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Research Article

A Novel Prediction Model of Strength of Paste Backfill Prepared from Waste-Unclassified Tailings

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Paste backfilling is an important support for the development of green mines and deep mining. It can effectively reduce a series of risks of underground goaf and surface tailings ponds. Reasonable strength of backfill is an effective guarantee for controlling ground stress and realizing safe mining function. Under the combination of complex materials and local conditions, ensuring the optimal design and effective proportion for paste backfill strength is the bottleneck problem that restricts the safety, economy, and efficiency of filling mining. The strength developing trend of paste backfilling prepared from waste rock and unclassified tailings has been studied. Different levels of cement contents, tailings-waste ratios, and slurry concentrations were investigated through orthogonal design to obtain the relationship between the *UCS* and the multi-influential factors. Combined with the experimental results and the previous strength prediction models, the waste rock-unclassified tailings paste strength prediction model was proposed. Introducing the water-cement ratio, the cement-tailings ratio, the amount of cement, and the packing density that characterizing the overall gradation of unclassified tailings and waste rock, as well as the curing time, a strength prediction model of multifactors was developed. Moreover, the microscopic structure of the paste prepared from waste-unclassified tailings was analyzed with an Environment Scanning Electron Microscope (ESEM), and the influence mechanism was ascertained. The weight coefficient of strength development is carded in this paper, and the strength model of unclassified tailings-waste paste considering five factors is obtained, which is of great significance to guide the mining engineering.

1. Introduction

In many countries, paste backfill mining technology is an important method for dealing with mine wastes and thus is widely recognized as a green and new technology in twenty-first century [1]. Paste backfill, without segregation and dewatering, also has flow ability [2], which is mainly composed of three parts, namely, unclassified tailings, cemented materials, and water. Unclassified tailings, containing a certain proportion of fine particles [3, 4], has a large surface area [5, 6], thus leading to a strong water saturation performance [7]. Therefore, the paste slurry possesses good plasticity properties and easy for transmission [8]. The C-S-H generated from the hydration of binders encapsulates the tailings particles, facilitating the condensation and hardening of paste slurry [9, 10].

Qi and Fourie [11] summarized recent progress in CPB design, with particular emphasis on flocculation and sedimentation, CPB mix design and CPB pipe transport, and envisaged a future in which the CPB design is optimized in an integrated CPB design system, accelerated by artificial intelligence and interpreted using atomic simulation. Qi [12–14] proposed a strength prediction model integrating boosted regression trees (BRT) and particle swarm optimization (PSO) and thought that more efficient reuse of waste tailings as CPB can be achieved by reducing the required number of mechanical experiments during engineering applications. At the same time, an intelligent modelling framework for the mechanical properties prediction using machine learning (ML) algorithms and genetic algorithm (GA) was proposed [15–17]. Lu et al. [18]

improved a method to estimate the unconfined compressive strength of CPB. The strength of paste is usually determined mainly on the demand of the adopted mining technology. Buck believed that it was more important to consider the impact of water-cement ratio on the strength of concrete [19, 20]. Under the same water-cement ratio, the compressive strength of recycled concrete declined about 8 Mpa than the ordinary concrete [21], but the same strength could be reached by reducing water-cement ratio. Rashad and Zeedan deemed that the compressive strength of all pastes increased with the increase in hydration time. In the initial 3~7 days, the strength growth rate was high while the strength showed a linear increase after 7 days [22].

Swan considered that the strength was closely related to the cement content, so he introduced the "cementation coefficient" and established the Swan model. However, this model is often unable to be accurately calculated because it is difficult to obtain its parameters. Adding waste rock aggregates makes the relationship between paste strength and its materials more complex [12, 23]. The traditional strength forecasting model is generally based on a fine granularity and good homogeneity of paste tailings [24], so the waste particles of a few millimeters and even 10 mm do not apply to this model. The forecasted strength is often determined according to rich experience or numerous experiments; at the same time, the strength formation mechanism of paste prepared from waste-unclassified tailings still needs some further research [25].

The present work is to identify the factors influencing the strength of paste prepared from waste-unclassified tailings via a series of tests and then to determine their effects on the strength by regression analysis. On the basis of the existed strength model as well as the compactness theory and with the analysis results, a paste strength prediction model applied to waste-unclassified tailings is developed.

2. Materials and Methods

The materials used mainly include unclassified tailings, waste rock, and cement, all of which were collected from the No. 2 mine area of Jinchuan Group in western China. The Jinchuan Nickel Deposit is located in Jinchang City, Gansu province in western China. In 1958, the amount of nickel metal reached 5.57 million tons, accounting for 79% of China's proven reserves, which is the largest copper nickel sulfide deposit in China and the third in the world. The deposit is famous for its thick ore body, deep burial, rock fragmentation, and high in-situ stress. It is a large complex and difficult underground deposit that is rarely seen worldwide. Before starting the experiment, materials were dried in an oven at 105°C for 12 hours. The materials were mixed with tap water to make a certain concentration of slurry paste for a series of tests.

2.1. Basic Physical and Chemical Properties. Tailing samples were collected from the underflow of an ordinary thickener in the processing plant. After outdoor drying, the density of the tailings was measured via pycnometer method, and the bulk density was measured by compacting density tube. The cement used is 32.5 ordinary Portland cement provided by Jinchang cement plant. The results are shown in Table 1.

