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Mechanical Calculation and Proportion Optimization for Paste Backfill of Upward Horizontal Slice Stope-Filling Method in Underground Mine

To improve mining production capacity, the upward horizontal slice stope-filling method (UHSSF) is employed at the LI Guanji iron mine. The height of the stage stope is approximately 100m and the height of layered backfill is 6m. At present, there is no systematic research on the mechanism of layered backfill in high-level mining. The strength design of backfill is mainly carried out by use of the experience method or the analogical method which often leads to cement being wasted or the strength being lower than that of the engineering requirements. According to the site-specific geological and mining conditions, the action mechanisms of backfill in different roles such as work platform and supporting roof were analysed. The corresponding strength models were developed by referring to the elastic and plastic theories. The analytical method for designing the required strength of backfill was obtained accordingly. The models and analytical methods have been applied in strength design and optimization of the cement-tailings ratios for backfill in the No.3 stope of the LI Guanji iron mine. It is concluded that the strength design method is reasonable and reliable, as well as conducive to saving filling costs.

Keywords: *Backfill mechanics, Cement-tailings ratio, Strength design, Tailing backfill, Upward horizontal slice stope-filling method.*

1. Introduction

The filling mining method can effectively control the stope ground pressure, decrease the subsidence, prevent rock burst, enhance the ore recovery rate, protect the mine environment and have a remarkable economic benefit. It has become the main mining technique in mine production. The one-time backfilling method, which requires high quality backfill, also produces high filling costs. Slice filling can also be used in the filling mining method. The slice filling method was superior to the one-time backfilling method because it increases the exposure height of the filling body without increasing the filling cost [1]. Therefore, many mines have been using the slice filling method for decreasing the filling cost and the upward horizontal slice stope-filling method (UHSSF) is widely used accordingly. UHSSF mines operate, step by step, from the bottom up. Each slice is filled in time after it is mined, which is intended to reinforce the two sides of goaf and then is used as the work platform for the next operation cycle. After slicing mining grows to the stage height and the filling body contacts the roof, the compressive stress is bore from the overburden rock as a supporter of the cavern roof. Therefore, how to make the strength of backfill more scientific and reasonable becomes important for UHSSF. If the design strength is too low, the filling body cannot effectively control the ground pressure activity, which has a serious consequence upon safe production. If the design strength is too high, the added volume of cementitious materials, such as added cement, will cause unnecessary waste and leads to high filling costs. Determining the backfill strength requirement is one of the three major reasons for backfill mechanics, which can help to control costs and produce a high-quality backfilling technique. As can be seen, one cannot over emphasize the importance of determining backfill strength [2-3]. The design of backfill strength varies from one mine to another, and largely depends upon the depth of deposits, the mechanical characteristics of rock and ore, the mining method, the exposed area of backfill and so on [4-6]. There are many strength design methods in the world, such as the experience analogy method, the empirical formula method, the mathematics method of mechanical modelling, the numerical analysis method and the probabilistic method [2, 3, 7-9]. The experience analogy method and mathematics method of mechanical modelling are the most representative methods. The experience analogy method is used to analyse the practical needs and to design the strength of backfill by drawing from other similar mines' experience. In the early days, the Canadian Strathcona mine, the Finnish Outokumpu mine, the Australian Mount Isa

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Copper Mine, the Chinese Jinchuan mine and the Fankou Mine mainly used this method for design [2, 9-10].

The essence of the mathematics method of mechanical modelling is based on the previous research of the mechanical characteristics of rock and backfill. In order to determine the necessary strength, some regular structures have been simplified and the analytical model has been expressed using the basic mechanical properties of cemented filling bodies. Thomas [11] considered the arching effect because of friction between the cemented filling body and the surrounding rock. He proposed a model to determine the backfill strength based on the stability analysis of a three-dimensional wedge of backfill by using the limit equilibrium principle. Mitchell [12] proposed the physical modelling of cemented backfills and found that the cement strength requirement can be reduced when rock walls are sufficiently close together to help with supporting the backfill by reducing shearing stresses at the wall-backfill contact. Lu Ping [2-3] researched Thomas model method and finds the method considered the bulk density and geometry size of backfill, without analysing its strength, made the corrections for Thomas' model, and subsequently proposed the new formula named the Luping model. Based on the experimental results, Liu Zhi-xiang [13] deduced the calculation formulae of the stratified backfill practice through the mechanical analysis of high backfill. Beyond that, many models and equations for the determination of backfill strength have been proposed [9, 14].

