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Research on the Resistance Characteristics of Pipeline Transportation for Shield Muck Paste

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Abstract. Earth pressure balance shield is widely used in urban tunnel construction due to its high excavation efficiency and strong geological applicability. For the traditional earth pressure balance shield the shield muck discharge method involves belt conveyor, battery truck and gantry crane, which can result in mud and water splashing and cause a harsh working environment. The power consumption of the dilute phase pipeline transportation is huge, and the post-processing is cumbersome. The paste like pipeline transportation of shield muck can achieve the full process and enclosed transportation of shield muck, and it can simplify the post-processing program. In this paper the pipe transport resistance characteristics of shield muck paste was explored using multifunctional paste ring pipe pumping experimental device by improving shield muck and producing muck paste. Experimental study shows that the modified shield muck sample with a slump of 19 cm～25.2 cm could be pumped by pipeline, and the larger the slump the smaller the pipe transport resistance; when paste flow in the pipes of the same size at a certain flowrate, the pressure loss of the horizontal pipeline is the largest. After adding THS-266 foam agent, the pressure loss of the horizontal section of the steel pipe is reduced significantly, and the yield stress is reduced by 20.9%, and the plastic viscosity is decreased by 38.4% for the paste transportation. Adding sodium hexametaphosphate and methyl acrylate can significantly reduce the yield stress of the paste. The research results provide a reference for the development of shield muck paste pipe conveying technology.

Keywords: Shield muck; Paste; Muck improvement; Pipeline resistance; Rheological properties.

1. Introduction

With the rapid progress of the economy and technology, tunnel construction projects, such as urban subways, have witnessed significant development both domestically and internationally [1]. As subway and other urban tunnel construction in China enter their peak period, the earth pressure balance shield has emerged as the primary method due to its high digging speed, safety, and effectiveness [2]. However, the traditional earth pressure balance shield typically relies on the shield muck discharge method involving a belt conveyor, battery truck and gantry crane, which can result in mud and water splashing during work. And this approach often faces challenges such as difficulty in making small radius turns and a poor working environment [3]. Dilute phase pipeline transportation of residue soil has a large flow rate, but consumes a significant amount of energy and requires cumbersome subsequent dewatering treatment [4]. During the shield construction process, the transport system of shield muck and engineering materials has increasingly become a key factor that restricts the shield advance rate. Therefore, there is an urgent need for in-depth research on new types of fully closed shield muck pipeline transportation technology that can address these issues.

In recent years, domestic scholars have conducted extensive research on slurry material pipeline conveying technology, involving mine tailings pipeline conveying and shield muck pipeline

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conveying, which has laid a solid foundation for the practicalization of slurry pipeline conveying technology in China. Hou Yongqiang et al [5] explored the rheological characteristics of tailing paste under different concentrations and the calculation model of pipe transport resistance through experimental research and theoretical analysis, and concluded that when the slurry concentration is lower than 70%, the tailing paste has considerable mobility, and the rheological parameters have a certain correlation with the slump. Xiong Youwei et al [6] carried out full-size annular pipe tests on ultrafine whole tailing sand filling materials for a large iron ore mine to obtain the characteristic parameters of frictional resistance for tailing paste transportation at high flow rates. Peng Zhengyang et al [3] 2020 proposed a pumping slag discharge system, which realizes the closed pipeline transportation of slag and reduces the impact of slag on the environment in the tunnel by setting up the transportation pipeline connected with the slag transfer pump, and at the same time applies the hose connection between the hard pipes, so that the pumping slag discharge system can make the turn with the trailer inside the tunnel, which enhances the adaptability of shield slag transportation system. Xiong Dongdong et al [7] designed a slag pumping system for the soil pressure balance shield machine start-up phase for the split start-up phase of the shield machine in MRT Line 2 of the Kuala Lumpur Metro, in order to improve the pumpability of the slag, the amount of water is added more, and a diaphragm pump is applied to drain the water in the slag pit to the wastewater treatment system. Boolekspoor Tunnel in the Netherlands and Sokatop project in Paris [8, 9], all of which applied slurry pumping technology, have high water content in the slurry, and all of them need post-treatment. Yang Zihan et al [10] proposed a shield slurry paste fully closed pipeline pumping system, which is characterized by high conveying efficiency and simple post-treatment.

At present, the research on paste production of shield muck and its resistance characteristics of pipeline transportation is not deep enough, which can not fully support the industrial application of shield muck paste transportation technology. In this paper, using the independently built experimental device for shield muck paste pipe transport by pumping, the muck paste conveying experiments through circulating pipes are carried out, which provides reference for the engineering application of shield muck paste pipe transport technology.

