The Rheological Property Study on the Slurry of Unclassified Tailings Cemented for an Iron Mine

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Abstract. There is a large iron mine deposit in Anhui province, the mining and dressing ability was designed to 4.5 million t/a, the main mining method is stage open stoping with subsequent filling and the filling ability is 100m³/h. The experiment process of rheological property for the slurry of unclassified tailings cemented will be shown in this paper. By the experiments of diffusion degree and viscosity test for slurry with different concentration and sand-cement ratio were carried on, the relation between rheological property of the slurry and ratio parameters can be got. The experimental results effectively evaluate the rheological properties of the filling slurry; the ratio parameters of filling material which were accordant with the requirements of the mine filling process about the filling slurry pipeline can be provided.

1. Introduction
There is a large iron mine deposit in Anhui province, the mining and dressing ability was designed to 4.5 million t/a, the main mining method is stage open stoping with subsequent filling. The filling ability is 100m³/h. The backfilling of iron ore with the characters of large quantity, high availability, the cheap price and low processing cost etc., it is precious secondary resources and should be a good development and utilization [1]. If the backfilling materials are used for filling goaf, not only the stockpiling tailings can be reduced, the cost of the building dam and flood control engineering can be saved, and pollution to the environment will also be improved and certain economic, social and environmental benefits will be achieved.

In the actual unclassified backfilling mine filling, the way to transfer slurry to the stope is usually adopting pipeline transmission. The pipeline transmission capacity of the slurry, pipeline resistance, as well as the safety and reliability of the transmission process depend on the concentration of the slurry, contrast and the properties of the cementitious materials. The study of rheological properties of unclassified backfilling slurry is the basis of optimization design of filling system and high concentrations of pipeline drag reduction of gravity transportation to be realized [2]. The research through the test to analyze the rheological property of unclassified backfilling cement slurry, the influence factors of rheological properties for filling slurry could be revealed, and the theoretical basis for the filling process could be provided.

2. Particle size analysis of unclassified tailings
The particle size compositions of backfilling had a great influence on cemented filling with unclassified tailings, the main influence factor is the content of fine particles. The appropriate content
of fine particle can help slurry transport. If there is too much fine particle content not only can impede the dehydration of filling body, but also adverse to the strength of filling body\cite{3, 4}.

The test for granularity of unclassified tailings by using malvern laser particle analyzer, the test results are shown in Table 1 and particle size distribution is shown in Figure 1.

| Particle size(μm) | Sift cumulative(%) | Particle size(μm) | Sift cumulative(%) | Particle size(μm) | Sift cumulative(%) | Particle size(μm) | Sift cumulative(%) |
|------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|
| 6                | 0.02               | 147               | 30.71              | 600               | 90.38              | 1300              | 99.36              |
| 10               | 0.28               | 150               | 31.55              | 700               | 92.31              | 1500              | 99.82              |
| 15               | 0.64               | 160               | 34.30              | 750               | 93.82              | 1600              | 99.97              |
| 20               | 0.98               | 200               | 44.38              | 800               | 95.05              | 1700              | 99.93              |
| 25               | 1.32               | 300               | 63.75              | 850               | 96.03              | 1800              | 99.98              |
| 30               | 1.64               | 400               | 76.62              | 900               | 96.82              | 1900              | 99.99              |
| 74               | 9.30               | 450               | 81.27              | 1000              | 97.45              | 2000              | 100                |
| 83               | 11.86              | 500               | 85.02              | 1100              | 98.38              |                   |                    |
| 100              | 16.83              | 550               | 88.03              | 1200              | 98.93              |                   |                    |

Figure 1. Particle size distribution of unclassified tailings

According to the grade of tailings, the uniformity can be characterized by non-uniformity coefficient $\alpha$, the calculation formula is that:

$$\alpha = \frac{d_{60}}{d_{10}}$$

In the formula 1, $d_{10}$ is the pore diameter 10% of total content who can pass through the sieve, the unit is μm; $d_{60}$ is the pore diameter that 60% of total content who can pass through the sieve, the unit is μm\cite{5, 4}. As the result of test, $d_{10}$ is 76.226μm, $d_{60}$ is 280.509μm, so the non-uniform coefficient of particle size composition $\alpha$ is 3.86.

