QIU JINGPING
YANG LEI
XIN JUN
and
SUN XIAOGANG

Determining method of backfill strength based on damage constitutive model

Backfill strength and ratio determining is one of the key for the stage of open stoping with subsequent filling mining method. Since some problems occur when adopting traditional method to determine filling strength, it is necessary to explore a more scientific approach to study reasonable match between backfill strength and rock mass. ZhongGuan iron mine's backfill were subjected to laboratory mechanics test, and their stress-strain curves were obtained, backfill's damage constitutive models before peak stress were established by using damage mechanics. According to the principle that the peak deformation energy of backfill should be corresponded to releasing energy from excavated rock mass, the optimum backfill strength and ratio of ZhongGuan iron mine were determined, which plays a significant role in fill mining production on site.

1. Introduction

Mines often produce massive waste during stoping and dressing process, which leads to serious destruction to surrounding environment. With the increasing attention of environmental protection, wasteless mining has become the inevitable trend of mineral industry development. Due to the advantages of controlling underground pressure, reducing dilution, enhancing resource recovery, improving minerals quality, and retarding environmental perturbations, tailings backfill method is becoming one of the world most important mining methods [1~3].

What plays a key role in backfill mining methods is determing backfill strength and cement-tailing ratio scientifically. Current designing methods of backfill strength are engineering analogy methods and theoretical calculation methods [4], which usually cause high filling cost and poor strength of backfill easily due to the different mining and filling conditions between each mine. Considering the aforementioned problems, it is necessary to establish damage constitutive model [5~8] of backfill to study the reasonable match between filling body's strength and rock mass to realize efficient and safe mining under the optimal filling cost.

ZhongGuan iron mine was selected as engineering background in this paper, which is in capital construction now. According to the recommendations from designing institute and results of total tailings settlement experiment, the optimal filling slurry concentration of ZhongGuan iron mine was 71%. Based on it, three kinds of backfills specimens with cement-tailings ratios of 0.250:1, 0.167:1, 0.125:1 respectively were made to carry on mechanical test and their unconfined compressive stress-strain curves were obtained. On the basis of test results, different kinds of backfills' damage rule were analyzed, and their relevant damage constitutive model were established by using damage mechanics. Furthermore, the optimal strength and cement-tailing ratio of backfill in ZhongGuan iron mine were ascertained according to the principle that cumulative strain energy in backfill should correspond to releasing energy from excavated rock mass [9].

2. Mechanical properties of different backfills

Massive backfill specimens (mass fraction 71%) were prepared by mixing unclassified tailings with grade 325 portland cement, with cement-tailing ratios of 0.250:1, 0.167:1, 0.125:1, respectively. Backfill samples were cast in plastic cylinders mold with a diameter of 10cm and a height of 5cm. They were then sealed and allowed to cure under standard condition with constant temperature of 20ºC for 28 days. The unconfined compressive test were conducted with rigid testing machine. Fig.1 presents the stress-strain curves of backfill with different cement-tailing ratios.

According to the stress-strain curves we can know, the curve slopes upward in the initial deformation stage due to the pressure consolidation of microcrack and microfissure in backfill. With stress increasing, backfill enters into linear elastic stage, and the curves is approximately straight-line. When curve reaches yield point, its slope drops off to zero gradually, and backfill steps into yield deformation stage. Contrasting the compressive curves of different cement-tailing ratios, the following law can be obtained: peak strain decreases with the increase of cement-tailing ratio. Lower peak strain owns higher stiffness and stronger carrying capacity.

Messrs. Qiu Jingping, Yang Lei, Xin Jun and Sun Xiaogang, College of Resources & Civil Engineering, Northeastern University, Shenyang 110 819, China. Corresponding author: Yang Lei; yanglei_neu@foxmail.com