2. Experimental Unit

The shield muck paste pumping pipeline transportation experiments were conducted using the multifunctional circulating pipe experimental device, as illustrated in Fig. 1. The experimental device comprises a sieve machine, wet material crusher, mixing blender, S-valve hydraulic reciprocating pumps, circulating pipeline, flowrate measurement box, and pressure gauges. The model of wet material crusher is SCF600*400, and the mixing blender has a capacity of 0.5 m^3, and the model of S-valve hydraulic reciprocating pump is HBMD60/13-110SF, with a maximum flow rate of 60 m^3/h and maximum discharging pressure of 13 MPa. The circulation line includes steel pipes and hoses, using DN80 pipes, and the total length of the circulation line is about 70 m. The flowrate measurement box is square-shaped, with an internal bottom surface of 0.992 m long and 0.992 m wide. Other measuring equipment also includes a slump cylinder, electronic balance, drying box, measuring cylinder, and so on. The measuring section of the circulating pipe includes a horizontal section, a vertical section, an inclined section, an elbow and flexible tube section. The measuring section of the pipe is equipped with pressure transmitters to measure the pressure difference. The flow rate was measured by the timing method and the moisture content was measured by the drying method.

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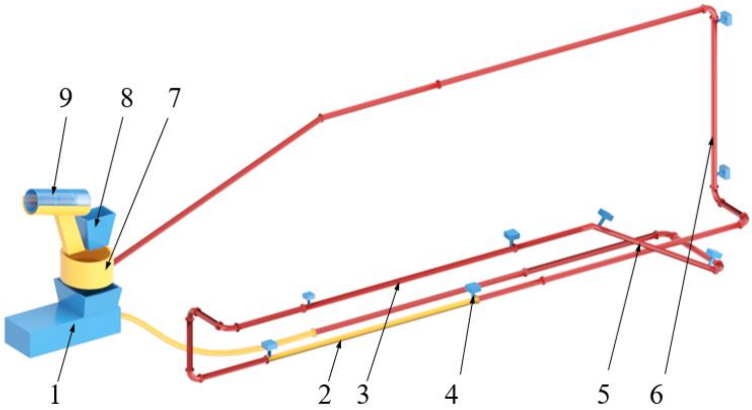

1- S-valve reciprocating pumps；2- flexible tube；3- horizontal steel pipe；4- pressure transmitter；5- Inclined pipe section；6- vertical section；7- mixing blender；8- crushing machine；9- sieving machine

Fig. 1 Multifunctional circulating pipe experimental device

3. Experimental Process

In the circulating pipeline transportation experiment, the original shield muck is from Changsha Metro Line 1. The shield muck was separated to large pieces of slag and small size muck by the sieve machine. The large pieces of slag was conveyed into the wet material crusher for crushing. Then the crushed muck entered into the blender, and small size muck directly into the blender. Appropriate amount of water was added to the blender for full mixing. When mixing is completed, the shield muck paste sample was obtained. The paste from the blender is put into the feed hopper of the S-valve hydraulic reciprocating pump, which is pressurized by the pump to convey the paste through the circulating pipe (Fig. 2). The pressure sensor in the measuring section displays the pressure value at the measuring point (Fig. 3).


Fig. 2 Circulating pipeline transportation of paste

Fig. 3 Pressure transmitter

By controlling different water contents and configuring six groups of basic residue pastes with different slumps ranging from 19 cm to 25 cm, the feasibility of residue paste piping was explored. And for the muck paste with a certain slump, the resistance losses under different flow rates were measured to analyze the rheological parameters of the paste. Also for a kind of muck paste with a certain slump, foam agent or dispersant was added to further improve the paste, and the resistance characteristics of the circulating pipe transport and the rheological parameters of the improved paste were studied.

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The pressure in the pipe was measured by a pressure gauge and the flow rate of the paste in the pipe was obtained by the time-volume method. Samples were taken after the completion of each set of annular pipe experiments to measure the slump, density and moisture content of the paste.

4. Feasibility of Pipeline Transportation

Strongly weathered slate muck and slightly weathered slate muck are mixed according to 1:1 to form mixed shield muck, and water was added to produce 6 groups of paste with different slumps. Then pipeline transportation experiments were made, and the flow rate of the paste and the pressure differential of the horizontal measuring section were measured. The experimental data of the mixed shield muck paste was obtained as shown in Table 1.