As the analysis of result, fine particles contains of unclassified tailings is less, it belongs to the type of the relative lack of fine particles; the natural grading of tailings is discontinuous gradation.

Based on the actual experience of mine filling, when the content of -25μm particles is more than 25% in solid filling material, the filling material just may become the filling slurry who had better stability, and has a certain transmission. According to the results of grain size analysis, the content of -25μm particles in the unclassified backfilling is 1.31%, the content of -25μm particles in the cement is more than 80%. The high concentration self-conveying of the whole tailings slurry can be realized by reasonable proportioning\cite{5}.
3. The diffusion degree test of slurries

Diffusion degree is derived from the concept of concrete and is used to reflect the flow characteristics of slurry. If the diffusion degree is too small, the slurry will be inhaled difficult and had big frictional resistance in transport, and the high pumping pressure of pumping will be required. In the situation of not properly solving, there will be a tube jam phenomenon occur. If the diffusion is too high, the slurry is likely to occured segregation deposition phenomenon, and the slurry is not suitable for conveying neither [6].

The tests of diffusion were carried on to unclassified backfilling slurry with different concentrations and different sand-cement ratio; the results are shown in Table 2.

Table 2. Test results of diffusion (cm)

| Slurry type | Slurry concentration (%) | Sand-cement ratio |
|-------------|--------------------------|------------------|
|             |                          | 4    | 6      | 8   | 10   | 12   |
| Slurry A    | 66                       | 19.21| 18.76  | 18.23| 15.43| 14.29|
|             | 68                       | 18.41| 18.14  | 18.22| 14.11| 13.52|
|             | 70                       | 17.74| 17.66  | 17.11| 14.47| 12.54|
|             | 72                       | 17.52| 16.11  | 13.86| 12.53| 10.16|
|             | 74                       | 17.03| 15.71  | 14.62| 11.71|  8.78|

(a) Pouring experiment slurry                          (b) Slurry diffusion result form

Figure 2. Slurry diffusion test

The test data analysis to the rheological properties of backfilling slurry was carried out and the results are shown as follow:

Figure 3. Relationship of diffusion degree between sand-cement ratio and concentration of slurry
(1) With the increase of filling slurry concentration, the dispersion of filling slurry decreases gradually. The experimental results show that the diffusion effect and slurry fluidity of filling cementing slurry are better as a whole.

(2) Under the same sand-cement ratio, the slurry diffusivity gradually decreases with the increase of the concentration, which is the main factor affecting the slurry fluidity.

(3) At the same slurry concentration, with the increase of sand-cement ratio, the diffusion of slurry decreases gradually, which is due to the cementation and lubrication of cement as fine-grained material in filling slurry, and bibulous rate of coarse particle in backfilling is small, it consumes less water, with the increase of the content of coarse particle materials is equivalent to increase the concentration of the slurry, which is the secondary affecting factor of the slurry liquidity.

(4) The facts had proved that when the dispersity of uniform granular mortar is greater than 16 cm, it can be transported by pipeline. When the sand-cement ratio is 4 and 6, the diffusivity of filling slurry is greater than 16 cm from 66% to 72%, and the fluidity of slurry is better.

(5) When the mortar-cement ratio of filling slurry is more than 10, the decrease range of diffusivity increases, and the diffusivity of slurry with different concentration is less than 16 cm, and the fluidity of slurry becomes worse.

4. The test of rheological characteristic parameters

4.1 The fluid models

Fluid will be flow deformation when it suffers external shear force, the resistance to deformation will be accordingly occurred in its internal, and as the form of internal friction are shown. It is a kind of inherent physical properties of fluid, we can call it viscosity. According to the different rheological properties, fluid can be divided into Newtonian fluid and non-Newtonian fluid [7~9].

