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*Research Article*

# Performance Comparison between Neutralization Tailings and Flotation Tailings Used for Backfill Mix and Mechanism Analysis

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A comparison test of different tailings used for underground backfill was conducted, using neutralized tailings from BIOX and flotation tailings of Jinfeng Mine. Laboratory comparison test results show that, with neutralized tailings, when the cement dosage is at 19%, backfill UCS after 7 days, 14 days, and 28 days are 105%–163%, 80%–102%, and 33%–43%, respectively, which are higher than those of flotation tailings. When the cement dosage is at 12%, backfill UCS after 7 days, 14 days, and 28 days are 58%–77%, 50%–60%, and 28%–51%, respectively, which are higher than those of flotation tailings. Slurry fluidity of neutralized tailings is lower than that of flotation tailings, while, in these two tailings, the difference of slump and diffusivity values is less than 6%, which is not a significant difference in slurry fluidity. The reason for neutralized tailings showing higher UCS is as follows: during backfill curing, neutralization tailings produce abundant crystals of $CaSO_4{\cdot}2H_2O$ in interlaced structure which helps in combining aggregates closely; $CaSO_4{\cdot}2H_2O$ hydrates with $C_3A$ $C_4AF$ contained in the cement and forms clavate cement bacillus which works as a micro reinforcing steel bar. The test proved that neutralized tailings are more optimal for backfilling.

## 1. Introduction

Backfilling the underground mining voids with tailings not only reduces or eliminates the waste pile, but also relieves the pressure on tailing storage, eliminating the risk of dam failure, and also prevents surface subsidence caused by underground mining. Backfill using tailings has become an inevitable choice for underground backfill [1–4]. Biooxidation (BIOX) leaching process is the fastest growing processing and most promising application of smelting technology. It not only increases the rate of metal leaching substantially, but also is an environmentally friendly process. China's biooxidation technology has entered the engineering application stage. Jinfeng Mine has built the world's second largest bacterial oxidation process. The neutralization tailings are a product from the BIOX process in the Jinfeng processing plant. Compared with flotation tailings, the neutralization tailings contain high chemical composition of $FeAsO_4$, $CaSO_4$, and $Fe(OH)_3$ (about 5% of the total tailing weight) and have finer grain sizes. In the present work, the backfill mix laboratory comparison test is carried out by using flotation tailings and neutralization tailings from Jinfeng Gold Mine. The result shows that UCS can increase by 58%–163%, 60%–80%, and 51%–84% over a period of 7 days, 14 days, and 28 days of backfill, respectively, in the case of neutralization tailings compared with that of flotation tailings. The backfill slurry fluidity for both kinds of tailings is almost the same; the difference in slump and diffusivity values is less than 6%. The present study is significant in reducing the cost of backfill in Jinfeng Gold Mine and can be a valuable reference for optimization of backfill mixing ratio to other mines with similar biological leaching processing.

## 2. Laboratory Backfill Mix Design and Optimization

*2.1. Experimental Purpose.* Constrained by high stowing gradient (ratio of whole backfill pipe length to vertical height of the pipe), the maximal slurry filling density in Jinfeng

Table 1: Backfill mix design scheme for 75% density.

| Number | Cement content/% | Aggregates/tailings ratio | Tailings type | Number | Cement content/% | Aggregates/tailings ratio | Tailings type |
|---|---|---|---|---|---|---|---|
| A1 | 19 | 1.4 | Flotation tailings | A11 | 19 | 1.4 | Neutralization tailings |
| A2 | 19 | 2.4 | | A12 | 19 | 2.4 | |
| A3 | 19 | 3.4 | | A13 | 19 | 3.4 | |
| A4 | 19 | 4.4 | | A14 | 19 | 4.4 | |
| A5 | 19 | 5.4 | | A15 | 19 | 5.4 | |
| A6 | 12 | 1.4 | | A16 | 12 | 1.4 | |
| A7 | 12 | 2.4 | | A17 | 12 | 2.4 | |
| A8 | 12 | 3.4 | | A18 | 12 | 3.4 | |
| A9 | 12 | 4.4 | | A19 | 12 | 4.4 | |
| A10 | 12 | 5.4 | | A20 | 12 | 5.4 | |

Table 2: The results of the first experiment.