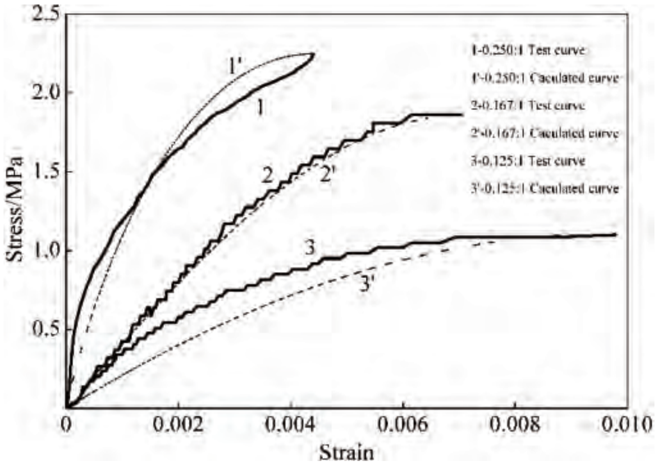

Fig.1 Stress-strain curves of backfill with different cement-tailing ratios

3. Damage constitutive models of different backfills

Backfill is treated as multi-phase composite consisting of mortar, bubble, and water. Its failure process is realized by initiation, extension, influx and perforation of internal microcrack, whose damage mechanism is very complicated. The complex damage failure process can be described easily by damage mechanics theory [10]. Strain-equivalence principle was proposed by the famous French scholar Lemaitre to measure damage indirectly [11]. He assumed that the deformation behaviour of damage material could be described by constitutive relation of non-damage material if effective stress was replaced by nominal stress. Therefore, the constitutive model of backfill can be expressed as:

$$\sigma = E\varepsilon\,(1\text{–}D) \quad \ldots \quad (1)$$

where σ is total stress, E is elastic modulus, D is the damage value, and ε is the strain.

When D = 0, the backfill is in non-damage state, when D = 1, the backfill is damaged totally.

According to the experimental stress-strain curves in Fig. 1, backfill is in elastic and yield state before peak strain ε_p (ε_p is the peak strain value corresponding to peak stress), and the crack initiation and propagation at a small scope can be seen clearly in backfill. The damage value D can be expressed as:

$$D = m\varepsilon^{n} \quad \ldots \quad (2)$$

where m and n are constants.

Combining Eq. (1) with (2), the damage constitutive equation of backfill before peak stress can be rewritten as:

$$\sigma = E\varepsilon\,(1\text{–}m\varepsilon^{n}) \quad \ldots \quad (3)$$

On the basis of stress-strain curves, geometrical boundary conditions can be obtained as:

$$\begin{cases} \sigma\big|_{\varepsilon=\varepsilon_P} = \sigma_P \\ \dfrac{d\sigma}{d\varepsilon}\Big|_{\varepsilon=\varepsilon_p} = 0 \end{cases} \quad \ldots \quad (4)$$

By solving Eq. (4), expression of constants m and n can be drawn as follows:

$$\begin{cases} n = \sigma_P / (E\varepsilon_P - \sigma_P) \\ m = 1/\left(\varepsilon_p^{\,n} + \beta\varepsilon_p^{\,n}\right) \end{cases} \quad \ldots \quad (5)$$

According to the test results and by solving Eq. (5) and (2), the values of m, n and D_p (damage value of peak point) of different backfill can be obtained (Table 1).

Substituting mechanical parameters of backfill and damage parameters into Eq. (2) and (3), we can obtain damage constitutive models of different backfills before peak stress (Table 2). By calculating the damage equations, the stress-strain curves of different backfills can be obtained (dashed lines in Fig.1). It can be found that the calculated curves coincide well with experimental data. And it reflects that the damage constitutive models which put forward in this paper are reliable and reasonable. According to the damage values of peak point we can know, backfills haven't damaged totally when it reaches to peak stress point, and the damage deformation still exists in the following stage of failure.

4. Match between rock mass and backfill

Backfill can support the wall rock and control ground pressure of stopes. Before mining activity happens, ore rock are in equilibrium state due to effect of ground stress. Rock mass releases energy gradually with the excavation carrying on. After filling the goaf, backfill are compressed by surrounding rock owing to its deformation, and backfill produces resistance force and accumulates strain energy to restrict the rock's compression [12]. Therefore, we can analyze the reasonable match between rock mass and backfill from the point of view of energy to guide the designing of cement-tailing ratio.

TABLE 1: MECHANICAL AND DAMAGE PARAMETERS OF BACKFILL WITH DIFFERENT CEMENT-TAILING RATIOS

Cement-tailing ratios	Peak stress	Peak strain	Elastic modulus	Damage parameters		
	σ_p/MP$_a$	ε_p	E/MP$_a$	m	n	D$_p$
0.125:1	2.25	0.004398	1890	5.452359	0.370642	0.7296
0.167:1	1.86	0.007050	889	5.746344	0.424289	0.7021
0.125:1	1.12	0.009780	356	5.940644	0.468023	0.6846

TABLE 2: DAMAGE CONSTITUTIVE MODEL OF BACKFILL WITH DIFFERENT CEMENT-TAILING RATIOS BEFORE PEAK STRESS

Cement-tailing ratios	Damage constitutive equations	Damage evolution equations
0.125:1	$\sigma = 1890\varepsilon - 1.0305\times10^4\varepsilon^{1.370642}$	$D = 5.452359\varepsilon^{0.370642}$
0.167:1	$\sigma = 889\varepsilon - 5.1058\times10^3\varepsilon^{1.424289}$	$D = 5.746344\varepsilon^{0.424289}$
0.125:1	$\sigma = 356\varepsilon - 2.1149\times10^3\varepsilon^{1.468023}$	$D = 5.940644\varepsilon^{0.468023}$