Although multiple methods are available, there still exist some problems with their use. It is easy to design, but also subject to extensive subjective discretion and difficult to scientifically determine the strength of the filling body. The design is intended to be cautious and relatively orthodox, and the strength is generally higher, which brings a lot of unnecessary cost. Experience analogy method is easy to operate and has wide application, but the prediction is subjective and difficult to scientifically determine the required backfill strength. For this reason, conservative estimations are used, so the strength value is generally higher, bringing a lot of unnecessary filling cost [2]. The commonality of the mathematics method of mechanical modelling is all based on the appreciation and analysis to the relation of interaction between the cemented filling body and the surrounding rock, but the comprehension of relation of interaction are totally different [15].

In general, these models and laboratory tests are dependent on local experience and empirically derived relationships between backfill support, material properties, and mine geometry [16]. The optimal design is for the backfill strength of UHSSF in the Li Guanji iron mine. The height of the stage stope is close to 100m which reaches the high-level filling body territory in situ. The backfill should provide a working platform and is supposed to support the overburden, reduce the volume of open space and protect the pillars. In this paper, the roles of the filling body of UHSSF are analysed, the mechanical models of layered backfill and backfill of cemented layers are established based on its role. Referring to the elastic and plastic theories, the strength of backfill subjected to dynamic load is designed by the mechanics analytical method. The results can optimize and determine the material ratio for cemented tailings backfill.

2. Geological and mining conditions

As shown in Fig.1, the Li Guanji iron mine is located at the Guocang Township, 72 km away from Tangshan, Shandong Province, China. The mine and the surrounding areas are fertile and flat watery land with a flat topography. The ore body is distributed in 14 layers and the depth is from 0m to 600m. The length along the strike of the main ore body is 1365m and the average SE-direction dip angle is 75°.

The upward horizontal slice stope-filling method with a pointed pillar is the common mining method adopted in this mine. The stopes were arranged along the strike of the ore body within the width of the horizontal thickness. The lengths varied from 60m-100m, according to the changes of the thickness of the ore body. The height of the stage stope is approximately 100m. It includes a main transport roadway, a 22.5m sublevel and an 8m high layer without any auxiliary section. The width of the interval pillars between stopes is

Fig.1 Location of Li Guanji iron mine in Shangdong, China

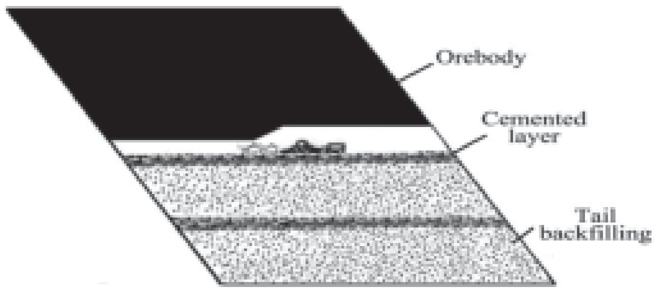


Fig.2 Constitution of backfill in upward horizontal slicing method

6m. Meanwhile, some methods such as pillars setting in stope and full-tailings backfill are utilised to avoid collapse of the farmlands and buildings on the surface due to mining activity. The cement-tailing ratio of the cemented layer was 1:4 at the top of 1m of each layer as the work platform used for the next operation cycle. The cement-tailing ratios of the other parts were 1:10 and the total of the filling height of each layer was 6m.

3. Mechanical calculation for backfill in upward horizontal slicing method

For UHSSF, based on its mechanics, the backfilling body can be divided into two parts: the upper filling body named cemented layer and the lower filling body which is the tailing filling body, as shown in Fig.2. The backfill should attain different strengths according to the different roles. Hence the strength of backfill of UHSSF is designed under certain circumstances by analysing two specific situations: the strength design of the cemented layer in the slicing and the strength design of backfill in the stage.

3.1 Mechanical calculation for cemented layer

3.1.1 Load of trackless equipment

As the cemented layer is the working platform for the next slice, the strength should satisfy the requirements of the trackless equipment. The jumbos, explosive charging vehicles and scrapers are the most common mining equipment with high frequency of usage in the stope. The weight and load of the scraper is greater than that of the jumbo and charging vehicle and the scraper is always running in the stope. The dynamic load of the scraper becomes the main load to the cemented layer, while the other two pieces of equipment mainly impose static loads. Therefore, the scraper mainly plays the destroying role in backfill. The cemented layer should resist not only the static load but also the dynamic load from the scraper, due to the pavement surface unevenness [17-18]. The dynamic load, which is not constant, is alternately greater and smaller than the static load. The existence of dynamic load increases the destruction to the backfill. For ensuring safety, the dynamic amplification factor (DAF) should be considered in the calculation of the strength of backfill [19].

$$P_v = DAF \times P_s \quad \text{... 1}$$

Where P_v is the dynamic wheel load, kN, P_s is the static wheel load of the scraper, kN, DAF is the dynamic amplification factor.

$$DAF = 1 + \beta\sqrt{v} \quad \text{... 2}$$

Where v is the speed, m/s, β is the coefficient of riding quality. According to the riding quality evaluation criterion of the pavement, for the cement concrete pavement, β = 0.020-0.145. The quality grade is excellent, β = 0.020 [17].

