Research Article

Effect of Compressive Behaviours of Tail Salt Filling Materials on Roof Deformation in Potash Mine

Jiaqi Wang , Qiang Zhang , Meng Li, Hengfeng Liu, and Cunli Zhu

State Key Laboratory of Coal Resources and Safe Mining, School of Mines, China University of Mining and Technology, Xuzhou City, Jiangsu Province 22116, China

Correspondence should be addressed to Qiang Zhang; leafkky@163.com

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To resolve the problem of top mine instability and the consequent ecological damage caused by different grades of ore deposits in the layered mining process, layered filling-pillar-mining-displacement method (LFPMD) is proposed using a potash mine as an example. Based on the operation principles of the tail salt filling system, the mechanical behaviours of the tail salt under initial tamping and overburden loading were obtained through compaction tests in the laboratory. In addition, the mining-filling mass ratio of tail salt was derived. Based on the mining geological conditions of a potash mine in Laos and the compaction characteristics of tail salt, a mechanical model of top control by tail salt and a numerical model of top control by the pillars were established to discuss the stability of the upper-layer top mine and the lower-layer top mine. It was found that when the elastic foundation coefficient of the tail salt is greater than $550 \text{ MN}\cdot\text{m}^{-3}$, and the width of the retained pillars is 10 m, stability of the upper layer and the lower layer can be guaranteed. The results revealed that the LFPMD method can ensure stability of the overburden in the stope and reduce environmental damage while treating tail salt underground.

1. Introduction

Mineral resources are indispensable for human survival as well as the sustainable development of society. For example, potash mines play an important role in agricultural production. Potassium is also one of the three major influencing factors of crops. Affected by regional ore-forming geological conditions, energy, and material sources, these ore bodies mostly exist in the forms of layers, columns, and veins. The occurrence characteristics showed that there was a dominance of paragenetic and associated mines, while there were a few mines with a single type of mineral. To facilitate the mining of thick and extra-thick layered ore bodies, as well as to distinguish paragenetic and associated ore resources with different mining grades, it is often necessary to carry out layered mining, in which different mining methods are used in different layers.

In the traditional layered mining process, the following problems often occur: (1) the upper-layer top mine is unstable in layered mining. Zhang et al. [1] stated that a Voussoir beam structure is formed following upper-layer

mining. The overlying broken rock blocks squeeze and rub against one another during the turning process, increasing the pressure on the supporting structure, and resulting in severe mine pressure; (2) the ore bodies between layers are unstable. Baryshnikov et al. [2] found, through a similar simulation analysis, that, during the lower-layer mining process, the development of overlying rock fissures will accelerate, and the original fissures will become wider and longer, accompanied by new fissures, resulting in further broken rocks from overburden; and (3) after layered mining of the ore body, the diversity of the ecosystem will be damaged in ways including (a) damage to the surface buildings and water resources, as well as surface subsidence and lowered groundwater level caused by continuous movement and breakage of overburden, and (b) environmental damage of surface soil and air pollution, where surface piling of tail salt will aggravate soil salinization and the evaporation of hazardous components. The surface and tail salt of potash mine are shown in Figure 1.

Taking a potash mine as an example, depending on the grade, the occurrence shows sylvite in the upper layer and

FIGURE 1: Surface and tail salt of potash mine. (a) Tailings reservoir. (b) Sylvite. (c) Carnallite.

carnallite in the lower layer. During the mining process, the overburdened rocks of the upper layer may break and cause subsequent connection of aquifers, which could lead to mine water bursting and the dissolution of the potassium salt ore body, causing disastrous consequences. At the same time, when lower-layer mining is carried out, it is necessary to pay attention to the stability of the upper-layer goaf.

Filling is effective method for resolving the above problems. Shi et al. [3] proposed use of the filling method to control roof fissure development and mine pressure in the process of potash mining and to prevent the water-conducting fissures from connecting with the aquifers. Andrusikiewicz et al. [4] suggested the use of continuous and highly mechanized mining methods for potash mines to increase mine productivity by a large extent. Xu et al. [5] proposed a method of controlling the filling rate during mining and filling and controlling roof movement by increasing the filling rate. Li et al. [6] explored the compaction characteristics of gangue as a filling material through compaction tests and selected a reasonable mining-filling ratio to control the compactness of the filling body to control the sinking of the roof.