| Number | Slump (mm) | Diffusivity (mm) | UCS (MPa) | | | Number | Slump (mm) | Diffusivity (mm) | UCS (MPa) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 7 d | 14 d | 28 d | | | | 7 d | 14 d | 28 d |
| A1 | 175 | 320 | 1.43 | 3.07 | 3.63 | A11 | 140 | 220 | 3.1 | 4.67 | 5.54 |
| A2 | 250 | 530 | 1.17 | 2.56 | 3.55 | A12 | 265 | 620 | 3.7 | 6.01 | 7.19 |
| A3 | 265 | 770 | 1.13 | 2.81 | 3.71 | A13 | 280 | 870 | 2.6 | 4.37 | 6.50 |
| A4 | 275 | 1090 | 1.37 | 2.88 | 3.93 | A14 | 285 | 1025 | 1.9 | 2.70 | 3.79 |
| A5 | 280 | 1140 | 1.57 | 2.87 | 4.22 | A15 | 285 | 845 | 2.1 | 2.60 | 4.19 |
| A6 | 160 | 280 | 0.77 | 1.24 | 1.74 | A16 | 140 | 268 | 1.33 | 2.24 | 3.53 |
| A7 | 265 | 735 | 0.67 | 1.12 | 1.36 | A17 | 255 | 503 | 1.20 | 2.41 | 2.70 |
| A8 | 270 | 825 | 0.57 | 1.00 | 1.51 | A18 | 283 | 850 | 1.07 | 1.49 | 2.07 |
| A9 | 273 | 865 | 0.56 | 1.11 | 1.47 | A19 | 278 | 885 | 0.84 | 1.23 | 1.77 |
| A10 | 260 | 960 | 0.68 | 1.18 | 1.66 | A20 | 288 | 1035 | 0.71 | 1.09 | 1.60 |

Gold Mine is not more than 76%, with 19% cement dosage for underhand mining and 12% cement dosage for overhand drift mining. The aggregate/tailings ratio by weight is 1.4–5.4 and the backfill mix design scheme based on actual Jinfeng mining condition is determined and shown in Table 1 [5–10].

*2.2. Experimental.* Backfill slurry is prepared according to Table 1. The slump and diffusivity values are tested after mixing by using JS-15 mixer. The slurry is poured into $\varphi$ 80 mm × 200 mm cylindrical molds and cured for 24 hours in the laboratory and then the specimens were kept in the curing tank in which the temperature is 30°C and humidity is 95%. The block is cut into $\varphi$ 80 mm × 160 mm size after it is cured for the scheduled curing period. And 7-day, 14-day, and 28-day uniaxial compressive strengths are found using a WES-100 hydraulic universal testing machine. In order to ensure the accuracy of the experimental results, the experiments in Table 1 were carried out twice separately.

## 3. Analysis of Experimental Results

*3.1. Experimental Results.* Experimental results are shown in Tables 2 and 3.

*3.2. Analysis of the Impact on Backfill Strength from Different Tailings*

*3.2.1. Comparative Analysis of Backfill Strength.* Figures 1–6 show backfill strength at the cement content of 19% and 12% over different curing periods. In the figures, Z refers to test results of backfill strength using neutralization tailings and F refers to test results using flotation tailings. ZR and FR refer to test results of repeat tests with neutralization and flotation tailings, respectively. 7 days, 14 days, and 28 days refer to curing period of backfill.

*3.2.2. Analysis of the Impact on Backfill Strength from Different Tailings.* The effect of two types of tailings on backfill strength is shown in Tables 4 and 5.

The results shown in Table 4 indicate the following:

(1) Two rounds of backfill comparison experiments with neutralization tailings and flotation tailings show that, at cement content of 19%, 7-day, 14-day, and 28-day strengths of neutralization tailings are higher than those of flotation tailings by 105%–163%, 80%–102%, and 33%–43%, respectively, and, at cement dosage of 12%, 7-day, 14-day, and 28-day strengths of

Table 3: The results of the second experiment.

| Number | Slump (mm) | Diffusivity (mm) | UCS (MPa) 7 d | UCS (MPa) 14 d | UCS (MPa) 28 d | Number | Slump (mm) | Diffusivity (mm) | UCS (MPa) 7 d | UCS (MPa) 14 d | UCS (MPa) 28 d |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 200 | 320 | 1.48 | 2.15 | 3.52 | A11 | 240 | 460 | 1.77 | 3.20 | 4.73 |
| A2 | 250 | 530 | 1.22 | 1.97 | 3.63 | A12 | 250 | 640 | 1.83 | 2.47 | 4.71 |
| A3 | 280 | 900 | 1.07 | 1.76 | 3.37 | A13 | 260 | 780 | 2.44 | 4.33 | 4.98 |
| A4 | 270 | 880 | 1.11 | 1.93 | 3.54 | A14 | 260 | 740 | 2.43 | 3.13 | 5.00 |
| A5 | 280 | 880 | 1.19 | 2.13 | 3.61 | A15 | 270 | 910 | 1.51 | 2.63 | 4.06 |
| A6 | 135 | 400 | 0.54 | 0.91 | 1.58 | A16 | 170 | 250 | 1.13 | 2.00 | 2.33 |
| A7 | 160 | 690 | 0.44 | 0.78 | 1.52 | A17 | 250 | 610 | 0.82 | 1.07 | 1.63 |
| A8 | 265 | 750 | 0.46 | 0.70 | 1.41 | A18 | 260 | 790 | 0.74 | 0.97 | 1.63 |
| A9 | 270 | 780 | 0.43 | 0.73 | 1.31 | A19 | 260 | 690 | 0.73 | 1.17 | 1.98 |
| A10 | 260 | 780 | 0.43 | 0.80 | 1.41 | A20 | 260 | 860 | 0.66 | 1.06 | 1.66 |