3.1.2 Force analysis of the cemented layer

The backfill filled stopes must have sufficient mechanical stability, which is usually evaluated by the compressive strength [20]. If the vertical stress within the cemented layer exceeds the ultimate compressive strength of backfill material, the fill will be unstable. Thus, the total vertical stress at any point in the fill includes the vertical stress ó$_z$ caused by the scraper and the weight. The forces from the scraper on the upper cemented layer are investigated, including vertical load and the horizontal load from the haulage force. To simplify the calculation, the cemented layer is considered to be homogeneous semi-space body. The vertical and horizontal loads act along the semi-space surface. The vertical stress σ_z of the backfill is calculated by the elastic mechanics method [21-22]:

$$\begin{cases} \sigma_z = -\int \zeta[(1+\zeta z)\bar{p}(\zeta) - \zeta z\bar{g}(\zeta)]e^{-\zeta z} j_0(\zeta r)d\zeta \\ \bar{p}(\zeta) = \int rp(r)J_0(\zeta r)dr \\ \bar{g}(\zeta) = \int rg(r)J_1(\zeta r)dr \end{cases} \quad \text{... 3}$$

Where $p(r)$ and $g(r)$ are the vertical load and the horizontal load, respectively, $J_0(\zeta r)$ is the Bessel function of the first kind zero-order, $J_1(\zeta r)$ is the Bessel function of the first kind one-order.

In Reference [23], the method for determining the strength of backfill based on thin plate theory was proposed for slice fill and the most dangerous point of backfill material was indicated. The maximum compressive stress occurred at the central axis of the layer. Analyzing the horizontal distributed load acting at the semi -space body, the vertical stress caused by the horizontal load at the central axis of the support layer, on the z-axis is zero in Fig.3a [24]. Therefore, the strength design only considers the vertical wheel load and the weight of backfill.

The shape of the contact surface between the cemented layer and tires is approximately rectangular when the scraper is running on the cemented layer surfaces. The vertical wheel load P_v can be simplified to the uniform distributed load p over the rectangular area, as shown in Fig.3b. The dimension of rectangular contact surface is 2a in length and 2b in width. The uniform distributed load is:

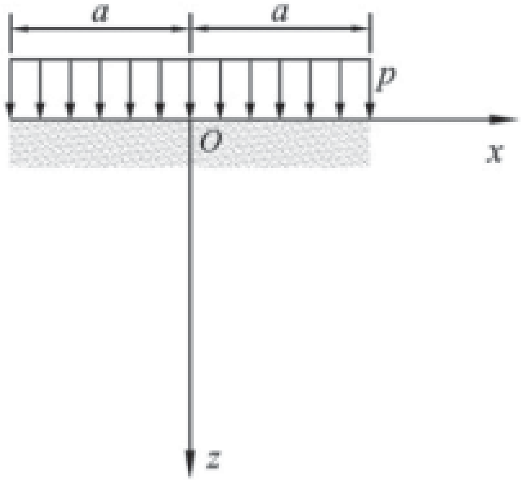
$$p = \frac{p_v}{4ab} \quad \text{... 4}$$

Based on the study of Boussinesq [24], the vertical point load P_v acts on the surface of the semi space body and the vertical stress at depth of z is:

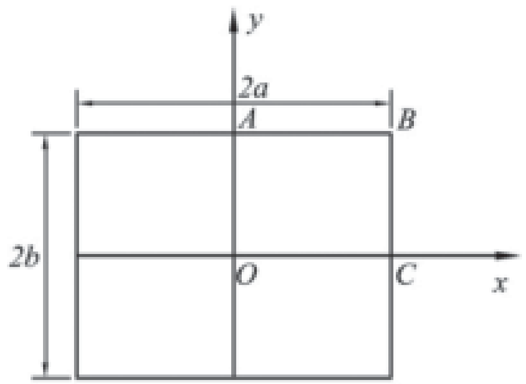
$$\sigma_z = \frac{3p_{v^{z^3}}}{2\pi R^5} \quad \text{... 5}$$

And

$$R = \sqrt{r^2 + z^2}$$



(a) The analytic calculation diagram of the uniform distributed load



(b) The uniform distributed load p over the rectangular contact surface

Fig.3 The analytic calculation diagram of the uniform distributed load over the rectangular area

Where *r* is the horizontal distance from line lock of action of force to the considering point, *z* is the depth.

