

To verify the validity of the constitutive model of CTB established in this paper, the experimental results are compared with those calculated using the theoretical model. The calculated and experimental results are in good agreement, especially in the pre-peak region (see **Figure 9**). Therefore, the proposed constitutive model can be used to describe the mechanical properties of CTB under uniaxial compression.

Ordinary cement mortar is also composed of gelling agents, aggregates and water, which is similar to the composition of CTB except that the aggregates are river sand and not tailings. To compare and illustrate the performance difference between the two materials under uniaxial compression, the peak point of the stress-strain curves for ordinary cement mortar M5 in reference [53] was scaled by the average peak value of each group of specimens in this paper. Then, the uniaxial compression stress-strain curves of the CTB and ordinary cement mortar M5 are compared in **Figure 9**. It can be seen that before the residual stress, the curves of the two materials are similar in shape. However, the CTB exhibits obvious residual stress, but the ordinary cement mortar M5 does not. Furthermore, the ordinary cement mortar M5 is slightly stronger than CTB at the pre-failure stage, but slightly weaker at the post-failure stage.

Meanwhile, it can also be seen from **Figure 9** that under uniaxial compression, the CTB cylinder specimens are subjected to axial compression and transverse tension. The major failure mode is columnar splitting failure caused by tensile stress.

Limitations and Future Work

The results of the two-stage constitutive model for CTB proposed in this paper is in good agreement with the experimental results and can be used to predict the constitutive relation of CTB under uniaxial compression. The constitute model provided here is generally applicable, but the model parameters need to be specifically determined by testing the tailings from different sources.

Meanwhile, the long-term stress state of the CTB is constrained in three directions rather than in one direction. Therefore, our future work will investigate the mechanical properties of CTB under triaxial compression by triaxial compression tests and provide a simple and universally applicable triaxial compression constitutive model.

CONCLUSIONS

In this paper, the constitutive model for low-calcium copper mine tailings under uniaxial compression has been studied. The validity of the proposed two-stage constitutive model for CTB was verified by a comparison with the test results. Meanwhile, the effects of solid content and cement-sand ratio on the mechanical properties of CTB were also analyzed. The results are described as follows:

i) With the increase of solid content or cement-sand ratio, the strength (σ_{pk} and σ_m), E and energy dissipation capacity of