The aforementioned studies resolved the problems associated with single ore deposit top instability and the mining of extra-thick ore bodies through mining and filling and investigated the compaction characteristics of gangue. However, layered mining and top mine protection of paragenetic and associated minerals have not been studied. To resolve these problems, we examined the layered mining method for paragenetic and associated minerals and the mechanical behaviour of tail salt compaction, using a potash mine as an example.

Based on the geological conditions of a potash mine in Laos, different grades of ore deposits were mined using the LFPMD method. The compaction characteristics of the tail salt under different initial compressive stress conditions were tested in laboratory compaction experiments, where the filling mass ratio of the mining and filling process of the upper layer was outlined. Then, based on the compaction characteristics of the tail salt, the main control effects of filling materials and the control effects of lower-layer pillar mining were analysed. The research results are intended to provide reference information for the development of potash mines and similar paragenetic and associated mineral resources, as well as for environmental protection around the mines, thereby enriching the theory of overburden movement control in filling and mining.

2. Materials and Methods

2.1. Technical Principles. The LFPMD method was proposed. This method is defined as the process of mining mineral resources under various spatial and temporal conditions using the layered mining method in paragenetic and associated deposits. Layered filling-pillar mining refers to the use of tail salt for mining and filling in the upper layer and the use of pillar mining in the lower layer; displacement mining means that mining is carried out in the lower layer, and the mining direction is not parallel after the filling materials stabilize in the upper layer.

As shown in Figure 2, the specific mining process is as follows: comprehensive mechanized mining is conducted in the upper layer, where tail salt from the aboveground ore-washing plant enters the storage bin through the feed well [7–9] and is further filled into the goaf using machines such as the underground belt conveyor, self-moving transfer machine, and porous bottom discharge conveyor. It is filled tightly under the tamping action of the filling hydraulic support [10–12]. After compaction of the tail salt is stabilized, mining in the lower layer is carried out, and the pillars were retained.

2.2. Test Principles. The tail salt is a granular material that has different densities after it is filled into the goaf. Different densities determine different elastic foundation coefficients and control the overburden to produce different degrees of deformation. Owing to the existence of pillars and filling hydraulic supports, the tail salt filling body is structurally constrained in the horizontal direction and is subject to the weight of the overlying roof in the vertical direction, as shown in Figure 3. Therefore, the compaction characteristics of tail salt can be investigated with a steel drum uniaxial compression test [13–15].

2.3. Test Method

2.3.1. Filling Material. The tail salt was solid NaCl selected by the beneficiation process. It is a colourless cubic crystal prone to agglomeration and caking and can be used as an excellent filling material. The tail salt used in the test was from a potash ore-washing plant in Laos. It was dried and crushed to a particle size below 50 mm and used for the tail salt compaction characteristics test to study the mechanical behaviour of tail salt compaction under different loads.

FIGURE 2: Diagram of the filling and pillar system of the LFPMD method.

FIGURE 3: Filling material state of the tail salt in the goaf. (a) Compact state of tail salt filling. (b) Internal microunit of tail salt. (c) Steel drum uniaxial compression test.

2.3.2. Test Devices. The compaction test was carried out on the electrohydraulic servo universal test system, which includes the WAW-1000D computer-controlled electrohydraulic servo universal testing machine (from Shandong OBT Test Equipment Co., Ltd., China) and compacted steel drum (from Huifeng Drums Factory, China). The test machine can provide a maximum loading force of 1000 kN. The self-made compacted steel drum comprises a steel drum, base, dowel bar, and loading plate. The inner diameter of the steel drum is 125 mm and the outer diameter is 137 mm. The height of the drum is 305 mm, and the thickness of the drum wall is 12 mm. The steel drum and the base are connected by a flange. The radius and height of the loading plate are 124 mm and 40 mm, respectively. Owing to these parameters, uniform pressure can be achieved on the sample during loading. The test equipment is shown in Figure 4.