Chemical compositions of the tailings, waste rock, and cement were analyzed by using X-ray diffraction and chemical element calibration method, as shown in Table 2.

Particle size distribution of the unclassified tailings and waste rocks is shown in Figure 1. As shown in Figure 1, the content of −200 mesh particles is 88.73%, and the −20 μm particles account for 47%, which means the overall particle size is a little fine, while waste rocks, with −200 mesh particles accounting for 20.12% and −20 μm particles accounting for 13.1%, are mainly coarse particles. It can be summarized from the composition of material particles that any of the materials cannot meet the requirements of the amount of −20 μm particles [9, 26]; thus, the two kinds of materials are needed to be mixed at a certain proportion.

2.2. Experiment Preparation. In order to consider the influence of multifactors on the strength development, orthogonal method was taken for the design of the experiments, of which the results could be analyzed by range analysis, variance analysis, and regression analysis. The factors taken into consideration included the waste content, tailings content, cement proportion, and slurry concentration. In total, 16 groups of specimens were prepared in $70.7 \times 70.7 \times 70.7$ mm molds and then maintained in a curing container with the temperature set at 20°C and the humidity at 90% in accordance with the underground conditions. The two smooth sides of the specimen were used to measure its 3 days, 7 days, and 28 days uniaxial compressive strength. The preparation of the specimen is shown in Table 3. Through a large number of experiments in the early stage, it is concluded that the cement content, paste concentration, and tailings-waste ratio are important factors affecting the paste strength, and other parameters can be derived from these basic parameters or be idealized as secondary factors [11, 27]. The proportion is based on previous exploratory experiments and slump tests with slump values ranging from 23 to 26, which are of good fluidity and stability. At the same time, the engineering application is also referred. Under the condition of low concentration, excessive waste rock content or larger waste particles can easily lead to serious segregation. However, if the maximum particle size of waste is less than 10 mm with high concentration, the segregation rate of slurry can be controlled within 5%~15%.

2.3. Experiments. The density of mixtures of different proportions of unclassified tailings and waste rock was measured and packing density under different proportions was obtained by compaction experiment in a copper cylinder [28]. Slump test was carried out to test the slurry flow ability and to observe its viscosity and water saturation property directly. Generally, a slump of approximately 23~26 cm can meet the requirements of paste pipeline transportation [29, 30]. Besides, because of simplicity and reliability, the unconfined compressive strength (*UCS*) test

Table 1: Physical properties of the materials.

Type of material	Density (t/m^3)	Bulk density (t/m^3)	Porosity (%)
Tailings	2.85	1.55	45.61
Waste	2.81	1.84	34.52
Cement	3.1	1.1	64.52

Table 2: Chemical compositions and some physical properties of the materials.

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	S	Ni	Cu	Others
Tailings (%)	36.41	7.77	9.9	3.09	27.79	1.63	0.28	0.2	12.93
Waste (%)	70.5	12.1	4.5	2.4	0.9	0.2	—	—	9.4
Cement (%)	21.5	4.5	2	63.5	4.0	2.5	—	—	2

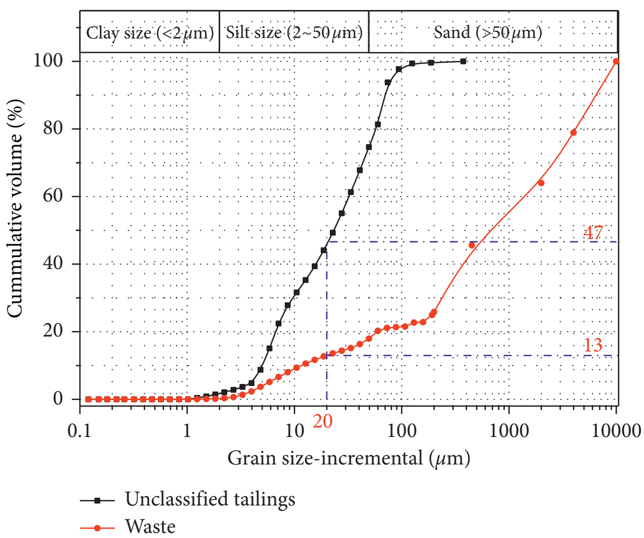


Figure 1: Grain size distribution (GSD) curves of the unclassified tailings compared to a typical range of GSD curves of waste.

was used to investigate the mechanical properties of the paste backfill samples [31]. In order to obtain the strength of 3, 7, and 28 days, all of the experiments were prepared and tested in triplicate, and the mean values of the *UCS* were presented in the results. The experimental process and samples are shown in Figure 2.

3. Results and Discussion

As orthogonal design was used in the experiments, to study the influence of multiple factors on the strength development, the experiment results needed to be processed by statistical analysis. Water-cement ratio $W/C = (M_{\text{water}} + M_{\text{binder}})$ and binder' ratio $B/(T+S) = (M_{\text{binder}}/(M_{\text{tailings}} + M_{\text{waste}}))$ were calculated.

