A Study to Determine the Minimum Theoretical Thickness of Permanent Sealing Wall for Goaf using FLAC 3D Software

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***Abstract* — The permanent sealing wall is an effective barrier to prevent coal spontaneous combustion for gob. In this paper we study: i) the physical mechanism of sealing wall is analyzed according to the actual situation in underground mines, ii) the mechanical model of sealing wall is established, and iii) the appropriate boundary conditions and the constitutive model are determined. Aiming at the permanent sealing wall constructed in return airway for 8617 fully mechanized caving face in YUNGANG Coal Mine, FLAC 3D software was adopted to build several three-dimensional numerical models of sealing wall, regard fly ash curing materials as the filling object, the corresponding numerical simulation conditions were determined in accordance with the actual situation and the theoretical formula of wall thickness, and then the stress and deformation of sealing wall under different conditions were simulated. Obtained the distribution of stress field, displacement field and plastic zone of sealing wall under different conditions. Some conclusions are: the theoretical minimum wall thickness for return airway in 8617 fully mechanized caving face was 5.6m, which was corresponding to the theoretical formulas and mechanical models.**

Keywords - Coal spontaneous combustion; permanent sealing wall; minimum theoretical thickness; numerical simulation; Mine pressure; Fly ash

I. INTRODUCTION

With the development of mining technology, on the one hand, numerous economic benefits has been brought. On the other hand, the increasing number of liaison lane underground and the heavy workload of airtight filling influence the normal production of mine [1]. However, the construction of traditional sealing wall is a nuisance and a waste of time, walls were fractured easily and produced air leakages, leading to coal spontaneous combustion. Scholars at home and abroad have studied various kinds of new airtight filling materials, especially fly ash curing materials in recent years. Unfortunately, the airtight effect of sealing wall still influenced by many factors, such as: material strength, mine pressure, sealing structure, thickness, and construction conditions. For the internal characteristic of sealing wall, airtight effect is directly determined by material strength and thickness of sealing walls.

But the reasonable thickness of sealing wall is seldom studied until now, there is no theoretical basis for the actual operation, in most cases, which was simply determined by empirical values. Huang Jianjun, Jordan Pan [2] analyzed the mechanical properties of slurry and special features of sealing wall, believed that the mechanical properties and failure mechanism of sealing walls are the keys to the design for sealing wall in coal mine. Accordingly, the mechanical model of sealing wall was deduced, and then proposed the theory of a single-phase liquid and loose medium body as a carrier, established the limit equilibrium conditions on Rankine theory, obtained the change of slurry composition and physical state of the property against time phase, optimized the mechanical calculation and structure for sealing wall, thus providing a more economical and reasonable theory for design of sealing wall. LU Hai-chao and He Tao [3] established the numerical model of sealing wall in mechanized caving face by ANSYS. Then they studied the laws of stress-strain under different conditions, gained the reasonable parameters of sealing wall. Zhang Jie and Li Yu [4] established the calculating model of permanent sealing structure for gob, further calculation for strength of sealing wall, and then determined the structural parameters and mechanical parameters of sealing wall.

In this paper, the mechanical mechanism of sealing wall was analyzed, the mechanical model of sealing wall was established based on relevant assumptions and stress analysis. According to the permanent sealing wall constructed in return airway for 8617 fully mechanized caving face in YUNGANG Coal Mine, FLAC 3D software was adopted to simulate the stress and deformation of sealing wall under different conditions, the distribution of stress field, displacement field and plastic zone of sealing wall under different conditions were calculated. By analyzing the numerical simulation results, the minimum reasonable thickness of sealing wall was determined.

II. MECHANICAL MODEL & CONDITIONS

A. *Mechanical model*

Due to the complexity and variability of site conditions, sealing wall was affected by various factors, such as the material, thickness, location, construction conditions, the mining impact and other factors[5]. Although the numerical methods and results are of great practicality, the process in simulation has some limitations. In general, the permanent sealing wall is constructed near the stopping line, whose position is rather determined.

Therefore, the part of direct reinforced in sealing structure can be put as straight-uniform parallel piped in the process of establishing model, the mechanical model was shown in Fig. 1.