2.3.3. Test Plan. To study the effect of the ramming force on the compaction characteristics of the tail salt filling material, different initial loading stresses (0 MPa, 0.5 MPa, 1.0 MPa, 1.5 MPa, 2.0 MPa, 2.5 MPa, and 3.0 MPa) were applied to the tail salt samples to simulate the effect of different tail salt densities on the compaction characteristics. After the initial loading stress was applied, a final loading force of 735 kN (15 MPa) was added to obtain the final compaction deformation of the tail salt filling material. A detailed plan is listed in Table 1.

The displacement and pressure sensors were zeroed before loading, and the tail salt sample was poured into the drum between 4 and 6 times. After the filling was done, the steel drum was placed on the test bench of the electrohydraulic servo universal testing machine controlled by a WAW-1000D computer. The tail salt was axially loaded, and the axial pressure and axial displacement during axial loading were monitored and recorded in real time.

3. Test Result Analysis

3.1. Stress-Strain Relationship during Tail Salt Compaction. During the test, the data were collected every 3.0 s. The stress-strain [16–18] relationship curves of the seven sets of tail salt filling materials during the compaction process were obtained through test data analysis, as shown in Figure 5. The strain conditions of each scheme under different compressive stress are listed in Table 2.

Figure 5 shows the following: (1) the tail salts of the seven sets grow exponentially during the compaction process, with a relatively high degree of fitting; (2) the resistances of the tail salt of the same set to deformation increase with loading force; (3) after the tail salt is compacted under 15 MPa, as the initial loading stress on different sets of tail salt increases, the strain decreases; and (4) as the filling hydraulic support can provide 2 MPa initial stress for the tail salt, the initial strain under a 2 MPa loading force is used as an indicator. The analysis revealed that the tail salt had a final strain of 0.159

FIGURE 4: Diagram of the test devices.

TABLE 1: Detailed test plan.

Name	Initial loading stress (MPa)	Initial loading force (kN)	Final loading force (kN)
S0	0	0	735
S1	0.5	24.5	735
S2	1.0	49	735
S3	1.5	73.5	735
S4	2.0	98	735
S5	2.5	122.5	735
S6	3.0	147	735

under the overburden pressure (8.5 MPa) after initial compaction under 2 MPa, and the resistance to deformation was increased 6.6 times compared with the initial stage.

3.2. Stress-Bulk Density Relationship during Tail Salt Compaction. The bulk density is an important parameter of the tail salt filling material that indicates the compactness of the tail salt filling body. It can be used to calculate the filling volume and mass. During the compaction process, the relationship between the stress and bulk density is given as follows:

$$\rho(\sigma) = \frac{\rho_0}{1 - \varepsilon(\sigma)}, \quad (1)$$

where ρ_0 is the initial density of the tail salt, 2.13 t/m^3 . The stress-bulk density relationship curves of the seven sets of tail salt filling materials in the compaction process were obtained, as shown in Figure 6.

Figure 6 shows the following: (1) the stress increases linearly with an increase in the bulk density; (2) the density and hardness of the tail salt of the same set increase with an increment in loading stress; (3) after being compacted under 15 MPa, different sets of tail salts show less variation and higher stability with an increase in the initial loading stress; and (4) the bulk density under a 2 MPa initial loading force is used as an indicator. The analysis revealed that the tail salt has a final bulk density of 28.02 kN/m^3 after initial compaction under 2 MPa. Furthermore, its compactness is 16% higher than that of the initial stage.

3.3. Stress-Foundation Coefficient Relationship during Tail Salt Compaction. Tail salt is not an elastomer. There is no fixed parameter indicating the stress-strain relationship. The deformation modulus of the filling body was defined as $E = \sigma/\varepsilon$, and the elastic foundation coefficient of the filling body was defined as $k_g = E/h_0$. During the compaction, the relationship between the stress and elastic foundation coefficients is expressed as follows:

$$k_g = \frac{\sigma}{\varepsilon h}. \quad (2)$$

The stress-elastic foundation coefficient relationships during the compaction process of the seven sets of tail salt filling materials were acquired, as shown in Figure 7.