It is assumed that the uniform distributed load P_v over the rectangular area is acting on the surface of homogeneous, isotropic, semi-infinite spatial elastic mass, as show in Fig.4. Point *O* is the centre of the contact surface, and the rectangular area is divided into four equal parts, as shown in Fig.3b. The vertical stress σ_z of any point under the point *O* caused by the uniform distributed load P_v is four times the vertical stress σ_z^1 caused by the uniform distributed load *P* over the small rectangular area OABC. Taking the corner point *O* in the orthogonal coordinate, the elementary area is taken as $dA = dxdy$ at any point in the small rectangular area OABC. The total load dP acts on the elementary area dA is:

$$dP = pdA = pdxdy \qquad \text{... 6}$$

Assuming the vertical stress at depth of *z* is caused by the load *dP* is $d\sigma_{z'}^1$

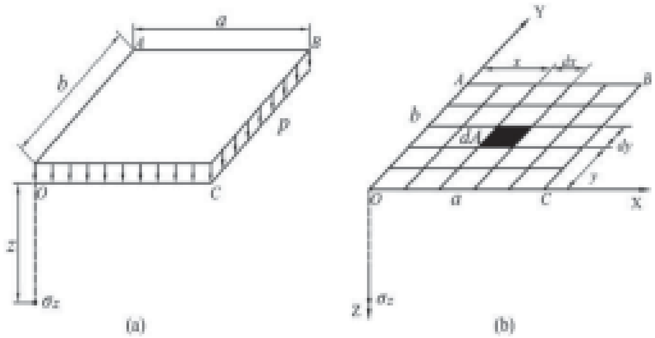


Fig.4 Half-space body loaded by the uniform distributed load over rectangular area

$$d\sigma_z' = \frac{3z^3 pdxdy}{2\pi R^5} \qquad \text{... 7}$$

The load *P* over the rectangular area a×b is uniform distributed and the vertical stress σ'_z of the point at depth of *z* is:

$$\sigma_z' = \int_0^a \int_0^b \frac{3z^3 pdxdy}{2\mu R^5} \qquad \text{... 8}$$

By integral:

$$\sigma_z' = \frac{p}{2\pi}\left[\frac{abz(a^2+b^2+z^2)}{(a^2+z^2)(a^2+b^2+z^2)^{\frac{1}{2}}} + \tan^{-1}\frac{ab}{z\sqrt{a^2+b^2+z^2}}\right] \qquad \text{... 9}$$

The vertical stress σ_z caused by the rectangular wheel load P_v is:

$$\sigma_z = 4\sigma_z' =$$

$$\frac{2p}{\pi}\left[\frac{abz(a^2+b^2+z^2)}{(a^2+z^2)(b^2+z^2)(a^2+b^2+z^2)^{\frac{1}{2}}} + \tan^{-1}\frac{ab}{z\sqrt{a^2+b^2+z^2}}\right] \qquad \text{... 10}$$

Considering the weight of backfill, the total vertical stress is:

$$\sigma_v = \frac{2p}{\pi}\left[\frac{abz(a^2+b^2+z^2)}{(a^2+z^2)(b^2+z^2)(a^2+b^2+z^2)^{\frac{1}{2}}} + \tan^{-1}\frac{ab}{z\sqrt{a^2+b^2+z^2}}\right] + \gamma' z + 10^{-3} \qquad \text{... 11}$$

Where γ' is the unit weight of the backfill.

It is known from equation 11 that the total vertical stress reduces with the depth of the increment, and increases beyond a critical depth. The height of the layer is 6m. In such depth, the wheel load has most of the impact to the backfill above the critical depth. If *z* = 0, the vertical stress is maximal,

$$\sigma_{v_{max}} = p = \frac{p_v}{4ab} \qquad \text{... 12}$$

Safety factors must also be taken into account. The safety factor k (1.2-1.5) should be considered in the calculation. By substituting Eq.1 and Eq. 2 to Eq. 12, the required strength of backfill in the cemented layer is ultimately developed:

$$R_7 = k\frac{(1+\beta\sqrt{v})P_s}{4ab} \quad \text{... 13}$$

Usually, the trackless equipments can operate on the cemented layer surface after 7 days for filling. Therefore, the strength of backfill R_7 in the cemented layer in 7 days should exceed the value calculated by Eq. 13.