Table 1. Experimental results of the mixed shield muck paste

Paste Number	slump (cm)	Dry basis moisture content (%)	Density (g/cm^3)	flow rate (m^3/h)	flow velocity (m/s)	pressure differential of horizontal measuring section (Pa/m)
1	19	29.45	1.994	30.69	1.70	54000
2	19.3	29.0	1.960	27.54	1.52	56000
3	21.1	32.83	1.932	30.00	1.66	47000
4	22.4	32.91	1.900	30.98	1.71	38000
5	24.7	33.50	1.875	28.54	1.58	33000
6	25.2	38.46	1.798	30.91	1.71	21000

The loss of resistance along the way was 56,000 Pa/m to 21,000 Pa/m for the mixed shield muck paste from strongly weathered slate and slightly weathered slate, with slumps ranging from 19 cm to 25.2 cm. With same slump value and same flow rate, the pipeline transportation resistance characteristics of the two types of pastes are very close. So it can be seen that the pipe transport loss for the paste delivery mainly depends on the slump value. When paste slump value is small, pipeline resistance loss is large, which is not conducive to pipeline transportation. If paste slump value is greater than 25 cm, the water content is large, and the material is relatively dilute and has low viscosity; but subsequent dewatering is required, and the stone is prone to sinking during conveying to produce pipe blockage. In summary, it is feasible to analyze the resistance characteristics of pipeline transportation for paste mainly based on slump in subsequent engineering design.

5. Pipeline Resistance Characterisation

Strongly weathered slate muck and super clay were configured into a muck mixture according to 2:1 and water was added to make a basic shield muck paste with a slump of 22.5 cm and total volume of about 0.8 m3. Then paste was conditioned by adding a foam agent. Firstly the foam agent THS-266 was mixed with water to make a foaming solution with a mass concentration of 3%, and the foaming ratio can be regarded as 7. And the ratio of foam injected to the paste is 20%, which is the ratio of the volume of foam to that of the paste. The foaming solution was fully foamed, then injected the foam into the paste, and thoroughly stirred and mixed. Pipeline transportation experiments were also carried out using the conditioned paste in the circulating pipeline. Resistance characteristics of the circulating pipeline transportation were measured for both the basic paste and the foam conditioned paste, and experimental results are shown as detailed in Table 2.

From Table 2, it is evident that for a given flow rate in the same pipeline, the horizontal pipeline arrangement incurs the highest pressure loss. As the pipeline inclination angle increases, the pressure loss gradually decreases, with the vertical pipeline experiencing the least pressure loss during conveyance (excluding the paste's static pressure). This phenomenon arises because in a

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horizontal pipe, the paste is influenced by gravity and pressure, resulting in maximum positive pressure between the paste and the pipe. This leads to greater pipe friction and subsequently higher pressure loss. As the pipeline incline angle increases, the effect of gravity on the positive pressure within the pipeline diminishes, and the pipeline friction reduce, which reduces the pipeline pressure loss. At equivalent flow rates, the pressure loss between a hose and a steel pipe is relatively similar. Prior to the addition of the foam agent, the hose exhibits slightly lower pressure loss compared to the steel pipe. However, after introducing the foam agent, the pressure loss in the hose slightly exceeds that of the steel pipe.

It can also be seen that with the addition of a foam agent, the pressure loss is reduced. For instance, at a flow rate of 27.94 m3/h, the pressure loss in a 10 m horizontal steel pipe decreases by 27.5% after adding the foam agent, while the pressure loss in a 12 m horizontal hose reduces by 11.4%. The utilization of the foam agent THS-266 can improve the pipeline transportation properties with a clear efficacy in reducing pipeline transportation resistance.

Table 2. Resistance characteristics for muck Paste unconditioned and conditioned

paste number	foam injection ratio (%)	slump (cm)	density (g/cm^3)	dry basis moisture content (%)	flow rate (m^3/h)	flow velocity (m/s)	inclined steel pipe pressure loss (Pa/m)	horizontal steel pipe pressure loss (Pa/m)	horizontal hose pressure loss (Pa/m)	elbow loss (MPa)	vertical steel pipe pressure loss (Pa/m)
1	0	22.5	1.836	38.1	14.56	0.80	28154	34000	31667	0.04	26447
2					20.5	1.13	29693	36000	35000	0.05	28670
3					27.94	1.55	34308	40000	36667	0.05	33114
4	20	22.5	1.830	36.4	16.18	0.89	25093	26000	27500	0.04	6515
5					27.94	1.55	28170	29000	32500	0.04	10959
6					29.59	1.64	29708	30000	33333	0.05	13182

6. Rheological Characterization of Pastes

6.1 Rheological Modelling of Pastes

Shield muck paste has high concentration, good homogeneity, high yield stress and plastic viscosity, and is a non-Newtonian fluid approximated as a Bingham fluid [11, 12]:

$$\tau_w = \frac{4}{3}\tau_0 + \mu \cdot \left(\frac{8V}{D}\right) \tag{1}$$

Where τ_w is the shear stress at the pipe wall, Pa; τ_0 is the yield stress, Pa; μ is the plastic viscosity, Pa·s; D is the inner diameter of the pipe, m; V is the pipe flow rate, m/s; ΔP is the differential pressure between two gauges, Pa; *L* is the distance between the two pressure gauges, m.