Table 4: UCS backfill strength comparison of two types of tailings.

| | UCS using 19% cement replacement (MPa) 7 d | 14 d | 28 d | UCS using 12% cement replacement (MPa) 7 d | 14 d | 28 d |
|---|---|---|---|---|---|---|
| First experiment using flotation tailings | 1.02 | 2.26 | 3.81 | 0.65 | 1.13 | 1.55 |
| First experiment using neutralization tailings | 2.68 | 4.07 | 5.44 | 1.03 | 1.69 | 2.33 |
| Second experiment using flotation tailings | 0.98 | 1.56 | 3.53 | 0.46 | 0.78 | 1.45 |
| Second experiment using neutralization tailings | 2.00 | 3.15 | 4.70 | 0.82 | 1.25 | 1.85 |

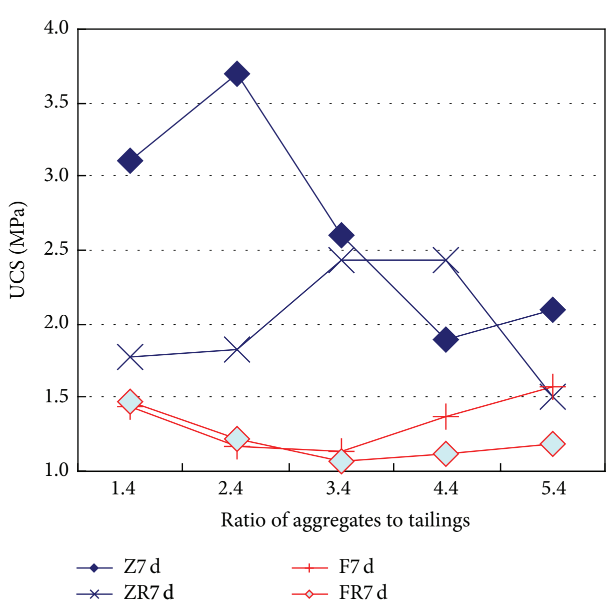


Figure 1: 7-day backfill UCS using 19% cement replacement.

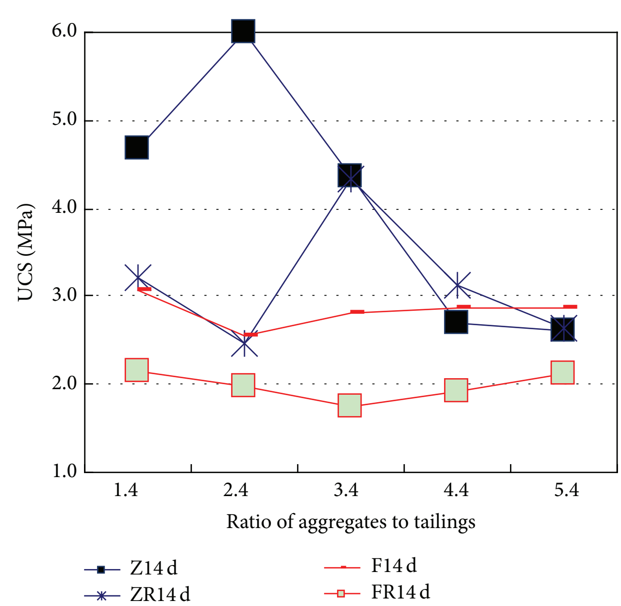


Figure 2: 14-day backfill UCS using 19% cement replacement.

neutralization tailings are higher by 58%–77%, 50%–60%, and 28%–51%.

(2) Neutralization tailing is helpful in gaining the early stage backfill strength, which is very important in reducing the curing time of backfill in drives and improving the production from stope.