3.2 Mechanical calculation for the slice filling body in the stage

For the lower tailing backfill, sufficient strength should be provided to bear the compressive stress, including the in-situ stress, the gravity and the stress from the upper cemented layer. Before roof contact, the stresses under the upper cemented layer are the weight of backfill and the trackless equipments. After roof contact, the stresses are the weight of backfill and the roof pressure. The stress after the roof contact is greater than that before roof contact. Therefore, the strength is designed according to the working situation of backfill after roof contact.

UHSSF extracts ore by slice filling technology and the strength design is different from the previous design. The previous design method considered the filling body as a whole and analysed the stress state by predicting the required strength for keeping self-stabilization. Actually, in addition to keeping self-stabilization, the layered backfill also needs to support the overburden rock. The mechanical calculation model of slice filling body bearing load from the roof in the stage is a necessary step. The strength of each layer of backfill can now be determined according to the stress analysis.

In order to establish the mechanical model and deduce the calculation equations of the strength, the following assumptions were made based on the characteristics of the mining method used in the Li Guanji iron mine: the filling body contacts the surrounding rock all around, the surrounding ore-rock is vertical, the height of the filling body in the stage is *H*, the length is *L* and the width is β. The geometric model is shown in Fig.5.

After the filling height reaches the stage height, the filling body contacts the roof and the filling body and surrounding rock form an interaction mechanical system. According to the roof pressure arch theory [25], the filling body bears the weight of ore-rock in the caving arch. Therefore, the top pressure of the filling body is,

$$\sigma_0 = \gamma(L/2 + H\text{ctg}\theta)/f \quad \text{... 14}$$

Where γ is the unit weight of the overburden rock, θ is the angle between rupture plane and horizontal plane, θ = 45°+φ/2, φ and *f* are the internal friction angle and the

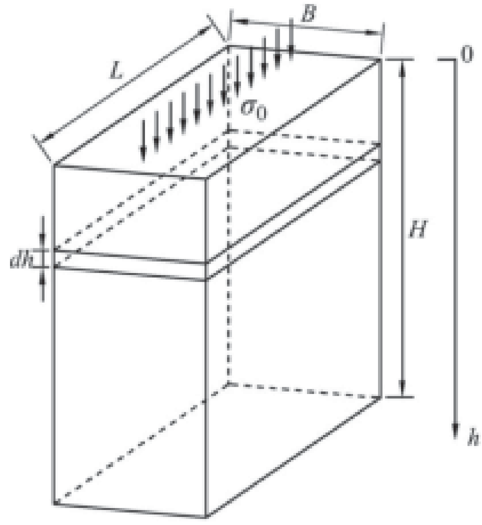


Fig.5 Geometric model of filling body in the stage

Protodyakonov coefficient of the rock.

The filling body has compacting effect on its surrounding rock under the action of the inside vertical stress ?v. According to the law of action and reaction, the side walls of the filling body bear a horizontal reacting force σ_h from the surrounding rock:

$$\sigma_h = \lambda\sigma_v \quad \text{... 15}$$

Where λ is the lateral pressure coefficient.

Referring to mining rock mechanics [25-26],

$$\lambda = \frac{(1-K)(1+K)}{2(1+2K)} \qquad K = \tan^2(45^\circ - \varphi'/2) \quad \text{... 16}$$

Where φ ' is the internal friction angle of the backfill.

Due to different material nature between the pointed pillar and the filling body, the deformation of them cannot be in synchronisation. The filling will be compacted as time goes on because of its weight and the crushing effect of the surface mining equipment. In this process, slippage or separation may take place on the contact surfaces. The contact interface between them is not smooth and, at the same time, the filling body provides a lateral constraint stress σ_h. It creates the friction in the vertical direction, as shown in Fig.6. Meanwhile, the hydration in the filling cements ore-rock particles and tailing reacts on the interface between the filling body and the surrounding rock wall. It should be noted that the cohesive force is exerted. The internal friction angle of the interface can be taken as the internal friction angle of the

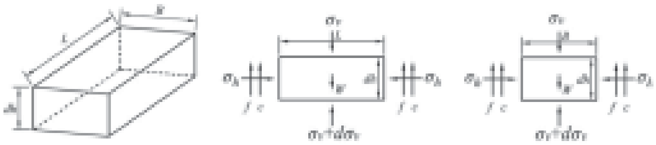


Fig.6 Force diagram for the horizontal microelement of the filling body

backfilling body. For the value of cohesion c, the references [15, 27] mention taking the cohesion of the backfill c' as an approximate value.