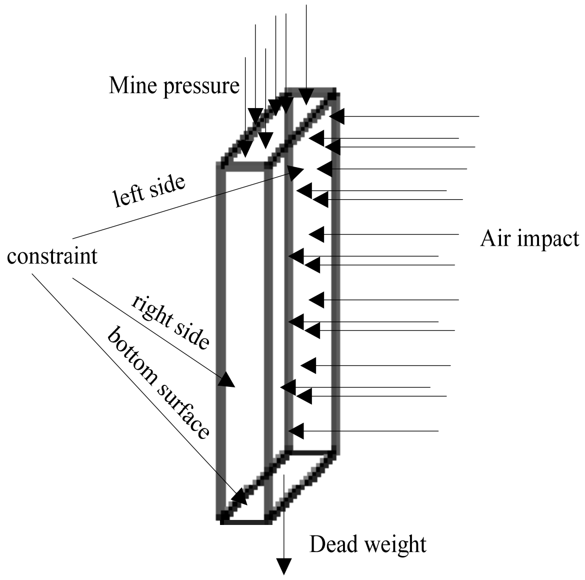


Figure 1. Mechanical model of sealing wall

In Fig. 1, every symbol is expressed as follows:

L --- the width of section of sealing, m ,
H --- the height of section Lane, m ,
D --- the thickness of the sealed structure, m ,
F --- the air pressure shock when suffered roof caving, pa ,
P --- mine pressure, pa ,
G --- the dead weight, pa .

B. *Constitutive Model*

In accordance with practical application, concrete curing materials was applied to filled sealing wall, and Moore-Coulomb constitutive model[6] is corresponding to the cement loose particles just as fly ash and other materials, whose guidelines governing equation is showed as follows:

$$f_s = \sigma_1 - \sigma_3 \frac{1+\sin\varphi}{1-\sin\varphi} - 2c\sqrt{\frac{1+\sin\varphi}{1-\sin\varphi}} \tag{1}$$

where,

σ_1 --- the maximum and minimum principal stress,
σ_3 --- the minimum principal stress,
c --- the adhesion,
φ --- the friction angle.
If fs> 0, the material will produce shear failure.

III. NUMERICAL MODEL & PARAMETERS

A. *Engineering Background*

The spontaneous combustion rank of coal in Shanxi Datong Yungang Mine 8617 Face is the first order. It is easily lead to the accumulation of energy and a large area of the roof dangling in the vicinity of stopping line and the presence of an irregular pillar. Once a pillar deformation instability, roof collapse suddenly, which will lead to a sudden ejection goaf areas even the accident. Super adding a large number of coal that oxidation a long time left near the stop mining line, which is likely to cause an explosion and spontaneous combustion of coal Gobs accident. According to project requirements, sealing wall will be built with fly ash curing materials at a distance of 5m away from the stopping line curable material in the return airflow airway. The basic parameters of return airflow airway and sealing wall are showed in table 1 and table 2

TABLE 1. BASIC PARAMETERS OF AIRWAY8617 IN THE YUNGANG COAL MINE

Hardness coefficient（N(kgf/mm^2)）	Rock density（kgf/m^3）	airway width（m）	airway height（m）
6	2.5	3.2	2.6

TABLE. 2 BASIC PARAMETERS OF SEALING WALL

Cutting depth/m	The width of sealing wall/m	The height of sealing wall/m	Bulk density/Kg·m^{-3}
0.5	4.2	3.6	13.75

B. Simulation working conditions

Reference[7] deduced minimum theoretical thickness formula of permanent sealing wall as follows:

$$\begin{cases} H_1 = \dfrac{0.15qL_0}{2Pb} \\ H_2 = \dfrac{3qL_0^2}{6f} \\ H = \max\{H_1,\ H_2\} \end{cases} \tag{2}$$

where,

P --- the average compressive strength of sealing wall, pa ,

b --- width of sealing wall, m ,

H_1 --- thickness of sealing wall1, m ,

H_2 --- thickness of sealing wall2, m ,

L_0 --- height of sealing wall, m .

By substitution of relevant parameters into the formula (2) the minimum theoretical thickness of sealing wall is 5.1m. In order to verify the reasonable thickness of sealing wall, different working conditions should be simulated and analyzed, the certain conditions were shown in table 3:

TABLE.3 DIFFERENT SIMULATION CONDITIONS OF SEALING WALL

The width of sealing wall/m	The height of sealing wall/m	codition2	codition3	codition4
3.2	2.6	5.1	5.6	6.1

C. Mechanical parameters, numerical models & boundary conditions

1) Mechanical parameters of fly ash curing materials

Samples that collected inside the wall conducted series of triaxial-uniaxial tests, the corresponding mechanical parameters was shown in table 4.