4.1.1 Newtonian fluid

The shear stress and shear rate gradient of Newtonian fluid are linear relationship, with the formula is expressed as:

$$\tau = \mu \frac{d\omega}{dy}$$

(2)

In the formula 2, \(\tau\) is shearing strength, the unit is Pa; \(d\omega/dy\) is shear deformation rate, the unit is S\(^{-1}\); \(\mu\) is kinetic viscosity coefficient, the unit is Pa\(\cdot\)s. This formula is also known as Newton's shearing stress formula, \(\mu\) is the proportionality coefficient which represents the fluid viscosity and reflects the size of the internal friction about fluid. If the type of function is non-linear, then the fluid is called the non-Newtonian fluid.

4.1.2 Non-Newtonian fluid

About the type of non-Newtonian fluid, a few rheological equation models for describing the internal friction characteristics have been proposed. For example, there is Ostwald-dewaele power-law model, Ellis model, Carreau model, Bingham model and so on. The Ostwald-dewaele power-law model is most commonly used. Power-law model defines that the viscosity function of non-Newtonian fluid is an exponential function of absolute value for velocity gradient or shear rate. The formula is:

$$\tau = K \left(\frac{d\omega}{dy}\right)^n$$

(3)

In the formula 3, \(\tau\) is shearing strength, the unit is Pa; \(d\omega/dy\) is shear deformation rate, the unit is S\(^{-1}\); \(K\) is viscosity coefficient, the unit is Pa\(\cdot\)s\(^n\), \(n\) is a flow characteristic index, it is dimensionless and indicates the deviates degree from Newtonian fluid. When \(n\) is less than 1, it is the pseudoplastic fluid; when \(n\) is equal to 1, it is the Newtonian fluid; when \(n\) is more than 1, it is the dilatant fluid. The most common fluid is pseudoplastic fluid.
Plastic fluid is also known as Bingham fluid, the character is that when the shear stress is greater than the yield stress, slurry flows occur and has the nature of the plastic fluid. When the shear stress is smaller than the yield stress, the slurry can't flow and shown as solid, the formula is:

\[ \tau = \tau_0 + \eta_p \frac{d\omega}{dy} \]  

(4)

In the formula 4, \( \tau \) is shearing strength, the unit is Pa; \( \tau_0 \) is yield stress, the unit is Pa; \( \eta_p \) is plastic viscosity coefficient, the unit is Pa•s, \( \frac{d\omega}{dy} \) is shear deformation rate, the unit is S\(^{-1}\).

4.1.3 Apparent viscosity

When the total solid particles of fluid are very fine and high density, the viscosity of slurry is different from conventional liquid viscosity \(^{[10]}\). In order to distinguish from defined of Newton fluid viscosity, for non-Newtonian fluid of slurry, the apparent viscosity \( \mu_a \) can be used to assess its flow characteristics. The apparent viscosity can be defined as the equivalent Newtonian viscosity of the non-Newtonian fluid under the constant shear rate. The expression formula is: under a constant velocity gradient, divide shear stress to shear rate, as:

\[ \mu_a = \frac{\tau}{\gamma} \]  

(5)

In the formula 5, \( \mu_a \) is apparent viscosity of slurry, the unit is Pa•s; \( \tau \) is shearing strength, the unit is Pa; \( \gamma \) is shear deformation rate, the unit is S\(^{-1}\).

4.2 The results and analysis of rheological test

The test by using new type rheometer made by USA Brookfield company to determine the rheological properties of slurry under different conditions, the test temperature is room temperature (28℃), the change range of rotate speed is from 10 to 30 r/min. Rheological properties tests were carried out in different contrast ratio and different concentration of unclassified backfilling cement slurry\(^{[11]}\). The results are shown in table3, and fitting curve of relationship between rheological parameter and shear rate are drawn in Figure 4. The fluid type can be confirmed by numerical fitting calculation and analysis of different concentration and sand-cement ratio under different shear rate.