$$f = \sigma_h \tan\varphi' = \lambda\sigma_v \tan\varphi' \quad \text{... 17}$$

$$c = c \quad \text{... 18}$$

A thin-layer element of the filling body in the horizontal direction may be analysed, as shown in Fig.6. The height of the thin-layer element is *dh*. The forces acting on the thin-layer element in the vertical direction are the force downward transferring from the overburden rock, the support force upward and the lateral shear force. The lateral shear force acting around the thin-layer element is composed of two parts: the friction force and the cohesive force between the surfaces of the filling body and the pillar. According to the principle of force balance, the vertical mechanical balance equation of the thin layer can be obtained:

$$\sigma_v BL + \gamma' BLdh = (\sigma_v + d\sigma_v)BL + 2f(B+L)dh + 2c(B+L)dh \quad \text{... 19}$$

By substituting equations 17 and 18 to equation 19, the following expression is obtained:

$$d\sigma_v BL = [\gamma BL - 2\lambda\sigma_v \tan\varphi'(B+L) - 2c'(B+L)]dh \quad \text{... 20}$$

Accordingly: to calculate the integral, the general solution is:

$$\frac{-2\lambda\tan\varphi'(b+L)}{BL}h = \ln\left[1 - \frac{2\lambda\tan\varphi'(B+L)}{\gamma' BL - 2c'(B+L)}\sigma_v\right] + C \quad \text{... 21}$$

Where γ' is the unit weight of the backfill, C is the constant determined by boundary conditions.

After the roof contact, the filling body has to bear the compressive stress from the overburden rock. The height of the filling (h) is zero, $\sigma_v = \sigma_0$. The constant C is,

$$C = -\ln\left[1 - \frac{2\lambda\tan\varphi'(B+L)}{\gamma' BL - 2c'(B+L)}\sigma_0\right]$$

By rearranging, the vertical stress of tailing backfill is,

$$\sigma_v = \frac{\gamma' BL - 2c'(B+L)}{2\lambda\tan\varphi'(B+L)} + \left(\sigma_0 - \frac{\gamma' BL - 2c'(B+L)}{2\lambda\tan\varphi'(B+L)}\right)e^{\frac{-2\lambda\tan\varphi'(B+L)}{BL}h} \quad \text{... 22}$$

From the above equation 22, it can be seen that as the cohesion has emerged, the value of the strength of filling body has decreased. For the safety of mining and simple calculation, it is assumed that the cohesion between the filling body and surrounding rock (c') is 0. At this point, the vertical stress σ_v can be simplified to:

$$\sigma_v = \frac{\gamma' BL}{2\lambda\tan\varphi'(B+L)} + \left(\sigma_0 - \frac{\gamma' BL}{2\lambda\tan\varphi'(B+L)}\right)e^{\frac{-2\lambda\tan\varphi'(B+L)}{BL}h} \quad \text{... 23}$$

When slice filling, the top stress of the filling body ?0 can be first calculated by using equation 14 based on the stope parameters. Afterwards, the vertical stress of the first slice filling body σ_{v1}, can be calculated by using equation 23 based on the slice height and the mechanical parameters of ore-rock and tailing backfill. When calculating the stress of the second slice σ_{v2} by using the equation 23, $\sigma_0=\sigma_{v1}$, the strength of each layered backfill can be calculated by layers from top to bottom. It should be noted that the strength of the tailing backfill is calculated by the limit equilibrium calculation above, regardless of the influence of the mining and construction factors. But in the real production process, the influence of blasting vibration and dynamic load should be considered. Thus, based on the results, a safety coefficient F can be multiplied to ensure the safety of the structure, taking the value of F 1.2~1.5.

4. Design of backfill in li guanji iron mine

4.1 Application background

The main backfill optimization solution of the third stope in the Li Guanji iron mine strength design is to save cost and ensure safety. The third stope on the level –320m in the south ore domain is chosen for the design. The structural parameters of the stope with a 10m sill pillar are the length across the strike direction L 85m and the width B 55m, the height H 100m. The filling height of each layer is 6m. The width of barrier pillars setting between two stopes is 6m. The roof rock is stable and strong, Protodyakonov coefficient f =10, the friction angle and the average density are 42°, 3100 kg·m^{-3} respectively.