3.1. Relationship between UCS Development and Concentration. The relationship between uniaxial compressive strength and weight concentration was obtained by regression analysis [32]. Figure 3 shows the 28-day strength of the CPB samples consisting of different content of materials. In the graph, it can be seen that the increase in cement content has a noticeable beneficial effect on the growth of uniaxial compressive strength. In Figure 3(a), when the cement content rises from 240 kg/m^3 to 300 kg/m^3, the strength increases 79.1%, from 4.01 MPa to 7.18 MPa at a concentration of 78%, while at the concentration of 81%, the strength increases from 4.74 MPa to 7.6 MPa, a growth of 60.3%. The gap caused by adding different proportion of cement reduces, which reveals that increasing the concentration at a certain extent will reduce the effect of cement, or in some other words, a smaller amount of cement is needed.

Table 3: Scheme of experiment $L_{16}(4^3)$.

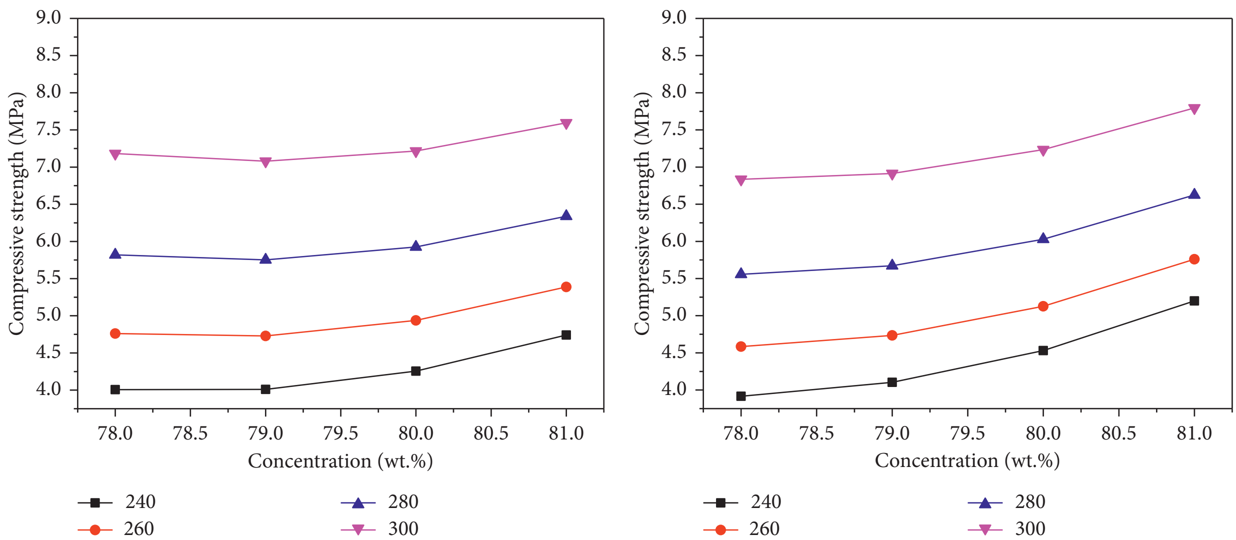
CPB sample no.	Binder (kg/m^3)	Concentration (%)	Tailings-waste ratio (T/S)
1	240	78	3 : 7
2	260	79	4 : 6
3	280	80	5 : 5
4	300	81	6 : 4

3.2. Relationship between UCS and Water-Cement Ratio. Water-cement ratio $W/C = (M_{\text{water}} + M_{\text{binder}})$ refers to the proportion of water to cement in per volume unit of slurry [33]. Water in paste slurry not only involves the hydration reaction with cement but also lubricates slurry, equipping the paste with good fluidity [20]. In Figure 4, it can be seen that generally, the uniaxial compressive strength gradually decreases with an increase in the water-cement ratio. By using regression analysis, the change trend was figured out to be a basically negative exponential growth. The correlation coefficient of the regression curve is between 0.864 and 0.963 and the credibility is high. Meanwhile, although different tailings-waste ratio has a certain different effect on the strength of CPB samples, the overall trend is similar.

3.3. Relationship between UCS and the Binder Content. Binder content $B/(T+S) = (M_{\text{binder}}/(M_{\text{tailings}} + M_{\text{waste}}))$ indicates the relation between cement and aggregates and also the capacity owned by the binder to enclose the aggregates and to make them stick together [34]. Figure 5 reveals the relationship between the 28-day *UCS* and the binder content. In Figure 5(a), it can be seen that at the same weight concentration but different tailings-waste ratios, the *UCS* basically rises with the increase in binder content. Through regression analysis, the developing trend is

(a) (b) (c)

Figure 2: *UCS* tests and experimental samples. (a) *UCS* tests. (b) Tailings sample. (c) Waste sample.



(a) (b)

Figure 3: Change in normalized *UCS* with weight concentration for all CPB samples. (a) Tailings-waste ratio 3 : 7. (b) Tailings-waste ratio 4 : 6.

basically like an exponential growth. In contrast *n*, Figure 5(b) shows that under the same tailings-waste ratio but different concentrations, the *UCS* also have a significant exponential growth with the increase in the binder content.