(3) When neutralization tailing is used for backfilling, the UCS value is nearly in inverse relation with aggregates-to-tailings ratio. The strength of backfill

Table 5: Comparison of backfill slurry flow behavior.

| Items | Average flow at 19% cement replacement | | Average flow at 12% cement replacement | |
|---|---|---|---|---|
| | Slump (mm) | Diffusivity (mm) | Slump (mm) | Diffusivity (mm) |
| 1st-round test with flotation tailings | 249 | 770 | 246 | 733 |
| 1st-round test with neutralization tailings | 251 | 716 | 249 | 708 |
| 2nd-round test with flotation tailings | 256 | 702 | 218 | 680 |
| 2nd-round test with neutralization tailings | 256 | 706 | 240 | 640 |

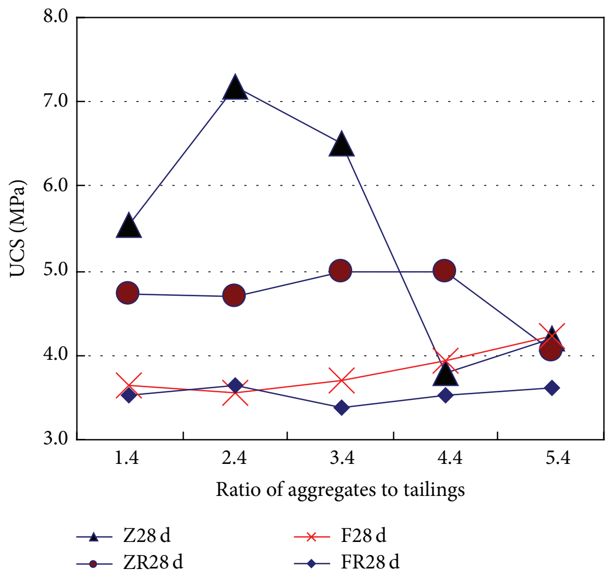


Figure 3: 28-day backfill UCS using 19% cement replacement.

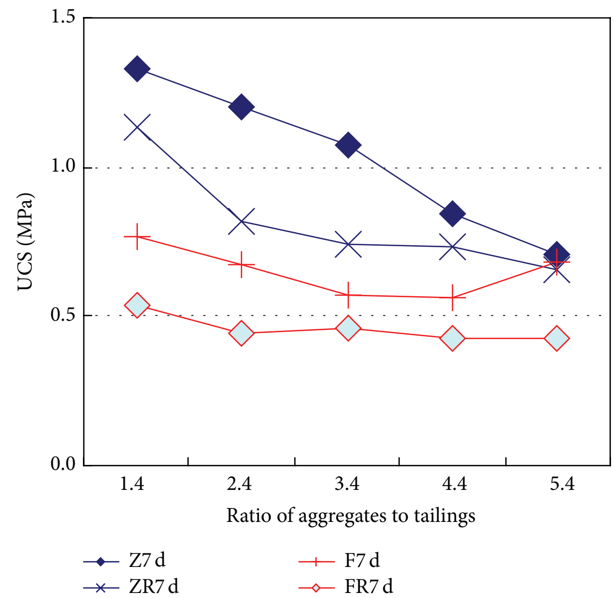


Figure 4: 7-day backfill UCS using 12% cement replacement.

reaches its maximum when the ratio of aggregates to tailings is 2.4; thus, using neutralization tailings for backfill can further increase the portion of tailings while reducing the consumption of crushed waste, with the benefits of not only reducing backfill cost but also developing green mine.

### 3.3. Impact on Backfill Slurry Application Liquidity from Different Tailings

*3.3.1. Comparative Analysis of Backfill Slurry Slump and Diffusivity.* The test results of backfill slurry slump and diffusivity using two kinds of tailings are shown in Figures 7–10.

*3.3.2. Impact on Backfill Slurry Liquidity from Different Tailings.* Table 5 gives the comparison on backfill slurry flow behavior with two kinds of tailings.

The result in Table 5 indicates the following:

(1) Neutralization tailings contain more of the fine particles when the percentages of cement replacement of both kinds of tailings are the same. The flow behavior of backfill with neutralization tailings is less active than that of flotation tailings. As the value of slump and diffusivity for two kinds of tailings is not more than 6%, it does not have any impact on liquidity.

(2) Because different tailings do not show significant impact on liquidity, the usage of neutralization tailings instead of flotation tailings does not need any modification to current piping system to backfill in Jinfeng, nor does it need to reduce the density of backfill slurry.

## 4. Mechanism Analysis of Impact on Backfill Strength from Neutralization Tailings

*4.1. Reaction Mechanism of Neutralization Process.* The slurry from BIOX goes through CCD (countercurrent decantering) and the overflow of CCD is added with flotation tailings and limed, going through a thickener, and the tailings from the underflow of the thickener are neutralization tailings. The overflow from CCD thickener contains high volume of sulfuric acid, ferrite, and arsenic. Due to environment concern, this overflow needs to be neutralized. To form a stable, safe, and environmentally friendly arsenic acid iron compound, wastewater must go through 2 stages of neutralization. The first stage neutralizes the pH value of flotation tailings to 5,