TABLE. 4 MECHANICAL PARAMETERS OF THE OPTIMAL RATIO

elastic modulus/Gpa	bulk modulus/Gpa	poisson ratio	cohesion/MPa	internal friction angle/°	shear strength/MPa
0.45	2.14	0.488	3.3	20.7	0.75

2) Numerical model

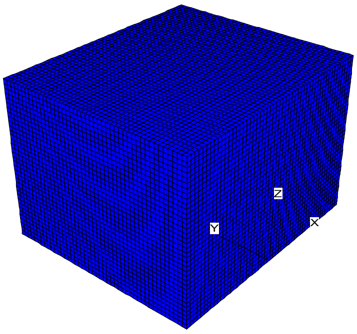


Figure 2. Numerical model of sealing wall

According to basic parameters in table 2, setting the condition1 as an example, the three-dimensional model was established with FLAC 3D, whose three-dimensional numerical model grid shown in Fig. 2.

3) Boundary conditions and constraint conditions

According to the mechanical analysis, the sealing wall is mainly affected by deadweight, mine pressure and air impact. Each of them under different conditions should be calculated.

①Deadweight: When the sealing wall and airway fully touch with each other, the system comes up to equilibrium, sealing wall restraint by deadweight in an instant when the roof collapse.

Deadweight of different working conditions are shown in table 5.

TABLE. 5 DEADWEIGHT OF SEALING WALL UNDER DIFFERENT SIMULATION CONDITIONS

	codition1	codition2	codition3	codition4
dead weight/ KN/m^3	956.82	1060.84	1164.53	1268.72

②Mine pressure

mine pressure under different working conditions are shown in table 6[8].

TABLE 6 MINE PRESSURE UNDER DIFFERENT WORKING CONDITIONS

	codition1	codition2	codition3	codition4
mine pressure/ KN	345.46	383.01	420.56	458.11

③Sealing wall in the access adited reinforced by air

The relation graph between the concentrated load of sealing wall and the height of roof caving by difference solution, shown in Fig. 3[9].

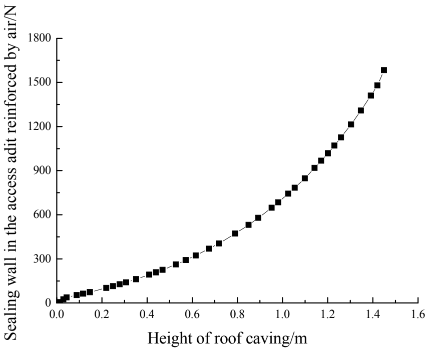


Figure 3. Relationship between the concentrated load of sealing wall and the height of roof caving

As can be seen from Fig. 4,if the roof collapse all at once, we can get the maximum load sealing wall suffered from air is 1583.72 KN.

4) Numerical model of sealing wall Constraint conditions

Making some assumptions as follows: the direction of the airway width is X axis, the direction of airway trend is Y axis, the direction of airway height is Z axis. According to the mechanical mechanism of sealing wall and practical conditions, some constraints should be made for the sealing wall:

Two boundaries of X direction, restrict displacement in the direction of X and Y,

Two boundaries of Z direction, restrict displacement in the direction of X and Y,

Lower boundaries of Z direction, restrict displacement in the direction of Y and Z

IV. ANALYSIS OF SIMULATION RESULTS

In order to verify the correctness of mechanical model and security of structural design established above, FLAC 3D was used to simulate the distribution of stress field, displacement field and plastic zones of sealing wall under different conditions.

A. *Stress Field*

The numerical model is on the symmetry of X=0 plane, Fish language was used to extract the positive and negative maximum shear stress in Z-Y cross section and the maximum shear stress under different conditions, shown in Fig. 4 and Fig. 5, respectively.

