STUDY ON PIPE-LINE FLOW CHARACTERISTICS OF MULTI-SOURCE COAL-BASED SOLID WASTE FILLING MATERIALS

by

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Aiming at the problem of long-distance transportation in the downhole filling process of multi-source coal-based solid waste cemented materials, the flow performance and pipe-line transportation performance of multi-source coal-based solid waste filling mixture were studied by physical experiments and numerical simulation. The main control parameters of the flow characteristics in the tube of the cemented material were determined, and the variation law of resistance along the course during the flow process in the tube was obtained.

Key words: *coal-based solid waste, pipe-line flow characteristics, backfill mining*

Introduction

The theory of the tempered xi (TX) function represents one of the newest developments in mathematics [1, 2]. It has a deep connection with the number theory, complex analysis, Fourier analysis, and partial differential equations in mathematical physics [3, 4]. It has become one of important branches of analytic number theory.

The integrated development of large-scale coal power bases (coal mines, coal chemical industry, coal power) in central and western China has led to the enrichment of solid waste such as gangue, fly ash, gasification slag, and desulfurized gypsum in surrounding areas. The storage of multi-source coal-based solid waste occupies a large amount of land, causing serious pollution of soil and atmosphere. On the other hand, underground mining of coal mines has led to surface collapse, which seriously threatens the fragile ecological environment in the western region. As an innovative green mining technology, multi-source coal-based solid waste cementation for underground filling in coal mines is of great significance for absorbing coal-based solid waste, protecting the surface ecological environment and alleviating the appearance of mine pressure at the underground working face, and controlling surface settlement. However, unlike the traditional belt conveying method of solid filling, the solid waste cemented material is filled downhole, which requires long-distance pipe-line transportation of multi-source coal-based solid waste cemented material. The precipitation, segregation and solidification of materials in the pipe-line transportation process have an important impact on the transportation

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efficiency and economy [1-3]. It is urgent to carry out research on the pipe flow characteristics of multi-source coal-based solid waste filling materials.

Many scholars at home and abroad have studied the problem of pipe-line transportation of materials and obtained many beneficial results: Wu [4] found that the two factors of glue sand ratio and concentration have a very significant impact on the strength and fluidity of new material fillers and cement fillers. Yang *et al.* [5] studied the particle adhesion effect and pressure water secretion effect of paste, and explained the boundary-layer effect of paste's steady-state tube transport. The thixotropy and transient boundary-layer effect of the paste were analyzed. Yu *et al.* [6] studied the self-flowing transportation of tailings cemented filling slurry pipe-line based on FLUENT software, and calculated the filling slurry transported by gravity on the basis of the filling material characteristic test, so as to realize the self-flowing transportation of this material.

This paper mainly studies the pipe-line flow characteristics of multi-source coal-based solid waste cementing materials such as gangue, fly ash, gasification slag and desulfurization gypsum, and provides theoretical and technical support for long-distance transportation and downhole filling of multi-source coal-based solid waste.

Test of characteristic parameters of pipe-line flow of coal-based solid waste filling materials

Raw material characteristics

The coal gangue, fly ash, desulfurization gypsum, gasification slag and furnace bottom slag used in the experiment came from Ningdong Energy and Chemical Industry Base in Ningxia. Tianrui elemental logging analyzer EDX5500H was used to analyze the chemical elements of solid waste raw materials, and the analysis results are shown in tab. 1.

Table 1. The XRF analysis results of solid waste raw materials [%]

Sample	SiO_2	Al_2O_3	CaO	S	Fe_2O_3	K_2O	MgO	Na_2O
Coal gangue	28.89	16.19	0.24	2.29	4.86	3.52	0.93	0.71
Fly ash	24.44	16.49	2.56	0.54	2.39	4.58	1.04	0.67
Desulfurization gypsum	1.10	0.20	19.07	30.03	0.00	0.27	1.32	1.41
Vaporized slag	13.89	10.58	4.53	0.32	2.79	4.47	1.54	1.68
Furnace bottom slag	13.33	9.33	6.57	0.60	11.69	4.41	1.23	1.28

Experimental scheme of fluidity of coal-based solid waste filling materials

The orthogonal experimental design was designed for six factors: fly ash, desulfurization gypsum, gasification slag, bottom slag content, gangue particle size, and mixture mass concentration. Each factor was set to five levels. Among them, the fly ash content was 20%, 30%, 40%, 50%, and 60% of the mass of gangue, respectively. The content of desulfurization gypsum, gasification slag and furnace bottom slag was 0%, 10%, 20%, 30%, and 40% of the mass of gangue, respectively. The mass concentrations were 72%, 74%, 76%, 78%, and 80%, respectively. The particle sizes of gangue are 1 mm, 3 mm, 5 mm, 8 mm and 10 mm, respectively. The cement content is fixed at 20% of the mass of gangue.