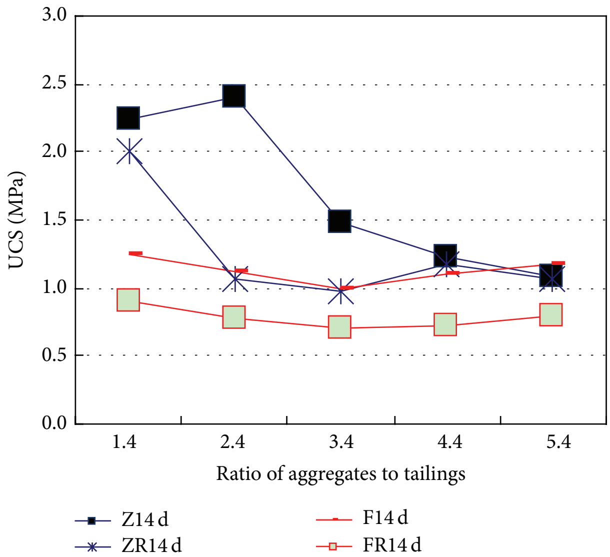


FIGURE 5: 14-day backfill UCS using 12% cement replacement.

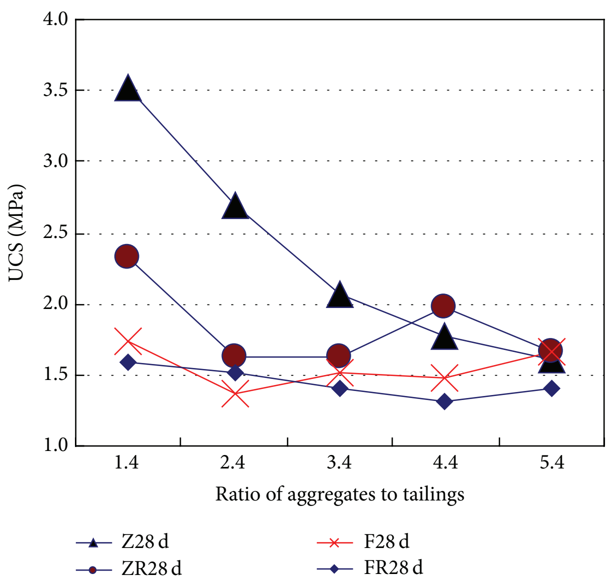


FIGURE 6: 28-day backfill UCS using 12% cement replacement.

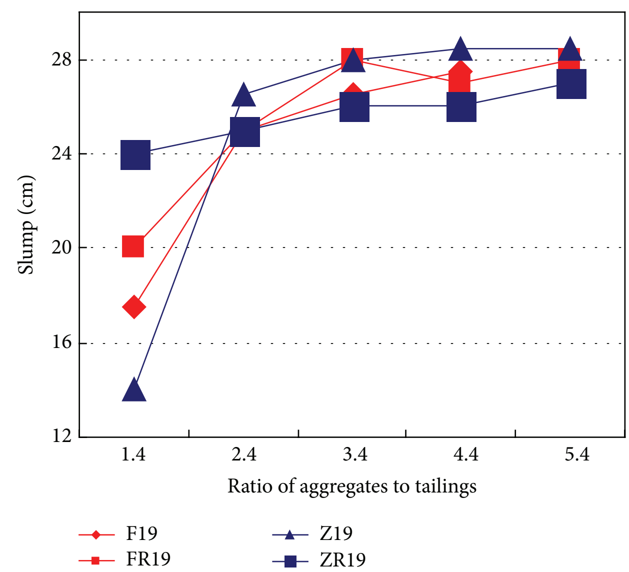


FIGURE 7: Backfill slurry slump using 19% cement content.

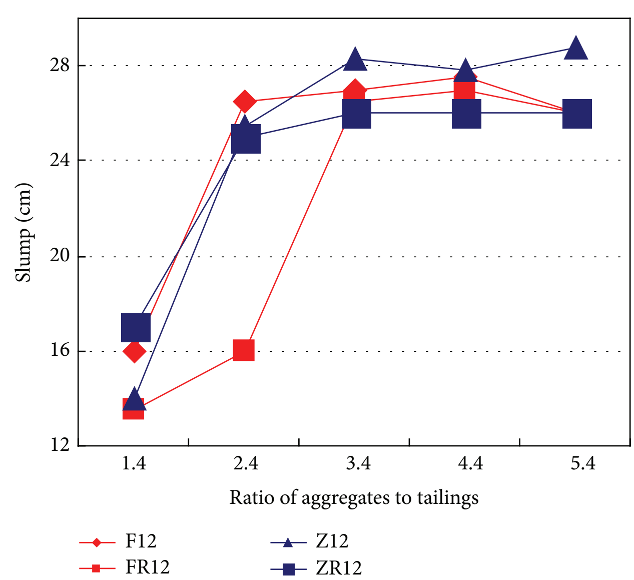


FIGURE 8: Backfill slurry slump using 12% cement content.

and, in the second stage, lime is added and the pH value reaches 7. The neutralization reaction process is as follows.