3.4. Relationship between UCS and the Packing Density. In the tests, different proportions of unclassified tailings and waste rock were mixed to obtain a series of aggregate densities (Figure 6(a)). The packing density was 0.66, when the aggregate was totally waste rock, while it gradually increased with the rising of the amount of unclassified tailings, and finally reached a maximum value of around 0.69 when the waste to tailings ratio was nearly 3 : 7. Figure 6(b) shows the change law of *UCS* at the 28th day to the tailings-waste ratio, with the paste concentration being 79 wt.% and the amount of cement being 280 kg/m^3. When the tailings-waste ratio is 7 : 3, the 28-day *UCS* was the maximum while it was the minimum when there was only tailings in the CPB samples. From the analysis results of the relationship between the packing density and *UCS*, we found a typical function relationship between them, as shown in Figure 6(c). The packing density not only reflects the porosity of the materials, but also has a certain relationship with the particle size of the aggregates. The higher the packing density, the better the proportioning of coarse and fine particles. The stable structure was formed by coarse and fine grain mosaic, which forms the foundation of strength.

3.5. Relationship between UCS and the Curing Time. Figure 7(a) shows the changes of the *UCS* with the curing time when the cement content was 260 kg/m^3 and the tailings-waste ratio was 4 : 6. The *UCS* value increased rapidly during the initial 3~7 days. During this period, the cement involved in an early hardening stage, and by the end of this stage, the hardening reaction completed almost about 38%~55%. In the following curing stage, the hardening reaction continued, but the growth rate of the *UCS* gradually slowed down, and by the end of the 28th day, the hardening process reached about 70%~80%, so the 28-day strength represents the long-term strength in actual production. In contrast, when the concentration was 79 wt.% and the tailings-waste ratio was 3 : 7, the changes of the *UCS* to the curing time is shown in Figure 7(b). The growth rate, from

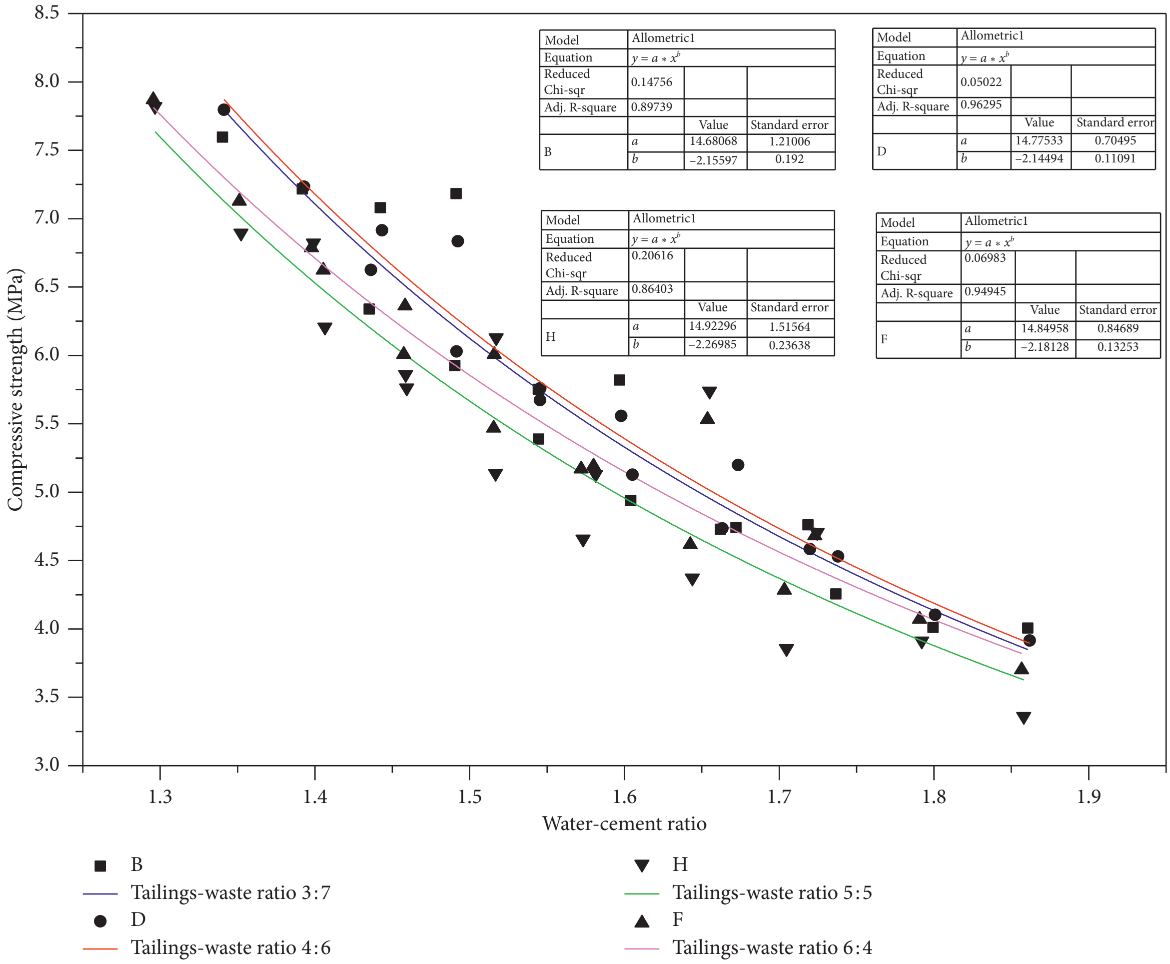


FIGURE 4: Relationship between normalized *UCS* and water-cement ratio.