The full tailings consolidated filling technology method is adopted in Li Guanji iron mine. Following the experience of the local area, the home-made cementation powder is used as the cementing material. The cemented paste backfills filled stopes must have sufficient mechanical stability and it is usually evaluated by the strength of the cemented paste backfill [20]. The common practice used is to assess the backfill strength was to conduct unconfined compressive strength (UCS) tests on small laboratory samples (10×5 cm) of backfill cured in conventional plastic molds at atmospheric pressure and temperature conditions. The materials used to manufacture test samples include home-made cementation powder, tailings and water. The fill slurry concentration is 70% for different proportions, as shown in Table 1. Unconfined compression tests were performed on the cemented paste backfill specimens with 3, 7 and 28 days of curing. At least two samples (to ensure the repeatability of the results) were tested at each curing age in accordance with

TABLE 1 .COMPRESSIVE STRENGTH OF CEMENTED BACKFILL SPECIMENS (MPA)

Cement-tailing ratio	Curing time			Cement-tailing ratio	Curing time		
	3d	7d	28d		3d	7d	28d
1:5	0.88	1.88	3.53	1:10	0.46	0.72	1.27
1:6	0.73	1.71	2.92	1:12	0.43	0.65	1.14
1:8	0.56	1.12	1.92	1:17	0.28	0.32	0.58
1:9	0.37	1.03	1.50	1:20	0.22	0.27	0.37

a standard test. The compression tests were carried out at a constant deformation rate of 0.8 mm/min. Direct shear tests were carried out to determine the shear strength behaviour and parameters (internal frictional angle and cohesion) of the cemented paste backfill samples. The UCS test results are showed in Table 1.

4.2 STRENGTH DESIGN OF THE CEMENTED LAYER

For the Li Guanji iron mine, the scrapers model WJD-2 are used and the main technical parameters are shown in Table 2.

TABLE 2. THE MAIN PARAMETERS OF CARRY-SCRAPER WJD-2

Weight/kg		Operating force/kN		Speed/(km/h)		
Empty weight G	Load weight P'	Maximum drawing force	Lifting force	Speed 1	Speed 2	Speed 3
13500	4000	100	75	2.1	4.5	10

When the scraper is at rest without load, the front wheel's load is 0.45 G, the rear wheel's load is 0.55G. When the scraper is in the full load, the front wheel's load is 0.57(G +P'), the rear wheel's load is 0.429(G+P'). G is the weight of the scraper and P' is the load weight. In the design, only the strength of cemented layer under the full condition is considered for safety. Therefore, the maximum static wheel load of the scraper arranged on the cemented layer is from the front wheel, it is:

$$P_s = 0.571(G+P')/2 \qquad ... 24$$

By substituting the parameters into the Eq.24, the maximum static wheel load P_s is about 50 kN.

Considering the scraper to always be running on the surface of the cemented layer, the dynamic amplification factor should be considered in the calculation of the strength of backfill. In general, the scraper drives at low speed in the stope. For the sake of security, the Speed 2 is put into the calculation. The riding quality of the cemented layer is lower than the quality of the general concrete pavement and β = 0.145. Based on the above parameters, the maximum dynamic load P_v is:

$$p_v = (1+\beta\sqrt{v})P_s = 50(1+0.145\sqrt{4.5}) = 65.4kN$$

According to the field measurement with full load, the width of the rectangular contact space between the wheel and the cemented layer is about 27cm and the length is about 30cm. By considering the safety factors, the safety coefficient k is chosen as the max value 1.5. When these parameters are substituted into Eq.13, the required strength of backfill after filled for 7 days in the cemented layer is ultimately obtained,

$$R_7 > k\frac{(1+\beta\sqrt{v})P_s}{4ab} = 1.21MPa$$

As the thickness of the cemented layer increases, the load from the trackless equipment decreases. Based on the experience and situation of the project, the thickness of the layer is 0.5m.

4.3 STRENGTH DESIGN OF THE PAST BACKFILL

The height of the mining level is 100m in the Li Guanji iron mine. The 10m sill pillars were set at the bottom of the stope because of the broken floor rock. Therefore, the actual filling height is 90m. The height of the filling layer is 6m and there are 15 filling layers in the stage. According to the stope structure parameters and ore-rock mechanical parameters, the roof pressure of the fill after roof contact can be first calculated by using Eq.14.

$$\sigma_0 = 0.031(85/2+90ctg(45^o+42^o)/2)/10 = 0.256MPa$$

The direct shear test results show the friction angle values of backfill range from 24° to 33° in different proportions. To simplify the calculation, the average of 31° is used as a reference value and the average density is 1900 kg·m^{-3}. By substituting them into the Eq.23, the safety coefficient of 1.2 is multiplied to ensure the safety of the fill while the pillars can support the roof together. The required strength of each filling layer can be calculated from top to bottom in the mining stage. The results are shown in Table 3. The compressive strength of backfill is slightly greater than the strength in Table 3.