The first stage neutralizes the pH value of flotation tailings to 5:

$$2H_3AsO_4 + Fe_2(SO_4)_3 + 3CaCO_3 \longrightarrow 2FeAsO_4 + 3CaSO_4 + CO_2 + H_2O \quad (1)$$

$$Fe_2(SO_4)_3 + 3CaCO_3 + 3H_2O \longrightarrow 2Fe(OH)_3 + 3CaSO_4 + 3CO_2 \quad (2)$$

In the second stage, lime is added and the pH value reaches 7:

$$H_2SO_4 + CaO \longrightarrow CaSO_4 + H_2O \quad (3)$$

The tailings formed by lime neutralization are called neutralization tailings, for which pH is 7.

Figure 11 shows the X-ray diffraction, which indicates high gypsum content in neutralization tailings.

*4.2. Cement Hydration Reaction Mechanism.* Backfill in Jinfeng uses 32.5 grand portland cement in which the main chemical content is silicate mineral (dicalcium silicate and tricalcium silicate), calcium aluminate mineral, and ferroaluminate mineral. The hydration reaction processes are as follows:

$$2(3CaO \cdot SiO_2) + 6H_2O \longrightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3Ca(OH)_2 \quad (4)$$

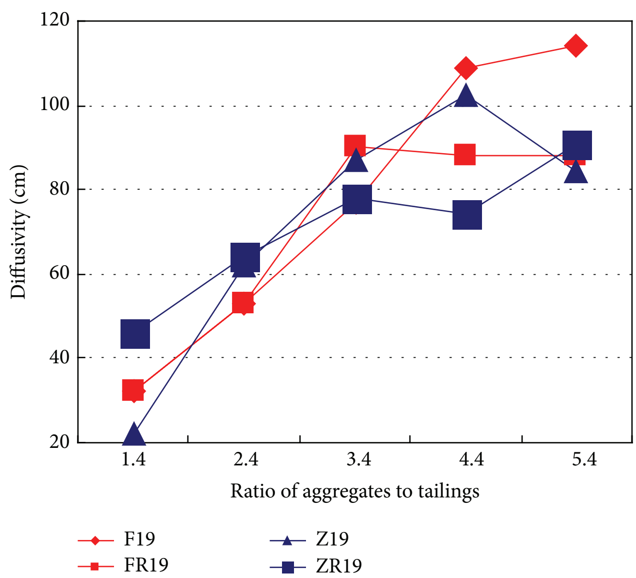


Figure 9: Backfill slurry diffusivity using 19% cement content.

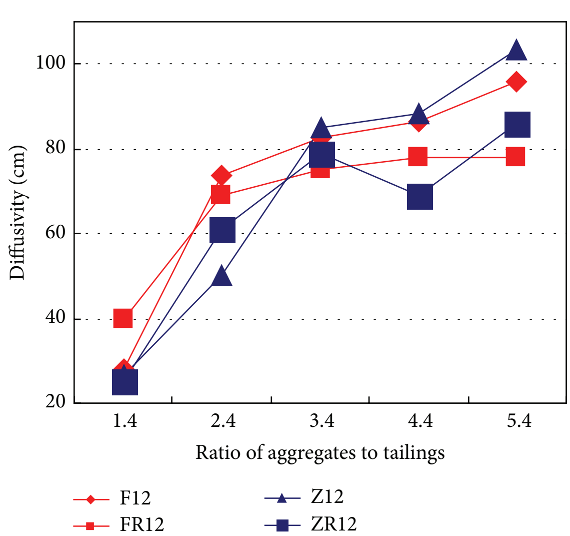


Figure 10: Backfill slurry diffusivity using 12% cement content.

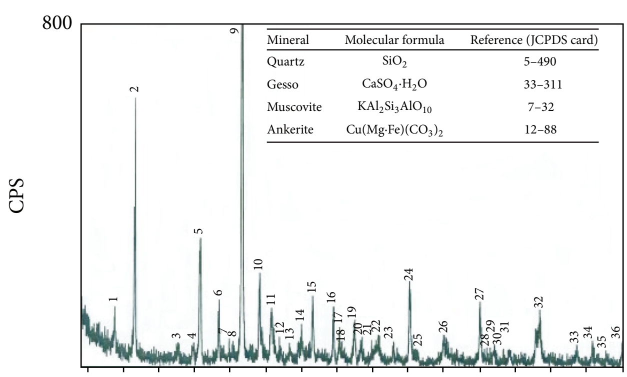


Figure 11: X-ray diffraction of neutralization tailings.