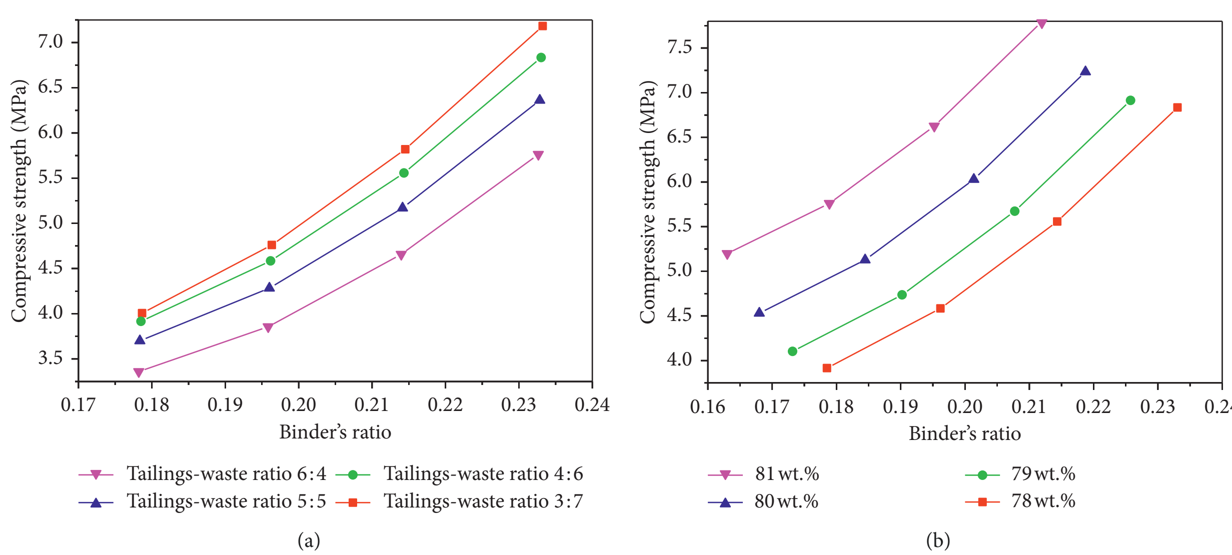


FIGURE 5: Relationship between *UCS* and binder content for CPB samples. (a) Concentration 78 wt.%. (b) Tailings-waste ratio 4 : 6.

27% at the 7th day to 76% at the 28th day, was significant. It was found from the regression analysis that the *UCS* of the paste backfill samples had a logarithmic increase to the curing time, and this feature was generally discovered when the CPB samples are at different concentrations and cement contents.