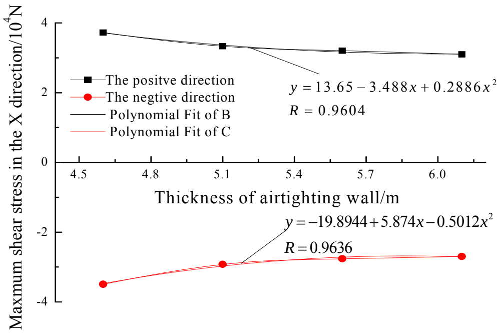


Figure 4. Maximum and minimum shear stress of sealing wall in the X direction

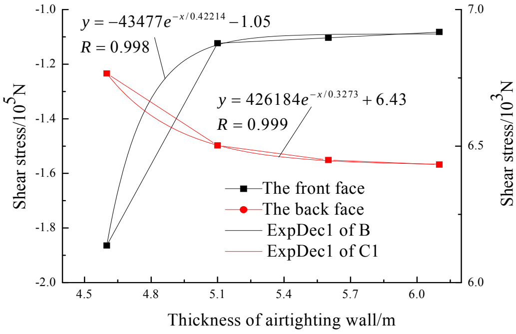


Figure 5. Maximum and minimum shear stress in the front and backface of sealing wall

According to the simulation and fitting results of sealing wall under different conditions, the relationship between the positive and negative maximum shear stress F in Z-Y cross section and the thickness of sealing wall H can be described as follows:

$$\begin{cases} F_{Xpositive} = 0.288H^2 - 3.488H + 13.65 \\ F_{Xnegative} = -0.501H^2 - 5.874H - 19.89 \end{cases} \tag{3}$$

As can be seen from Fig. 5, the relationship between the positive and negative maximum shear stress F in Z-Y cross section and the thickness of sealing wall H follows the law of Quadratic. When thickness of sealing wall is 4.6m, the positive maximum reaches at 3.72×10^4 N, the negative maximum reaches at 3.49×10^4 N. With the increase of the thickness of sealing wall, the positive and negative maximum shear stress F in Z-Y cross section decreases continuously. When the thickness exceeding 5.6 m, change of shear stress is small. Due to the increase in thickness, the compressive and shear properties are enhanced if the load is a determined value.

According to the simulation and fitting results of sealing wall under different conditions, the relationship between the maximum shear stress F in fore-rear and the thickness of sealing wall H can be described as follows:

$$\begin{cases} F_{frontface} = -43477e^{-H/0.42214} - 1.05 \\ F_{backface} = -426184e^{-H/0.3273} + 6.43 \end{cases} \tag{4}$$

As can be seen from Fig. 6, the maximum shear stress F in fore-rear and the thickness of sealing wall H follows the law of negative exponential function, When thickness of sealing wall is 4.6 m, the front face maximum reaches at 1.864×10^5 N,the back face maximum reaches at 6.76×10^3 N, With the increase of the thickness of sealing wall, the maximum shear stress of the wall reduced continuously. When the thickness exceeding 5.6 m, change of shear stress is decreasing. Due to the increase in thickness, the compressive and shear properties are enhanced if the load is a determined value, thus the value of concentration stress and the stress concentration range are decreasing. Therefore, if the material strength is determined, the reasonable thickness of the wall could be deduced.

B. *Displacement field*

Numerical simulation model on symmetry of X axis, fish language was adopted to extract the maximum displacement of fore-rear and the maximum displacement of X=0 plane under different conditions, are shown in Fig. 6 and Fig. 7, respectively.

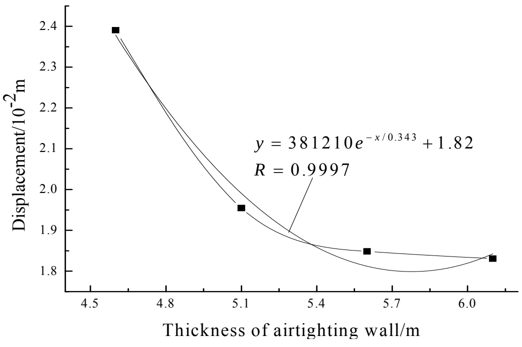


Figure 6. Maximum displacement at the point of X=0

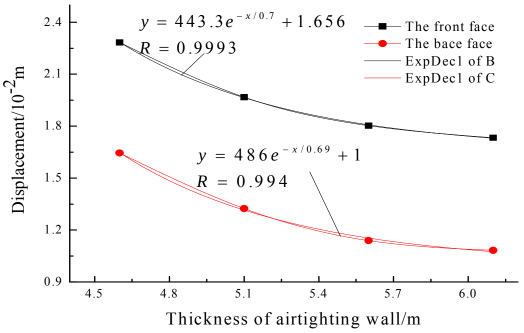


Figure 7. Maximum and minimum displacement in front and back of sealing wall

According to the simulation and fitting results of sealing wall under different conditions, the relationship between the maximum displacement D of fore-rear and the thickness of sealing wall H can be described as follows:

$$\begin{cases} D_{fore} = 2505e^{-H/0.54} + 1.736 \\ D_{rear} = 1250.2e^{-H/0.6} + 1.052 \end{cases} \quad (5)$$