4.4 OPTIMIZATION OF CEMENT-TAILING RATIO FOR BACKFILL

Under the original preliminary design, the cement-tailing ratio for cemented tailings backfill in the stope filling of the Li Guanji iron mine is: 1:4 at the top and bottom layers. For the rest of layers, the cemented layer was 1:4 at the top of 1m of each layered fill, the ratio of the lower part was 1:10. According to the above formulas, the backfill required strength in the third stope was calculated and the corresponding ratio was optimized, as shown in Table 4. To meet the need of mining technology and for safety, the cement-tailing ratio of the backfill with high strength at the top-most layer, the top 6m,

TABLE 3. THE REQUIRED STRENGTH OF PASTE BACKFILL OF EACH LAYER

No. of layers	Height/m	σ_v/Mpa	No. of layers	Height/m	σ_v/Mpa	No. of layers	Height/m	σ_v/Mpa
1	0-6	1.48	6	30-36	1.20	11	60-66	0.82
2	6-12	1.44	7	36-42	1.13	12	66-72	0.73
3	12-18	1.38	8	42-48	1.06	13	72-78	0.63
4	18-24	1.32	9	48-54	0.99	14	78-84	0.53
5	24-30	1.27	10	54-60	0.91	15	84-90	0.42

TABLE 4 THE COMPARISON OF THE CEMENT-TAILING RATIO OF BACKFILL BEFORE AND AFTER OPTIMIZATION

No. of layers	Required strength/Mpa	Cement-tailing ratio before optimization	Meet or not	Cement-tailing ratio after optimization	Meet or not
1	1.48	1:4	Yes	1:6	Yes
2	1.44	1:10	No	1:9	Yes
3	1.38	1:10	No	1:9	Yes
4	1.32	1:10	No	1:9	Yes
5	1.27	1:10	Yes	1:10	Yes
6	1.20	1:10	Yes	1:10	Yes
7	1.13	1:10	Yes	1:12	Yes
8	1.06	1:10	Yes	1:12	Yes
9	0.99	1:10	Yes	1:12	Yes
10	0.91	1:10	Yes	1:12	Yes
11	0.82	1:10	Yes	1:12	Yes
12	0.73	1:10	Yes	1:12	Yes
13	0.63	1:10	Yes	1:12	Yes
14	0.53	1:10	Yes	1:17	Yes
15	0.42	1:4	Yes	1:6	Yes
Cemented layer	1.21	1:4	Yes	1:6	Yes

is 1:6. The comparison of the cement-tailing ratio of backfill before and after optimization is made as shown in Table 4.

From the comparison, it can be found that the ratio before optimization cannot meet the requirement of backfill for strength of filling materials at the bottom of the stage from Layer 2 to Layer 4 and the strength of the backfill exceeds the requirement from Layer 7 to Layer 14, also including Layer 1, Layer 15 and all the cemented layers. However, the cement-tailing ratios after optimization can solve the problem successfully. The filling practice in Li Guanji iron mine shows that the strength design of backfill with reliability calculation and optimization can save cementitious material costs, meet the practical engineering needs and is conducive to on-site construction.

5. Conclusions

According to the mining characteristics and different roles of backfilling body in the upward horizontal slice stope-filling method, the strength design is targeted. As a result the cost of filling is greatly reduced and the main conclusions are listed as follows:

1) The backfilled body has two major roles in the upward horizontal slice stope-filling method: first, the backfill must be sufficiently strong to function as a work platform for the running equipment and second, hold up the roof. The strength design of backfill has different requirements in different roles. In order to analyze the mechanism of the upward horizontal slicing backfilled body more accurately, and to establish a more appropriate strength model of the backfilled body, the backfill is classified into two parts: namely the cemented layer with high strength and the tailing backfill with lower strength.

2) According to the action mechanism and the stress analysis of backfilled body under the dynamic scraper load, the corresponding strength model is worked out using the theory of elastics and plastics, and the strength design method of the cemented backfilled body under trackless equipments load is developed. Referring to the demands of the scraper working or running on the surface filling respectively in different curing dates, the strength of backfill in the cemented layer R_7 is designed.

3) After the roof contact, the fill needs to support the roof. The tailing backfill not only carries the weight of the upper backfill, but also bears the load transferred from the roof and surrounding rock. According to the technological character of high backfill, analyzing the mechanical actions between wall rock and backfill, a mechanical model of layered filling body is established. The strength of the paste backfill in different

layers can be designed.

4) According to the mechanical models and strength calculation formulas, a complicated problem to optimize the cement-tailings ratios for backfill was solved successfully, of which, the excellent effects were applied in optimizing the ratios of cement to tailings in the No.3 stope in LI Guanji iron mine. The new strength design method can be applied in the mines using the horizontal slice stope-filling method. It can provide a guide for optimising the cement-tailings ratios in order to save filling costs under the premise of ensuring safety.

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