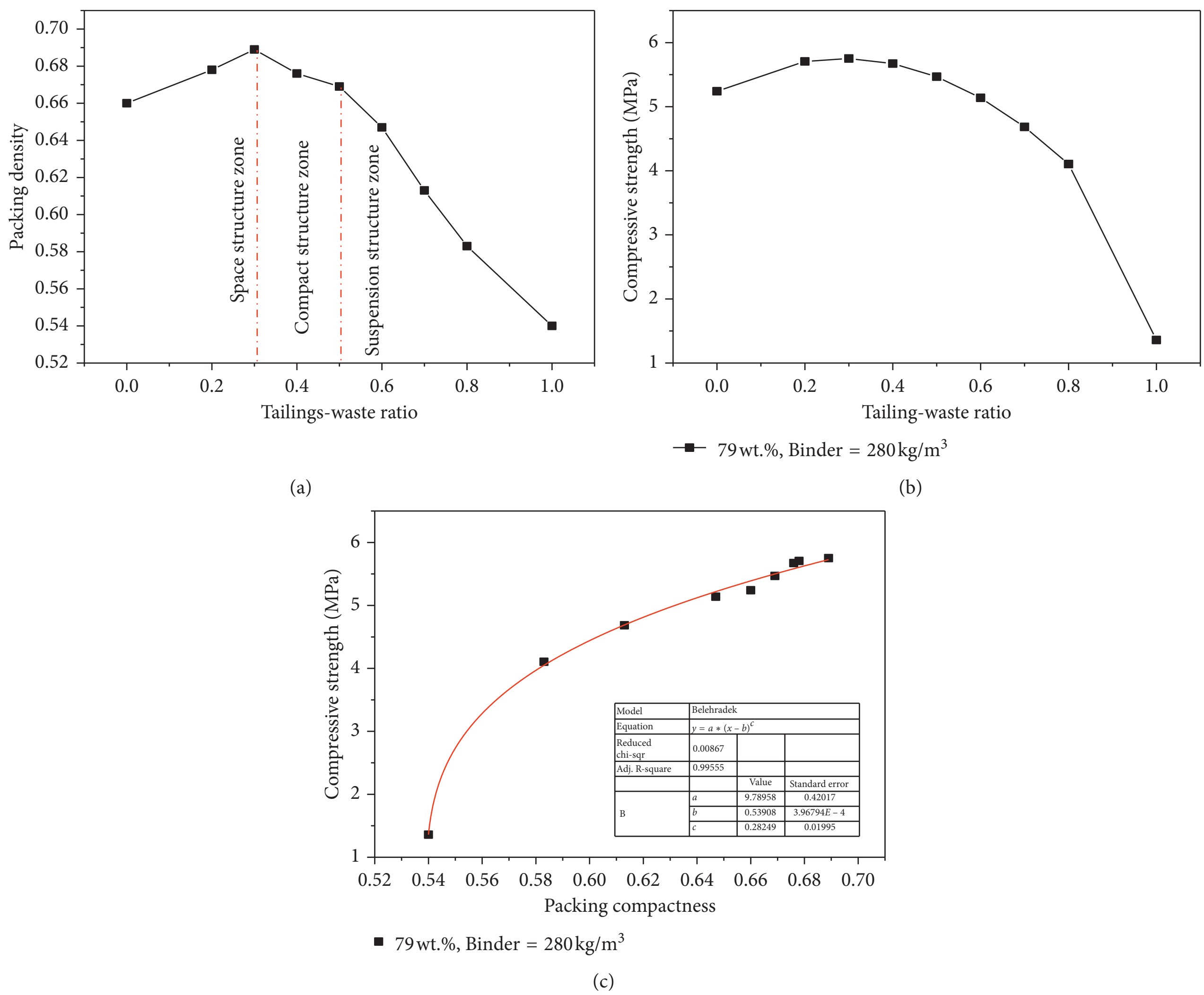


Figure 6: Packing-density analysis. (a) Relationship between tailings-waste ratio and packing density. (b) Tailings-waste ratio and the strength in the 28th day. (c) Relationship between density and strength.

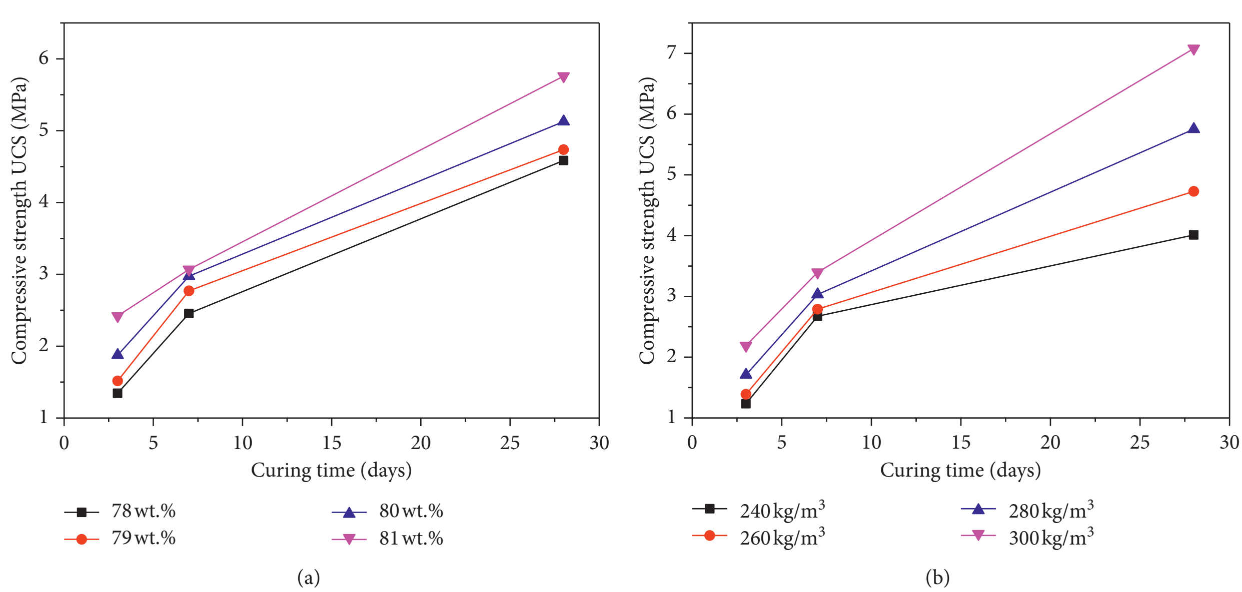


Figure 7: The relationship between uniaxial compressive strength and curing time. (a) Cement content was 260 kg/m^3 and the tailings-waste ratio was 4 : 6. (b) Concentration 79 wt.% and the tailings-waste ratio was 3 : 7.

Based on the comprehensive analysis of various factors affecting the strength development of backfill, it is concluded that the cement content has the most significant influence on the early strength and long-term strength, the concentration secondary, and then the tailings-waste ratio has a certain influence on the strength development. The analysis of strength influencing factors and their relation, as well as the study of strength model, are instructive.

4. Strength Prediction Model

4.1. Analysis of the Present Prediction Model. The filling body is a product that is prepared artificially from different proportions of materials, and naturally the strength development is influenced not only by the preparation proportions but also by the intrinsic properties of the materials [35, 36]. In other words, it reflects that there is some inevitable correlation between the strength development and the two factors mentioned above. In the past many years of research in backfilling technology, some scholars have already discussed the strength prediction model of the filling body [37].