As can be seen from Fig. 6, the maximum displacement D in fore-rear and the thickness of sealing wall H follows the law of negative exponential function, when the hen thickness of sealing wall is 4.6m,the front face maximum reaches at 2.28cm, the back face maximum reaches at 1.64cm. With the increase of the thickness of sealing wall, the maximum displacement of the wall reduced continuously. When the thickness exceeding 5.6m, change of shear stress is decreasing.

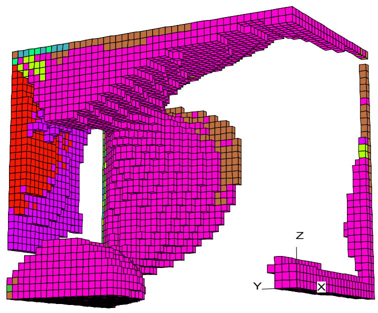
According to the simulation and fitting results of sealing wall under different conditions, the relationship between the maximum displacement D' of X=0 plane and the thickness of sealing wall H can be described as follows:

$$D' = 381210e^{-H/0.343} + 1.82 \quad (6)$$

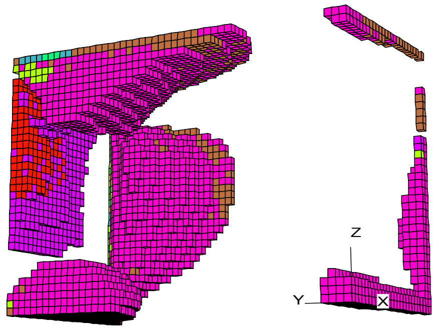
As can be seen from Fig. 7, the relationship between the maximum displacement D' of X=0 plane and the thickness of sealing wall H follows the law of negative exponential function, When thickness of sealing wall is 4.6 m, the maximum of this face reaches at 0.24m,With the increase of thickness of sealing wall, the maximum displacement of the wall reduced continuously. When the thickness exceeding 5.6m, displacement variation tends to zero, the displacement tends to be stable, Because of the compactness of fly ash curing materials, particles bonding with each other, between which some microfissure still exit. Impacted by the air instantaneously, microfissure inside wall will close, thus enhance its pressure-bearing capacity. Therefore, with the increase of wall thickness, the displacement decreased gradually and tends to be stable thereafter.

C. *Distribution of plastic zones*

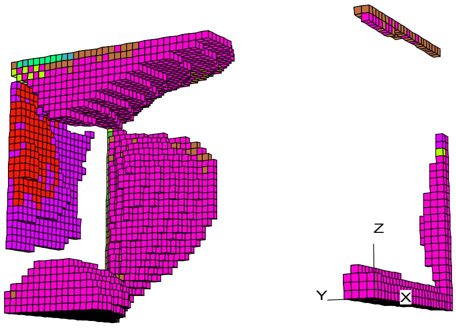
Numerical simulation model on symmetry of X axis, take half were analyzed, the distribution of plastic zone was shown in Fig. 8.