$$2\left(2CaO\cdot SiO_2\right)+4H_2O \longrightarrow 3CaO\cdot 2SiO_2\cdot 3H_2O+Ca\left(OH\right)_2 \quad (5)$$

$$3CaO\cdot Al_2O_3+6H_2O \longrightarrow 3CaO\cdot Al_2O_3\cdot 6H_2O \quad (6)$$

$$4CaO\cdot Al_2O_3\cdot Fe_2O_3+7H_2O \longrightarrow 3CaO\cdot Al_2O_3\cdot 6H_2O+CaO\cdot Fe_2O_3\cdot H_2O \quad (7)$$

*4.3. Mechanism of Neutralization Tailings Improving the Backfill Strength.* (1) As stated in the reaction mechanism, neutralization tailings contain large quantity of $CaSO_4{\cdot}2H_2O$. During backfill curing, $CaSO_4{\cdot}2H_2O$ will dissolve from water and crystallize. The crystal grain accretion continues and becomes larger and greater and forms interlaced structure, in which the porosity decreases gradually and the strength increases gradually. This structure combines the aggregates closely and improves the strength of the backfill significantly. Relevant scholars studied the impact of $CaSO_4{\cdot}2H_2O$ on early stage strength of cement and the result suggests that with appropriate dosage of $CaSO_4{\cdot}2H_2O$ the early strength of cement increases [11–13].

(2) $CaSO_4{\cdot}2H_2O$ hydrates with $C_3A$ $C_4AF$ from cement and forms cement bacillus. The following is the reaction mechanism for $C_3A$:

$$3CaO\cdot Al_2O_3\cdot 6H_2O+3\left(CaSO_4\cdot 2H_2O\right)+19H_2O \longrightarrow 3CaO\cdot Al_2O_3\cdot 3CaSO_4\cdot 31H_2O \quad (8)$$

The calcium silicate forms a spatial network structure (see Figure 12). Many calcium silicate hydrate (CSH) gelatum ions adhere around it making it a smaller void and hence it has better density. The clavate calcium silicate can be randomly distributed among C-S-H, which works similar to micro reinforcing steel bar [13].

(3) Neutralization process produces tailings with crystal grains of $FeAsO_4$, $Fe(OH)_3$, and $CaSO_4$, which form hydrates in three-dimensional network with C-S-H, which is one of the reasons for higher strength from neutralization tailings backfill.

(4) From the granular composition, flotation tailings have an average granular size of 33.5 $\mu$m, with 32% at $-20$ $\mu$m; and the average granular size of neutralization tailings is 24.5 $\mu$m, with 44% at $-20$ $\mu$m. From the granular composition, the average size of neutralized tailings is 0.73 times the average size of flotation tailings and the content of size at $-20$ $\mu$m is 1.37 times that of flotation tailings. Thus, the two kinds of tailings do not have prominent differences on granular composition. Hence, the granular composition of neutralization tailings contributes to a higher backfill strength [14–17].

## 5. Conclusion

(1) Neutralization tailings are a product from Jinfeng BIOX process compared to flotation tailings; neutralization tailings have higher content of $FeAsO_4$, $CaSO_4$, and $Fe(OH)_3$. Besides, neutralization tailings show smaller average granular size with lesser content of granular composition at $-20$ $\mu$m;

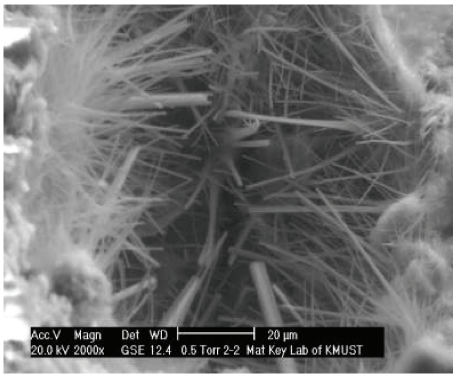


Figure 12: SEM picture of calcium silicate.

the two kinds of tailings do not have prominent differences on granules composition. Thus, it is not the granular composition of neutralization tailings that contributes to higher backfill strength.

When the cement content is at 19%, 7-day, 14-day, and 28-day strengths of neutralization tailings are higher than those of flotation tailings by 105%–163%, 80%–102%, and 33%–43%, respectively; when the cement dosage is at 12%, 7-day, 14-day, and 28-day strengths of neutralization tailings are higher by 58%–77%, 50%–60%, and 28%–51%.

(2) Neutralization tailing is helpful for improving the early stage backfill strength, which is very important for short curing time of backfill in drives and improves the production from stope.

(3) When neutralization tailing is used for backfill, the UCS value is nearly in inverse relation with aggregates-to-tailings ratio. The strength of backfill reaches its maximum when the ratio of aggregates to tailings is 2.4.