From the results of experimental study, Mitchell considered that there was a power function correlation between the compressive strength of the filling body and the water-cement ratio as well as the porosity. And it was also related to the proportion of the cementing agent, as shown in the formula below [38]:

$$R_{UCS} = aC^m\left(N^{-n}W^{-k} + b\right), \tag{1}$$

where R_{UCS} is the unconfined compressive strength, MPa; C is the content of the cementing agent, t/m^3; N is the porosity, %; W is the water-cement ratio; and a and b are experimental constants.

Swan thought the unconfined compressive strength of the filling body was related to the content of the cementing agent, where C_y was used to represent the volume content of cementing agent. At the same time, a certain relation existed between the *UCS* of the filling body and the specific surface area of tailings a_{p} and the free distance of particles in slurry d_{avg}. It can be shown in the following formula:

$$R_{UCS} = 0.283\left(\frac{C_v}{d_{\mathrm{avg}}a_{\mathrm{p}}}\right)^{2.36}. \tag{2}$$

How to measure the distance between particles is essential for this model, but it is of operational difficulty for the calculation of this kind of parameters. Arioglu proposed a formula to predict the *UCS* by studying the cohesive force and water-cement ratio of the backfill slurry:

$$\begin{gathered} R_{UCS} = a \times \alpha^{-n}, \\ C = bR_{UCS} + c, \end{gathered} \tag{3}$$

where α is the water-cement ratio; C is the cohesive force; and a, b, and c are experimental constants. Traditionally, the studies on prediction model of strength were mainly focused on the effect of water-cement ratio on the strength development or the effects of cement content or porosity. Therefore, those empirical formulas were mostly based on the unclassified tailings and cement, without considering the effect of waste rock and other large particles. Besides, the curing time and some other important factors were not involved in those models. Different mining technology determines different exposure period of the filling body [39]. For instance, the layering mining method emphasizes the short-term strength of 3 to 7 days, while the subsequently fill mining method pays more attention to the strength of 28 days or longer periods. If the effect of curing time on the strength could be definitely understood and the function of the curing time to the *UCS* could be given, then it will be of significant importance for a well-coordinated schedule of both backfilling and mining.

4.2. Development of a New Prediction Model. By analyzing the effects of multifactors on the strength of CPB samples, it could be concluded that with the water-cement ratio increasing, the *UCS* of CPB samples presented a power-exponential growth. The same growth trend also occurred when the influence factor was binder' ratio. The packing density of aggregates consisting of different proportions of unclassified tailings and waste rock, to some extent, reflects their effects on the strength of paste samples. Through analysis, we could see that the *UCS* of the paste basically presented a logarithmic growth with curing days increasing. At the same time, the content of cementing agent had a positive correlation with the *UCS*. According to the researches and analyses mentioned above, the prediction model of the strength of CPB prepared from waste-unclassified tailings was presented in this paper:

$$R_{UCS} = \alpha \times B \times Ln\, D \times \Phi^m \times \left(\frac{W}{C}\right)^n \times \left(\frac{C}{A}\right)^k, \tag{4}$$

where B is the content of cement, $\mathrm{t/m}^3$; D is the curing time; Φ is the aggregate packing density; W/C is the water-cement ratio; C/A is the binder's ratio; and α, n, and k are experimental constant. Model parameters need to be regressed according to the material properties and experimental conditions. The model is suitable for the prediction of paste strength from the combination of unclassified tailings and waste of which the five factors are taken into account.

In order to obtain the experimental constants of this model, the parameters used in the experiments were carried into this model to conduct some fitting analysis. The results were shown as follows:

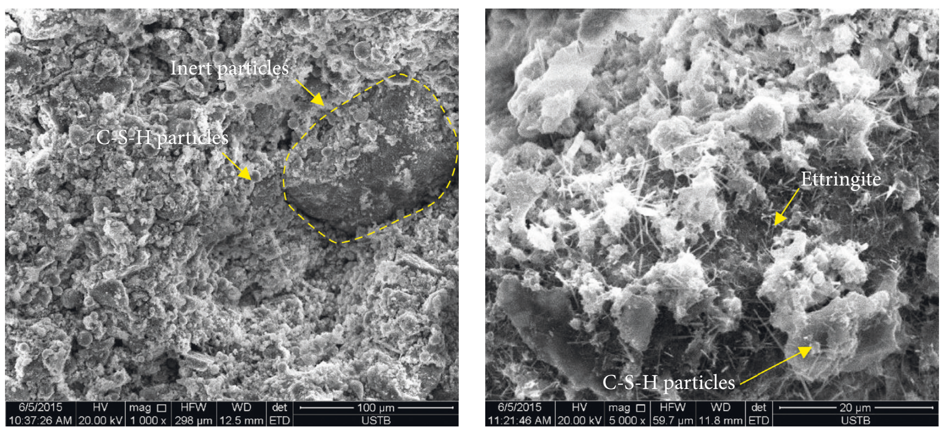
$$R_{UCS} = 4.8614 \times B \times Ln\, D \times \Phi^{0.5894} \times \left(\frac{W}{C}\right)^{-1.7519} \times \left(\frac{C}{A}\right)^{-0.7645}. \tag{5}$$

Adj. R-square = 0.93, $F = 3371.0383 > F_{0.01}(4, 188) = 3.42$.