Figure 7 illustrates the following: (1) the stress increased linearly with an increase in the elastic foundation coefficient; (2) the elastic foundation coefficient of the tail salt of the same set had increased with an increase in the loading stress; (3) for different sets of tail salts, the elastic foundation coefficient increased with an increase in the initial loading stress, and the bearing capacity was enhanced; (4) when the initial loading stress was greater than 1.5 MPa, the elastic foundation coefficient of the tail salt changed moderately; and (5) the elastic foundation coefficient under the initial loading force of 2 MPa was taken as an indicator. The analysis revealed that the tail salt had an elastic foundation coefficient of 539.02 MN/m^3 under the overburden pressure (8.5 MPa) after undergoing an initial compaction of 2 MPa.

FIGURE 5: Stress-strain relationships. (a) Stress-strain relationships during the entire process. (b) Stress-strain relationships during specific stages.

TABLE 2: Strain conditions under different compressive stress processes of individual plans.

Initial loading stress (MPa)	0–2 MPa strain	2–8.5 MPa strain	8.5–15 MPa strain	0–2 MPa strain percentage (%)	Stress-strain fitting equations
0	0.1039	0.2437	0.3133	33	$\varepsilon = -0.09489 + 0.14417 \ln(\sigma + 1.97227)$ $R^2 = 0.99$
0.5	0.0605	0.1903	0.2613	23	$\varepsilon = -0.20653 + 0.16111 \ln(\sigma + 3.24689)$ $R^2 = 0.99$
1.0	0.0370	0.1616	0.2632	14	$\varepsilon = -1.74921 + 0.5509 \ln(\sigma + 23.59429)$ $R^2 = 0.99$
1.5	0.0230	0.1664	0.2432	9	$\varepsilon = -0.24938 + 0.17066 \ln(\sigma + 2.93484)$ $R^2 = 0.99$
2.0	0.0341	0.1586	0.2400	14	$\varepsilon = -0.50367 + 0.23888 \ln(\sigma + 7.50037)$ $R^2 = 0.99$
2.5	0.0269	0.1475	0.2405	11	$\varepsilon = -1.2226 + 0.42359 \ln(\sigma + 16.63269)$ $R^2 = 0.99$
3.0	0.0163	0.1431	0.2255	7	$\varepsilon = -0.46865 + 0.2242 \ln(\sigma + 7.11966)$ $R^2 = 0.99$

3.4. Mining-Filling Mass Ratio. After the goaf was filled with tail salt, the compression mass was m_n , and the ratio of m_n to the raw coal mass of the mining area, m_c , was the mining-filling mass ratio. Based on the principle that the volumes of the mining and filling are equal, the mining-filling ratio is given as follows:

$$e = \frac{m_n}{m_c} = \frac{\rho(\sigma)}{\rho_c} = \frac{\rho_0}{\rho_c(1 - \varepsilon(\sigma))}. \quad (3)$$

The filling-mining mass ratios under various initial loading stresses were obtained, as shown in Table 3.

Table 2 reveals that, at a depth of about 330 m in the mine, under an overburden rock stress of 8.5 MPa and initial loading stress of 2.0 MPa, the mechanical bearing capacity of the filling body was ensured with a compaction strain of 0.159 and a mining-filling mass ratio of 1.19.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results and their interpretation as well as the experimental conclusions that can be drawn.

4. Discussion

After determining the mechanical behaviour of the tail salt, key parameters of the tail salt filling material in the filling-mining process were obtained. Theoretical analysis and numerical simulation were then conducted to analyse the top stability controlled by the tail salt.

4.1. Stability of the Upper-Layer Top Mine. The stability of the upper-layer ore is directly related to the compaction characteristics of the tail salt and is controlled by adjusting the elastic foundation coefficient of the tail salt. The mechanical

FIGURE 6: Stress-bulk density relationship curves. (a) Stress-bulk density relationship in the entire process. (b) Stress-bulk density relationship in specific stages.

FIGURE 7: Stress-elastic foundation coefficient relationship curves. (a) Stress-elastic foundation coefficient relationship in the entire process. (b) Stress-elastic foundation coefficient relationship in specific stages.

model of the tail salt top control was established by taking the profile along the strike of the stope, as shown in Figure 8. The ore body and tail salt on the mine face were simplified to the Winkler elastic foundation [19–21].