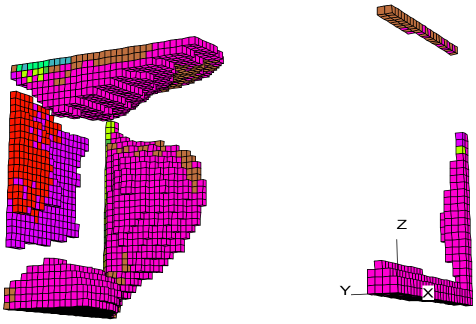
(a) the wall thickness: 4.6m



(b) the wall thickness: 5.1m



(c) the wall thickness: 5.6m



(d) the wall thickness: 6.1m

Figure 8. Plastic Zone distribution of different working conditions

As can be seen from Fig. 9, the plastic zone mainly concentrated in the back the top and bottom corner of wall, failure patterns of different conditions are similar, which are tension-shear, shear and tension, respectively. When the wall thickness was 4.6m, damage at top of airtight wall is very serious, the damage area penetrate the top of wall, leakage channel occur in the wall, thus leading to coal spontaneous combustion. When the thickness exceeding 5.1 m. As can be obviously seen, the rear end of the failure zone decreases gradually, the front damage area almost diminished, it's hard to form a leakage channel ,with the increase of the wall thickness, the damage area is much smaller, However, with the increase wall the thickness will increase in labor and costs. The failure volume and failure percentages of tension, shear and tension-shear was extracted with fish function, shown in Fig. 9 and Fig. 10, respectively:

According to the simulation and fitting results of sealing wall under different conditions, the relationship between the failure volume V , V' and failure percentages of tension, shear and tension-shear and the thickness of sealing wall H can be described as follows:

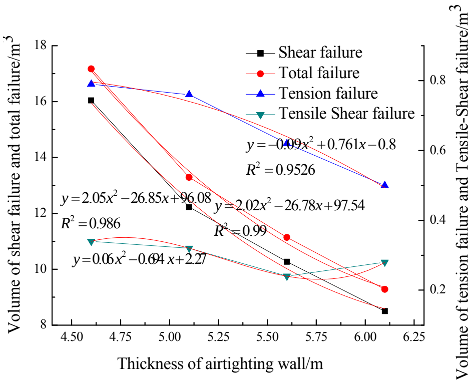


Figure 9. The volume of failure in total and different types

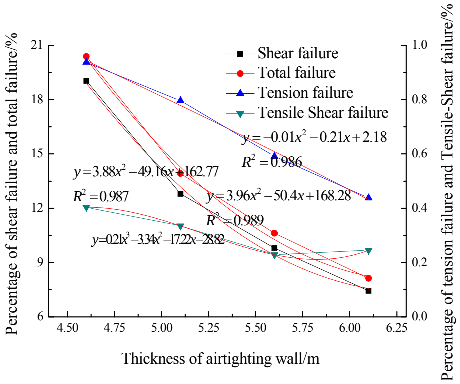


Figure 10. The percentage of failure in total and different types

$$\begin{cases} V_{shear} = 2.05H^2 - 26.85H + 96.08 \\ V_{tension} = -0.09H^2 + 0.671H - 0.8 \\ V_{tension-shear} = 0.24H^3 - 3.972H^2 + 19.79 - 33.82 \\ V_{total} = 2.02H^2 - 26.78H + 96.54 \end{cases} \tag{7}$$

$$\begin{cases} V'_{shear} = 3.88H^2 - 49.16H + 162.77 \\ V'_{tension} = -0.01H^2 - 0.21H + 2.18 \\ V'_{tension-shear} = 0.21H^3 - 3.34H^2 - 17.22 - 28.82 \\ V'_{total} = 3.96H^2 - 50.4H + 168.28 \end{cases} \tag{8}$$

As can be seen from Fig. 10 and Fig. 11, the failure volume V ,V' and failure percentages of tension, shear and tension-shear and the thickness of sealing wall H follows the law of nonlinear, if air impact load is a certain value, with the increase of wall thickness, the shear failure, tensile failure and total destruction volume gradually decreases, the proportion of the 4 failure modes follows the similar trend. But the tension and shear failure played a major role, which shows that roof collapse behind air impact is the direct cause of the destruction of sealing wall, deadweight and underground pressure cause indirect damage. The fitting degree was bigger than 0.95, the fitting degree was satisfied, The failure volume V , V' and failure percentages of tension, shear and tension-shear and the thickness of sealing wall H follows the law of nonlinear. The volume and percentage of shear failure, total destruction, tension failure decrease with the increase of wall thickness. As the wall thickness increases, its bearing capacity increases, the volume and percentage of shear failure reduce at first and increase thereafter. When the wall thickness was 5.6m, the shear damage come up to the minimum, but has little effect on the overall damage. We can come to the conclusion that: with the increase of wall thickness, the impact resistance of the bearing is enhanced and the damage volume decreases. Therefore, once the ratio of the material is optimal, increasing the thickness of the wall can improve the performance of its resistance to failure.