According to force equilibrium, the flow resistance of paste through unit length of pipe is equal to the friction between the paste and the wall per corresponding unit area of the pipe, so the wall shear stress of the horizontal straight pipe section can be expressed as [13]:

$$\tau_w = \frac{D}{4} \cdot \frac{\Delta P}{L} \tag{2}$$

By combining formula (1) and formula (2), we can obtain：

$$i = \frac{16\tau_0}{3D} + \frac{32V}{D^2} \cdot \mu \tag{3}$$

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The wall shear stress of a Bingham fluid exhibits a linear relationship with the flow velocity, the yield stress and plastic viscosity of the paste can be obtained by calculating the longitudinal coordinate pipe wall shear stress τ_w and $8V/D$ through Eq. (1) and Eq. (2), and linear fitting based on the experimental data. Utilizing Eq. (3), pipe resistance at various flow velocities can be determined through circulating pipeline experiments, and yield stress and plastic viscosity of the paste can be obtained via linear regression. Consequently, the actual rheological parameters of the paste can be derived from circulating pipeline transportation test with a single pipe diameter. In order to reduce the scale of the experiment, the rheological parameters of the paste can be obtained by the small diameter circulating pipeline, and then the pipeline transportation resistance in large diameter pipe can be predicted by Equation (3).

6.2 Rheological Characterization

6.2.1 Foam Agent Improvement

For the basic paste the foamer was added, and ring pipe experiments were performed with different flow rates. By linear fitting, the rheological parameters of can be obtained for the two kinds of muck pastes, as shown in Table 3. As can be seen from Table 3, the yield stress and plastic viscosity of the paste transported in the steel pipe were significantly reduced after the addition of the foamer, with the yield stress reduced by 20.9% and the plastic viscosity reduced by 38.4%.

Table 3. Yield stress and plastic viscosity of two kinds of pastes

Paste condition	pipe	slump (cm)	yield stress (Pa)	plastic viscosity (Pa·s)
Basic paste	steel pipe	22.5	409.62	1.6136
Add Foam	steel pipe	22.5	324.04	0.9938

6.2.2 Dispersant Modification

In another case dispersants were added to the basic paste, and the dispersant is composed of sodium hexametaphosphate and methyl acrylate in a 3:2 ratio. The dosage of dispersant in 1 m^3 of basic muck paste is about 3.26 kg, then a paste with a slump of 22.6 cm was obtained. The flow rates were 16.09, 19.13, 24.36, and 28.84 m^3/h respectively for the ring pipe test. Through data calculation and linear fitting, the yield stress and plastic viscosity of the pipeline flow of the paste with added dispersant can be obtained. And the yield stress is 90.42 Pa, and the plastic viscosity is 1.63 Pa·s.

Comparing with the previous basic paste of slump of 22.5, it can be found that in the case of the same slump, the yield stress of the muck paste improved by adding dispersant is greatly reduced, and the plastic viscosity does not change much. The dispersant added consists of sodium hexametaphosphate and methyl acrylate, and methyl acrylate belongs to the polymer copolymer, so it is not easy to reduce the viscosity of the material. But from the formula (3) it can be seen that the yield stress accounted for a large proportion in pipe resistance, and the influence of plastic viscosity is relatively small. Overall, the improvement effect of adding dispersants is very significant.

7. Conclusions

Shield muck paste belongs to Bingham fluid, and pastes with slump of 19 cm～25.2 cm can be pumped through pipeline. And the larger the slump the smaller the pipe transmission resistance. For a certain flow rate of paste in the same sized pipe, the pressure loss in the horizontal pipeline is the largest, and the pressure loss of the pipeline decreases with the pipeline tilt angle increasing. After the basic type of paste was added THS-266 foam, the pressure loss in the horizontal steel pipe was reduced significantly, and the yield stress is reduced by 20.9%, and the plastic viscosity of paste transportation is reduced by 38.4%. The yield stress of the paste can be significantly reduced by adding sodium hexametaphosphate and methyl acrylate.

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