In Figure 8, point O was set at the junction of the coal wall and the hydraulic support, and the coordinate system was established with the displacement function $\omega(x)$ as the basic unknown variable. The variable q_0 is the overburden rock stress, k is the peak coefficient of the supporting stress of the coal wall, $q_1(x)$ is the overburden top mine stress function of the ore body, q_c is the load intensity of the overburden top mine of the goaf, k_j is the elastic foundation

coefficient of the ore body, k_g is the elastic foundation coefficient of the filling material, q_z is the supporting strength of the support, l_1 is the length of the ore body, l_2 is the length of the support, and l_3 is the length of the goaf.

According to the Winkler hypothesis [22–24], the calculation process for the upper-layer top mine deflection and bending moment is shown in Figure 9.

The effect of the elastic foundation coefficient on the deformation and bending moment of the top mine was investigated based on the following parameters: with other engineering parameters kept constant, the overburden rock stress was set at 8.5×10^6 MPa, the stress concentration

TABLE 3: Filling-mining mass ratios under various initial loading stresses.

Initial loading stress (MPa)	0.5	1.0	1.5	2.0	2.5	3.0
Bulk capacity ($\text{kN} \cdot \text{m}^{-3}$)	22.67	23.37	23.99	24.81	25.59	26.32
Filling-mining ratio after compaction	1.09	1.12	1.15	1.19	1.23	1.26
Strain after compaction under 8.5 MPa	0.18	0.17	0.16	0.13	0.12	0.11

FIGURE 8: Model of top control by tail salt.

FIGURE 9: Process for calculating the upper-layer top mine deflection and bending moment. *Note.* In the figure, ω , θ , M , and Q refer to the deflection, corner, bending moment, and shear force of each selection of the roof; d_{1-12} refer to constant coefficient; and $[\sigma]$ refers to the allowable tensile stress of the roof.

coefficient was set as 1.8, hydraulic support top control distance was set as 6.81 m, the filling length was set as 50 m, the elastic foundation coefficient of the potash salt $k_c = 2 \times 10^8 \text{ N} \cdot \text{m}^{-3}$, and top mine elastic modulus $E = 18 \text{ GPa}$. The elastic foundation coefficients of the filling body were 500, 550, 600, 650, and $700 \text{ MN} \cdot \text{m}^{-3}$. The results are shown in Figure 10.

Figure 10 shows that the deflection curve of the top mine under the control of the tail salt filling body increased logarithmically, and the top mine became stabilized 30 m behind the goaf. When the elastic foundation coefficient increased from $500 \text{ MN} \cdot \text{m}^{-3}$ to $700 \text{ MN} \cdot \text{m}^{-3}$, the sinking range of the top mine was significantly reduced from 0.23 m to 0.17 m, and the extreme value of the bending moment was substantially reduced from $3.8 \times 10^7 \text{ N} \cdot \text{m}$ to $3.1 \times 10^7 \text{ N} \cdot \text{m}$. By solving the extreme value of the bending moment, it is confirmed that when the bending moment is $3.5 \times 10^7 \text{ N} \cdot \text{m}$ and the elastic foundation coefficient of the corresponding filling body is $550 \text{ MN} \cdot \text{m}^{-3}$, the stability of the top mine is ensured, which is in agreement with the experimental results.

4.2. Stability of the Lower-Layer Top Mine. Pillar mining was used to control the stability of the upper-layer top mine to ensure the overall stability of the top mine and the tail salt

filling body in the upper layer. Based on field practice, the width of the pillar was set at 10 m and that of mining was set at 8 m. According to the histogram of the ore layer in the mining area and the parameters of the mine face, a model with the dimensions $172 \text{ m} \times 150 \text{ m} \times 347 \text{ m}$ was established based on the results of laboratory tests on rock mass mechanical parameters, as shown in Figure 11. The model had a fixed horizontal displacement around the sides and fixed horizontal and vertical displacements on the bottom surface. The overall applied gravitational acceleration was 9.8 m/s^2 . The physical and mechanical parameter model of the tail salt was determined by the stress-bulk density and stress-foundation coefficient relationships of the tail salt (using the elastic model). The Mohr-Coulomb model was used for other rock formations in this simulation, and the physical and mechanical parameters of each rock formation are listed in Table 4.