Orthogonal experimental design and results

The experimental design and results are shown in tabs. 2 and 3:

Table 2. Range analysis of slump

Levels	Fly ash	Desulfurization gypsum	Gasification slag	Furnace bottom slag	Particle size	Concentration
1	202.8 mm	196.6 mm	271.4 mm	175.2 mm	115.0 mm	268.8 mm
2	194.8 mm	180.0 mm	264.4 mm	203.8 mm	222.0 mm	218.8 mm
3	214.0 mm	230.0 mm	203.4 mm	214.4 mm	212.6 mm	221.6 mm
4	205.2 mm	170.2 mm	156.6 mm	232.8 mm	243.2 mm	181.2 mm
5	198.0 mm	238.0 mm	119.0 mm	188.6 mm	222.0 mm	124.4 mm
R	19.2	67.8	152.4	57.6	128.2	144.4
Ranking	6	4	1	5	3	2

Table 3. Range analysis of water secretion rate

Levels	Fly ash	Desulfurization gypsum	Gasification slag	Furnace bottom slag	Particle size	Concentration
1	1.9320%	2.2400%	2.6140%	1.2040%	0.6680%	1.8360%
2	1.1680%	1.2360%	1.5120%	2.3440%	1.0020%	2.1280%
3	1.2140%	1.0980%	1.0160%	1.6220%	1.7380%	2.1680%
4	2.3560%	2.0240%	1.8540%	1.0360%	1.4840%	1.1140%
5	1.1940%	1.2660%	0.8680%	1.6580%	2.9720%	0.6180%
R	1.1880	1.1420	1.7460	1.3080	2.3040	1.5500
Ranking	5	6	2	4	1	3

The slump and water secretion rate were analyzed as the orthogonal test indicators, and the range R could be obtained from tabs. 2 and 3, and the primary and secondary relationships of six different influencing factors on the pipe-line flow characteristics of multi-source coal-based solid waste filling materials were obtained by comparing the range values:

- Gasification slag > particle size > desulfurization gypsum > furnace bottom slag > fly ash, gasification slag content has the greatest effect on slump, the concentration is second, fly ash content has the least effect;
- Particle size > gasification slag > concentration > furnace bottom slag > fly ash > desulfurization gypsum, gangue particle size has the greatest effect on water secretion rate, gasification slag content is second, desulfurization gypsum content is the least affected.

Numerical model of pipe-line flow characteristics of coal-based solid waste filling materials

The ANSYS FLUENT (3-D) software was used to establish a horizontal straight pipe conveying model with a length of 100 m and a diameter of 100 mm, and the influence of three factors: concentration, flow rate and inner diameter of coal-based solid waste filling materials on the flow characteristics of the pipe-line.

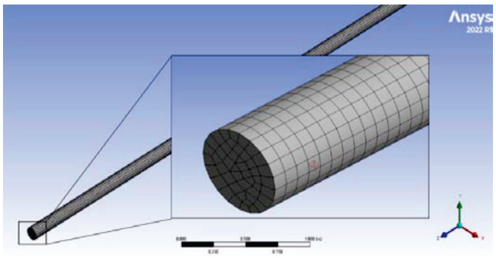

Figure 1. Model building and meshing

Simulation scheme

The model is a horizontal straight pipe with a length of 100 m and a pipe diameter of 100 mm. The concentration is set to 0.72, 0.74, 0.76, and 0.78 levels, the flow rate is set to 1.4 m/s, 1.6 m/s, 1.8 m/s, and 2.0 m/s are set to four levels, and the inner diameter of the pipe-line is set to 100 mm, 150 mm, 200 mm and 250 mm, respectively. The model meshing is shown in fig. 1.

Basic assumptions

According to the flow characteristics of the filling material, the following assumptions are made:

– the flow of the material is continuous and gapless,
– the material is isotropic,
– the material is incompressible,
– the material satisfies the stable flow assumption, and
– heat exchange is not considered.

The inlet is set with a velocity boundary, the flow rate is 1.4 m/s, 1.6 m/s, 1.8 m/s, 2.0 m/s, the outlet is set with a free boundary, the pipe wall is set as a solid wall boundary, the wall roughness of the wear-resistant seamless steel pipe is 1.6 μm, considering the laminar flow state, the influence of the pipe wall roughness when calculating is 0. The outside of the pipe is set to standard atmospheric pressure.