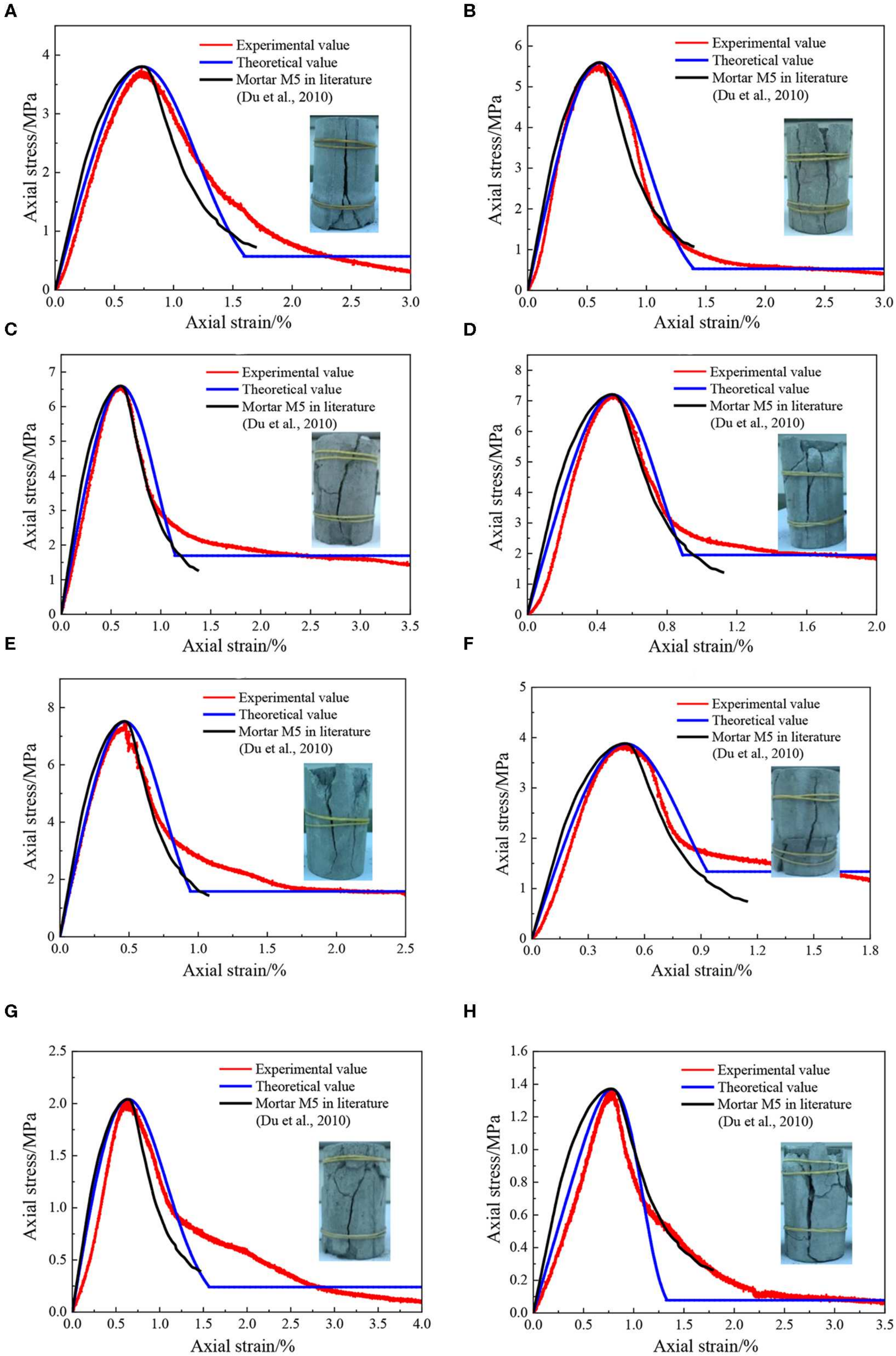

FIGURE 9 | Comparison of theoretical and experimental results for stress-strain curves (cement-sand ratio = C/S, solid content = SC): **(A)** C/S = 1/4 and SC = 70 wt%, **(B)** C/S = 1/4 and SC = 72 wt%, **(C)** C/S = 1/4 and SC = 74 wt%, **(D)** C/S = 1/4 and SC = 76 wt%, **(E)** C/S = 1/4 and SC = 78 wt%, **(F)** C/S = 1/6 and SC = 76 wt%, **(G)** C/S = 1/8 and SC = 76 wt%, **(H)** C/S = 1/10 and SC = 76 wt%.

the CTB increased, but ε_{pk} and the ductility decreased. The influence on σ_{pk} is more obvious than that on the other quantities (E, ε_{pk} and σ_m).

ii) Regardless of the initial compaction stage, for CTB specimens with solid contents of 70–78 wt% and cement-sand ratios of 1/4–1/10, the corresponding value of E remained between 0.5 and 2.0 GPa, σ_{pk} remained between 1.5 and 7.5 MPa, ε_{pk} remained between 0.5 and 0.8% and σ_m remained between 0.5 and 2.0 MPa. Then, if the initial compaction stage was considered, σ_{pk} ranged from 2.0 to 8.5 MPa and σ_m ranged from 0.3 to 3.0 MPa.

iii) The stress-strain curve of CTB is similar to that of ordinary cement mortar M5 but exhibits obvious residual stress. The failure mode of the CTB samples under uniaxial compression is mainly columnar splitting failure caused by tensile stress.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

BT and KC: writing-original draft preparation. LL: conceptualization. BZ: methodology. YZ: data curation. KS: validation. QY: supervision. All authors have read and agreed to the published version of the manuscript.

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