The numerical simulation scheme was used to carry out coal pillar mining in the carnallite layer after the sylvite filling-mining was stabilized. The stress and displacement distribution of the lower-layer top mine were obtained and are shown in Figures 12 and 13.

Figures 12 and 13 show the following: (1) the peak stresses at the two ends of the mining area and the excavation site were 14.8 MPa and 4.12 MPa, respectively. As the

FIGURE 10: Deflection and bending moment distribution patterns of the top mine.

FIGURE 11: Diagram of the numerical simulation model.

TABLE 4: Physical and mechanical parameters of the ore body.

No.	Lithology	Height (m)	Density (kg/m ³)	Tensile (MPa)	Cohesion (MPa)	Internal friction angle (°)	Bulk modules (GPa)	Shear modulus (GPa)
12	Silty clay	5	2500	3.83	4.2	31	2.0	1.6
11	Ferromanganese nodules	3	5500	2.67	5.3	27	4.0	2.1
10	Sandy gravel	4	3000	2.29	6.5	28	3.0	2.1
9	Carbonaceous mudstone	47	3500	2.27	5.4	27	3.5	1.6
8	Anhydrock	15	2000	1.49	6.3	26	2.0	1.8
7	Silty mudstone	50	2510	2.27	5.0	26	2.51	1.5
6	Halite	113	2125	2.17	5.0	25	1.1	0.6
5	Mudstone	60	2239	2.23	3.90	25	1.18	0.58
4	Sylvite	4	2081	2.13	3.93	28	1.08	0.56
3	Tail salt	4	2802	—	—	—	0.5	0.36
2	Carnallite	12	1830	1.43	3.13	26	0.6	0.3
1	Halite	30	2125	1.87	3.5	26	2.0	1.2

FIGURE 12: Stress and displacement distribution in the middle of the mine face.

FIGURE 13: Peak stress and peak displacement under different numbers of excavation.

number of excavations increased, the peak stress of the top mine increased gradually at a moderate magnitude; and (2) the peak displacements at the two ends of the mining area and excavation site were 13.68 mm and 3.46 mm, respectively. As the number of excavations increased, the peak displacement of the top mine increased gradually, but the overall variation was less than 8%. The top mine of the lower layer was stable.

The stress distributions in the upper-layer tail salt and the lower-layer pillar are shown in Figures 14 and 15.

Figures 14 and 15 illustrate that the stress distributions of the tail salt filling body and the pillars were stable after LFPMD method. The stress distribution of the tail salt filling body was between 1 MPa and 3 MPa, and the stress distribution of the pillars was between 4 MPa and 6 MPa. With an increase in the number of lower-layer excavations, there was no obvious change in the internal stress of the tail salt filling body and pillars, and both could steadily support the top mine.

FIGURE 14: Stress distributions of tail salt filling material and pillars.

FIGURE 15: Peak stress of the filling material and top mine with different excavation numbers.

5. Conclusions

In this study, the compaction mechanical behaviour of the potash mine tail salt filling body was tested. Based on the test results, the LFPMD method was used to protect the stability of the top mine in each layer. The main conclusions are as follows:

- (1) Owing to the challenges associated with mining ore bodies with different grades, LFPMD method was proposed to ensure the stability of the top mine in each layer. Taking the potash mine as an example, tail salt filling was used to simultaneously protect the stability of the top mine and handle a large amount of tail salt.
- (2) The relationships among stress-strain, stress-bulk density, and stress-elastic foundation coefficient of each set of tail salt were obtained, and the mining-filling mass ratio was obtained as 1.19.
- (3) The mechanical model of tail salt top control revealed that when the elastic foundation coefficient

of the filling body was kept at $550 \text{ MN}\cdot\text{m}^{-3}$, the stability of the top mine could be ensured.

- (4) The numerical simulation experiment revealed that when the pillar mining method of “8 m mining–10 m pillar” was adopted, the stability of the lower-layer top mine and the upper-layer goaf could be ensured.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors contributed equally to this research.

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