4.1 COMPRESSION DEFORMATION ENERGY ANALYSIS OF BACKFILL

Regarding backfill as elastic medium, its elastic deformation energy can be calculated by effective stress when damaged. Take out an element (*dxdydz*) from backfill as research object, and its strain increases from zero to ε_t respectively when its stress increases from zero to σ_t. So the element's elastic deformation energy (*dw*) can be expressed as:

$$dw = \int_0^{\varepsilon_t} \sigma_t d\varepsilon_t (dxdydz) \quad ... \quad (6)$$

Through Eq. (6), the deformation energy of unit volume of backfill can be obtained as:

$$U = \frac{dw}{dv} = \int_0^{\varepsilon_t} \sigma_t d\varepsilon_t \quad ... \quad (7)$$

Backfills' deformation energy reaches maximum when it arrives at peak stress point, substituting Eq. (3) into Eq. (7), peak deformation energy (U_p) can be obtained as:

$$U_p = \int_0^{\varepsilon_p} \left(E\varepsilon - Em\varepsilon^{n+1}\right) d\varepsilon_t = \frac{E\varepsilon_P^2}{2} - \frac{Em}{\beta+2}\varepsilon_P^{n+2} \quad ... \quad (8)$$

4.2 RELEASED ENERGY OF EXCAVATED ROCK MASS

We assume that the rock stress of rock mass before excavation is σ_0, the elastic modulus of rock mass is E_0. The mechanical model of rock mass can be described as linear elastic model ($\sigma = E_0\varepsilon$) due to its high stiffness. If there is no filling after excavation, released energy of unit rock mass can be expressed as:

$$U_r = \int_{\varepsilon_0}^{0} \sigma d\varepsilon_x = \int_{\varepsilon_0}^{0} E_0\varepsilon d\varepsilon_x = -\frac{1}{2}E_0\varepsilon_0^2 = -\frac{\sigma_0^{\ 2}}{2E_0} \quad ... (9)$$

According to the Eq. (9) we can know that released energy of excavated rock mass is in inverse ratio to its elastic modulus, and in direct ratio to the square of primary rock stress. The higher rock stress and lower elastic modulus rock mass has, the higher released energy after it excavated [13].

4.3 MATCHING ANALYSIS BETWEEN ROCK MASS AND BACKFILL

There exists some proportional relationship between released energy (U_r) of rock mass and peak deformation energy (U_p). We assume that K is the matching coefficient between U_p and U_r, according to Eq. (7) and (8), the matching coefficient can be expressed as:

$$K = \frac{U_p}{U_r} = \frac{EE_0(n+2)\varepsilon_P^2 - 2EE_0 m\varepsilon_P^{n+2}}{(n+2)\sigma_0^2} \quad ... \quad (10)$$

On the basis of the principle that peak deformation energy of backfill should be corresponded to releasing energy from excavated rock mass, the backfills' strength can be reasonable matching with rock mass when K>1, and it will lead to energy instability during the mining process if K<1.

5. Engineering example

ZhongGuan iron deposit is genetically of contact metasomatic skarn type, with a burial depth of more than 300m, with total reserves of 95 million tonnes. The length is nearly 2000m along the strike of the orebody, the width of orebody ranges from 300m to 1000m, and obliquity between 10º and 15º. The deposit gives priority to large size orebody, thin and medium thick orebody account for smaller proportion, therefore, the mining engineers intend to use stage open stoping with subsequent filling mining method to stoping orebody. In order to save filling cost efficiently on the basis of safety production, it is necessary to determine the reasonable strength and cement-tailing ratio of backfill according to the mining conditions of ZhongGuan iron mine.

The result of rock mechanic research suggested that ZhongGuan iron deposit's surrounding rock are mainly focused on marble, and local for skarn, which are moderate in the stability. And the elastic modulus (E_0) of marble is 9.0GPa, the maximum primary rock stress of deposit is 14.77MPa. Substituting the released energy of excavated rock and peak deformation energy of backfill into Eq. (10), we can obtain the matching results between backfills with different cement-tailing ratios and rock mass, as shown in Table 3.