From formula (5), it can be seen that several influence factors are already involved in this prediction model, and the test parameters also have good adaptability. This new strength model is more applicable for predicting the *UCS* of CPB samples consisting of waste-unclassified tailings.

Table 4: Proportions of materials and strength results.

No.	Binder (t/m^3)	Curing time (days)	Packing density	W/C	$B/(T+S)$	Observed UCS (MPa)	Calculated UCS (MPa)	Error (%)
1	0.28	7	0.703	2.450	0.167	1.676	1.759	−4.94
2	0.25	7	0.689	2.250	0.125	2.235	2.249	−0.60
3	0.15	7	0.654	3.463	0.100	0.763	0.727	4.66
4	0.28	14	0.703	2.450	0.167	2.289	2.385	−4.21
5	0.25	14	0.689	2.250	0.125	3.009	3.049	−1.34
6	0.15	14	0.654	3.463	0.100	1.021	0.987	3.37
7	0.28	28	0.703	2.450	0.167	2.959	3.012	−1.78
8	0.25	28	0.689	2.250	0.125	3.901	3.850	1.30
9	0.15	28	0.654	3.463	0.100	1.309	1.246	4.83



(a) (b)

Figure 8: Microstructural images of waste-unclassified tailings paste. (a) Microcosmic image 1000x. (b) Microcosmic image 5000x.

Meanwhile, the relationship between the influence factors and the strength is basically explained, where the strength presents a positive power exponential function with and packing density Φ, which represents the contents of tailings and waste rock, while a negative exponential relationship with the water-cement ratio W/C and cement-tailings ratio C/A, and a typical logarithmic relationship with the curing days D, and a linear relationship with the cement proportion B. This paper also tested the applicability of this model to some other different materials by sampling from several different mines. Model parameters are obtained based on limited experiments, and the strength range of 3–28 days can be predicted accurately. The development rule of paste strength using complex materials still needs further verification. When applied in specific mines, the model parameters can be adjusted through several sets of additional experiments.

4.3. Examination of the New Developed Model. The unclassified tailings and waste materials were derived from a copper mine in Xinjiang, China, where the density of the unclassified tailings is 2.662 t/m^3, and the dense packing density is 0.603. The contents of −74 μm particles, −45 μm particles, and −20 μm fine particles in the unclassified tailings account for 64.32%, 43.1%, and 29.8%, respectively. The value of C_U ($C_U = d_{60}/d_{10}$) is 18.36, and $C_C (C_C = d_{30}^2/(d_{10} \times d_{60}))$ is 1.62, from which it can be indicated that the unclassified tailings cover a wide range of particle size distribution and have a good continuous condition. The waste rocks were sampled and then broken into particles of about −10 mm before being transported to the laboratory. The rock density is 2.663 t/m^3 and the packing density is 0.699. The contents of −1 mm particles, −3 mm particles, and −5 mm particles account for 28.82%, 48.6%, and 74.09%, respectively. The value of C_U of waste rock is 17.05 and C_C is 1.47, showing a wide range of waste particle size distribution and a proper gradation. In order to verify the overall reliability of the strength prediction model, three groups of material proportions were designed for the verification of the predicted strength of 7 days, 14 days, and 28 days. The experimental and calculated results are shown in Table 4. In this table, it can be seen that the strength model is widely applied for predicting the strength of paste prepared from materials of different characteristics, with forecast errors being basically controlled within 5%.

4.4. Strength Formation Mechanism of Paste. A large number of C-S-H gels and CH crystals have been found in the microstructure through environmental scanning electron microscopy (ESEM), which covered the surface of inert particles such as tailings and waste rocks, as shown in Figure 8(a). It is observed that there is a large amount of fine fibrous ettringite between C-S-H gel particles and inert particles, as shown in

Figure 8(b), which made the connecting structure stronger. At the same time, ettringite [40, 41] can increase the solid volume of paste by more than 1.2 times, which can fill the void structure and increase the strength effectively.

5. Conclusions

This paper analyzed the properties of the unclassified tailings-waste paste materials and the influential factors of strength. Through the analysis on the existed strength models, combined with the experimental results, a prediction model of strength of waste rock-unclassified tailings was proposed. The applicability of the model was verified. The main results of the research are as follows:

(1) The strength value can increase by 4.7%~16.5% with 1% growth of concentration. At the same time, with a higher concentration, the effect of cement on the strength will be reduced to some extent. The relationship between strength and the water-cement ratio is negative exponent. The *UCS* and cement-tailings ratio also shows an exponential relationship.

(2) The growth of strength is nonlinear with the tailings-waste ratio but has a stable growth relationship with packing density. The power function of strength and density is obtained by single factor regression analysis. Through the analysis on the relationship between strength and curing time, it can be seen that the relationship between the strength and curing time is logarithmic.

(3) A strength prediction model of waste-unclassified tailings paste is proposed. Through validation, the predicted results of the model are stable, with high reliability. The error range is basically controlled within 5%.

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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