In summary, if the ratio of fly ash according to construction requirements in underground coal mine is optimal, reasonable thickness of sealing wall exists. If the thickness is too small, sealing wall will suffer from severe damage impacted by air, sealing effect is difficult to guarantee. Therefore, an appropriate increase in thickness will reduce the total volume of destruction. Increase the wall thickness excessively, damage range did not significantly reduced, on the contrary, will increase labor and cost greatly. Therefore, according to the Datong Yungang Mine 8617 working face tailentry, the minimum theoretical thickness of the sealing wall is 5.6m.

V. CONCLUSIONS

(1) As to the permanent sealing wall for the gob, the mechanical mechanism of sealing wall is mainly determined by two key points: first, the structure form of surrounding rock composed with sealing wall, second, the ratio of mechanics and deformation characteristics of sealing wall in contrast with surrounding rock. The instability, deformation and failure of wall is mainly influenced by dead weight, mine pressure and air impact.

(2) The boundary conditions and constraints under different working conditions are established according to the mechanical model, and the actual values of the mine pressure, impact load and weight are obtained. Moreover, different working conditions were determined by the theoretical formula and corresponding parameters.

(3) FLAC 3D was used to simulate the stress, deformation and failure of sealing wall under different working conditions. Results show that: with the increase of the wall thickness, the stress, displacement decreases gradually and tends to be stable thereafter. The relationship between the positive and negative maximum shear stress in Z-Y cross section and the thickness of sealing wall follows the law of Quadratic, the maximum shear stress F in fore-rear and the thickness of sealing wall abides by the law of negative exponential function, the maximum displacement in fore-rear and the thickness of sealing wall complies to the law of negative exponential function, the relationship between the maximum displacement of X=0 plane and the thickness of sealing wall follows the law of negative exponential function. The plastic zone mainly concentrated in the back the top and bottom corner of wall, failure patterns under different conditions are similar, the patterns are tension-shear, shear and tension, respectively, Combined with the 8617 working surface of the coal mine parameters and mechanical parameters, the minimum reasonable thickness of sealing wall is 5.6m, numerical results was corresponding to the theoretical calculation, but the results are to be verified in the application.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

ACKNOWLEDGMENTS

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REFERENCES

[1] Zhihai Li, Zhanyuan Wang. Prevention for Mine Fire. Beijing: Coal industry Press, 2007.pp. 123-135.

[2] Jianjun Huang, pandeng Qiao. Calculation and Optimizing Analysis of the Force of Filling Airtight-wall for Underground Mined-out Area. METAL MINE, vol10, pp 32-36, sep, 2014.

[3] Hai-chao Lu, Tao He. Definition of Reasonable parameters of Airtight Wall in Crossheading of Fully Mechanized Caving Face. Coal Technology, vol 7, pp 118～120, June, 2014.

[4] Jie Zhang, Yu Li. On sealing wall to prevent air bursting disaster in gob areas. China Coal.Vol 35, pp 94～96, Jan 2010.

[5] Li Ruihuan. Application of low concentration of fly ash cement filling technology in Quanxing coal mine. Shandong university of science and technology,pp 46-48, 2013.

[6] Linwei Dong. Study on Geotechnical Constitutive Models and parameters Commonly Used in Numerical Simulation. Qingdao Technological University, pp 95-97, 2011.

[7] Haitao Li. Numerical Simulation Study on Characteristic parameters of Airtight Filling with Solidification of Fly Ash. Xian university of science and technology, 2015.

[8] Botao Qin, Lu Yi. Experimental research on inorganic solidified foam for sealing air leakage in coal mines. International Journal of Mining Science and Technology, Vol 23, pp 151～155, Jan, 2011.

[9] GU Tie-feng. Analysis of hurricane impact disaster in mining faces. Journal of Liao-Ning Technical University, Vol 19, pp 11～14, Feb, 2007.

[10] Zhaolong Ge, Xudong Mei, Yiyu Lu & Jiren Tang. Optimization and application of sealing material and sealing length for hydraulic fracturing borehole in underground coal mines.Arab J Geosci. Vol 17, pp, 1604～1621, 2014.

[11] Wei Jia, Huoxing Liu. Numerical investigation of the effect of rim seal on turbine aerodynamic design parameters and end wall flows in low aspect ratio turbine. Computers & Fluids. Vol21, pp 1114～1125, May, 2013.

[12] Dening Wei. New type of coal mine permanent airtight research and stability analysis. China Coal. Vol28, pp, 10～12, Jan, 2009.