(4) The flow behavior of backfill with neutralization tailings is less active. As the value of slump and diffusivity of two kinds of tailings is not more than 6%, it does not have any impact on liquidity.

(5) $CaSO_4 \cdot 2H_2O$ is produced in abundance during tailings neutralization. As the crystal grain accretion continues, the grain size becomes larger and larger and forms interlaced structure, in which the porosity decreases gradually and the strength increases constantly. This structure combines the aggregates closely; and $CaSO_4 \cdot 2H_2O$ reacts with cement and forms a clavate cement bacillus, which creates a spatial network structure and works similar to micro reinforcing steel bar, thus increasing the early stage strength of cement.

(6) Compared to flotation tailings, the use of neutralization tailings for backfill does not impact the fluidity of backfill but helps in improving the strength. Hence, it is favorable to use neutralized tailings to replace currently used flotation tailings for underground stope backfilling.

## Competing Interests

The authors declare that they have no competing interests.

## Acknowledgments

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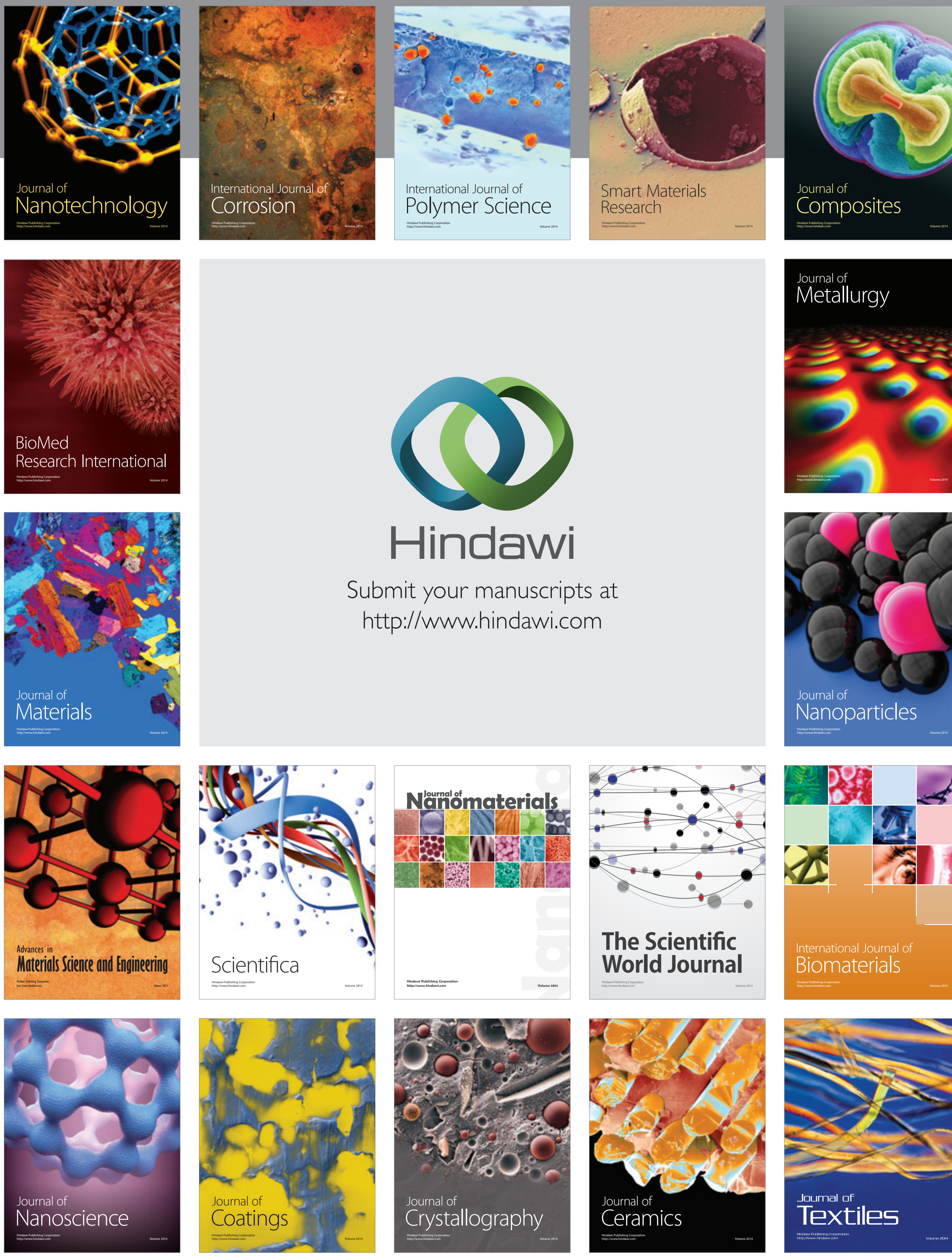
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