As can be seen from Table 3, the cement-tailing ratios with values of 0.125:1 and 0.167:1 can meet the demand of underground safety in mining in ZhongGuan iron mine, while

TABLE 3: MATCH RESULTS BETWEEN BACKFILLS WITH DIFFERENT CEMENT-TAILING RATIOS AND ROCK MASS

Rock mass		Cement-tailing ratios	Backfills' deformation energy	Matching coefficient K	Match or not
E_0/GP$_a$	σ_0/MP$_a$				
9.0	14.77	1:4	0.053012	4.37	Match
		1:6	0.027902	2.30	Match
		1:8	0.007643	0.63	Not

the ratio of 0.125:1 is infeasible. To guarantee the energy instability will not happen and reduce filling cost efficiently, the deposit can choose the cement-tailing ratio of 0.167:1 as the optimal filling ratio, with a strength of 1.86MPa.

6. Conclusions

1. It is reasonable that use of the damage mechanics theory to study backfills' mechanical behaviours which are treated as multi-phase composite. And the damage constitutive models which are established on the basis of damage mechanics can reflect the damage process of backfills with different cement-tailing ratios commendably.
2. Backfill has not damaged totally when it reaches peak stress point, and the damage deformation still exists in the failure stage. The lower cement-tailing ratio is, the lower peak damage value it owns.
3. The optimal cement-tailing ratio and strength of backfill which can meet the demand of ZhongGuan iron mine have been calculated based on the principle of energy matching between rock mass and backfill, whose values are 0.167:1 and 1.86MPa. The stopes can maintain stable during the mining process under that strength, which matches well with rock mass.

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References

1. Jones, H. and Boger, D. V. (2012): "Sustainability and waste management in the resource industries [J]." *Ind. Eng. Chem. Res.*, 2012, 51 (30): 10057-10065.
2. Kermani, M., Hassani, F. P. and Aflaki, E. et al. (2015): "Evaluation of the effect of sodium silicate addition to mine backfill, Gelfill - Part 1 [J]." *Journal of Rock Mechanics and Geotechnical Engineering*, 2015, 7(3): 266-272.
3. Li, Li. (2013): "A new concept of backfill design-Application of wick drains in backfilled stopes." *International Journal of Mining Science and Technology*, 2013, 23(5): 763-770.
4. Cai, Si-jing, Huang, Gang and Wu, Di, et al. (2015): "Experimental and Modeling Study on the Rheological Properties of Tailings Backfill [J]." *Journal of Northeastern University:Natural Science*, 2015, 36(6): 882-886.
5. Belem, Tikov and Benzaazoua, Mostafa (2008): "Design and Application of Underground Mine Paste Backfill Technology [J]." *Geotechnical and Geological Engineering*, 2008, 26(2): 147-174.
6. Zhang, Fa-wen, Liu, Wen-xia and Shen, Lian-feng (2012): Damage constitutive model for cemented paste backfill after mixing waste rock [C]//2012 World Automation Congress (WAC). Puerto Vallarta: IEEE, 2012: 1-4.
7. Yu, Gen-bo, Yang, Peng and Chen, Yin-zhou (2013): "Study on Damage Constitutive Model of Cemented Tailings Backfill under Uniaxial Compression [J]." *Applied Mechanics and Materials*, 2013, 353-356: 379-383.
8. Zhang, Qian-gui, Yin, Guang-zhi and Fan, Xiang-yu, et al. (2012): "A damage constitutive model of tailings based on the analysis of elastic-plastic and sliding of skeleton grains [J]." *Disaster Advances*, 2012, 5(4): 730-735.
9. Liu, Zhi-xiang, Li, Xi-bing and Dai, Ta-gen, et al. (2006): "On damage model of cemented tailings backfill and its match with rock mass [J]." *Rock and Soil Mechanics*, 2006, 27(9):1442-1446.
10. Xue, Zhi-cheng, Yang, Lu and Yang, Zeng-jie (2010): A damage model with subsection curve of concrete and its numerical verification based on ABAQUS[C]// 2010 International Conference on Computer Design and Applications (ICCDA), Qinhuangdao: IEEE, 2010, 5:34-37.
11. Lemaitre, J. (1984): "How to use damage mechanics [J]." *Nuclear Eang. & Design*, 1984, 80(1):233-245.
12. Liu, Zhi-xiang, Lan, Ming and Xiao, Shi-You, et al. (2015): "Damage failure of cemented backfill and its reasonable match with rock mass [J]." *Transactions of Nonferrous Metals Society of China*, 2015, 25(3): 954-959.
13. Liu, Yu-long, Ding, De-xing and Li, Guang-yue, et al. (2013): "Match between the solidification of the cemented backfill and the vertical stress in the excavated ore body [J]." *Journal of Mining and Safety Engineering*, 2013, 30(4):526-530.