| Concentration (%) | Sand-cement ratio | 10 | 20 | 30 |
|-------------------|-------------------|----|----|----|
|                   | Apparent viscosity| Fluid type | Apparent viscosity | Fluid type | Apparent viscosity | Fluid type |
| 68                | 4                 | 5.69 | Newtonian | 1.91 | Bingham | 0.83 | Pseudoplastic |
|                   | 6                 | 11.68 | Newtonian | 3.03 | Pseudoplastic | 1.9 | Bingham |
|                   | 8                 | 14.01 | Newtonian | 4.1 | Pseudoplastic | 2.69 | Pseudoplastic |
|                   | 10                | 14.59 | Newtonian | 6.09 | Pseudoplastic | 3.81 | Pseudoplastic |
|                   | 12                | 27.74 | Newtonian | 12.03 | Pseudoplastic | 7.61 | Pseudoplastic |
| 70                | 4                 | 5.49 | Pseudoplastic | 2.63 | Pseudoplastic | 1.41 | Bingham |
|                   | 6                 | 6.8 | Bingham | 3 | Pseudoplastic | 1.67 | Bingham |
|                   | 8                 | 8.46 | Pseudoplastic | 2.71 | Pseudoplastic | 1.7 | Pseudoplastic |
|                   | 10                | 15.7 | Pseudoplastic | 5.07 | Pseudoplastic | 3.12 | Pseudoplastic |
|                   | 12                | 16.19 | Pseudoplastic | 6.08 | Pseudoplastic | 4 | Pseudoplastic |
| 72                | 4                 | 6.03 | Pseudoplastic | 3 | Pseudoplastic | 1.61 | Pseudoplastic |
|                   | 6                 | 14.19 | Pseudoplastic | 5.14 | Pseudoplastic | 3.11 | Pseudoplastic |
Through the analysis of the experimental data, it is found that the apparent viscosity of slurry shows good regularity with the change of shear rate, slurry concentration and sand-cement ratio.

1) When the slurry concentration remains unchanged, the apparent viscosity increases as the ratio of sand to cement increases. When the sand-cement ratio is greater than 6, the increase of apparent viscosity becomes larger.

2) When the ratio of sand to cement is constant, the apparent viscosity increases with the increase of slurry concentration. This is because with the increase of slurry concentration, the free water in filling slurry decreases, and the friction force inside the slurry increases \[^{[12]}\]. When the slurry concentration is more than 70%, the friction resistance increases rapidly, resulting in a rapid increase in apparent viscosity.
When the sand-cement ratio and concentration are constant, the apparent viscosity of slurry decreases gradually with the increase of shear rate, the fluid properties of shear thinning are shown. This is because there is always a certain velocity gradient between the liquid layers when the polymer in the slurry flows. If the slender and long macromolecules pass through several liquid layers with different velocities at the same time, each part of the same macromolecule will advance all into the same flow velocity layer. The parallel distribution of liquid layers at different velocities leads to the orientation of macromolecules in the flow direction. This phenomenon is like a slender rope flowing along with the flow in a river. They always arrange along the flow direction naturally and longitudinally. The slurry increases with the increase of shear rate or shear stress in the flow process. The viscosity decreases due to the orientation of molecules, which is consistent with the results of the fluid model.

5. Conclusions
In this paper, the rheological properties of cemented mortar with full tailings from an iron mine are experimentally studied, and the following conclusions are drawn from the analysis of experimental data:

(1) The fine particles of unclassified tailings are less, the natural gradation belongs to relatively discontinuous gradation. Therefore, the content of fine particles in filling materials can be adjusted by different tailings-cement ratio.

(2) The good regularity is reflected between the dispersion of filling slurry and slurry mass fraction, cement content and tailings content. The diffusion effect and flowing effect of slurry are both good. Especially when the sand-cement ratio is less than 6, the concentration of filling slurry ranges from 66% to 72%, and the diffusion degree is greater than 16 cm.

(3) When the slurry concentration remains unchanged, the apparent viscosity increases as the sand-cement ratio increases, when the sand-cement ratio of slurry is constant, the apparent viscosity rises up with the increase of concentration; when the concentration and sand-cement ratio of slurry are constant, the apparent viscosity decrease gradually with the increase of shear rate, it shows the characteristics of the shear thinned fluid. It was consistent with the fitting results in the fluid flow model.

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