Results and discussion

Effect of material concentration and flow rate on resistance along the way

As shown in fig. 2, the resistance along the course increases regularly with the increase of concentration, and the goodness-of-fit degree is 98.81%. When the concentration is less than 76%, the increase in resistance along the course is slower, and when the concentration is greater than 76%, the increase in resistance along the course accelerates. The increase of concentration of 74-76% is nine times the increment of 72-74%. The concentration is 76-78% increment, which is 35 times the increment at 72-74%. This is due to the increase in the concen-

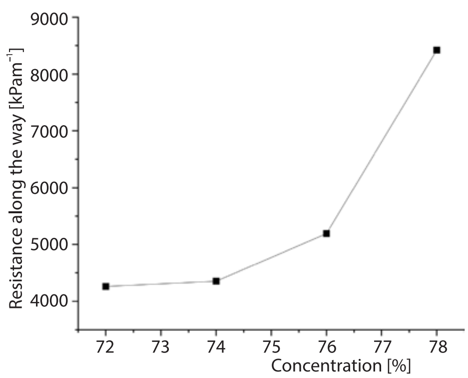

Figure 2. Effect of concentration on resistance along the way

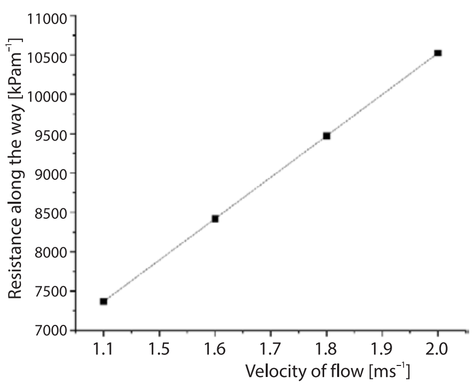

Figure 3. Effect of flow rate on resistance along the way

tration of the material, resulting in an increase in plastic viscosity, and the viscosity between the filling materials and the friction between the material and the pipe wall are positively correlated with the plastic viscosity. The increase in resistance along the way will cause the pumping of the same material on site requiring greater pumping pressure or thicker pipes, which is not conducive to economy, so it is necessary to control the concentration of filling material in the field within 76%.

It can be seen from fig. 3 that the resistance along the way increases with the increase of flow velocity, which is linearly distributed, and the curve fitting formula is $y = 1052.5x + 6314.4$. The larger the flow rate, the greater the work of the filling material to overcome the frictional resistance of the pipe wall, that is, the greater the resistance along the way. For on-site application, the flow rate should be as small as possible under the premise of ensuring the transportation capacity of multi-source coal-based solid waste filling materials.

Influence of pipe-line parameters on resistance along the way

It can be seen from fig. 4 that with the increase of the inner diameter of the pipe-line, the resistance along the way decreases in a polynomial law, the curve fitting formula is, the goodness-of-fit degree is 99.41%, when the inner diameter of the pipe-line is greater than 150 mm, the increase rate of resistance along the way begins to slow down, because the increase of the inner diameter of the pipe makes the filling material in the unit volume to overcome the frictional resistance work is relatively reduced. While ensuring the conveying efficiency, the smaller the inner diameter of the pipe-line, the smaller the hole that needs to be drilled on site, and it is recommended that the on-site pumping pipe-line be between 150-200 mm.

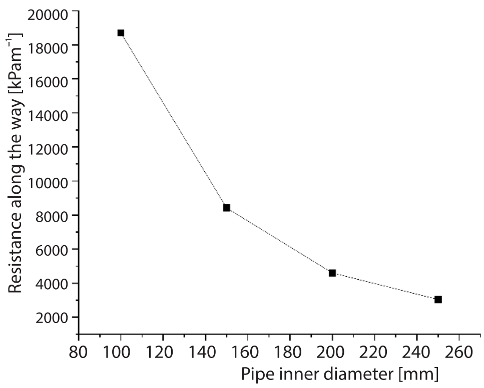

Figure 4. Influence of pipe inner diameter on resistance along the course

Conclusion

Under the premise that the fly ash content is 20-60% of the mass of gangue, the amount of remaining solid waste is 0-40% of the mass of gangue, the mass concentration is 72-80%, and the particle size of gangue is 1 mm, 3 mm, 5 mm, 8 mm, and 10mm, respectively, the main and secondary orders of influence on the slump of the filling material are: gasification slag > concentration > particle size > desulfurization gypsum > furnace bottom slag > fly ash. The main order of influence on water secretion rate is: particle size> gasification slag > concentration > furnace bottom slag > fly ash > desulfurization gypsum. The resistance along the course increases with the increase of concentration, the concentration of the material increases, resulting in an increase in plastic viscosity, the viscosity between the filling materials and the friction between the material and the pipe wall are positively correlated with the plastic viscosity, from economic considerations, the concentration of filling materials on site should be controlled within 76%. The resistance along the course increases linearly with the increase of flow rate, the larger the flow rate, the greater the work that the filling material needs to overcome the frictional resistance of the pipe wall, and the flow rate should be as small as possible when applied on site. With the increase of the inner diameter of the pipe-line, the polynomial law decreases, and the increase of the inner diameter of the pipe-line makes the work of the filling material in the unit volume to overcome the frictional resistance relatively decrease. While ensuring the conveying efficiency, the smaller the inner diameter of the pipe-line, the smaller the hole that needs to be drilled on site, and it is recommended that the on-site pumping pipe-line be between 150-200 mm.

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